Materials Forming, Machining and Tribology

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Advanced Machining and Manufacturing Processes

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Preface

A design coming out of the mind of a designer sees light of the day, in the form of a tangible product, by a manufacturer. Manufacturing industries play a pivotal role in socio-economic development of a nation. The industries have to compete worldwide to manufacture the products that not only meet the intended functionality requirements but are also least detrimental to environment. As a result, industries keep on hunting for the new manufacturing processes that not only reduces time and effort but are at the same time eco-friendly. The growing environment of competitive pressure has lead to the evolution of advanced designing and manufacturing concepts. Further, the necessity to use newer materials for different applications and control of their dimensional accuracies has led to evolution of modern manufacturing methods or processes.

Main objective of this book is to introduce and explore the various techniques in advanced manufacturing technologies. It is also aimed to explore its efficacy and its application towards effective product development. The main emphasis, hence, is directed towards industrial engineering outlook. The target audience is academics students, researchers and industry practitioners, engineers, research scientists/ academicians working in this vast field.

This book is divided into three parts that provide coverage of the various advanced manufacturing processes that may be employed by manufacturing industries to improve their productivity with the sole motive of socio-economic development.

Part I deals with **Automated Conventional Machining Techniques**. The part contains four chapters. Chapter 1 describes the basic principles and functions of machine tools. It introduces the reader to various material removal techniques emphasizing on 'form and size'. It then moves towards the kinematics principles of machining operation including generation, copying and forming. The chapter ends with concept of surface texture.

Chapter 2 deals with different control mechanism of machine tools. After an introduction, it talks about the various levels of control and starts with zero level of control, then first level of control, then second level of control and so on. It finally directs the attention of the readers to fifth level of control, i.e. numerical control.

From here on, the chapter moves towards computer numerical control, explaining functions, controls, In-process compensation, diagnostics and advantages of CNC systems. The chapter further explores direct numerical control or DNC detailing components and functions of the same. The chapter concludes with discussion on adaptive control of machining systems.

Although Chap. 2 deals with numerical control, but Chap. 3 goes deeper into the concept and introduces with its basic components and program of instructions. It talks about controller unit, machine tool, NC procedure, process planning, part programming. It also discusses topic like Tape preparation, tape verification and production. The programming of an NC system cannot be performed without some basic knowledge, and hence, the chapter also highlights NC coordinate system, NC motion control systems involving point-to-point NC, straight-cut NC, contouring NC. Applications of NC systems, its advantages and disadvantages are the concluding part of the chapter.

Chapter 4, the last chapter of the part, provides the reader with some illustrations of part programming in CNC lathe, CNC milling and CNC electrical discharge machining (EDM) for different operations including a discussion on coordinate system, dimensioning basics. It also provides an insight on miscellaneous and preparatory functions, i.e. M-Codes and G-Codes for various operations.

Part II covers **Non Conventional Machining Techniques**. The part contains six chapters. Chapter 5 describes traditional (or conventional) machining techniques and introduces to the concept of non-traditional (or non-conventional) techniques. The chapter starts with the fundamental difference between conventional and non-conventional machining techniques and highlights the requirements of non-conventional machining techniques.

Non-conventional techniques are ones in which there is no physical contact between the tool and work-piece and hence requires different energy sources for such process. They are thermal, mechanical and chemical and electrochemical. Chapter 6 deals with mechanical machining processes. It includes detailed discussion on ultrasonic machining, water jet machining, abrasive jet machining, abrasive water jet machining, ice jet machining and magnetic abrasive finishing. For each of the technique, discussion includes working principle, material removal rate, applications, advantages and disadvantages.

Chapter 7 discusses chemical machining techniques including chemical milling, photochemical milling and electro-polishing. Alike to the earlier chapter, here also the processes are described in details including process, performance, applications, advantages and disadvantages.

Chapter 8 deals with electrochemical processes. The description includes electrochemical machining, electrochemical drilling, shaped tube electrolytic machining, electrostream (capillary) drilling, electrochemical jet drilling and electrochemical deburring. Following the trends of the earlier chapters, here also various processes are focused with working, tools, process parameters, output, applications, advantages and disadvantages.

In Chap. 9, thermal processes are discussed. It includes electro-discharge machining (EDM), electro-discharge drilling (EDD), electro-discharge milling, micro-EDM, laser beam machining, laser-based cross/hybrid/assisted machining, electron beam machining, plasma beam machining and Ion beam machining (IBM). The discussion on each of the processes is dedicated to working, tools, process parameters, output, applications, advantages and disadvantages.

Today is the era of hybridization. Hence, the last chapter of the part, i.e. Chap. 10, talks about processes which are a hybrid of the above techniques like hybrid electrochemical process, electrochemical honing, electrochemical superfinishing, electrochemical buffing, ultrasonic-assisted ECM and laser-assisted ECM. Each of them are explained lucidly including the working, process parameters, output characteristics, accuracy, applications, advantages and disadvantages.

The last part of the book Part III focuses on another budding concept **Virtual Manufacturing**, i.e. manufacturing on computers. Today in manufacturing world, words like Internet of Things (IoT), Big Data, Industry 4.0 (I40) wherein amalgamation of Internet and information and communication technologies (ICTs) with traditional manufacturing processes are being utilized. Virtual manufacturing is the stepping stone for the same. This part comprises of three chapters. Chapter 11 introduces the reader to the concept of virtual manufacturing, providing the taxonomy and virtual manufacturing and virtual machine tool. It emphasizes on virtual reality-based systems, associated mathematical modelling and hardware interaction.

In order to allow the readers to have a feel of the subject, Chap. 12 illustrates a case study of virtual manufacturing of a transmission element (Gear). A customer is allowed to input the various requirements in different rollouts created using a software (in present case on a 3D Max Studio Platform) and gets the virtual product. In the manufacturing sequel, customer visualizes transformation of a blank to a gear with formation of chips making it realistic. Various programs and the rollouts are shown for the convenience.

Chapter 13, the last chapter of the part and also the book, explores scope, socio-economic aspects and future trends of virtual manufacturing. It deals with design-centred, production-centred and control-centred virtual manufacturing. It discusses the economics and socio-economic aspects also. A review has been provided to explain the trends and exploitable results in machine tool, automotive and aerospace sectors. It ends with a note on future scope of virtual manufacturing.

First and foremost, we would like to thank God. In the process of putting this book together, it was realized how true this gift of writing is for anyone. You have given the power to believe in passion, hard work and pursue dreams. This could never have been done without the faith in You, the Almighty. We would like to thank all of our colleagues, friends in different parts of the world for sharing ideas in shaping our thoughts. We are grateful to all quality managers whose kind contribution helped in shaping this. Our efforts will come to a level of satisfaction if the professionals concerned with all the fields related to manufacturing processes will get benefitted. We owe a huge thanks to all of our technical reviewers, editorial advisory board members, book development editor and the team of publisher Springer International Publishing AG for their availability for work on this huge

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Throughout the process of writing this book, many individuals, from different walks of life, have taken time out to help us out. Last, but definitely not least, we would like to thank them all, our well-wishers, for providing us encouragement. We would have probably given up without their support.

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Part II Non Conventional Machining Techniques

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Part I
Automated Conventional Machining Techniques

Chapter 1
Machine Tools: Numerical Control Perspective

1.1 Introduction

Pieces of bone or hard rock with pure silica were the earlier forms of cutting tools used by the mankind. However, mankind searched for better tool materials with the deficiencies of these materials. With the search for better materials, the better cutting methods were also explored. This process of search and exploration of new materials and methods is continuous and is done primarily when the existing methods are not efficient.

Using the chopping action to divide a piece of material into two parts would have been the first cutting action. The use of tools with knife edged shape or the other thin wedge shaped tools would have made it possible to accomplish the chopping action. However, using these simplest tools it was difficult to achieve the final part with desired accuracy and precision. Therefore, it was needed to employ cutting action that would control the amount of material to be removed. One such cutting action is that of shaving. The control movement of the tool could remove thin sections of material from the selective areas of the workpiece producing parts of desired shape and size. It was possible to accurately control the depth of cut with the shaving action.

With the experience, it was established that the relative motion of the tool with respect to the workpiece was responsible for the accuracy of the workpiece produced by the cutting method. Therefore the requirement of machines was felt which could control the relative position of the tool with respect to the workpiece producing components of accurate shape and size. The first evidence of the development of the machines was reflected in the bow drill and lathe. The machines developed used copper or bronze as the material of construction for the cutting tools used.

It was in 1772, that the boring machine was developed by Wikinson for machining of relatively larger pieces of job. The boring machine developed by Wilkinson was used for making bores in the cylindrical workpiece to be used for the first steam engine. The material of construction for the cutting tool used was

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high-carbon steel. A screw cutting lathe was developed in the year 1792 by Maudsley. The machine developed had slide rest and was more efficient than the previously developed machines. There was development of large number of machines during the industrial revolution. There was new range of machining systems from the middle of the nineteenth century to the end of the century. The machines such as capstan lathe, turret lathes and other cam controlled machines were developed during the phase. The machines developed during this phase were capable of high rates of production which facilitated for mass production.

With the advancements the machines have been developed that produces parts with relatively lesser production time and cost. This has been made possible with the production of automated machining systems. Such machining systems have a wide range of control systems which are complex in nature. These systems may be mechanical, electrical, electro-mechanical or combination of these. One such machining system is the numerically controlled machine. The term numerical is justified in the sense that the information related to the feed rate and the number of tools is fed in form of numbers.

The advancements in the field of material have led to the development of materials that are able to withstand higher operating temperature and high stresses. The machining of such materials with enhanced with mechanical and physical properties is a challenging task. This has led to the development of machining techniques and the machine tools that are capable to machine materials with wide range of mechanical and physical properties. The development and progress has led to the development many new types of machining systems that are highly sophisticated and produces parts with higher precision and accuracy.

The present chapter is an introduction to machine tools with discussion on material removal techniques, size and form, principle of operation with focus on kinematic behavior and surface texture.

1.2 Material Removal Techniques

There are wide ranges of techniques for material removal which are accomplished using different machine tools. There are wide ranges of cutting tool materials which are used by the machine tools. The different material removal techniques involved are:

- Material removal using single-point cutting tool made of metal.
- Using multi-point cutting tool of metal for material removal.
- Abrasives as cutting tool.
- Ultra-sonic machining.
- Electro-chemical machining.
- Electrodischarge machining.
- Laser beam machining.
- Plasma machining.

The different machine tools have different applicability depending upon the material that can be machined. The efficiency of the different machine tools has been increased with the numerical control. However, for the functioning of certain machine tools special machining environment is required.

The machine using numerical control and the machine tools with different control systems do not differ in the actual cutting process given the fact that in both the cases same material removal technique is employed. This is because numerical control is just a technique of controlling the operation of the machine tool and is not a machine tool. The efficiency of the machining operation is improved by feeding the information related to cutting process to a control unit which can then control the relative movement between the tool and the workpiece. However, in some cases of machine tools, the numerical system can't be linked directly to the actual cutting process.

The tool or the workpiece is mounted on a table. The amount of table movement, the direction of movement and the rate at which the table should be moved is controlled precisely and accurately through the numerical control mechanism. The numerical control also controls the other features of a machine such as selection of the suitable cutting tool, turning on and off the flow of the cutting fluid and proper selection of the spindle speed. This aids in production of products with higher accuracy and precision.

The numerical control provides for a wide range of applications. These include controlling of plotters, oxyacetylene machines for flame cutting, turret presses, inspection equipment, measurement equipment and control of robots.

1.3 Form and Size

The repeatability and the constancy of the position and the movement of the workpiece relative to the tool is one of the major determinant factors for the similarity of the size of component produced. The minimum obtainable depth of cut decides on the accuracy and the level of precision with which the components are made. For instance, cylinders with diameters as close to as 0.01 mm will be obtained by maintaining the position of the tool within 0.005 mm relative to the axis of rotation of the workpiece. This would require repositioning the tool and therefore accuracy can be obtained with the numerical control.

Further, an inverse relation has been observed between the accuracy of the component and the time required to manually position the tool. More time will be required to manually position the tool to obtain a more accurate component. The numerical control mechanism has a greater influence on maintaining a consistent work/tool positional relation.

1.4 Kinematics Principles of Machining Operation

The relative movements between the tool and the workpiece determine the type of geometry produced on the workpiece. The three different kinematic principles used for the production of required geometry on a machine tool are: generation, copying and forming.

1.4.1 Generation

The relative movement of the tool with respect to the workpiece produces the desired shape on the workpiece. The generation principle encompasses to produce the parameters of the workpiece. The parameters are typically the solid of revolution and a straight line. These are the two main components and their combinations that make up the required shape on the component. It is usually recommended to use these shapes as it would be otherwise difficult to control the relative positional movement of the tool and the workpiece. However, any other shapes can be used with the usage of numerical control techniques.

For instance, the generation of a cylinder takes place through combination of circle and straight line. There are four different ways of using this combination to generate a cylinder. One such method involves the rotation of the tool and its axial movement. This method is typically used in the case of smaller tool relative to the workpiece. Similar technique is also adopted by drilling and vertical boring machines. The second method involves the rotation of the workpiece with its axial movement. The method is suitable in cases where the dimensions of workpiece are smaller than the tool. The example includes that of cylindrical grinding. Another method of generating cylinder involves rotational motion of the tool and the axial movement of the workpiece. This method could be used in cases where the rotation of workpiece is relatively difficult than that of the tool. Prominent example is that of bearing housings on a lathe headstock. The last of the technique involves rotation of the workpiece and axial motion of the tool such as that in the case of turning operation on a lathe machine.

In this simple example of generation of cylindrical form it is easy to control the motions of tool and the workpiece. The straight line motion can be controlled using the carriages which are guided by the sideways and the rotational movement being achieved using the rotational motion of the spindle in the bearings. The precision of rotation of the spindle ensures the accuracy of roundness and the accuracy with which the slideways are aligned with the spindle determines the parallelism of the cylinders.

Therefore it is quintessential to control and synchronize the position of the tool and the workpiece to obtain the desired form and shape. The synchronization can be easily achieved with the development of numerical controlled techniques which have made it easier to control the actual movement of the tool and the workpiece. It has become easier to design and fabricate components with complex shapes and forms.

1.4.2 Copying

The desired forms and shapes are repeatedly produced as a result of relative movement of the tool and the workpiece. The stylus or the tracer traces over a pattern and therefore forms the movements. The pattern is the shape desired on the work. Copying is used typically for the workpiece having complex profile. The profile changes in form or is non-circular in nature. The profile for cylinder with multi diameters or cavities and moulds in case of dies are some of the complex profile examples where copying can be used effectively. Numerical control technique can be used for such complex shaped profiles. The process of copying in combination with numerical control saves both the cost and the time. The shape of the profile produced will be dependent on the movements of the tool relative to workpiece and is controlled by the input information in numerical form to the control unit of the machine tool. The manufacturing companies can do away with the task of producing templates or patterns since the numerically control machines can produce the required templates more easily and economically in comparison to the traditional methods.

1.4.3 Forming

This principle produces the shape of the tool on the workpiece. For using the forming operation to produce components the machine tool needs to be rigid. The maximum form length is of the order of 50 mm. The time of production of a component is very less when produced using forming principle in comparison t the other principles. The movement of the tool to the form depth is the only movement required at the feed rate. However, the forming process is justified only for large scale production since the tool used id pretty expensive.

The forming operation with numerical controlled tools is rarely used. One of the typical forming operations with the combination of numerical technique is that of producing a slot with concave base using a ball-nosed end mill. It is easier to produce curves of various shapes and angles by using lathe machine employing a programmed single-point cutting tool than to grind a form tool for producing desired shape and profiles.

1.4.4 Surface Texture

The feed rate and the geometry of the tool are determining factor for the desired surface texture. The smooth surface can be obtained using grinding wheels or by using abrasives as multi-point cutting tools as in case of honing or laping. A single point cutting diamond tool can be used for obtaining a smooth surface finish on a surface made of copper or aluminum alloy.

1.5 Conclusion

The present chapter provides a overview of the material removal techniques, size and form, principle of operation with focus on kinematic behavior and surface texture. The importance of the numerical control technique has been discussed. The numerical control aids in production of components with high quality and with reduction in time and cost. It is easier to produce complex shapes on workpiece and provides a flexibility to produce components on large scale. The changes in engineering design can be easily adapted by the components manufactured with the aid of numerical control techniques. Thus numerical control techniques have revolutionized the machining sector.

Chapter 2
Machine Tool Controls

2.1 Introduction

The different controls for a machine tool are: powering on and off the machine tool, guiding the tool or the workpiece, controlling the tool or workpiece movement, rate of movement of the tool and the workpiece, selection of appropriate facilities required for production and so on. The machine tools can be controlled either manually or automatically. The clear distinction between successive levels of control is a tedious task since one level overlaps with the next successive level.

Increase in level is often designated whenever there are major changes in the operational characteristics of a machine tool. Hierarchy is thus established between different levels of machine control. The introduction of enhanced features that increases the capacity of the machine tool also can be considered as next hierarchical level of machine control.

The present chapter provides an overview of different levels of machine controls. A brief in the CNC and DNC systems has been provided with a discussion on working, functions and advantages over the conventional NC systems. The chapter also discusses on the adaptive control of the machining systems.

2.2 Levels of Control

2.2.1 Zero Level of Control

The machines in earlier years of development were controlled manually. Bow drill is one of the exclusive examples which was controlled manually and was used for over six thousand years for carrying out the different production activities. Different operations of the machine tools such as the powering of the machine for the removal of material, the positioning and the control of the tool and the workpiece

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were all manually controlled. The other example of manually controlled machine tool is that of treadle lathe. In both the cases of bow drill and treadle lathe the control of movements and the powering of the machines were done manually. Due to the absence of external source for controlling the movements and the power to the machine, these are regarded as zero level machines.

2.2.2 First Level of Control

The continuous research efforts to derive power from external source led to the development of water wheel and then the steam engine. With the continual advancements and development, electric motors came into existence as a source of power. The developed sources of power were then used to control and power on/off the different machine tools. Control was done using the mechanical components such as clutches and switches.

The application of on/off control mechanism to different machine tools was designated as first level of control. Examples of machines using the first level of control are lathe machines powered by wood turner and simple pedestal drill. The level of control doesn't change with the mechanism of changing speeds through the use of pulleys or gear trains.

2.2.3 Second Level of Control

A new level of control was developed with the development of Maudsley's screw cutting lathe. It was with the advent of Maudsley's lathe machine that synchronization of the tool and workpiece movements were done using the gear trains. The choice of speed is left to the discretion of the operator. Control of movement of tool and workpiece as well as the operator's role in speed selection defines the second level of control.

The screw in the Maudsley's lathe was known as the leadscrew. The machine was equipped with a slide rest. Workpiece was mounted on the main spindle which was driven through a set of gear trains. Slide rest was supported on the saddle and had the tool holder mounted on it. Saddle movement was controlled through a nut on the leadscrew. The two movements i.e., axial motion of the lead screw and rotational motion of the nut were synchronized. The machine was used for producing threads on screw.

The other example of second level control machines is that of horizontal and vertical milling machine. With the second level of control, production of components is economically feasible if the shape to be produced is simple, requires small changes in the tool/workpiece positional relationship and small scale production.

2.2.4 Third Level of Control

The third level of control includes machines that operate on a fixed cycle of movements. Example includes that of cam-controlled automatic machines. The shape on the cam lobes is reflected onto the workpiece surface. The machines with third level of control are only suitable for large scale production of components.

The machines wherein the sequences of operations are controlled using plug board, also falls into the third level of control category. The setting of stops and tools determines the size of workpiece produced on these machines. Milling or turning machines equipped with tracer control mechanism are another example of third level control machines.

With the third level of control the size of the workpiece produced is difficult to be analyzed until all the required operations on the workpiece are completed.

2.2.5 Fourth Level of Control

The transducers are used to monitor the actual size of the workpiece being produced and the machines with such capabilities falls into fourth level of control. The transducers aids in the production of parts with desired size. The size control is regarded as in-process control.

The in-process size control is economical when parts are produced within close dimensional tolerances. Specialized machines such as cylindrical and surface grinders, honing machines are some of the examples of machines with fourth level of control. The machines employ abrasive particles with self sharpening effect.

The size is controlled with measuring instruments which feeds the information to the power units. On reaching the desired work size, the feed movement of the tool is stopped automatically. The machines however control only one dimension of the workpiece at one setting of the machine.

2.2.6 Fifth Level of Control: Numerical Control

The fifth level control machines uses the program of instructions in the form of numerical values to control the machine tool. The information such as dimension of the workpiece, coolant, tools required, feed rate and spindle speed is fed to the control unit of the machine. Such machines are categorized into fifth level of control and numerical controlled machines are examples of this category of level of control.

2.3 Computer Numerical Control

When the basic and even in some machines all the features is controlled using program of instructions and stored in a computer, then the numerical control system is referred to as computer numerical control systems. The increasing market trend of reducing the size of machinery equipments has led to the selling of CNC systems equipped with microcomputer based controller unit. CNC systems are also equipped with minicomputers and thereby saving floor space.

The CNC machining systems looks very well similar in appearance to that of conventional numerical controlled systems. The program of instructions is input to the machine using the punched tape readers. The difference between the conventional numerical control and computer numerical control systems is that in the case of conventional systems the tape is cycled through the reader for every job, however in case of computer systems the program is input once and is then store permanently into the computer memory. Additional flexibility and computational capability is offered by the CNC systems in comparison to the conventional control systems. For addition of new features to the system only reprogramming of the control unit is required. CNC systems are also referred to as soft wired NC because of the reprogramming capacity of the CNC.

2.3.1 Functions of CNC

The CNC systems have numerous functions which provide an added advantage over the CNC systems. The following are the main functions of a CNC machine.

2.3.1.1 Controlling Machine Tool

The main function of the CNC systems is the controlling of machine tool. The control of machine tool is done using part programs that are fed through the computer interface to the machine tool. There are two variants of a CNC system: Hybrid CNC and straight CNC.

In case of hybrid CNC systems, the control unit is composed of soft-wired computer and hard-wired logic circuits. The functions such as feed rate generation and circular interpolation are accomplished using hard-wired components. The other functions that are not accomplished using the hard-wired components are performed using the computer of the soft-wired components. Further, there are certain components that are common with the conventional NC systems and therefore these components are hard-wired logical circuits that can be produced in large quantities and relatively lesser cost. These also save the computer to perform any other additional task and thereby saving computational expenses. Therefore to make the CNC systems more economical, the lesser cost computer systems are provided with the hybrid CNC systems.

However, in case of straight CNC variant all the functions are performed using a computer. Only the interfacing of the machine tool with the computer is done using the hard wired elements. Therefore, a more powerful computer is required for a straight CNC in comparison to the hybrid CNC system. The added flexibility is one of the major advantages of a straight CNC system. The interpolation programs can be altered easily; however it is not possible to alter the logic contained in the hard-wired circuits.

2.3.1.2 In-Process Compensation

In-process control is one of the functions closely related to the control of the machine tool. The in-process compensation aids in dynamically checking of machine movements and changing of errors that may occur during the machining process. the in-process compensation consists of the following:

- Error adjustment, the error being sensed by gauges and probes.
- Adjustments for offset for tool length and radius.
- Axis position recomputation.
- Adjustments for control of speed or feed.
- Tool life prediction and use of alternative tooling when indicated.

2.3.1.3 Diagnostics

The CNC machining systems are capital intensive. Complex structure of the machine systems increases the risk of component failure of the system and thereby leading to the system shut down. To make the necessary repairs, the personnel required must be highly trained so that required repairs can be made. Therefore, personnel are motivated to take proper care of the CNC machining systems in order to avoid the machine shut down. CNC machines are also equipped with diagnostic features that aid the personnel for maintaining and repairing the system. The diagnostic features serve to identify the reason for the occurrence of any fault in the machining system. This could then help the personnel to make the repairs more quickly. Any signs of intermittent failure of any machinery component will also be alerted in advance to the operator by the diagnostic feature. This will help in replacing the failed component within the scheduled downtime and thereby leading to uninterrupted production. The diagnostic capability of the CNC system also allows switching to another standby component if the main operational component fails. This is only possible if the CNC machining system has the provisions for stand by component.

2.3.2 Advantages of CNC Systems

CNC systems possess a number of advantages. The ensuing discussion enlists some of the advantages of CNC systems over conventional NC systems:

- **Editing of tape at the machining site**: the program of instructions on the tape can be optimized for parameters such as feed, speeds and tool path during the running of the machine tool.
- **Limited use of tape**: the tape is read once and the program of instructions written on it is store in the computer memory. The reliability is therefore increased as a result of limited use of tape.
- **Metric conversion**: CNC machining systems have the capability to convert the tape into international systems of units from that of inches.
- **Greater flexibility**: CNC machining systems are flexible in comparison to the conventional NC systems. The new control features such as the new schemes for interpolation can be adopted with ease and at least cost. Further, the risk of CNC systems getting obsolete is also reduced.
- **Total manufacturing systems**: CNC systems can be conveniently used with the computerized factory wide manufacturing system which is one of the major advantages of CNC over the conventional NC systems.

2.4 Direct Numerical Control

A more advanced version of NC system is that of direct numerical control (DNC) machines wherein a computer controls a number of machines in real time. DNC system is not equipped with the tape reader and therefore increasing the reliability of the machining system. The prepared part program is transmitted from the computer memory directly to the machine tool. More than hundred machines can be controlled at once by a single large computer system. The required instructions to a particular machine are provided on demand by the main computer. For instance, a machine requiring control commands will be communicated to it immediately by the computer. The DNC systems are also equipped to collect the required data back from the machine tools.

2.4.1 Components of DNC Systems

There are four basic components for a DNC system: a central computer, bulk memory, machine tools and telecommunication lines. The part programs store in the bulk memory are called by the central computer and fed to the machine tools. Different machine tools are connected together by telecommunication lines. Central computer also receives the real time data from the different machine tools. Thus the two way information flow must be properly synchronized by the central computer for the effective functioning of the DNC systems. Serving of a large number of computers in a real time is one of the remarkable features of the DNC system.

The satellite computers may be required depending on the number of machining systems and the computational requirements. These satellite computers serve to take the computational burden form the central computer. A group of machines is served by a satellite minicomputer.

Depending on the type of communication link between the control computer and the machine tools, the DNC systems can be categorized into two types of variants. One of the variant makes use of specialized machine control unit and the other is known as behind-the-tape reader system.

2.4.2 *Functions of DNC*

DNC systems serve to perform a variety of functions. The functions performed by DNC systems are difficult to be accomplished using ether the conventional NC or the CNC systems. The primary functions of the DNC system are: NC without punched tape, storage for part program, collection, processing and reporting of data and communications to and fro the machine tools.

2.4.2.1 NC Without Punched Tape

Unreliability of the conventional NC systems was due to the presence of tape reader. The risk of failure of the machine was mainly due to the fragile tape reader. Further, the production of punched tape is capital intensive. The different DNC systems have replaced the punched tape and therefore resulted in increased machining reliability and optimized the cost of machining equipment.

2.4.2.2 Storage of NC Part Program

Storing of part program is another important function of DNC systems. The subsystems for program storage must be structured appropriately. Structure subsystems must be able to provide the programs readily to the machine tools. The subsystems must have the feature to allow for accommodating new part programs, delete the old programs and modify the existing part programs if any. Post processing function of converting the CLIFILE format of the stored part program to the downloadable instructions to the machine tool must be precisely accomplished by the DNC system. The other functions that are required to be performed by the subsystems include processing and management of data, program display and manipulation of data.

2.4.2.3 Collection, Processing and Reporting of Data

One of the other important functions of the DNC system is to collect the data from the machine and transfer it to the control unit. This helps in real time monitoring of the production in the factory. Data related to the number of components produced, usage of tool, utilization of machine tool and other data pertaining to the measuring characteristics of the machine shop are collected and processed by the DNC system. The processed data is then used by the management for taking any corrective actions.

2.4.2.4 Communication

To accomplish the above mentioned functions, a communication network is required. Following components of a DNC system are linked to each other via communication network: machine tool and the central computer, terminals of NC part program wand the central computer and connection between central computer and bulk storage.

2.4.3 Advantages of DNC

The DNC systems have advantages over the conventional NC systems. Following is the list of some advantages of DNC system:

- **Elimination of punched tapes**: the least reliable component of a NC system i.e., the tape reader and the punched tape have been eliminated in the case of DNC systems. The hard-wired control unit has also been replaced in some cases of the DNC systems. These have been replaced with the specialized control systems.
- **Greater flexibility and computational capacity**: the large computers have enhanced the computational capability and provided greater data flexibility in comparison to the traditional NC systems. The flexibility has been resulted because of the presence of software instead of hard-wired devices.
- **Storage of part programs**: the storage of the DNC system is relatively larger than the conventional NC systems that use tapes to store the part program instructions. This has lead to the storage of data for processing of large number of machine tools simultaneously.
- **Reporting of shop performance**: one of the important functions of the DNC system is to collect the data regarding the measurement of shop performance. The processed data can then be analyzed by the managers and therefore the monitoring of the shop performance can be kept in control.

2.5 Adaptive Control of Machining Systems

Adoptive control mechanism can be regarded as sixth level of control for the machining systems. The machines are equipped with sensors to provide the real time data. The sensors are mounted on the tools and the shafts. The information such as the temperature generated during the material removal forces or the cutting forces is provided by the mounted sensors. The computer than analyzes the information. This then adjusts the parameters of machining such as speed and feeds as required for carrying out the machining operation. The machine is protected against any kind of overloading.

The important responses that are required in particular to monitor the machining operation are: maximum allowable force that is exerted against the cutting tool, torque at the spindle and the maximum temperature permitted at the tool tip. The temperature generated during the machining operation is one of the most influential parameter. Temperature generated is determined by the cutting speed. It is possible to maximize the tool life by keeping the cutting speed under check so that the temperature at the tool tip can be maintained.

Another prominent method is placing of the force sensor under the tool tip. This could be found generally in turning centers. The feed rate is monitored so that optimum machining conditions are always maintained. The force will increase rapidly on the failure of the tool. The sensor monitoring the force will then automatically signal to switch off the main motor and therefore stop the machining process. Any serious incident may then be avoided.

Other than turning centers, the force transducers can also be found fitted in the drive system of the milling machine. The information regarding the speed and depth of cut are provided in real time and therefore the machining parameters are adjusted to obtain the optimum conditions for the material removal rate.

The other parameters that can be monitored in adaptive control of the machine involve the following: measurement of surface finish that links the surface measuring instrument with the machine control. Surface finish is measured as the component is produced and the feed rate is automatically adjusted to produce the desired surface quality. Control of vibrations during material removal process is another feature of adaptive control. The controllable vibration dampers are used for this purpose. Reduction in the variation of tool-tip position which may occur due to the presence of thermal gradients is another characteristics feature for the adaptive control mechanism. This would be possible by in-process measurement of the workpiece.

2.6 Conclusion

The present chapter provides an overview of the different levels of controls for machine tools. A brief discussion is provided on CNC and DNC systems. These systems not only provide flexibility in terms of part programming but also lead to enhanced productivity. The CNC and DNC systems are much better alternatives in comparison to the conventional NC systems. However, costs of the systems are only justified if the machining systems are used for mass production of goods and services. More control of the output responses can be obtained using the adaptive control mechanism wherein the parameters such as surface finish, surface roughness and forces at the tool tip interface can be monitored in real time.

Chapter 3
Introduction to Numerical Control Machines

3.1 Introduction

Numerical control can be defined as the automation of manufacturing process using programming languages that is controlled using letters, symbols and symbols. The instructions to produce a particular work job are in the form of numbers in numerical control machines. The instructions form program which changes with the job. The numerical control systems are therefore flexible systems that are potential enough to change the program for each new job. Numerical control has provided the users to minimize the difficulty to make the major changes in the machine equipment.

The scope of NC technology is wide enough to include number of operations such as drafting, assembly, sheet metal working, inspection and welding. However, the majority of the numerical machine applications are restricted to the metal machining operations. A series of operations may be required to produce a work part or a particular machining operation such as turning or drilling may have to be repeated number of times in case of mass production. Therefore in such situations it is easier to program the machine using the numerical control codes. This not only saves time and cost but also produces components with uniformity and enhanced quality.

Much of the achievements and advancements in the manufacturing field have their origin to the numerical control technologies. Further refinement and enhancements in the numerical control technologies can lead to major innovations in the manufacturing environment. The present chapter is therefore an attempt to introduce the numerical control machines. The chapter discusses on the basic components of the NC system. It outlines the basic NC procedure. Discussion is made on the NC coordinate systems and the motion control systems. The chapter concludes with the discussion on applications, advantages and disadvantages of NC.

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3.2 Basic Components of NC System

The three main components of a NC system are: program of instructions, machine tool and a control unit.

3.2.1 Program of Instructions

The detailed sets of instructions are the program of instructions which aids the machine tool to follow the step by step procedure to produce the desired job. The set of instructions are coded using numerals and symbols. Coding is done on some kind of input medium that is easy to comprehend by the control unit. Punched tap is one of the most widely used input medium. Other commonly used input mediums include magnetic tape, punched cards and 35-mm motion picture film.

The input methods of input to the NC system can be categorized into two main types. First type of input includes the manual input of data to the controller unit. This method is commonly known as manual data input (MDI). The MDI is commonly used for relatively simpler jobs. The other type of input method is by using a direct link with a computer. This type of input method is regarded as direct numerical control (DNC).

3.2.2 Controller Unit

Controller unit is another basic component of a NC system. The controller unit serves to interpret the input set of instructions and then convert the same to mechanical action of the tool. This conversion is done using hardware and software units. The elements of NC controller unit includes: data buffer, tape reader, signal output channels, sequence controls and the feedback channels. NC controller units are nowadays microcomputers. NC systems with microcomputers as controller unit are known as computer numerical control (CNC).

The programs of instructions on the punched tape are read using an electromechanical device known as tape reader. Data is read by the data buffer from the data on the tape reader. Instructions once read are stored in the form of logical blocks of information. A complete sequence of procedure is represented by a block of information. Complete procedure may be to move a machine tool to a required position and then to bore a hole in the workpiece.

The role of the signal output channels is to send the program of instructions from the controller unit to the machine tool. These channels are connected to the servomotors and other controls in the machine tool. Feedback channel ensures that the instructions received by the machine tool are properly executed. These feedback channels sends back the feedback data to the controller. The feedback loop also ensures that the workpiece table and the workpiece have been properly located with respect to the machine tool.

Activities of other elements of the controller unit are controlled using sequence controls. The sequence of activities that are required to be coordinated by the sequence control consists of reading the program instructions from the tape into the buffer, to and fro signals to the machine tool and so on.

Control panel is another important element of the NC system. Machine is run by the operator using the control panel that consists of required dials and switches. Information to the operator regarding the sequence of activities is also facilitated to the operator via control panel. Several tasks such as turning on and off the machine, changing the tool, loading and unloading of the machine and other such similar tasks requires the manual intervention of the operator which are done via the control panel.

3.2.3 Machine Tool

Machine tool is the most basic of NC system components. Machine tool is an important part of the NC system that performs the machining work. Machine tool consists of spindle, the worktable, and the motors that drives and control the various units of a machine tool. The other auxiliary components such as fixtures for the workpiece, cutting tools are important elements for the machine tool.

NC machining systems ranges from simple systems such as tape-controlled drill presses to highly complex systems such as that of versatile machining centres. Multifunction capability of the NC machining system is one of the main advantages. Several time saving features are incorporated into a single automated structured machining system. For instance, a machining centre performs a number of operations such as tapping, drilling, milling, boring and reaming. The other function of the machining centre includes the automated process of changing the tool on the basis of the command received from the tape reader. The tool drum houses the number of cutting tools which rotates to position the tool as per the tape command. Tool is then inserted to the spindle. Other capability of the machining centre involves the positioning of the workpiece. The machine table automatically orients the job according to the operation to be performed on the workpiece. Some of the machining centers also have two tables: one for holding the workpiece and another from which the finished job can be unloaded by the operator when the operation is being performed on the workpiece on another table. The presence of two tables therefore improves the machining tool utilization.

3.3 NC Procedure

Following steps are required to be accomplished for a successful operation of the NC machine tool.

3.3.1 *Process Planning*

Drawing of the job to be manufactured must be interpreted in terms of the manufacturing processes required to be performed on the job. The process of interpretation of the engineering drawing into the manufacturing process is known as process planning. Process planning is concerned with the preparation of the route sheet. Route sheet list the sequence of operations required to be performed on the job to get the desired final product. The term route sheet is justified as it also lists the machines through which the job must be routed in order to perform the listed machining operations. It may be possible that a single NC machine performs one or more operations.

3.3.2 *Part Programming*

There are typically two methods to program the NC machine: Manual and computer assisted. The program instructions are prepared on a form in case of manual part programming. This form is known as part program manuscript. The instructions on the program manuscript lists the relative machine and cutter position in accordance to the machining operation required to be performed. In case of the computer assisted part programming the tedious task of computational work is transferred to the computer. The computer assisted part programming is mainly suitable for the complex geometries and jobs involving a number of machining operations. Use of computer for programming saves a lot of time and improves the accuracy.

3.3.3 *Tape Preparation*

Punched tape is prepared using the NC part programming and the process planning prepared by the NC operator. A device similar to typewriter having the capability to punch the tape is used in preparation of tape in case of the manual part programming. The part programming prepared on the program manuscript is used directly. However, in case of computer part programming, computer interprets the programming instructions, converts the instructions to useful machine tool motion by performing the necessary calculations and finally prepares the tape by controlling the punch device. The prepared tape then can be used for the N machine.

3.3.4 Tape Verification

Prepared tape is then verified for accuracy of the part program. Numerous methods are available to accomplish this task. One of the methods involves running the prepared tape through a computer program that plots the different tool and table movements on a piece of paper. This results in identification of any error in the part program.

3.3.5 Production

Final step involves the use of NC tape for the production of the part. The tasks involved include ordering of the required raw materials, preparation of the required tooling and any other arrangements required for setting up the NC machine tool for the job. The role of operator is to only load the raw workpiece in the machine. The starting position of the cutting tool relative to the workpiece also needs to be specified by the operator. NC machine then performs according to the loaded part programming. The operator then removes the part from the machine on its completion.

3.4 NC Coordinate System

A standard axis system helps in specifying the relative position of the workpiece and the toll. Therefore with the established standard axis, it becomes easier for the operator to plan the sequence of movements and positions for the tool with respect to the job. For instance in case of NC drilling operation the spindle of the drill tool remains in vertical position whereas the movement of the table is controlled with respect to the drill spindle. However to make things easier from the programming perspective it is assumed that the workpiece is stationary while the drill bit is moved relative to the stationary workpiece. Therefore, the coordinate system is established with respect to the table.

The x and y axes for the drilling and milling operation defines the plane of the table. The z axis is perpendicular to the plane of the machine table and vertical motion of the spindle controls the movement in the z direction. Capability to control the z axis categorizes the NC drill machines into two axis and three axis machines.

The axis system similar to described above is also used for other NC machine tools such as milling, boring mill and other similar machine tools. In addition to above three linear axes, the other similar machines may possess capability to control the rotational axes also. The rotational axes specify the angles about the three linear axes. Right hand thumb rule may be used for distinguishing the positive and negative angular motions. The positive direction of rotation is specified by using the right hand thumb to point towards the positive linear axis direction and then curling the fingers.

In case of turning operation only two axes are normally required for commanding the cutting tool relative to the workpiece. The x axis determines the radial location of the cutting tool on the rotating workpiece and the z axis is the rotational axes of the workpiece.

The main objective of the coordinate system is to provide a means of locating the tool in relation to the workpiece being machines. There are several options available with the part programmer to specify the location.

Position of the tool is generally specified with respect to the origin of the coordinate system. Fixed zero and floating zero are the two most used methods for specifying the origin of the NC coordinate system. In case of fixed zero method, origin is always fixed at a particular location of the machine table. The lower left-hand corner of the workpiece is generally the origin in the fixed zero method. The x and y coordinates then specify the location of the cutting tool.

The floating zero allows the operator to set the origin at any location on the machine table. This is the most common feature on the modern machine tool. The location of the zero point is left at the discretion of the part programmer. For instance, the operator may set the zero at the centre of the workpiece if it is symmetric. The operator has to manually move the tool to some "target location" on the workpiece. Target location may be predrilled hole in the job. The part programmer has to fix the zero or the origin at the target location while preparing the program instructions. Operator presses zero on the machine tool console once the target position has been located by the operator. The pressing of zero instructs the machine about the location of zero from where the subsequent tool movements initiate.

3.5 NC Motion Control Systems

An accurate relative motion of the tool with respect to the workpiece is necessary to accomplish the desired machining process. The motion control systems in NC machining systems can be categorized into three basic types: point-to-point, straight cut and contouring.

3.5.1 Point-to-Point NC

This type of motion control system is also referred to as positioning system. The main objective of the point-to-point (PTP) NC motion control system is to move the tool to the desired location. Speed of the tool movement is not important factor in PTP motion control system. The machining operation incepts at the location once the tool reaches the required position. One of the examples of PTP system is that of NC drill presses. In the case of drill press, spindle is first positioned at the target location which is done using the PTP motion control method. Drilling operation is then performed by the spindle. The PTP control is not required when the tool moves between two holes.

The PTP systems are the simplest types of motion control systems and are therefore also the least expensive of the three types of motion control methods.

3.5.2 Straight Cut NC

These types of systems moves the cutting tool parallel to one of the major axes. The cutting tool is moved at a controlled rate that is suitable for machining process. The straight cut motion control method is therefore more suitable for the fabrication of the rectangular workpiece by milling operations. However, it is not possible to combine movements in more than one major axis which means that the straight cut motion control methods are not suitable for making angular cuts. NC machines with the straight cut motion control methods are also capable of producing PTP movements.

3.5.3 Contouring NC

The contouring NC motion control method is the most complex and expensive amongst the three types of motion control systems. The method has the capacity to perform PTP and straight cut NC operations. System can control the movement of cutting tool for more than one axis simultaneously. The required geometry can be produced by continuously controlling the path of the cutter. Therefore, the contouring NC is also known as continuous path NC systems. Any kind of shapes can be produced under the contouring NC systems.

3.6 Applications of NC Systems

NC systems are widely used in industries for a wide range of machining operations. The most common of all applications is for cutting of metal in the metal working process. The ranges of material removal processes that can be performed using the NC systems include drilling, milling, sawing, boring, grinding and turning. The NC systems are however only suitable for production of following types of job:

- The parts that are produced frequently and in small lot sizes.
- The geometry of the part is complex.
- A number of machining operations are required to be performed on a job.
- High volume of material is to be removed from the workpiece.
- The parts are required to be produced with close tolerances.
- The parts requiring inspection.

The manufacturing industries produces parts in a lot size which is less than or equal to 50. NC machining systems are suitable for such small lot sized parts. This NC machining systems have the capability to use the program of instruction created once by the programmer to use repeatedly for the production of products of similar nature. The parts with complex geometries require long and complicated program of instructions. NC machining systems has the potential to handle such parts and their programs. Any changes in the engineering drawing of a part can be easily implemented in the final product by changing the program of instructions accordingly. The tape control provides the flexibility to adapt to changes in engineering drawing. NC machining systems are capable to produce products with close tolerances and therefore are more suitable for the production of high quality products with high accuracy and repeatability.

Apart from metal working, the NC systems find a wide range of applicability to other machining operations such as welding, flame cutting, tube bending, plasma arc cutting, cloth cutting and automated riveting.

3.7 Advantages of NC Systems

NC machining systems have following advantages in the field of production:

- **Reduced idle time**: NC machining system doesn't effects the actual machining processes; however it increases the utilization of the machine. The utilization of a machine is increased with the fewer steps, less time for setting up the machine, reduced time for handling of the job under machining, automatic changing of tool and so on.
- **Reduced fixturing**: the fixtures required by NC machining systems are relatively less costly and are also simpler to fabricate. The positioning is done by NC tape instead of using any jigs or fixtures.

- **Reduced lead time**: lead time to deliver the final product to customer is very less since the time involved in setting up is lesser and fewer steps are involved with the NC manufacturing environment.
- **Greater flexibility**: NC machining systems can easily adapt to changes in the engineering design, the changing schedule of production and so on.
- **Enhanced flexibility**: the parts with complex geometries and involving higher chances of human error can be ideally handled by NC manufacturing systems. The parts produced are with higher accuracy and therefore requires lesser inspection time.
- **Optimum inventory**: the quantum of inventory to be stored by a company reduces because of the reduced number of steps for manufacturing and reduced lead time to deliver the final product to the customer.
- **Reduced floor space**: NC machining centre has the capability and potential to perform a number of tasks which are required to be performed by individual machines, the floor space utilization is enhanced.

3.8 Disadvantages

There are also certain disadvantages associated with NC manufacturing systems. These are listed as below:

- **Higher cost of maintenance**: the maintenance of NC manufacturing systems is relatively difficult in comparison to the conventional machining systems. This is because of the presence of complicated hardware and software systems. The cost of maintenance is therefore higher when compared with the conventional machine tools.
- **Higher cost of investment**: NC manufacturing systems involves a highly complex and sophisticated technology and therefore is capital extensive. The return on investment from the equipment can be reasonable only if the utilization of the manufacturing system is higher and to achieve this, the machine shops are required to run the machines two or three shifts per day.
- **Highly skilled labor**: the skills required to operate the NC manufacturing systems are higher than that required to operate conventional machine tools. The skills are required to program the machine and maintain the software and software associated with the manufacturing systems. Thus it is one of the disadvantages of the NC manufacturing systems to employ highly skilled labor force for the operation of NC systems.

Chapter 4
Fundamentals of Part Programming

4.1 Introduction

The concept of numerical control has been widely accepted by the manufacturing industries. Operators can communicate with the machine tool directly using the program of instructions written in symbols and numbers. With the passage of time and advancement in the manufacturing field led to the development of Computer Numerical Control (CNC) systems. There has been a tremendous change in the productivity of the manufacturing industries with the introduction of CNC systems. CNC systems are able to produce parts with unmatched accuracy. Further, the same part can be reproduced any number of times with the same degree of accuracy. However, the part programs must be prepared properly and accurately.

Therefore, there is a dire need of personnel that can accurately perform the part programming so that industries can meet the market demand in shortest possible time with enhanced product quality. Keeping this in mind, the present chapter is dedicated to part programming. The fundamentals of part programming have been demonstrated using three illustrations: CNC turning, CNC milling and program sample for Electric Discharge Machining (EDM).

4.2 Part Programming with CNC Lathe

4.2.1 Co-ordinate System for a CNC Lathe

A coordinate system is required for a CNC program for the machining of a work piece. The coordinate system is applied to the machine tool. The movements can take place in three planes: Longitudinal, Vertical and Transverse. A letter is assigned to each of the plane and is referred to as axis: Axis X, Axis Y and Axis Z.

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The upper case letters are used to identify the three axes and these are: X, Y and Z. The PLUS (+) and the MINUS (−) signs are used to describe the movement along each of these axes. Spindle of the machine and the Z axis are parallel to each other while the X-axis is parallel to the surface holding the workpiece and is therefore perpendicular to the Z-axis. The Y-axis is perpendicular to both the X and Z axis. The coordinate system is represented using the right hand and is therefore the "Right Hand Coordinate System". The direction of the Z-axis can be established by aligning the fingers of the right hand in the direction of X axis and rotating the fingers in the direction of Y axis and then the direction in which the thumb points is the direction of Z axis.

The workpiece is assumed to be stationary in the part programming. It is the tool that moves in the coordinate system. The *Machine Zero point* is specified by the manufacturer. For turning lathes, the centre of the nose of the spindle is the machine zero point. Another point is the *Reference point* that serves to control the measuring system of slides and tool. The workpiece coordinate system relative to the machine zero point is specified by *Workpiece Zero point.* The programmer chooses the workpiece zero point.

4.2.2 Dimensioning Basics

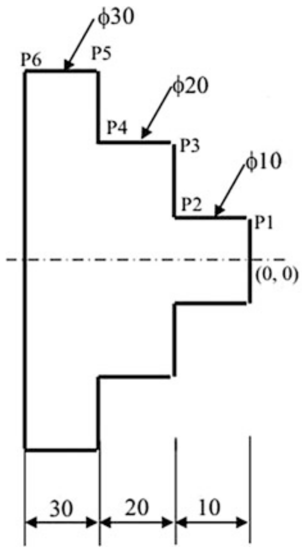
The dimension related information for a workpiece can be stated in two ways: absolute and incremental. The dimensioning system always referring to affixed point is the absolute dimension system. The point is the reference point and functions as zero for the coordinate system. however, in case of incremental dimensioning system the reference point changes its position and will be the previously dimensioned position. Such a dimensioning system is also referred to as "chain dimensioning system". The difference between the two dimensioning systems has been illustrated in the Fig. 4.1.

4.2.3 Miscellaneous and Preparatory Functions

List of miscellaneous functions (M codes) and the Preparatory functions (G codes) used for CNC lathe is depicted in Figs. 4.2 and 4.3 respectively.

4.2.4 Part Programming for Turning Operation

Figure 4.4 shows a workpiece drawing for turning operation. The part program is reflected in Fig. 4.5.



ABSOLUTE DIMENSIONING			INCREMENIAL DIMENSIONING		
POINTS	X	Z	POINTS	U	W
P1	10	0	P1	10	0
P2	10	-10	P2	0	-10
P3	20	-10	P3	10	0
P4	20	-30	P4	0	-20
P5	30	-30	P5	10	0
P6	30	-60	P6	0	-30

Fig. 4.1 Absolute and incremental dimensioning systems

Fig. 4.2 M codes used for part programming for CNC lathe

M Codes	Description
M00	Program Stop
M01	Optional Stop
M02	Program End
M03	Spindle Rotation Clockwise
M04	Spindle Rotation Counter Clockwise
M05	Spindle Stop
M06	Tool Change
M08	Coolant On
M09	Coolant Off
M10	Chuck Open
M11	Chuck Close
M30	Program Stop and Rewind
M62	Output 1 On
M63	Output 2 On
M64	Output 1 Off
M65	Output 2 Off
M66	Wait input 1 On
M67	Wait input 2 On
M76	Wait input 1 Off
M77	Wait input 2 Off
M98	Sub-program Call
M99	Sub-program Exit

Fig. 4.3 Preparatory functions (G codes)

G CODE	Group Function
G00	Positioning (Rapid traverse)
G0l	Linear interpolation (Cutting feed)
G02	Circular interpolation (Clockwise)
G03	Circular interpolation (Counter Clockwise)
G04	Dwell
G17	XY plane selection
G18	ZX plane selection
G19	YZ plane selection
G20	Input in inch
G21	Input in mm
G28	Return to reference point
G40	Tool Nose Radius compensation cancel
G41	Tool Nose Radius compensation left
G42	Tool Nose Radius compensation right
G70	Finishing Cycle
G71	Multiple Turning Cycle
G72	Multiple Facing Cycle
G73	Pattern Repeating Cycle
G74	Drilling Cycle
G75	Grooving Cycle
G76	Multiple Threading Cycle
G90	Turning Cycle
G92	Threading Cycle
G94	Facing Cycle
G96	Constant Surface Speed Control
G97	Constant Surface Speed Control Cancel
G98	Feed Per Minute
G99	Feed Per Revolution

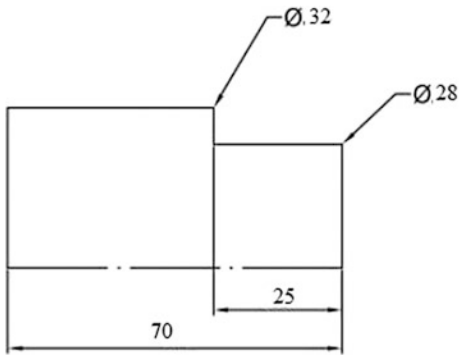


Fig. 4.4 Drawing of a part for turning operation

Program code	Code description
G21 G98	Initial Settings
G28 U0 W0	Going to home position
M06 T1	Tool Change Position No. 01
M03 S1500	Spindle clockwise with 1500 RPM
G00 X32 Z5	Tool Moving to Tool Entry Point of X32 Z5 at Rapid Traverse
G01 X31 F80	Giving First depth of cut of 1 mm at a feed rate of 80 mm / min
G01 X3	Retract the tool in X axis
G00 Z5	Moving the tool to Z5 position
G01 X30 F8	Giving Second depth of cut of 1 mm at a feedrate of 80 mm/ min
G01 Z-25	Moving the tool towards Z-25 mm
G01 X32	Retract the tool in X axis
G00 Z5	Moving the tool to Z5 position
G01 X29 F80	Giving Third depth of cut of 1 mm at a feedrate of 80 mm / min
G01 Z-25	Moving the tool towards Z-25 mm
G01 X32	Retract the tool in X axis
G00 Z5	Moving the tool to Z5 position
G01 X28 F80	Giving Fourth depth of cut of 1 mm at a feedrate of 80 mm/ min
G01 Z-25	Moving the tool towards Z-25 mm
G01 X32	Retract the tool in X axis
G00 Z5	Moving the tool to Z5 position
G28 U0 W0	Going to home position
M05	Stop the spindle
M30	Program stop and rewind

Fig. 4.5 Part program for the part drawing shown in Fig. 4.4

4.3 Part Programming with CNC Milling

4.3.1 Miscellaneous and Preparatory Functions

List of miscellaneous functions (M codes) and the Preparatory functions (G codes) used for CNC milling is depicted in Figs. 4.6 and 4.7 respectively.

4.3.2 Part Programming for Linear and Circular Interpolation Using Milling Operation

Figure 4.8 shows a workpiece drawing for milling operation. The part program is reflected in Fig. 4.9.

Fig. 4.6 M codes used for part programming for CNC milling

M Codes	Description
M00	Program Stop
M01	Optional Stop
M02	Program End
M03	Spindle Rotation Clockwise
M04	Spindle Rotation Counter Clockwise
M05	Spindle Stop
M06	Tool Change
M08	Coolant On
M09	Coolant Off
M10	Vice Open
M11	Vice Close
M13	Spindle Rotation Clockwise, Coolant On
M14	Spindle Rotation Counter Clockwise, Coolant On
M19	Spindle Orientation
M20	ATC Arm in
M21	ATC Arm out
M22	ATC Arm down
M23	ATC Arm up
M24	ATC draw bar clamping (Manual)
M25	ATC draw bar releasing (Manual)
M27	ATC Reset
M30	Program Stop and Rewind
M70	X – Mirror ON
M71	Y – Mirror ON
M80	X – Mirror OFF
M81	Y – Mirror OFF
M98	Sub-Program Call
M99	Sub-Program Exit

4.4 Part Programming with Electrical Discharge Machining (EDM)

4.4.1 Program for Z Depth

Figure 4.10 shows the part program for the Z depth in EDM.

Fig. 4.7 G codes used for part programming for CNC milling

G CODE	Function
G00	01 Positioning (Rapid traverse)
G01	Linear interpolation (Cutting feed)
G02	Circular interpolation (Clockwise)
G03	Circular interpolation (Counter Clockwise)
G04	Dwell, Exact stop
G17	XY plane selection
G18	ZX plane selection
G19	YZ plane selection
G20	Input in inch
G21	Input in mm
G28	Return to reference point
G40	Cutter radius compensation cancel
G41	Cutter radius compensation left
G42	Cutter radius compensation right
G43	Tool length compensation + direction
G44	Tool length compensation - direction
G49	Tool length compensation cancel
G50	Scaling Off G51 Scaling On
G54	Datum Shift
G68	Rotation On
G69	Rotation Off
G73	High speed peck drilling cycle
G74	L.H. Tapping cycle
G76	Fine boring
G80	Canned cycle cancel
G81	Continuous drilling cycle, spot drilling
G82	Continuous drilling cycle, drilling with dwell
G83	Peck drilling cycle
G84	R.H.Tapping cycle
G85	Boring cycle with feed retraction
G86	Boring cycle with rapid retraction

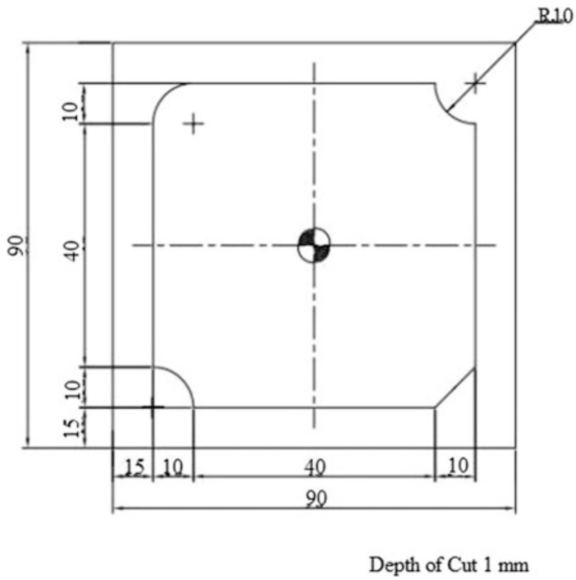


Fig. 4.8 Drawing of a part for milling operation

Fig. 4.9 Part program for the part drawing shown in Fig. 4.8

G21 G94
G91 G28 Z0
G28 X0 Y0
M06 T1
M03 S1500
G90 G00 X-30 Y-20 Z5
G01 Z-1 F100
G01 X-30 Y20
G02 X-20 Y30 R10
G01 X20 Y30 G03 X30 Y20 R10
G01 X30 Y-20
G01 X20 Y-30
G01 X-20 Y-30
G03 X-30 Y-20 R10
G00 Z5 G91 G28 Z0
G28 X0 Y0
M05
M30

Fig. 4.10 Part program for Z depth

G9
G17
G27
G27
G40
G71
G90
G29
G0 X0 Y0 Z50
G0 Z5
G29 Z5
G1 Z-5
G1 Z1
G0 Z50

4.5 Conclusion

The present chapter provides a basic overview on CNC part programming. Discussion on the workpiece dimensioning has been discussed. Three examples of part programming have been discussed from turning, milling and EDM. The examples clearly illustrate the capability of the CNC machines to different domains of manufacturing processes. The only requirement to obtain an accurate product is the accuracy with which the part programming is done.

Part II
Non Conventional Machining Techniques

Chapter 5
Introduction to Machining Processes

5.1 Introduction

Often further operations are required for the parts manufactured by forming, casting and the other shaping processes to ensure an accurate and precise assembly. The control of dimensional tolerances and the surface finish for the parts manufactured is of utmost requirement because of necessity for the parts to have interchangeable characteristics so that they function as expected during their service life. The machining process entails the mechanism for removal of material from the work-piece surface to achieve the desired geometry with the desired degree of surface quality and accuracy.

5.2 History of Machining

The earliest tools used for the machining operations were made from stick, stone or bones. With the advancement, the elementary metals such as iron and bronze were employed to produce hand tools. Up till 17th century, the tools for machining operations were either hand tools or mechanically driven. Such tools aided in the manufacturing of warships, wagons, furniture and utensils for daily use. Later on, the power driven tools came into existence with the introduction of steam, water and electricity. The mechanically driven tools were therefore replaced by the power driven tools for a large number of applications.

A new class of machine tools came into existence in 18th and 19th centuries with the advent of alloy steels as cutting tool materials and on the basis of above developments. John Wilkinson was one of the major contributors. He in the year 1774 constructed a machine tool for boring of engine cylinders which overcame the difficulties associated with the first set of machine tools which were steam powered. A screw cutting lathe was then devised in the year 1797 by Henry Maudslay.

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Machine tools for shaping and planning were developed by James Nasmyth for machining flat surfaces, shoulders, grooves, angular surfaces and T-slots. A single point cutting tool was used by such machines. Another set of machine tools was the drilling machine using twist drills to cut holes.

The first milling machine was developed in 1818 by Whitney for cutting of T-slots, dovetails and grooves. J. R. Brown invented the universal milling machine in the year 1862 which was used to cut helical flutes of twist drills. The grinding machine was introduced in the late 19th century. With the advancements, the lapping machine came into existence to produce surfaces with very high quality and very tight tolerances of as low as ± 0.00005 mm.

One of the notable inventions includes that of the turret lathe which was devised in the midst of the 19th century used for the automatic production of screws. F. W. Fellows devised a machine in the year 1896 that was capable of producing any kind of gears. Other noteworthy examples significant of the advances in the machine tool technology include those of the multiple-station vertical lathes, production millers, gang drills and other special-purpose machines such as honing, broaching and boring (McGeough 1988). In later part of the 19th and the early 20th century, electrical energy replaced the steam for powering the different machine tools. Further refinements were made to the basic machine tools to result into advanced versions of the same. For instance, multi-point cutting tools were introduced for milling machines. However, the machine technology relied heavily on the principle to use cutting tools of material harder than that of the workpiece being machined.

Operator is provided with the drawing of the required part for machining with any of the above conventional machining techniques. Operator is then required to select the optimum machining strategy such as the speeds, tooling and the feed rates. The operator has to manipulate the machine control and as such the produced surface quality and the product accuracy are not satisfactory. The existing machines were further advanced with the use of cams and automatic mechanisms and thereby reducing labor cost and enhancing the product quality.

The product accuracy was the prime focus of the advancements taking place after 1950s. With the advent of numerical control, computer numerical control (CNC) and direct numerical control (DNC) machines came into existence in 1953 that led to enhancement of the surface quality. The rapid advancements in the computer and electronic industries showed a continuous and a rapid development in the machine technology for 50 years. The recent advancements are that of the jig grinding, jig bores and superfinishing machines.

In the modern era of materials, the materials used for the fabrication purposes are harder, stronger and relatively more difficult to be cut. Therefore, the attention has shifted to the development of machining processes which do not limit their performance because of the mechanical properties of the materials. The non-conventional machining processes came into existence as a result of continual development in machine technology. The non-conventional machining processes came as an alternative to producing complex shapes and concerning surface integrity, machinability. The combination of the different machining processes was a requirement to further extend the capabilities of the present machining tools. The combination was known as hybrid machining system which combined the advantages of the processes involved in the combination and thereby negating the adverse effects of the individual constituents.

Reduction of the workpiece size and dimensions came to the forefront of the research community after the possibility of drilling ultrasmall-diameter holes. Further reduction of workpiece sizes was possible with the advent of micromachining. Micromachining aims to produce completely integrated systems integrating microelectronics circuitry into micro machined structures.

Some of the recent applications of micromachining include excimer lasers, silicon micromachining and photolithography. Surface accuracy of the level of ±0.01 μm is possible with the precision grinders. Laser and electron beam lithography are other trends of the micromachining processes (McGeough 2002).

The material removal mechanism can now involve removal of atoms or molecules rather than chips as in the case of ion beam machining. Tanigushi (1983) introduced nanomachining which could machine components with tolerances down from submicron levels to that of nanometer levels and thereby covering the trend of miniaturization. The requirement of high performance and the efficiency in different fields such as aircraft industries calls for the production of components to such small levels of tolerances. Scanning electron microscope (SEM), electron diffraction equipment or ion beam analyzer are the instruments that can be used to measure such ultra precision levels.

5.3 Traditional Machining

Traditional machining is also known as conventional machining. The traditional machining processes removes material from the workpiece surface by using tools those are harder than the workpiece material being machined. Tool used for the material removal process should penetrate to a certain depth. The desired shape is generated as a result of relative motion between the workpiece and the tool. The process becomes traditional one if any of the above mentioned elements are missing. Different traditional machining processes can be classified on the basis of mechanical abrasion and mechanical action of cutting.

5.3.1 Machining by Abrasion

The machining by abrasion results into material removal process because of number of angular and hard abrasive particles referred to as grits. These abrasive grains may or may not be bonded to form a tool. The depth of penetration is small for the randomly oriented individual cutting edges. Further, the depth of penetration is not uniform for all the abrasive particles that are in contact with the workpiece material simultaneously. The material removal takes place in the form of minute chips, invisible in some of the situations (Kaczmarek 1976). Machining by abrasion is employed by processes employing either abrasive sticks or solid grinding wheel with abrasive particles. Example of processes with machining by abrasion includes honing, grinding and superfinishing. There are other processes that use loose abrasive particles in liquid medium as tools. Lapping, buffing and polishing are examples of such processes.

5.3.2 Machining by Cutting

The tool is penetrated in the workpiece material to a required depth of cut. The geometry of the workpiece is determined by the nature of relative motion between the tool and the workpiece. For instance, cylindrical parts are produced with turning operation, flat surfaces are produced with milling and shaping operation and holes of different diameters are produced using the drilling operation. The cutting tool has a specified number of cutting edges of known geometry. The material removal process takes place in the form of chips that can be observed with the naked eyes. Cutting tool having the contour of the finished part produces the contour shape on the workpiece by forming. Accuracy of the form cutting tool determines the accuracy of the surface profiles produced on the workpiece material. Several motions of cutting tool may result in the generation of the surface in which case the main motion comprises of the chip formation process and the feed motion is achieved with the movement of point of tool engagement along the workpiece surface. The slot milling operation combines the principles of forming and generation.

Temperature generated at the zone of machining is the determining factor for the resistance offered by the workpiece material to machining by cutting. The strength of the workpiece material decreases with the rise in temperature but the ductility is increased at the same time. The machining performance increases with temperature since the cutting forces and hence the power consumption decreases. The machinability of materials such as ceramics and glass has been improved using hot machining. The heating of workpiece also results in the formation of continuous chips besides reducing the hardness of the workpiece material. The formation of continuous chips is indicative of improved surface finish (El-Kady et al. 1998).

5.4 Non Traditional Machining

The ever growing material database with materials having enhanced mechanical and thermal properties made it difficult for the traditional machining processes to machine such materials. The reason for this can be attributed to the fact that tools used in case of traditional cutting processes are always harder than the workpiece being machined. For instance, the volume of worn out material of the grinding wheel was very high in comparison to the volume of metal removed and therefore the grinding process was limited to machining of polycrystalline diamond profile tools.

The major restriction for machining of ceramics and composites is the high cost associated with their machining and the damages incurred by these materials during their machining. Further, with the growing market demand, micro machined, low rigidity and complex shapes with high surface quality components are also difficult to machine using the traditional machining processes. Therefore to meet the growing market demand with such materials and components, new machining processes have been developed.

The new manufacturing processes play a very critical role for the industries such as aircraft, automobile, die and tool making. These processes are referred to as nontraditional machining processes and can be categorized on the basis of number of actions required to remove the material from the workpiece specimen.

5.4.1 Single Action Nontraditional Machining

As the name indicates, only a single machining action is required to remove the material from the workpiece. The source of energy used categorizes the single action nontraditional machining into: thermal, mechanical, electrochemical and chemical.

5.4.1.1 Thermal Machining

The material removal in this case takes place by melting or vaporizing the workpiece material. Secondary phenomenon such as formation of heat affected zones, microcracking etc. also occurs as a result of the machining process.

The source of energy can be plasma as in the case of plasma beam machining (PBM) and electrodischarge machining (EDM), electrons in electron beam machining (EBM), laser for laser beam machining (LBM) and ions for ion beam machining (IBM). Further, the different machining processes take place in different machining medium such as dielectric fluid for electrodischarge machining, vacuum during laser beam machining and ion beam machining.

5.4.1.2 Mechanical Machining

The typical examples of mechanical machining are ultrasonic machining and water jet machining. Mechanical abrasion is the main mechanism for the material removal in case of ultrasonic machining whereas in case of water jet machining it is the cutting action of the fluid jet. The medium under which the machining takes place is abrasive slurry in case of ultrasonic machining while the water jet machining is performed in the presence of fluid. Introduction of abrasive particles in the fluid enhances the machining performance and is referred to as abrasive water jet machining (AWJM). If abrasive particles are ice then the process is referred to as ice jet machining (IJM).

5.4.1.3 Chemical and Electrochemical Machining

The chemical dissolution action forms the basis of material removal in case of chemical milling (CM) and photochemical machining (PCM). The ion transfer in an electrolytic solution results in material removal in case of electrochemical machining (ECM) and the process of ion transfer is known as electrochemical dissolution (ECD).

5.4.2 Hybrid Machining

Different machining processes can be combined to result in an improvement in the machining processes. For instance, the action of mechanical abrasion can be combined with machining phase of electrodischarge in EDM process. The combination is referred to as hybrid machining process. Hybrid machining processes have been developed to mainly make use of advantages of the processes involved in the combination and to reduce the adverse effects of processes in combination that would have been produced when applied individually.

The hybrid machining processes can be classified into hybrid thermal processes and hybrid chemical processes depending on the major machining phase involved in the process.

5.4.2.1 Hybrid Thermal Process

The thermal energy is the main source of material removal in hybrid thermal processes. A family of double action processes results from the combination of mechanical abrasive action, ECD phase and ultrasonic vibration. The hybrid combination leads to enhanced material removal rate with better surface finish quality.

5.4.2.2 Hybrid Thermal Electrochemical and Chemical Processes

The main source of energy for material removal is either the electrochemical dissolution or the chemical dissolution phase. Either of the phases can be combined with other energy source to result in hybrid process. For instance in case of laser-assisted electrochemical machining, the electrochemical dissolution phase is combined with the laser energy. The combination of the ultrasonic component with the electrochemical phase results in ultrasonic-assisted electrochemical machining process (USMEC).

The conditions for the anodic dissolution are improved by the mechanical interaction with the workpiece material (Kozak and Rajurkar 2000). The dissolution phase and hence the material removal process becomes more intensive with the combination of different phases. The flushing of the electrolytic solution is enhanced with the mechanical action.

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Chapter 6
Mechanical Machining

6.1 Introduction

The typical examples of mechanical machining are ultrasonic machining and water jet machining. Mechanical abrasion is the main mechanism for the material removal in case of ultrasonic machining whereas in case of water jet machining it is the cutting action of the fluid jet. The medium under which the machining takes place is abrasive slurry in case of ultrasonic machining while the water jet machining is performed in the presence of fluid. The introduction of abrasive particles in the fluid enhances the machining performance and is referred to as abrasive water jet machining. If abrasive particles are ice then the process is referred to as ice jet machining. The machining under the influence of magnetic field results in magnetic abrasive machining. This chapter discusses the different mechanical nontraditional processes.

6.2 Ultrasonic Machining

6.2.1 Introduction

Ultrasonic Machining, shown in Fig. 6.1, is a mechanical machining process of non-conventional type. Both the non-metallic materials as well as the electrically conductive materials can be machined using the ultrasonic machining process. It is generally preferred for materials having hardness value above 40 HRC and having low ductility (Rozenberg 1973; Saha et al. 1988; Snoyes 1986; Weller 1984). Examples include ceramics, inorganic glasses, and quartz to name a few. L. Balamuth is credited to the invention of the ultrasonic machining process that was granted patent in the year 1945. Ultrasonic machining has got different versions

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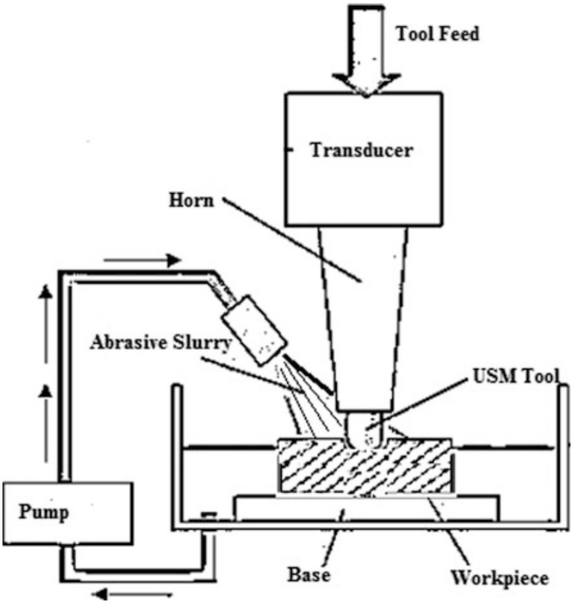

Fig. 6.1 USM schematic

such as ultrasonic cutting, slurry drilling, ultrasonic drilling and ultrasonic abrasive machining.

A transducer/booster combination leads to the conversion of electrical energy of high frequency to mechanical energy in the form of vibrations. These are then transmitted to horn or a sonotrode that focuses and amplifies the received energy. The amplified and focused energy causes the tool to longitudinally vibrate along its axis. The amplitude of vibration ranges between 12 and 50 μm and the frequency is greater than 20 kHz (Benedict 1987; Farago 1980; Farzin-Nia and Sterrett 1990; Frederick 1965; Kennedy and Grieve 1975; Kremer 1981; Neppiras 1964; Pandey and Shan 1980). In order to ensure that the tool provides feed in the longitudinal direction, a controlled static load is applied.

The gap between the tool and the work-piece, ranging 25–60 μm, continuously receives abrasive slurry through pumping. The abrasive slurry is consists of a mixture of abrasive particles such as silicon carbide, alumina or boron carbide suspended in some carrier medium such as water. The material removal by micro-chipping takes place when the vibrating tool makes the abrasive particles to impact the work surface (Miller 1957).

The different variations to the basic USM described include the following:

- *Rotary Ultrasonic Machining*: the material removal rate in this variation of the basic USM is improved through the simultaneous rotation and longitudinal vibration of the tool. This also minimizes the geometric inaccuracies such as out of roundness (Hu et al. 2002; Li et al. 2005; Pei and Ferreira 1999; Prabhakar and Haselkorn 1992; Treadwell et al. 2002; Ya et al. 2002; Zeng et al. 2005).

A rotary-spindle with power rating ranging 0.37–0.56 kW with spindle speed up to 5000 rpm is an additional component to the basic USM version.

- *Combined USM and electric discharge machining* (Thoe et al. 1999; Wansheng et al. 2002).
- *Ultrasonic assisted grinding or cutting*: one of the most common processes in this variation of USM is the USM assisted turning. This process has led to reduction in machining time and residual stresses. Further, it has claimed to improve the tool life and surface quality (Babitsky et al. 2004; Balamuth 1966; Chang and Bone 2005; Ishikawa et al. 1998; Kai and Takahira 1999; Kohals 1984; Markov 1977; Moore 1985).
- Other non-machining operations: welding, coating, cleaning, polishing etc.

USM has low material removal rate. However, the process is not limited by the thermal or electrical properties of the material. Further, the properties of materials being processed are not altered either metallurgically or chemically (Weller 1984; Kumar and Khamba 2008; Kumar et al. 2012, 2013a, b). For efficient machining, resonance must be achieved to meet the capability of the machine and therefore the horn and the tool must be designed with due consideration given to mass and shape.

6.2.2 *Main Elements of an USM Tool*

Ultrasonic machine tools are available in a wide range of sizes ranging from small part capacity to large capacity part. Power rating is another parameter determining the suitability of the machine for a particular application. Irrespective of the part size capacity and power, all USM tools have certain subsystems common in them (Benedict 1987). These include the power supply system, horn, transducer element and the abrasive supply system. The aforementioned subsystems are discussed in the subsequent sections.

6.2.2.1 The Power Supply System

The power supply of a USM is a high power sine wave generator. The power supply system provides control of power and frequency to the operator. The main function of the system is the conversion of electrical power of low frequency (50 Hz) to high frequency of the order of 20 kHz. The high frequency sine wave is transmitted to the transducer. The size of the transducer is the determining factor to the power supply. Safety features such as auto cut-off accompanies the power supply system that provides safety in case of tool failure, overloading or horn fracture (Frederick 1965).

6.2.2.2 The Magnetostrictor

The Magnetostrictor is one of the two types of transducers used for the USM, piezoelectric being the other. The magnetostrictor comprises of a magnetostrictor having high frequency winding around it and an armature with polarizing winding around it. Joule in 1984 discovered the magnetostriction effect according to which any ferromagnetic object experiences change under the influence of magnetic field undergoing ultrasonic frequencies. The oscillation of the USM tool at ultrasonic frequencies ranging 18–20 kHz is the result of the same magnetostrictive principle.

The magnetrostrictive transducer has the potential to transmit vibrations over a wide frequency band (Kazantsev 1966). This is because of its lower Q value, where Q is the measure of the sharpness of the peak value of energy. This potentiality of the magnetostricter transducer leads to a greater degree of design flexibility of the horn. However, low energy efficiency and high electrical losses adds to the major drawbacks for the magnetostrictive transducer.

A higher value of magnetomechanical coupling, K_m is required for any magnetostrictor material to have maximum amplification and a good efficiency. This is because the magnetostrictor converts the magnetic energy to mechanical energy.

$$K_m = \sqrt{\frac{E_w}{E_m}}$$

where, E_w is the mechanical energy and E_m is the magnetic energy. Table 2.1, shows some of the materials for the magnetostrictor.

6.2.2.3 The Mechanical Amplifier

The magnetostrictor operating at resonance will be at its optimal efficiency. Therefore, its natural frequency must be equivalent to that of the frequency of the magnetic field. The resonance frequency f_r is given by the following equation:

$$f_r = \frac{1}{2l}\sqrt{\frac{E}{P}}$$

Table 6.1 Coefficient of magnetomechanical coupling for magnetostrictive materials

Material	Coefficient of magnetomechanical coupling (K_m)
Permalloy (40% Ni, 60% Fe)	0.17
Hypernik (50% Ni, 50% Fe)	0.20
Permendur (49% Co, 2% V, 49% Fe)	0.20
Alfer (13% Al, 87% Fe)	0.28

where, P is the density (kg/m^3), E is the young's modulus, l is the magnetostrictor cores' length.

The elongation of the magnetostrictor core obtained at f_r is very small ranging between 0.001 and 0.1 μm for magnetostrictor core length equivalent to 0.5 λ. The elongation thus obtained is too small for the practical applications. The amplitudes ranging between 40 and 50 μm are found to be suitable for any practical applications. Therefore an acoustic horn is used as an amplification device increasing the vibration amplitude. This is attached at the end of the magnetostrictor and serves to hold the tool to the transducer besides amplifying the vibrations. Large, loose-fitting screws are used to attach the horn to the magnetostrictor (Merkulov 1957).

One or more horns can be employed for the desired amplitude. The shape of the acoustic horn is another deciding factor in controlling the final amplitude. The different shapes of acoustic horns as reported by Youssef and El-Hofy (2008) are: stepped, cylindrical, conical, hyperbolic cosine and exponential. Stepped and exponential are usually preferred to conical and hyperbolic horns because of the flexibility in design.

The materials used for the fabrication of the horn should have good resistance to wear, fatigue and corrosion resistance properties and should be elastic. Therefore the suitable materials used are titanium, aluminum bronze, stainless steel and monel (Merkulov 1957).

6.2.2.4 Tools

High fatigue strength and high wear resistance are the desirable properties for the tool tips used in USM. Some of the tool materials include copper and chromium silver steel tools, silver and chromium nickel steel, polycrystalline diamond etc. screw fitting, soldering or brazing can be used to attach the tool to the horn. The tool can also be machined alternatively to the end of the horn. To provide luxury in changing the tool, threaded joints have also been adopted in certain instances, however problems such as loss in acoustic power, self loosening and even the fatigue strength loss have been reported (Kumehara 1984).

Different tool feed mechanism such as pneumatic, counterweight technique, solenoid and compact spring loaded systems are used to hold the tool stationary against the workpiece (Kremer 1981; Pandey and Shan 1980; Snoyes 1986). The different mechanisms are required to maintain a uniform working force and the same time should be sensitive enough to overcome the cutting force resistance. The value of static load ranges between 0.1 and 30 N (Rozenberg 1973; Rozenberg et al. 1964).

6.2.2.5 Abrasive

The cutting action in USM is achieved using abrasive slurry which is a mixture of abrasive and fluid such as water. Materials such as boron carbide, silicon carbide and aluminium oxide with grain size ranging between 100 and 800 grit number are commonly used to make the abrasive slurry. The fluid used as a transportation medium for the abrasive particles should possess good wetting properties, low viscosity and high thermal conductivity that will aid in rapid cooling (Barash and Watanapongse 1970; Koops 1964; Thoe et al. 1995).

The circulated abrasive slurry is hammered on to the workpiece under the effect of static feed force and ultrasonic vibrations. This leads to mechanical chipping of the particles from the workpiece surface. Recirculating pumps are used to circulate the abrasive slurry between the tool and the workpiece. The rate of abrasive circulation is up to 36 L/min.

The effectiveness of the slurry declines as the machining progresses. The continuous supply of the abrasive slurry is maintained in order to ensure that the proper flushing of the debris takes place. This also serves to ensure effective cooling of the suspension.

6.2.3 The Material Removal Process and Models for MRR

The mechanism of material removal in USM can be clearly divided into three distinct phases:

- The mechanical abrasion phase: this results because of the hammering of the abrasive grains onto the workpiece (Cook 1966; Kainth et al. 1979; Lee and Chan 1997; Miller 1957; Nair and Ghosh 1985; Rozenberg et al. 1964; Shaw 1956).
- The microchipping phase: this occurs due to the particles flying across the machining gap and making impacts at free locations of the workpiece (Miller 1957; Rozenberg et al. 1964; Sreejith and Ngoi 2001)
- The erosion phase: in this phase, because of the cavitation phenomenon the erosion of the worksurface takes place in the abrasive slurry (Shaw 1956; Soundrajan and Radhakrishnan 1986).

The dominant of the three phases is that of the mechanical abrasion phase while the contribution of the erosion phase in the material removal process is the least. In case of the elastic materials the plastic deformation is followed by the material removal at the lower rate whereas the material removal rate is high in case of the brittle materials. Further the role played by the microchipping phase can also be clearly noticed in case of the hard and brittle materials. The erosion phase can be noticed while machining porous materials such as graphite. The collapsing of the cavitation bubbles on to the worksurface during the machining generates a pressure more than 1000 kgf/cm^2 which in turns contributes in the material removal process (Riddie 1973; Bulat 1974; Willard 1953).

The above phases are a result of number of models that have been proposed by different researchers for the prediction of material removal rates.

6.2.4 The Operating Characteristics of USM

Four primary factors have been reported on which the material removal rate is dependent. These factors are: workpiece; slurry; tool and factors relating to the machine. The subsequent sections discuss these factors. The MRR in USM can be obtained using the following formula:

$$MRR = 5.9F\left(\frac{S}{H_0}\right)R^{0.5}Y^{0.5}$$

where,

F frequency of oscillation
S static stress on tool, kg/mm^2
R mean radius of grit, mm
H_0 surface fracture strength, BHN
Y amplitude of vibration.

6.2.4.1 Properties of Workpiece

Influence of properties such as hardness and fracture toughness on the material removal rate have been studied and was found that with the increase in the fracture toughness and the material harness the MRR decreases (Komaraiah and Reddy 1993a). For instance the whisker-reinforced composites possessing a high fracture toughness was found to have low MRR while a higher MRR was reported for particle reinforced composites having low fracture toughness (Deng and Lee 2002). The results obtained after machining of $Al_2O_3/LaPO_4$ composites showed that there is increase in the MRR to a certain limit with the hardness, stabilizing thereafter (Majeed et al. 2008). Tough material undergoes a considerable amount of plastic deformation before failure while on the other hand for hard and brittle materials machining takes place by brittle fracture at certain cleavage planes.

The MRR is also found to be dependent on the ratio of work hardness to elastic modulus i.e., brittleness ratio. The brittleness of the workpiece determines the productivity of the USM process. Low productivity of USM results with the plasticity of the workpiece. The machining rate is adversely affected by the impact hardness.

6.2.4.2 Tool Characteristics

The productivity or the machining rate in the USM increases with the hardness of the tool material (Komaraiah and Reddy 1993b). This is attributed to the significant amount of work hardening undergone by different tool material (Kumar et al. 2008).

Machining performance of diamond has been found to be excellent (Kazantsev 1966). The productivity of the USM process is reported to be directly proportional to the shape factor and tool form. Shape factor is the ratio of tool perimeter to the tool area and tool form defines the resistance offered by the tool to the slurry circulation (Kennedy and Grieve 1975; Farago 1980; Neppiras 1957). Hence, a tool with narrow rectangular section leads to better productivity in comparison to the tool having square cross-section and same area. Further, the tools with solid geometries have lower machining performance in comparison to that of the hollow ones having the similar cross-sectional area. The tool penetration rate is directly proportional to the tool perimeter for tools with equal contact areas. This is due to the difficulty that arises in distributing the abrasive slurry adequately over the machining zone.

Several reports have been made on the design of tool horns from different researchers; however there is still a lacuna in this regard. Rozenberg et al. (1964) have laid down detailed guidelines for designing of the tool for the optimum MRR. The traditional design methodology consists of the formulation of the differential equations on considering the equilibrium of the infinitesimal element under the action of different forces and then integrating the equations over the entire horn length to achieve resonance. Stepped, cylindrical and conical are some of the typical tool shapes. Efforts have been made to design symmetric tools using finite element modeling.

The MRR increases with the amplitude of tool oscillation. The velocity of the abrasive particles at which they strike the work surface is determined by the amplitude of tool vibration. As a result of the increased amplitude the kinetic energy of the abrasive particles increases which in turn leads to increased chipping action and hence the MRR. However, increasing the amplitude beyond the threshold results in splashing and hence reduction in the number of abrasive particles striking the work surface thereby decreasing the MRR. The MRR decreases with the increasing frequency of vibration. This may be attributed to the fact that lower time is provided to each grain and hence lower chipping action prevails.

6.2.4.3 Slurry Properties

The MRR is a function of abrasive's concentration, hardness and grain size. An optimum value of MRR is reached with the increasing grain size and slurry concentration. However, after the threshold limit for either of the aspects leads to decrease in the MRR because of the difficulty that the larger grains faces in reaching the cutting zone. The stress resulting due to the impact of large grains is another factor attributed to the increasing MRR. The optimum level of MRR is reached when the size of the abrasive grain is equivalent to that of the amplitude of the vibration.

The value of slurry concentration for the optimum MRR is inconsistent, with different researchers reporting different ranges such as 30–60% (Markov 1959), 15–40% (Nishimura 1954) etc. One of the factors that can be attributed to such inconsistency is the variation in abrasive slurry concentration under the tool within the working zone. This is obvious when for a particular setting the static load is too high. The unevenness in the slurry distribution leads to machining problems such as while machining a flat at the bottom of a whole.

The machining performance is improved by adopting the forced slurry circulation system without increasing the grit size or the power of the machine. The yield is two-three times when compared to the suction circulation system (Kazantsev 1963, 1966). On increasing the fluid pressure to 90 psi from 10 psi, four-five times increase in MRR was reported by Barash and Watanapongse, (Barash and Watanapongse 1970). The forced slurry circulation system also overcomes the adverse problems such as that of contamination and blockage.

Hardness of the abrasive slurry is another important factor that affects the MRR. For instance, MRR is 15–20% more for machining of soda glass with boron carbide in comparison to machining the same with silicon carbide. While machining ceramics, a 75% MRR is reported with boron carbide in comparison to silicon carbide for a grit size of 400 and about, while the yield is as high as 320% for a grit size of 220 (Ramulu 2005). Normally, with the hardness the MRR increases provided that the other experimental factors such as tool properties, work material properties etc. remain unchanged.

6.2.4.4 Operating Parameters

The mass of the tool horn is dependent on the machine power. Power of the machine also determines the frontal cutting area of the tool. A larger frontal cutting area of the tool can be supported for an application if the machine power is more. MRR is affected by the amplitude of vibration (Y) which in turn depends upon the transformation ratio i.e. the ratio of diameter of the transducer to that of the tool. A tool with large transformation ratio will result in higher amplitude of the tool. For a constant static load conditions and frequency of vibration different relationships have been advocated by researchers. MRR was reported to be proportional to $Y^{0.75}$, (Shaw 1956) or Y (Goetze 1956; Kazantsev 1966; Miller 1957; Thoe et al. 1995) or Y^2 (Neppiras 1957; Pentland and Ektermanis 1965; Rozenberg et al. 1964; Wang and Rajurkar 1995). The linear relationship between MRR and amplitude is much more prevalent for the machining of high strength materials or when using fine abrasive powders for machining. The MRR resulted is poor on coupling abrasives of large grit size with low amplitude. This is on account of poor circulation of the slurry under the tool.

The relationship between MRR and natural frequency as reported by researchers is proportional to $F^{0.5}$ (Neppiras 1957; Kazantsev 1966) or F (Gilmore 1989; Goetze 1956). The Non linear relationship may be accounted to the variation of the concentration of the abrasive slurry in the working zone. The linear relationship exists up to a certain threshold value beyond which the MRR falls of rapidly and the relationship becomes non-linear.

A linear relationship between the static load and MRR exists. A value slightly below the optimum value is suggested for carrying out the USM process with optimum MRR. Above a threshold vale the MRR decreases and the decrease in the MRR may be attributed to the poor slurry circulation and the reduced abrasive grit size reaching the working zone (Graff 1975; Kennedy and Grieve 1975; Rozenberg 1973; Snoyes 1986). The factors on which the optimum value of the static load depends on are amplitude, configuration of the tool and grit size.

6.2.5 Surface Quality and Dimensional Accuracy

6.2.5.1 The Surface Quality

USM doesn't lead to generation of layer/zone that is thermally damaged or has residual stresses. This is mainly because the process is free from generating significant heat. The main factor that governs the surface finish and accuracy of the workpiece is the grain size of the abrasive. Lower values of surface roughness are obtained with smaller grain sized (large grit size) abrasive particles. Besides grain size, the other factors that affect the surface finish are: amplitude of tool vibration, static load, feed rates, depth of cut, materials being machined. Increased depth of cut and feed rates results in better surface finish. The increased static load resulting in reduced grain size and lateral vibrations of the tool too results in a good surface finish. The amplitude on the other hand has an adverse but insignificant affect on the surface finish. Increased amplitude of the tool vibration results in greater pressure on the abrasive grains thereby leading to deeper crater and hence poor surface finish. The viscosity of the liquid carrier of the abrasive grains also affects the surface finish. Reducing the viscosity of the liquid carrying the abrasive slurry decreases the surface roughness.

Material being machined is another important factor affecting the surface finish of the surface being machined. The surface quality for a material with higher ratio of hardness to elastic modulus is low. The surface finish improves with the hardness of the workpiece material being machined. As for instance, ceramics have comparatively smoother surface finish to the ones with lower hardness materials. A poor surface finish results on carrying out USM for graphite. Cavitation, contamination and debris blockage are some of the factors that can be attributed to the poor surface finish of graphite. For glass the surface roughness is almost double than that for the graphite.

The sidewall surfaces of the cavities have comparatively larger surface irregularities than that of the bottom. This occurs mainly because of the scratching taking place at the sidewalls due to entering and leaving abrasive grains in the machining zone.

The surface quality obtained is the best while machining with H.C.S. tool, lower power rating machine and medium grit size. The slurry concentration has insignificant impact on the surface finish.

6.2.5.2 The Dimensional Accuracy

Dimensional inaccuracy and form inaccuracy are the two forms of inaccuracies that the parts produced from the USM suffer. A number of factors such as wear of the USM tool, uneven supply of the abrasive slurry, abrasive wear etc. leads to conicity, oversize and out of roundness.

Overcut the overcut i.e. oversize occurs when drilling of holes is performed. The oversize for hole is measured by calculating the difference between the tool diameter and the hole diameter at the top surface. The abrasive grain size is thus one of the main factors affecting the overcut since the gap between the hole and the tool is necessary to allow the abrasive grains to flow into the machining zone. The other factors affecting the size of the overcut include type of workpiece material being machined and the tool feed method. For instance, while machining tungsten carbide and glass the size of the overcut is generally about 2–3 times the mean size of the abrasive grain, while on the other hand it is three times the mean abrasive grain size for boron carbide. The oversize is greatest at the entry and greater oversize is resulted with increased lateral vibrations due to increased diameter-length ratio.

Conicity since overcut is greater at the entry in comparison to the exit, tapering of the hole results. For instance, the conicity for a hole with diameter of 20 mm and length 10 mm is around 2 degrees. A number of measures can be adopted to decrease the conicity. Use of tools with negative tapering and wear resistant tools is one such remedy. The use of undersize tool in the first cut and then using the tool of the desired size will also aid in reducing the conicity. Further, the direct injection of abrasive slurry and the use of high static pressure are some of the other remedies to reduce the conicity.

Out of roundness the lateral vibrations of the tool causes out of roundness of the drilled holes. The factors leading to the out of roundness of the holes include the out of perpendicularity of the tool face and the tool centerline and misalignment of the acoustic parts of the machine. To take care of the out of roundness of the hole, wide array of solutions have been reported by the researchers. For instance, researchers have reported the use of wax coating on the substrate such as glass that reduces the out of roundness of the machined hole at the exit section.

6.2.6 Applications

Ultrasonic machining is used particularly for more brittle and sensitive materials than the traditional metals. This is because of its advantage of non-alteration of physical properties of the material being machined. Ultrasonic machining finds numerous industrial applications such as fabrication of microelectromechanical system components, creation of high quality shapes etc.

6.2.6.1 Rotary Ultrasonic Machining

Rotary ultrasonic machining (RUM) is a hybridized version of the non-conventional machining process. It is combination of static USM and the conventional diamond grinding. This hybridization results in higher MRR than the static USM or the conventional grinding process. The MRR mechanism involves the removal of material by the grinding and micro chipping action of the abrasives (Pei et al. 1995; Cong et al. 2014; Jiao et al. 2005; Zvoncan et al. 2012).

The RUM process overcomes some of the drawbacks of static USM such as that of hole out-of-roundness, conicity and oversize and that of low MRR. Deeper and accurate holes can be drilled using the diamond impregnated tools without the problems of erosion of walls of machined holes due to existence of abrasive slurry. Therefore, it becomes easier to achieve closer tolerances while drilling holes.

The basic elements of RUM comprises of a data acquisition system, ultrasonic spindle assembly and a coolant supply system. The ultrasonic spindle system can be subdivided to comprise of a transducer, an electric motor, ultrasonic spindle and power supply system. A low frequency (50–60 Hz) is converted to high frequency (20 kHz) electrical signals using the sine generator in the power system. This energy is transmitted to the piezoelectric transducer which then converts the electrical signals to mechanical vibrations. The amplified ultrasonic vibrations are then transmitted to the diamond-impregnated cutting tool. The function of the electric motor is to provide rotary motion to the tool. The data acquisition system aids in measurement of several process response of interest and plots the measured data. Coolant system consists of pump, gauges, control valves and pressure regulator. Coolant fluid is supplied by the coolant unit for internal cooling to the spindle and for external cooling to the machining zone.

Material removal mechanism can be divided into three phases:

Hammering the material removal takes because of the indentation and crushing of the material being machined by the vibrating tool.

Abrasion the material removal here takes place due to rotational motion of the tool. The abrasion action is similar to that of conventional grinding.

Extraction material removal takes place because of the simultaneous vibration and rotational motion of the tool.

Out of the above described material removal mechanisms; hammering action is the most dominant one contributing for the material removal towards the tool tip, while on the other hand close to the drilled hole it is the abrasion action that is found to be dominant. The extraction action too is prevalent at the drilled hole's wall and is responsible for mixing of the debris with the pressurized coolant.

Brittle fracture is the most prevalent mode of material removal. However while machining of ceramics using the rotary USM, plastic flow in addition to the brittle fracture has also been identified by the scanning electronic microscopy (SEM). A new mode of material removal mode in the form of pulverization has been identified while machining of optical glass K9.

Rotary USM finds umpteen industrial applications such as that in aircrafts, automobiles, electronics, optical etc. The process has the capability to machine a wide array of engineering materials. Frequently used engineering materials such as stainless steel can also be machined using the rotary USM. Rotary USM has the capability to machine dental ceramics such as dental zirconia and macor. Material used in fabrication of chips and electronics circuits such as sapphire, optical materials such as BK7 and K9 have also been machined using the rotary USM.

6.2.6.2 Micro-ultrasonic Machining

With the rising need of miniaturization, the requirements of the micromechanical systems to fabricate miniaturized products have also risen exponentially. Micro-ultrasonic machining is one of the micromechanical systems that provide the process capability to produce three-dimensional microstructures with high aspect ratio. The materials that can be employed for the fabrication of miniaturized products using the micro-ultrasonic machining includes borosilicate glass, silicon, quartz i.e., materials where commonly known micromachining methods such as LIGA, micro-electrodischarge machining (micro-EDM) and the likes are restrictive.

The USM process lacks the capability to drill holes that are less than 100 μm. To overcome this, micro-ultrasonic machining exploits the combination of EDM, USM and wire electro discharge grinding (WEDG). The WEDG/EDM combination is used to manufacture the co-axial micro tools. These are then employed directly in USM to drill micro holes. The tool is attached to the tool system by soldering.

The set up does not require any horn for amplification of electronic signal, since the diameter of the hole drilled is too small.

6.2.6.3 Ultrasonic Polishing

There is quite a resemblance of ultrasonic polishing with ultrasonic machining. The minute distinction between the two is that in addition to the PC based controller a moving table is also employed in case of ultrasonic polishing. Vibrations with low amplitude and generated at high frequency are favorable for carrying out ultrasonic polishing. Ultrasonic polishing is suitable in applications requiring higher degree of precision and accuracy in finishing. A patterned path is followed by the vibrating tool covering the entire surface requiring polishing. One can easily find on the polished surface the plowing, indentation and microcutting by abrasives. However, the material removal rate is pretty low (1 mm^3/min).

6.2.6.4 Hybridization of USM

The applicability of ultrasonic assisted turning was reported by Babitsky et al. (2004) for the aviation materials. The ultrasonic assisted turning provides for better surface finish and improved roundness in comparison to that of the conventional machining. There are four stages in which the material removal mechanism can be divided. The cutting tool approaches the chip in stage 1 and the contact is made by the tool with the chip in stage 2. In stage 3, the tool starts to penetrate the workpiece. The maximum penetration depth is marked by the maximum stress level reached. In stage 4 the direction of tool is reversed marking the unloading of the tool from the workpiece.

The research has been reported for production of angular vibrations of the order of 40 kHz at the cutting tip. A new eccentric horn design together with a new longitudinal mode ultrasonic transducer aids to achieve the above objective (Sharma et al. 2003). The designed process provides its applicability to machine straight micro-grooves with excellent surface finish in comparison to the conventional grooving operation.

The ultrasonic vibrations were combined with the conventional drilling operation leading to decrease of about 70% in the drilling force. The ultrasonic assisted drilling operation results in decrease in chipping at the edge of the hole, however there is an increase of the surface roughness in comparison to the conventional drilling operation. The applicability of the ultrasonic drilling operation leads to improved circularity, cylindricity and therefore an overall improved quality of hole.

Another hybridized USM process is the ultrasonic grinding. Usually in the conventional grinding process, although the majority of the abrasive grains make contact with the workpiece but only a small number is engaged in cutting action. The grains that are not involved in cutting are the main source of heat generation. This leads to an overall reduced efficiency of the conventional grinding process. The dimensional accuracy of the machined surface is reduced due to the heat generation leading to the increased temperature in the cutting zone. Therefore in order to increase the efficiency of the process the main objective lies in increasing the engagement of the majority of the abrasive grains in cutting. This is achieved by imposing vibrations of high frequency and small amplitude in the working zone. The combination is known as ultrasonic grinding. The process finds applicability both for the ductile and brittle materials. A two-dimensional ultrasonic grinding method has been reported (Liang et al. 2010) that consists of an elliptical ultrasonic vibrator. The ultrasonic grinding leads to improved surface quality and decrease in the grinding force as well as the surface roughness.

6.3 Water Jet Machining (WJM)

6.3.1 Introduction

A water jet with high velocity (900 m/s and Mach 3) is the key element of the water jet machining process. The material removal takes place by erosion due to the high velocity jet striking the workpiece. A narrow groove is cut on the workpiece by the water jet and thereby the water jet acts like a saw.

6.3.2 Main Elements of Water Jet Machining

The main elements of the water jet machining are discussed in the subsequent sections. Figure 6.2 depicts the water jet machining process.

6.3.2.1 Pump

A 30 kW electric motor powers the hydraulic pump. The main function of the hydraulic pump is to drive the intensifier. An intensifier is a reciprocating plunger pump. The hydraulic pump supplies the oil at a high pressure of 117 bars which provides the driving force for the intensifier. A greater flexibility is offered by the pump for the water jet cutting. To take care of the increased production schedule, it offers to support multiple stations for cutting.

6.3.2.2 Intensifier

An intensifier functions to convert the pressure of the working fluid from low to ultra high pressure. The conversion is as high as 3800 bars from an extreme low pressure of 4 bars. The intensifier is powered by the fluid from the hydraulic pump which provides the oil to intensifier centre section. The direction of the piston is reversed by the directional control valves operated by a limit switch at each end of the piston travel. The pressure is generated in both the directions of because of the

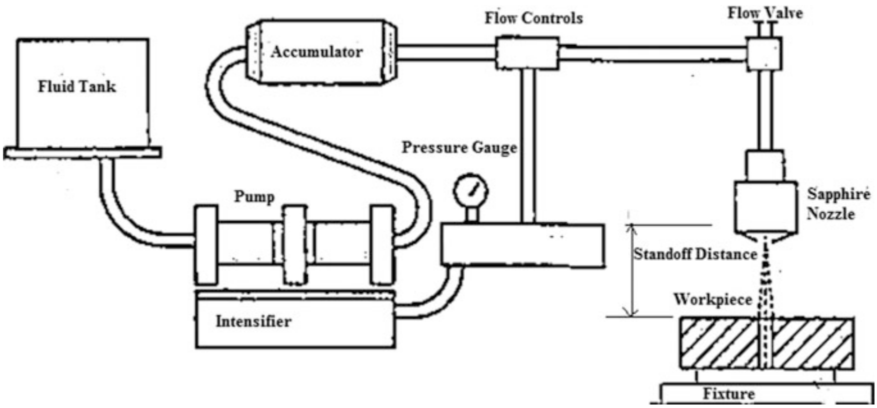

Fig. 6.2 Water jet machining process

plunger arrangement on either side of the piston of the intensifier assembly. One side is connected to inlet stroke receiving water while the other end is the output stroke that generates the ultra high pressure.

6.3.2.3 Accumulator

Any fluctuation in the water pressure is taken care of by the accumulator and thereby the continuous supply of high-pressure water is ensured. The compressibility of water during reversal of piston direction plays a critical role in maintaining a uniform water pressure and water jet velocity.

6.3.2.4 High-Pressure Tubing

The pressurized water is transported to the cutting head using high-pressure tubing. The specially designed manually operated or electronically operated valves control the cutting action.

6.3.2.5 Cutting Nozzle

The jet cutting nozzle provides for the coherent jet stream. The ultra high pressure jet stream has the potential to machine low-density soft materials that otherwise are difficult to machine using the conventional methods. The material of construction for the nozzle is generally synthetic sapphire. The life span of a nozzle is around 200 h. The damage to the nozzle takes place mainly by the particles of dirt and the mineral deposits arising due to the hardness of the erosive water. A multistage filtration is mainly adopted to remove the undesirable solid particles greater than 45 μm thereby aiding to increase the nozzle life. The flexibility of the cutting head provides for the integration with different control motion systems ranging from two-axis tables to the multi-axis ones.

6.3.2.6 Catcher

The collection of the debris from machining by the water jet is collected in a reservoir known as catcher. The reducing velocity of jet leads to increased noise level which is reduced by the catcher.

6.3.3 Process Parameters

The material removal rate and the surface quality and its accuracy are affected by a number of factors such as jet nozzle, jet fluid and workpiece. These factors are discussed next.

6.3.3.1 Jet Nozzle

The distance between the nozzle and the workpiece is known as the standoff distance. The typical values for the standoff distance lies between 2.5 and 6 mm. however, the value can be increased to 13–19 mm for printed circuit boards. The standoff distance impacts the depth of cut. The depth of cut decreases with the increasing standoff distance. Another factor influencing the width of damaged layer is the nozzle diameter. An increase in width for the damaged layer was reported for machining of fibre-reinforced plastics with the increasing machining rate and use of small nozzle diameter.

6.3.3.2 Jet Fluid

The velocity, type, flow rate, pressure and viscosity of the jet fluid impacts the machining rate. An increased pressure results in more power for the machining process and hence greater depth of cut provided that the diameter is kept constant. Power ranging between 8 and 80 kW is produced for pressure ranging between 150 and 1000 MPa. The typical values of jet velocities range between 540 and 1400 m/s. The lower transverse speeds and wide diameter of the jet under high pressure conditions leads to favorable conditions for machining of materials with high density and thickness. Further, the fluid must possess low viscosity, be nontoxic and non-corrosive. The low viscosity aids in minimizing the energy loss. For cutting of alloy steels, water is used, for meat it is alcohol while it is cooking oil for cutting frozen foods.

6.3.3.3 Workpice Material

The machining performance of the WJM is affected by the workpiece thickness, type and the feed rate. The ductile materials will cut well while the brittle ones will fracture. The thickness of the workpiece that can be cut well ranges between 0.7 and 25 mm or more. The feed rate also varies for different types of materials used. For instance, the optimum feed rate while cutting Kevlar is as low as 3 m/min while that for corrugated board it is as high as 200 m/min.

6.3.4 Applications

Many industries have explored the benefits of the water jet technology. A large number of industries have adopted one of the fastest evolving machine technologies in the form of water jet technology for sufficient efficiency gains and achieving higher productivity. The water jet machining process is environmentally sustainable and cost effective.

6.3.4.1 Water Jet Cutting of Stones

Over the decades the there has been a marked advancement in the water jet cutting of stones and tiles. The popularity of the machining technology is growing mainly because of the introduction of ultra-hard sintered ceramics such as porcelain. These materials are hard to cut using conventional saws. Although these new generation ceramics provides umpteen advantages to the end user, but the fabricators faces a wide array of problems to cut and mitre these materials. Water jet machining has proven to be the best answer for cutting and mitering these new generation ceramics. Besides ceramics, the water jet can pierce almost all stones, tiles and marble, irrespective of the degree of brittleness of the material being machined.

The current water jet technology allows for cutting the entire slab in one single operation by allowing the fabricators to load common DFX files onto the equipment, set the required edge finish and the mitre positions. The water machine incorporates "taper compensation technology" that aids in delivering a perfect 90 or 45° on the faces to be joined.

6.3.4.2 Water Jet Cutting of Glass

Water jet is one of the ideal alternatives to make internal cutouts in glass as it has the potential to pierce through most thickness. Currently, water jet is applied in a variety of glass processing applications that includes mirrors, kitchen and bathroom splashbacks, window panels, table top inlays, frameless shower screens etc.

6.3.4.3 Water Jet Cutting of Metal

The potentiality of the water jet has been exploited by many industries to cut a range of standard and exotic materials which includes aluminium, titanium, copper, brass, inconel, mild steel and stainless steel. The water jet cutting is often regarded as the cold process as the workpiece is free from any heat affected zone. Further, the materials under machining don't require any further finishing process. All these capabilities make the water jet cutting process one of the most versatile machining processes for metal cutting.

6.3.4.4 Water Jet Cutting of Foods

Cross contamination of foods is one of the major problems in the food industries while making high quality cuts. Water jet cutting technology has been used effectively in the food industry and thereby eliminating the problem of cross-contamination. The technology has proven to be the best for portioning of celery, fish and chicken. The use of water jet cutting has grown exponentially in the food industries as it offers to save time, reducing the risk of cross-contamination and increasing the shelf life of the food products. Further it leads to less wastage due to the ultra narrow cut and improved safety as it eliminates the use of sharp knives.

6.3.4.5 Water Jet Cutting for Automotive Industry

The water jet cutting has the ability to integrate itself with the robotic arm and therefore is a versatile technology for automotive industries. The water jet machining is preferred for production of automotives' insulation, carpets and head linings as the process supports minimum wastage with no mess.

6.3.4.6 Water Jet Cutting of Rubber and Composites

Speed, edge quality and reliability are some of the advantages offered by water jet cutting technology. These advantages makes the water jet cutting to cut foam, rubber, circuit boards, plaster boards, leather and fiberglass. A printed circuit board can be cut at a speed as high as 8 m/min or more.

6.3.4.7 Water Jet Cutting for Surface Treatment

Water jet cutting lends its applicability for the following:

- It removes residues and deposits without the use of any toxic chemicals and thereby eliminating costly disposal and cleanup problems.
- It provides to clean surfaces of castings, food utensils, surface texturing, degreasing and polishing.
- It prepares the surface for coating or painting by making the surface free from corrosion, soluble salts, spray residue and any damage caused to surface.

6.3.5 Advantages and Disadvantages of Water Jet Machining

6.3.5.1 Advantages

Water jet machining is one of the most versatile machining technologies, the advantages of which have been exploited by a number of manufacturing industries. The advantages of water jet cutting are listed below:

- The water jet machining process is free from the heat and therefore is suitable for materials the machining of which leads to generation of excessive heat which in turn results in change of properties of the material being machined.
- No dust particles are produced unlike the other conventional machining processes. The dust particles are harmful if inhaled.
- Very little material is wasted since the kerf width in water jet machining is very small.
- The prototypes can be efficiently produced. The water jet machining will cut the parts exactly as per the dimensions once the operator has programmed the dimensions of the part into control station.
- The water jet machining eliminates the use of further machining process such as finishing as the process doesn't leave a burr or a rough edge.
- The tool used doesn't require sharpening as the tool doesn't wear during the machining process.
- The process has the capability to cut multi directionally.
- The process offers for the lower turnaround time and cost because of the simple fixturing and elimination of complicated tooling.
- The water jet can penetrate to high thickness such as 383 mm in titanium.

6.3.5.2 Disadvantages

The water jet machining process has certain limitations which are discussed below:

- The numbers of materials that can be cut economically are low. Although it can cut hard material such as tool steel but the hourly rates are high. As such the process becomes a costly affair.
- The high maintenance cost involved doesn't make it a suitable choice for mass production.
- Although the water jet can penetrate the thick materials but it is difficult to hold the dimensional accuracy.

6.4 Abrasive Jet Machining (AJM)

6.4.1 Introduction

In abrasive jet machining, a stream of high pressure gas or air carries the abrasive grains, configured in focused stream. This focused stream impinges the work surface at a very high velocity of 200 m/s through the nozzle of very small diameter ranging 0.3–0.5 mm and stand-off distance of around 2 mm. The abrasive grains are directed towards the workpiece via a controlled delivery system comprising of nozzle. The abrasive action of the abrasive particles results in the material removal by abrasion. Further, the material removal also takes place by the brittle fracture of the workpiece material. The AJM process lends its applicability in cutting, deburring, cleaning, peening etc., of ceramics, hard metals or glass.

On the basis of abrasive flow media, the abrasive jet machining can be classified into:

- One-way AJM: the abrasive particles are pushed in one direction.
- Two-way AJM: to and fro motion of the abrasive particles takes place.
- Orbital AJM: the workpiece is provided small orbital motion.

6.4.2 Main Elements of AJM

The schematic of the AJM process is shown in the Fig. 6.3. The main elements of the AJM process comprises of gas propulsion system, machining chamber, abrasive feeder, nozzle and abrasives. These elements are discussed in brief in the following sections.

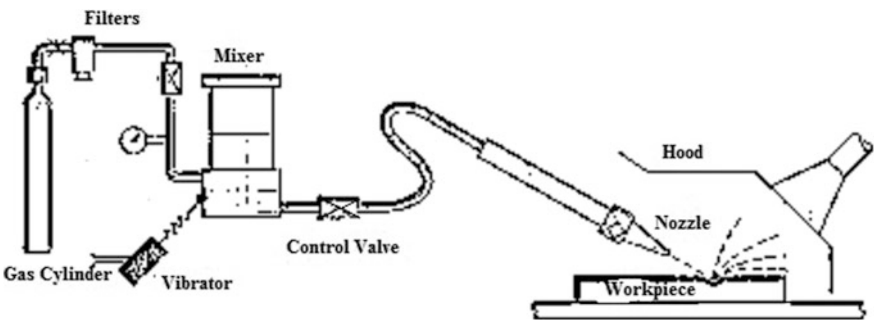

Fig. 6.3 AJM schematic

6.4.2.1 Gas Propulsion System

The role of the gas (nitrogen, Air, CO_2) propulsion system is to supply gas for carrying the abrasive particles. A cylinder or a compressor may be used to supply gas. An air-filter cum drier must be used in case the gas is supplied from the compressor. This ensures the prevention of contamination of the abrasive particles due to water or oil. Pressure ranging 2–8 kg/m^3 is generally used for supplying of the gas. Care should be taken to avoid oxygen as it can lead to violent chemical reaction with abrasives or the workpiece chips.

6.4.2.2 Abrasive Feeder

The abrasive feeder supplies the required quantity of abrasive particles. The abrasive particles are fed to the mixing chamber via a vibrating sieve. The frequency of vibration for the sieve is 50–60 Hz. The sieved abrasive particles mix with the filtered gas from the gas propulsion system in the mixing chamber. The amplitude of sieve vibration controls the mixing ratio. The mix of abrasive particles and gas then passes on to the nozzle.

6.4.2.3 Nozzle

Sapphire or tungsten carbide is the material of construction for the AJM nozzle. The cross sectional shape of the nozzle used is either rectangular or circular. The design of the nozzle is such that the pressure loss is as low as possible. High inaccuracy can result due to increasing divergence of jet nozzle which takes place due to increasing wear of the nozzle.

6.4.2.4 Abrasive

Aluminum oxide, magnesium carbonate, silicon carbide, sodium bicarbonate are some of the abrasive particles used in the AJM machining. The type of abrasive to be used depends on the type of workpiece material, machining accuracy and MRR. For heavy cleaning, deburring and cutting silcon carbide and aluminum oxide are employed, whereas for light cleaning and etching magnesium carbonate is recommended. Further, for cutting soft materials and fine cleaning, sodium bicarbonate is preferred. The commercial grade abrasive particles may contain silica dust and hence are not deemed suitable for the machining. The abrasive particles should not be reused as there may be decline in the machining rate due to the worn out particles.

6.4.2.5 Machining Chamber

The machining chamber is well isolated from the immediate surroundings. The chamber is equipped with glass, rubber or copper masks to make the stream of abrasive particles concentrate on the desired location on the workpiece. The machining chamber is well equipped with the dust removal equipment to take care of the dust generated due to machining of toxic material such as beryllium.

6.4.3 Material Removal Rate in AJM and Machining Characteristics

Before the abrasive particles flares out from the nozzle, the particles follow parallel paths inside the nozzle. On striking the brittle or fragile workpiece surface at high speed, the abrasive particles dislodge the particles from the surface through the brittle fracture mechanism. The carrier gas carries away the dislodged workpiece particle. The MRR in the AJM process is given by the following equation:

$$MRR = KNd_a^3 v^{3/2} \left(\frac{\rho_a}{12H_w} \right)^{3/4}$$

where,

N	number of abrasive particles striking the surface per unit area
v	velocity of abrasive particles, m/s
ρ_a	density of abrasive particles, kg/mm^3
H_w	hardness of the workpiece material
K	constant
d_a	mean diameter of the abrasive particles, μm

There are certain process criteria that must be analyzed for the successful utilization of the AJM process. These process criteria are: MRR, wear rate of nozzle and the surface finish and geometry of the workpiece. These process criteria are influenced by certain process parameters such as abrasive particles, abrasive jet, carrier gas, and nozzle. The influence of process parameters on the process criteria are discussed briefly.

6.4.3.1 The Effect on MRR of Abrasive Flow Rate and Grain Size

For a given pressure, the MRR in the AJM process increases with the abrasive flow rate up to a certain optimum value beyond which the MRR drops. The fall in MRR after optimum value can be attributed to the fact that with the increasing abrasive flow rate the mass flow rate of the carrier gas decreases. This leads to decreasing mixing ratio and hence less energy is then available for the erosion.

6.4.3.2 The Effect of Abrasive Particle Density and Exit Gas Velocity

The density of the abrasive particle affects the velocity of the carrier gas. With the increasing particle density the exit velocity of the carrier gas decreases. The exit velocity of the carrier gas is at its critical value when the internal gas pressure is twice that of the pressure at the nozzle exit. The same can also be achieved when the density of the abrasive particle is zero. The exit velocity decreases beyond the critical value as the carrier gas is responsible for the transportation of the abrasive particles and as such the MRR will also decrease.

6.4.3.3 Effect on MRR of Nozzle Pressure

Increasing the gas glow rate will result in increasing abrasive flow rate if the internal pressure of the gas is increased. The increasing internal gas pressure results in increasing abrasive mass flow rate and hence the MRR.

6.4.3.4 Standoff Distance

The distance of the nozzle tip from the workpiece surface is known as the standoff distance. The flaring of jet results on increasing the standoff distance and hence poor accuracy. The MRR increases with the increasing standoff distance and then decreases. The penetration rate too increases with the standoff distance. The accuracy is improved with the decreasing standoff distance. Further, the kerfwidth and taper in the groove machined is decreased with the decreasing standoff distance.

6.4.4 Applications

- The AJM process abrades the glass surfaces more economically in comparison to other processes such as grinding or etching.
- AJM is useful in cleaning smears on oxides of metals, ceramics, resistive coating etc.
- Cuts germanium, silicon and other thin and fragile components.
- Hard and brittle material can be cut, deburred, polished and etched.
- Is useful in machining of heat sensitive materials such as quartz, mica, silicon, ceramics etc.
- The AJM process is useful in drilling of small holes and milled slots.
- Deburrs cross holes, threads and slots in small precision parts such as hydraulic valves, medical instruments etc., requiring burr free surfaces.
- Trims hybrid circuit capacitors, resistors, gallium etc.

- Since the stream of abrasive particles has the capability to follow contours it finds application in removal of films, cleaning of irregular surfaces.
- Stripping of the wire and cleaning the wire without causing any effect to the conductor.

6.4.5 Advantages and Disadvantages of AJM

6.4.5.1 Advantages of the AJM Process

- The AJM process has the capability to machine heat sensitive and brittle materials
- Since there is no contact between the tool and workpiece, the process is free from vibrations and chatter.
- The maintenance of the AJM equipments is very low.
- AJM process has the potential to cut holes of intricate shapes in hard materials.
- Refractory and superalloys can be easily machined using the AJM technology.
- The AJM process doesn't demand any change in the tool.
- Machining capacity utilization is high.
- For starting the operation there is no requirement of initial hole.
- Sharp corners of intricate parts can be machined.
- The power consumption in the AJM process is low.
- No damage to the workpiece surface since no heat is generated during the process.

6.4.5.2 Disadvantages of the AJM Process

- The material removal rate is low.
- The accuracy of the machined hole is one of the major problems in AJM process which may occur due to flaring of abrasive jet leading to tapered hole.
- While machining of soft materials the abrasive particles may get embedded in the work surface.
- The life span of the nozzle is limited.
- Damage of nozzle due to short stand off distances occurs.
- The silica dust generated during the machining process is hazardous to health.
- Only hard and brittle materials can be machined.

6.5 Abrasive Water Jet Machining (AWJM)

6.5.1 Introduction

Abrasive water jet machining (AWJM) was commercialized in the year 1993. It was used for the linear cutting of plates and sheets made of different materials. With the advancement and research in the field of non-traditional machining process, the AWJM process is being used in a wide array of operations such as cutting, turning, deburring, milling and polishing. The AWJM process is a versatile technology that finds application in a wide range of industries ranging from small machine shops to large industries such as shipbuilding, automotive etc.

In the AJWM process, high pressurized water strikes the material to be machined and thereby leading to material removal by abrasion (Ramulu and Arora 1993; Vikram and Babu 2002; Wang 1999). The pressurized water has a higher velocity when it passes through a narrow container (Wang 1999; Chen and Siores 2001; Harish 1984) where it mixes with the abrasive particles. The high level of energy associated with the mixture of high velocity water and abrasive discharges through a nozzle. The stream containing the mix strikes the workpiece material causing its wearing and hence machining is achieved.

No heat is generated during the AWJM process and therefore it is regarded as the cold-working process. The material removal mechanism employs the erosion property of the fluid to remove the material at the workpiece surface. Since there is no heat generation in the cutting area, significant improvement can be observed in the machining performance and the quality of the workpiece surface (Hlaváč et al. 2009; Liu et al. 2004; Ma and Dream 2006; Momber and Kovacevic 2012).

There have been several advancements in terms of material and hardware structure with the use of AWJM process in the metal industry. AJWM finds application for a wide range of materials ranging from ductile and soft materials to brittle and tough materials. Further, a considerate saving in machining time and increase in efficiency has been achieved with AWJM process employing multiple cutting heads (Hashish 1988, 1989a, b, 1991a). The AWJM process has therefore become one of the most versatile technologies to be employed by a wide range of industries manufacturing consumer products such as aeronautics and automotive (Choi and Choi 1997; Fowler et al. 2009; Hlaváč et al. 2009; Liu et al. 2004; Ma and Dream 2006; Hashish 1991b; Kovacevic et al. 1997; Kunaporn et al. 2005).

6.5.2 Construction and Working of AWJM

The machining system consists of the following elements.

6.5.2.1 Reservoir

The reservoir stores water that is used for machining.

6.5.2.2 Hydraulic Pump

The water from the reservoir is pumped to the intensifier at a low pressure of around 4 bars.

6.5.2.3 Intensifier

It accepts water pumped by the hydraulic pump. As the name implies the function of the intensifier is to raise the pressure of water ranging 3000–4000 bars.

6.5.2.4 Accumulator

The role of the accumulator is to store the high pressurized water temporarily.

6.5.2.5 Flow Regulator and Control Valve

The direction and the pressure of water to be supplied to the nozzle are controlled by the control valve while the flow regulator regulates the flow of water in accordance with the cutting requirements.

6.5.2.6 Nozzle

The nozzle receives the high pressurized water converting it to high velocity jet. Natural sapphire stone is generally the main construction element for the nozzle. The diameter of the nozzle is dependent on the application for which the AWJM process is to be used. Nozzle wear is one of the prominent problems that can lead to reduction in cutting ability of the nozzle. Typically the nozzle life ranges 100–200 h.

6.5.2.7 Mixing Tube

The mixing jet of water discharging through the nozzle and the abrasive particles takes place in the mixing tube. Tungsten-carbide is generally the construction material of the mixing tube. The mixing tube however needs frequent replacement because of the wear caused by the abrasive particles.

6.5.2.8 Catchers

The function of catcher is to collect the abrasive particles after the cutting operation is complete. Often the design of the catchers is customized in accordance with the specific job.

6.5.3 Working of AWJM Process

A hydraulic pump is used to pump the water from the reservoir to the intensifier. The pressure of the water received at the inlet of the intensifier is low which is increased to the level as desired by the machining requirement. The accumulator then receives the high pressurized water from the intensifier where it is stored temporarily. The water from the accumulator passes on to the nozzle through the control valve and the flow regulator. The pressure energy of the water is converted to result in high velocity water jet at the exit of the nozzle. This high velocity water jet with abrasive particles leads to removal of material on striking the workpiece surface.

6.5.4 Nozzle Characteristics

Nozzle is one of the most important components in the AWJM process and therefore its characteristics need a brief discussion. Nozzles of varying length and diameters are employed in the AWJM process. Different materials such as silicon carbide, composite carbide, boron carbide and tungsten carbide are used for the construction of nozzle with each material having unique physical properties aimed at increasing the life span of nozzle.

Three different regions can be observed by understanding the physical representation of the water jet stream. A continuous linear structure is observed in the initial region. However due to interaction with the surrounding air the linear structure of the jet falls apart and transforms to droplets in the transition region. The velocity of the droplets in the transition region remains unchanged. However, as the interaction with the surrounding increases the velocity of the droplets decreases. The decrease in velocity could be observed in the final region of the jet characteristics (Yanaida and Ohashi 1974, 1980).

The wear characteristic is another important aspect which influences the economics, performance, and precision of the AWJM process (Nanduri et al. 2000). The nozzle wear will lead to undesirable changes in the geometry of machined surface and thereby degrading its quality. In order to obtain the nozzle wear profile, wear tests are required to be done which can be categorized into regular wear test and accelerated wear test. While on the one hand hard abrasive particles or soft nozzle materials are used for performance of the accelerated wear test, the regular wear tests are performed using standard nozzle or abrasive particle (Nanduri et al. 2000, 2002; Gupta 2012). Several methods such as gage pin method, weight loss method and bore profile are also used for the determination of the nozzle wear profile.

Some of the important parameters affecting the nozzle wear characteristics are nozzle length, nozzle diameter, nozzle inlet angle, water pressure, orifice diameter and abrasive flow rate. The longer the nozzle the slower is the rate of wear at the exit section as there will be delay for the wear rate to reach the nozzle exit section owing to the length of the nozzle. The suction and mixing characteristics is affected by the nozzle diameter. A large diameter results in inefficient entry of the abrasive particles i.e., the water flow rate will increase while the abrasive concentration decreases. The nozzle diameter and the nozzle weight decreases with the increasing nozzle length. Further, the exit diameter of the nozzle decrease with the increasing nozzle inlet angle.

The nozzle wear need to be prevented as it results in problems in the performance of AWJM process. An online tracking system was proposed (Kovacevic 1991) which make use of wear sensor to track the wear in the AWJM process. The tracking system comprises of conductive loops being divided into four sections. Each conductive loop is implanted on the tip of the nozzle and located on the ceramic's substrate. The sensing system tracks the direction of wear propagation. An alternative to the sensing system is the use of lubricated nozzle to prevent the nozzle wear. The collision between the nozzle wall and the abrasive particles is prevented by the presence of oil between the wall and the abrasive particles and hence the nozzle wear is also prevented.

6.5.5 Application of AWJM Process

The section discusses the different applications of the AWJM process.

6.5.5.1 AWJM for Advanced Ceramic Materials

Ceramics are used in electronics, optical, biological and mechanical industries because of their superior corrosion and wear resistance, hardness and high temperature strength. Therefore machining of ceramics using conventional machining processes is a costly affair owing to the hardness and strength of ceramics. Hence, non-traditional processes such as electro discharge machining, ultrasonic machining and lasers are being used for the machining of the ceramics. However, these non-traditional processes come with their own limitations such as the laser cutting leaves behind a heavy crust, the level of accuracy etc. The process capabilities of the non-traditional machining process are extended by the AWJM process for the machining of ceramics.

Studies have been conducted by researchers to establish the relationship between the different machining parameters and the quality of ceramics produced using the AWJM process. For instance, the slotting operation using the AWJM process on aluminum oxide and silicon nitride ceramics produces a smoother kerf surface when using the fine-mesh abrasives at moderate transverse speeds and with sufficient supply of hydraulic energy. The hole quality obtained by carrying out precision drilling on the ceramic-coated components can be controlled by the jet feed rate and dwell time.

6.5.5.2 AWJM for Composite Materials

Despite of higher market price, composites have gained popularity in manufacturing of products with less weight and high strength. The composite manufactured components find application in aircraft, space and automotive sectors. However, machining of composites with conventional machining process doesn't provide the accuracy as provided by the non-conventional machining process such as AWJM process. AWJM process is found to be suitable for their machining because of number of advantages such as low thermal damage, small cutting forces etc.

6.5.5.3 Abrasive Water Jet Turning (AWJT)

Since the days of its inception, several experiments have been conducted for the machining, designing and application of the AWJT process. The experiments have been conducted on the materials with growing attention in a large number of engineering applications such as composites, ceramics, glass etc. AWJT is a faster process that machines a surface without damaging its surface integrity and hence is now replacing some of the prevalent non-conventional machining processes such as ultrasonic machining, laser beam machining etc. Several attempts have been made to study the impact of AWJT parameters on the machining performance with the different materials. For instance, an increase in material removal rate was reported with the pump pressure and the abrasive flow rate while machining Al6061 alloy (Hanish 1995), increased surface roughness was reported with the increased nozzle feed rate, pump pressure and standoff distance while machining glass (Zhong and Han 2002), a high surface roughness was reported while machining low density polyethylene material (Kartal et al. 2014).

Several customized AWJT experimental setups have been developed for machining of a wide range of materials of different shapes and sizes. For instance, a testing apparatus involving a direct connection of electric motor to the insulated spindle have been used for machining of glass samples (Hanish 1995), a safety cabinet for the driving motor and the spindle was used while machining of the cylindrical samples to avoid the unfavorable conditions during the AWJT process (Kartal et al. 2012).

Owing to the versatility of the AWJT process several mathematical models have been developed to study different machining parameters of the process. A mathematical model based on the Bernoulli equation has been developed to study the surface roughness and material removal rate for machining of AISI 4340 steel (Li et al. 2012). Another mathematical model was developed to study the final diameter for the ductile material (Zohourkari and Zohoor 2010).

In order to improve the machining performance of the AWJT process, several modifications such as controlled nozzle oscillation, forward angling and multi-pass cutting have been proposed by the scientific community which however requires further investigation. The possibility to cut a free-form object needs to be explored. For instance, to overcome the drawbacks of grit contamination and dirt accumulation further investigation needs to be done. Further, a fully automated monitoring system for the AWJT process is required for its applicability in many more industrial applications.

6.5.6 Advantages and Disadvantages of AWJM

6.5.6.1 Advantages of AWJM

- The AWJM is comparatively process in comparison to the other machining processes
- It is a cold process and hence doesn't leads to thermal damage of the machining surface
- The AWJM doesn't produces any hazardous gases and is therefore eco-friendly
- Is capable of producing all sorts of shapes with only single tool.
- The AWJM process is relatively cheaper process in comparison to other process
- A very little material is wasted because of the small kerf width in waterjet cutting
- The process is easy to operate as the operator only needs to program the dimensions into the machine and the part will be produced exactly as desired.

6.5.6.2 Disadvantages of AWJM

- The process is capable of cutting only a limited number of materials economically.
- The AWJM process cannot cut very thick parts as the jet will deflect and cut diagonally. A wave pattern on the surface can also be produced.
- The machining of very thick parts can also lead to taper and thereby leading to dimensional inaccuracy.

6.6 Ice Jet Machining (IJM)

A number of limitations and inconveniences are encountered while using the mixture of water and particles. The AWJM has lower energy efficiency and the cost of processing is increased with the addition of abrasive particles. Further, the use of abrasive particles in some of the applications is not possible. Examples include cleaning of sensitive surfaces, processing of meat products etc. Therefore, it has always been a quest to increase the productivity of the water jet while avoiding solid emissions. The objective has been achieved with the use of ice as the abrasive particles resulting in the development of ice water jet machining. Although ice as an abrasive particle has low productivity but the IJM process is a versatile technology for biomedical, food and other industries where contamination of the workpiece is a major source of concern. The IJM is one of rapidly growing green machining tools.

One of the main objectives in the ice jet machining processes is to make use of smaller sized ice particles, as smaller the grain size the better is the surface finish. A wide array of research has been carried out in this regard. In one of the arrangements, the ice cube blocks are cooled using liquid nitrogen. The blocks are then transferred to a mechanical crusher where the bigger ice cube blocks are reduced to smaller sized particles. The smaller sized ice particles are then transferred to a venture nozzle. In another arrangement, an apparatus to produce ice particles was developed that consists of a pressure reservoir, a flow spreader, a mixing chamber, freezing chamber and a pneumatic atomizer.

To achieve the maximum efficiency from the process it is desirable to keep the temperature of ice grains as low as possible. This is because of the decreasing trends shown by different deformation properties with the increasing temperature. For instance, the hardness of ice has been reported to decrease with increasing temperature. The hardness of ice as measured at a temperature of −78.5 °C is 6 Mohs which increases further at temperatures below −78.5 °C and is quite comparable to hardness of soft mineral abrasives which have the hardness of 6.5 Mohs. Further, the thermal conductivity coefficient increases with the decreasing temperature and is an important during the injection phase where the smaller sized ice particles are accelerated by high-temperature water jet.

IJM process has the process capabilities and advantages of both the water jet and abrasive water jet machining processes. It can machine various materials such as ceramics, glass metals etc. Further, the process doesn't contaminate the site of impingement. The green nature of the IJM process makes it one of the versatile tools to be used in a large number of industries on a large scale.

The main drawback of the IJM process lies into generate and handle the ice particles. Further, the productivity of the process is low in comparison to the AWJM process owing to the reduced hardness of the ice abrasive particles.

Several applications of ice jet machining are emerging such as material processing, reengineering and product reclamation. The IJM process is being used for the precision cleaning of highly delicate and complex biomedical, mechanical and electronic components. Some of the other important applications of the process include cleaning of sensitive parts such as the linings of food processing reactors, pharmaceutical reactors, aircraft skin etc. and that of discarded parts for reuse.

6.7 Magnetic Abrasive Finishing (MAF)

6.7.1 Introduction

In different fine finishing operations such as lapping, grinding, honing etc., microcracks may occur in the workpiece surface because of the normal stresses from the rigid tool. As a result of the induced stresses, a reduction in the reliability and strength of the machined surface is observed. One of the new finishing processes is the magnetic abrasive finishing process in which the possibility of the microcracks on the workpiece surface is reduced owing to the controlled forces acting on the abrasive particles. The MAF process employs the magnetic field to produce surfaces with high surface quality. Internal and external surfaces can be produced with surface roughness in the nanometer range. Further, the MAF process is capable to finish non-rotatable workpiece such as bent tubes and elbows. A number of advantages such as self-adaptability, controllability, self-sharpening etc. are associated with the process.

6.7.2 Working Principle of MAF

Flexible magnetic abrasive brushes are formed by the magnetic abrasive particles that joins with each other along the line of magnetic force owing to the magnetic field between the north and south poles. The magnetic abrasive particles are composed of ferromagnetic particles and abrasive powder. There are two types of magnetic abrasive particles- bonded and unbonded. On the one hand sintering of the abrasive powder and the ferromagnetic particles produces bonded magnetic abrasive particle, the unbonded particles are produced adding the lubricant in the mixture of ferromagnetic particles and the abrasive powders. The magnetic abrasive brushes formed by the magnetic abrasive particles acts as multi-point cutting tool for performing the finishing operations. The magnetic abrasive brush rotates as the north pole of the magnet rotates.

6.7.3 Material Removal in MAF

Microcutting is the basic mechanism for material removal in the MAF process. The material is removed in the form of tiny chips. The volume of the tiny chips produced is equivalent to the grooves produced on the workpiece surface. The MAF process makes use of the mechanical and magnetic energies. The rotation of the North Pole generates tangential force at the cutting edge of the magnetic abrasive particles. The radial and normal force on the abrasive particles is created by the magnetic energy. The compressive reaction on the workpiece surface is a result of the normal magnetic force which is responsible for the cutting edge penetration into the workpiece. The material removal taking place in circular paths is a result of the resultant of the mechanical tangential force and the magnetic radial force. However, the effect of magnetic radial force is negligible in comparison to that of the mechanical tangential force and therefore the cutting force on the edge can be taken equal to the mechanical tangential force. Further, the force required to remove the material from the workpiece surface is dependent on the shear strength of the workpiece material.

Three main conditions may exist between the resultant cutting force and the force required to remove the material describing the material removal process:

- The force required to remove the material is equal to the resultant force at the cutting edge which indicates the start of the finishing operation
- The force required for material removal is less than the force at the cutting edge indicating the material removal process.
- The force required is greater than the force at the cutting edge indicating that no action is taking place.

6.7.4 Applications of MAF

6.7.4.1 MAF of Rollers

Economical machining of advance ceramics while meeting the requirements of minimal surface defects and hence the accuracy is difficult by the conventional polishing and grinding techniques. To cost effectively machine the advanced ceramics such as silicon carbide, silicon nitride etc. alternative technology in the form of magnetic assisted polishing is employed. There are two variants to the magnetic assisted polishing: magnetic abrasive finishing and magnetic float polishing. In case of the magnetic abrasive finishing process the ceramic rollers or steel rollers are clamped in the chuck of the spindle that provides the rotator motion. The relative oscillating motion of the magnetic poles with regard to the workpiece results in the axial vibratory motion of the workpiece material in the magnetic field. The required finishing pressure is exerted by the conglomerate of magnetic abrasive particles inserted in between the magnetic heads and the workpiece material.

6.7.4.2 MAF of Cutting Tools for Machining of Titanium Alloys

A number of advantages are associated with the titanium alloys such as low coefficient of thermal expansion, excellent corrosion resistance, light weight, good biocompatibility and high strength-to-weight ratio. Even at elevated temperatures these advantages are exhibited by the titanium alloy. Titanium alloys therefore finds applications in airframe components and aerospace engines. However it is difficult to machine titanium alloys because of their chemical affinity to the cutting tool materials and the low thermal conductivity leading to tool wear. One of the main reasons for the tool failure is the high temperature at the tool-chip interface and therefore a reduction in friction between the chip and the tool encourages smooth flow of the chips and hence slows down the tool wear rate. This can be achieved using the magnetic abrasive finishing process which by means of magnetic abrasive particles smoothes the surface while following the workpiece.

6.7.4.3 Micro Deburring for Precision Parts with MAF

Surface and edge quality is the important parameters which can help in evaluating the quality of precision parts. The rounding process and the deburring process determine the geometry of the edge whereas the surface quality is determined by the stress state of surface and the surface roughness. MAF process is used as one of the finishing methods for the precision parts that removes defect such as burrs, roughness and scratches.

6.7.4.4 MAF for Internal Finishing of Capillary Tubes

The capillary tubes made of Austenitic stainless steel has got a wide range of applications in medical devices such as needles and catheter shafts for biopsy procedure or biopsy procedure. Owing to their application, a smooth interior tube is required so that the tube can be kept free from any kind of contamination. However with the increasing tube diameter the finishing process becomes a more difficult task. A variety of magnetic assisted finishing processes such as MAF have therefore been developed to aid in finishing operation to be performed not only on the easily accessible areas but also on difficult to access areas. However, the finishing process is carried out in a number of steps and thereby increasing the time of finishing.

6.7.5 Advantages and Disadvantages of MAF

6.7.5.1 Advantages of MAF

The MAF process involves loose abrasive particles, very low forces and therefore the damage to the workpiece surface is minimized. Following are some of the advantages of the MAF process over some of the conventional processes such as honing, superfinishing and lapping:

- The machining of conical and cylindrical surfaces or any other mutually perpendicular configuration and any other combination simultaneously is possible.
- The finished surface is free from thermal defects and buns.
- The MAF is simple to implement, ecologically sage.
- Several non-ferrous alloys such as brass and aluminum alloys can be easily finished.

6.7.5.2 Disadvantages of MAF

A number of disadvantages exists with the MAF process and are listed as follows:

- It is difficult to finish a wrinkled surface of workpiece.
- The finishing of micro-scale material using the MAF process can cause damage to the workpiece surface.
- Surface finishing on ferromagnetic materials such as nickel and cobalt is negligible.
- The MAF process has low efficiency and low MRR on application to hard materials.
- There is a possibility of impregnation of MAF media into the workpiece surface.

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Chapter 7
Chemical Machining

7.1 Introduction

The material removal in the chemical machining processes takes place by the controlled chemical dissolution of the workpiece specimen in the presence of strong reagent. The regions from where the material removal is to be restricted are protected by the maskants. The chemical energy is therefore the main source for the material removal process.

The chemical machining process has number of advantages such as ease of machining complex contours with weight reduction, low scrap rates, burr free surfaces, no residual stress etc. With the advantages the chemical machining processes however suffers from number of limitations such as difficulty in handling of the chemical reagent, requirement of metallurgically homogeneous surfaces for best results etc.

The chemical machining assumes various forms such as photochemical machining, chemical milling and electropolishing depending on the application for which it is intended to serve. These different forms of the chemical machining process are discussed in the present chapter.

7.2 Chemical Milling

7.2.1 Introduction

Chemical milling, shown in the Fig. 7.1, utilizes the chemical etching process for milling of metals. It is also referred to as “Chemical contour machining”. To create the three dimensional features the etching depth with this technique is kept equal to the thickness of the material. The process is employed to remove materials from parts that have a strength-to-weight ratio. It also finds application in producing

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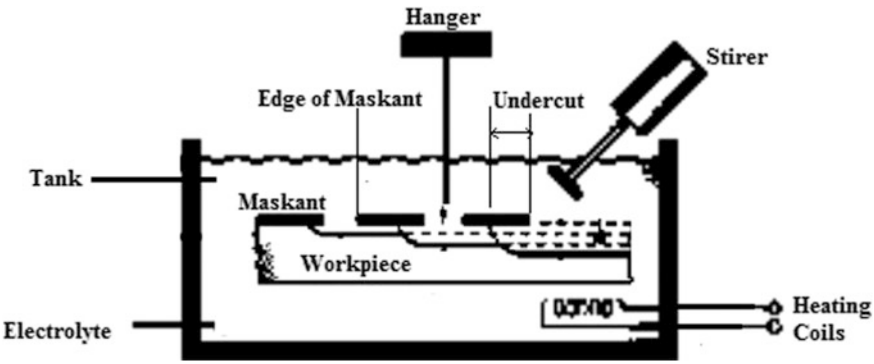

Fig. 7.1 Chemical milling

shallow cavities on sheets, plates, extrusions and forgings. *Etchant* and *maskants* are the two key elements used in the chemical milling process. To protect the material parts from which the material removal is not required maskants are used. Chemical milling consists of four major process steps:

- *Pre-processing*. In this step the workpiece material is prepared and pre-cleaned. The pre-processing steps aid to keep the workpiece material free from the contaminants and ensure a good adhesion of the maskant.
- *Masking*. A mask known as maskant is used to protect the parts not undergoing the chemical milling process. The mask used should be strippable, chemically impregnable and should be adhesive enough so that it has the capability to withstand the chemical abrasion during etching. Number of factors such as desired resolution of details, the number of parts to be produced and size of the workpiece material determines the type of the type of masked to be used.
- *Scribing*. To expose the parts for the chemical milling process, scribing of the mask is done using a wide range of available templates.
- *Etching*. Etchants are used to chemically mill the exposed parts of the workpiece.
- *Post-processing*. After the process is completed, the parts should be thoroughly rinsed to prevent any further reaction with any of the residual etchant. The masking material is then stripped and the part is finally inspected.

Given the corrosive nature of the chemicals used, safety precautions must be properly ensured before the initiation of the chemical milling process. Further, fresh chemicals must be used in order to take care of any uneven machining. Excessive flow of the solution must be avoided to prevent ridges, grooves or channeling. Channeling from gas bubbles may be prevented by inclination of the workpiece material. Heat is generated during the chemical process and therefore care must be taken for the uneven heat distribution which may otherwise lead to dishing of the machined surface (Bellows 1982; Metals Handbook 1989). High temperature results in a faster etching rate, however to ensure uniform machining the process

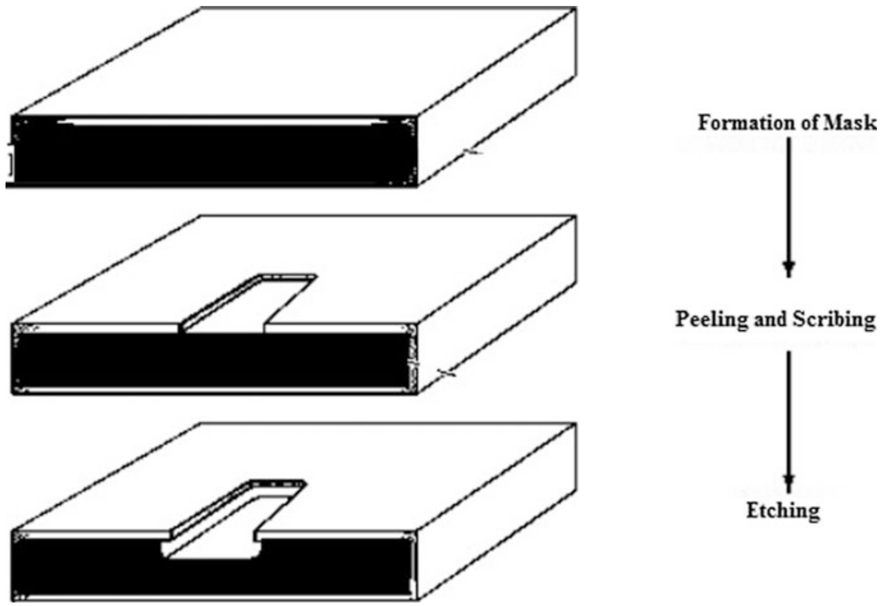

Fig. 7.2 Chemical milling

must be controlled within ±5 °C of the desired temperature which ranges between 37 and 85 °C.

Etch factor is created because of the machining operation proceeding both inwardly and laterally from and beneath the mask respectively. Etch factor is the ratio of undercut to the depth of cut. The ratio must be given due consideration when the mask is scribed using the templates. With deeper cuts the etch factor reduces. Racks or handling fixtures are employed for the submersion of the work in chemical reagent. This arrangement is particularly helpful in machining of large number of parts simultaneously. Demasking operation is initiated once the workpiece has been rinsed off the chemicals. Chemical stripping, mechanical brushing or hand stripping is utilized to complete the demasking operation.

Stepped cuts, as shown in the Fig. 7.2, can be achieved by successive steps of mask removal and immersion. Further, by controlling the depth and rate of immersion the tapered cut can also be produced. While producing tapered cuts, number of immersion also play a critical role.

7.2.2 Tools for Chemical Milling

The chemical milling process employs four tools: maskants, etchants, accessories and scribing templates. These are inexpensive and can be easily modified.

7.2.2.1 Maskants

Maskants is the masking material that protects the workpiece material from the etchant.

The materials that are generally used as maskants are rubber or polymer based material. Following properties are required to be possessed by a maskant:

- The material should be able to withstand handling and therefore should be tough.
- The adhesiveness of the material should be high enough to stick to the workpiece wall.
- Scribing could be done easily.
- Inertness to the chemical etchant used.
- Heat resistance should be high to withstand the heat from the chemical reaction.
- Should be inexpensive and easy to remove after the completion of the etching process.

There are number of methods for application of the maskant. Following is a discussion on two of the most commonly used techniques for application of the maskant:

- Masking by brush, dip, spray or roller the maskant is applied on the entire workpiece material by dipping, spraying, brushing. The scribing template is then used to remove the maskant from the area that is to be exposed to the chemical etchant. Stiffeners are employed to prevent the movement of the template from the thin sections while the scribing operation is performed.
- Applying mask using silk screens This method of application of the mask is used when fine details are demanded in case of the complex configurations or patterns. The screens consist of the design imposed on them and the maskants are applied through the imposed design on the screen. Since no peeling operation is required, the masking operation is accomplished along with the scribing operation. Further, the quality of the product is improved. However, the mask applied using the screens will not be able to last for long against the etching agent used.

7.2.2.2 Etchants

Etchants are the alkaline or acid solutions used in the chemical milling process. The etchants achieve the following functions:

- High level of surface finish.
- Uniform metal removal rate.
- In case of titanium alloys, to control the hydrogen absorption.
- Maintain the personal safety.
- Cost per unit weight should be low.

- Maintain the desired levels of air quality.
- Avoid the problems related to the environment.

7.2.2.3 Scribing Templates

The area of exposure to the etching agent is defined by utilizing the scribing templates. Using a sharp knife to cut the mask and then peeling of the mask carefully from the selected areas is one of the most common methods of scribing the workpiece. The scribing process is guided by the simple templates of glass or metal or layout lines. Care must be taken to include the etch factor allowance in any scribing method.

7.2.2.4 Accessories

These are employed to carry out single-or-multiple workpiece handling in and out of the etching agent and further for rinsing. The different accessories consist of brackets, racks, hooks, tanks and fixtures.

7.2.3 Process Parameters in Chemical Milling

The different chemical milling process parameters include the solution type of the reagent used, properties, circulation, concentration and operating temperature. The maskant and the application method used also affect the process. These parameters affect the workpiece by affecting the rate of machining and etching; etch factor, surface finish and the production tolerance. To ensure a high quality final product with low costs the following must be given due consideration:

- The heat treatment state of workpiece.
- The grain size
- Direction of rolling and weld joints
- Size and finish control prior to chemical machining
- Degree of cold work.

7.2.4 Material Removal Rate

The metallurgical and chemical uniformity as well as the uniformity in the temperature of the electrolytic solution are the determining factors for the material removal rate. The material removal rate is lower for the materials with large grain size (El-Hofy 1995). Further the roughness of the surface is also the highest for the material with large grain size. Higher material removal rates with better surface quality are obtained while machining rolled metal sheets. Hard materials have higher machining rates in comparison to the softer ones (Metals Handbook 1989). Low surface roughness is obtained with high machining rates (El-Hofy 1996).

7.2.5 Surface Finish and Accuracy in Chemical Milling

The chemical deposition action causes the metal to dissolve in the chemical machining process. Since both the grain surfaces as well as the grain boundaries are involved in the machining phase, therefore for the fine quality of the surface, a fine grain size and hence homogeneous structure is the main machining requirement. Regular lay pattern is seldom observed in surface machined using the chemical milling process. Every material will have a certain degree of surface finish as a result of chemical milling for certain period of time. The degree of surface finish will depend on grain size, heat treatment, orientation of grains and induced stresses. The chemical milling will however not remove surface imperfections but will eliminate any surface waviness, scratches or dents.

The surface roughness and hence the tolerance produced are affected by the machining rates. A surface finish similar to the original ones will be produced with slow etching. Also for a good surface finish, equally important is the orientation of the areas being etched with respect to the direction of rolling. With the increasing depth of cuts and machining rates the tolerances for depth of cut too increases. Some of the materials such as magnesium alloys can be controlled relatively more closely in comparison to others such as titanium alloys.

The initial workpiece roughness too impacts the surface roughness and it increases with the rising metal concentration in the etchant. The surface roughness increases roughly with the increasing depth of cut for materials with low depth of machining while for materials with higher machining depths there is only a slight change in surface roughness. Roughness of as low as 0.025 μm can be achieved using the chemical machining process under special conditions (Machining Data Handbook 1997).

The mechanical properties of the material under machining are also affected by the chemical machining process. This is because the surface layers have different mechanical properties than the base material and their removal leads to changes in average mechanical properties. The chemical milling aids in the removal of surface conditions such as decarburized layer, titanium oxide layer and thereby resulting in improved mechanical properties. Material properties such as fatigue properties have been reported to be lost after the chemical milling of aluminum which however can be restored using the grit blasting or shot peening.

7.2.6 Advantages and Disadvantages of Chemical Milling

7.2.6.1 Advantages

The chemical milling process has the following advantages:

- The complex contours that are difficult to be machined using the conventional methods, reduction in weight is possible.
- The productivity of the process is improved with the material removal from different surfaces simultaneously.
- The machined surface is free from burrs.
- Machining of delicate parts is possible.
- The machined parts are free from residual stresses and hence minimized distortion.
- For machining of large components the capital cost involved is less
- The process of chemical milling can be performed with less skilled operators.
- Any changes in design can be implemented with ease and in lesser time.
- Need of finishing operation is eliminated.
- Parts with fine details which are used for decorative purposes can be machined.
- The wastage involved is pretty less.

7.2.6.2 Disadvantages

The chemical milling process has number of disadvantages that are discussed as follows:

- The process is capable only to produce shallow cuts for instance 3.83 mm on extrusions, 12.27 mm for sheets and plates.
- Handling of chemical used in the process is troublesome.
- Some of the processes are tedious and time consuming, for instance, scribing, stripping, hand masking etc.
- Reproduction of surface imperfections is inevitable.
- Best results are obtained only with the metallurgical homogeneous structures.
- It is difficult to produce deep narrow cuts.
- Etched surface are uneven in case of porous castings.
- The etching rates are different for the welded areas and the base metal.
- Considerable distortion can occur in case of material removal from residually stressed parts.
- Unfavorable fatigue strength can result on the chemically machined parts while the rest of the part will have residual compressive strength.
- Some materials have the problems of intergranular attack and hydrogen absorption.

7.2.7 Applications

Chemical machining can be performed on almost all common metals such as steel, zinc, nickel, lead, copper, aluminum; exotic metals such as zirconium, molybdenum etc. and even the non-metallic materials as for instance ceramics, plastics and glass. Chemical machining can be used in the manufacturing of large aluminum wings for airplanes as well as for small chips of integrated circuits. The most popular of all the applications is the cutting of thin sheets for shallow depths which aids in achieving the goal of weight reduction of the components used in the aerospace industries. Chemical machining also finds application in thinning out walls of parts produced by castings, sheet metal forming, forgings etc. the applications of chemical machining for the surface characteristics improvement include the following:

- Removal of alpha case from superplastics and titanium forgings.
- Removal of decarburized layer.
- For the parts machined using EDM, chemical machining is used to remove recast layers.
- Chemical machining aids in sharp burrs elimination for the parts that have been machined using the conventional machining methods.

7.3 Photochemical Milling

7.3.1 Introduction

Photo chemical milling makes use of the photographic techniques for the application of chemically resistant mask on to the workpiece. It is therefore a variation of chemical milling process. Both the chemical milling and photochemical milling removes material from the workpiece by the chemical deposition technique. Further, a number of steps followed in the process of material removal are also similar with the two processes. However, the chemical milling process is used on components that have been manufactured using other manufacturing techniques such as castings and forging, the photo milling process is used on areas that are not to be machined. Therefore, photochemical milling leads to the production of new parts instead of improving or modifying the parts manufactured from other manufacturing methods. Since the process is capable to machine thin, flat gauge complex parts to high precision, the process is also known as photochemical blanking. Sometimes surfaces with lettering and graphics are also surface etched using the photochemical milling process in which case the etchant flows to a certain depth only.

7.3.2 Process Outline

The photo milling operation (Tlusty 1999) incepts with the production of required shape on a glass plate or photographic film which is a photo tool. The required shape is produced using the Computer-aided design (CAD) artwork. Chemical cleaning of the metal sheet is followed by a coating of light-sensitive photoresist film that will adhere to the metal sheet and protect it during the etching process. The part in some cases has to be dipped and dried, for instance when the photoresist is a liquid. The metal sheet is often sandwiched between the top and bottom photo- tool. Due to this arrangement, the undercutting of the photoresist is minimized as the material is etched from both the sides.

Next, the photoresist coated metal sheet is sandwiched between the photo-tool and is exposed to the ultraviolet light source in vacuum. On complete exposure to the ultraviolet light source, the image of the photo-tool is precisely transferred onto the resist. On immersion or spraying the exposed image is developed. Washing of the exposed material area follows next to remove the unexposed photoresist area (Allen 1993).

The imaged metal sheet next passes through the acid etch spray or it is dipped in the etchant where the image is dissolved away selectively. The parts are then dried and rinsed. The stripping operation of the protective resist is finally performed either using chemicals or using the combination of mechanical techniques and chemicals.

7.3.3 Applications

A wide range of materials can undergo the photochemical milling process as for instance copper, steel, aluminum, zinc, titanium, zirconium, ceramics, glass, nickel and some plastics. On machining very high tempered or brittle materials using the traditional methods results in stress concentration and breakage and are therefore machined using the photochemical milling process. Further, the photochemical milling process is equally suitable for springy materials which are difficult to punch. Graphics and decoration industries use photochemical milling process to produce labels and signs. One of the typical applications of the photo milling process is to etching to produce flat components from fold lines for fabrication of enclosures and boxes. A wide range of industries uses the photochemical milling process as for instance computer, automotive, medical, aerospace etc. to produce different components such as fuel cell board, blades for RF switches, encoder disk, flat springs, filter net etc. shown in the Fig. 7.3.

Fig. 7.3 Applications of photochemical milling

Some of the other products produced by photochemical milling have been categorized and discussed below:

- **Precision products**: the industrial demand of relatively thin precision and complex parts of the electronics, micro-electronics and mechanical industries at an economic price has been fulfilled via a rapid-response service provided by the photochemical machining process. the examples include leadframes of integrated circuits, fine sieves, screens and meshes, washers, shims, optical shutters, laminations, filters and cutting blades. The etched gaskets used in mobile phones are the recent developments.
- **Micro-engineering products**: the photochemical machining process lends itself to fabricate components used in MEMS, biomedical applications and diagnostic equipments used in the medical field. There has been a recent surge in the non-silicon MEMS application as for instance the miniature wings used in micro air vehicles.

- **Aesthetic products**: photochemical machining has the process capability to fabricate parts with the intrinsic aesthetic value and is therefore used for the fabrication of signage, jewelry and commemorative plaques. Additional contrast and color is can also be given by combining the etching process with anodizing and electroplating process.

The photochemical machining has the high resolution capability and is therefore used by railway enthusiasts demanding a great attention to the technical details such as the rivet requirements on an engine boiler. The high resolution capability is also employed by the luxury watch industries to chemically engrave the logos.

7.3.4 Advantages and Limitations

7.3.4.1 Advantages

- **Inexpensive and effective tools** A wide variety of precision parts can be produced using the relatively faster, flexible and inexpensive photochemical machining process. Conventional dies and tools have been replaced by the phototools which can be generated in a less span of time and are even inexpensive. It generally takes around a day to produce a phototool.
- **Easy and fast to produce** Quantities ranging from a handful to 100,000s can be produced using the photo chemical process. It takes about 3–5 days to complete entire photo chemical process right from the initial tooling to the finished parts. Typical lead times for new parts ranges 3–4 weeks. Further, if the raw material is in stock, repeated orders can be processed more quickly. Two weeks are enough for prototype orders. The secondary operations such as forming, plating, assembly and silk screening require additional time.
- The photochemical process is free from burrs.
- The process doesn't change the properties and composition of the metal.

7.3.4.2 Disadvantages

The main limitation of the photochemical process is in the isotropic etching where the etchant also attacks sideways beneath the photoresist layer besides attacking it underneath. Further, the minimum hole diameter that can be etched through a certain thickness of a metal sheet is limited by the etch factor.

7.4 Electropolishing

7.4.1 Introduction

Electropolishing is an electrochemical process of material removal which aims to deburr, polish and passivate the metal parts. The process is also referred to as electrolytic polishing or electro-chemical polishing. The process of electropolishing involves the passage of direct current in an electrolyte through the electrolytic cell in which the anode is the metal workpiece. The positive terminal of the power supply connects the workpiece (anode). The workpiece is then inserted into the electrolytic solution. The oxidation of the workpiece takes place on activation of the power supply. The process of oxidation results in removal of irregularities and impurities from the workpiece surface which gets dissolved into the electrolytic solution and diffuses to the cathode at a controlled rate. Hydrogen is produces at the cathode as a result of the reduction reaction taking place at cathode. The material removal rate depends on a number of factors such as current density, temperature of the bath, the type of electrolytic solution used and the metallic workpiece being polished. The electrolytic solution used is acid solution that is highly concentrated with high viscosity such as the mixtures of phosphoric and sulphuric acid. The reproducible surface finish can be obtained by controlling time and the current. Faraday's law of electrolysis describes the process of electropolishing.

Because of the simplicity of the electropolishing process for complex shapes, the process is used by the metal finishing industries. Examples include the electropolished stainless steel drums used in washing machine and the surgical devices. Further, because the electropolishing process doesn't cause mechanical deformation, the process is also suitable for producing thin samples of metal for the electron microscopy. The electropolishing process lends itself to produce smoother surfaces for ultra high vacuum components.

7.4.2 Surface Phenomenon Occurring During Electropolishing

Understanding the surface phenomenon is a key to optimize the parameters of the electropolishing parameters. The process capability may be limited by the mass transport which is mainly the diffusion of the dissolving metal ion. A salt film, either compact or porous or both, precipitates onto the surface and subsequently a salt layer formation takes place at the bottom of the pits. Presence of high electric field across the salt layer results in ionic transport through this layer. No evolution of the gas bubbles takes place at the surface. The solid state conduction in the compact layer simulates for the mechanism of conduction and the mobility of the ions defines the resistance of the compact film. A high resistance can be attributed to the low mobility of the ions.

The migration phenomenon in the electric filed forms the basis of conduction in the porous layer. Further, since the pores are filled with the saturated electrolytic solution, no diffusion takes place. The high resistance of the porous film can be attributed to the large thickness and high porosity of the porous film. The concentration gradient across the diffusion layer of the metal ions controls the current density. A contaminated oxide layer characterizes the film formed on the surface.

The electrochemical polishing process takes place by the dissolution of the metal. During the process of dissolution the cations are released and adsorbed onto the surface. The acceptor ions cause the cations to be removed from the surface by diffusing with the surface and thereby solvating the metal ions. Hydrodynamic flow results because of the difference in density near the electrode and the bulk solution. The concentration of the acceptor ions will be equal to zero under steady state in which case the acceptor ions will be consumed as soon as they reach the surface.

7.4.3 Electrolyte, Cathode and Viscous Layer

The positive terminal of the direct current source connects with the anode whereas the cathode is connected is connected to the negative terminal. The current flows back through the cathode to the power supply. The polarity of the cathode with respect to the anode depends on the operation of the device and may be positive or negative. The movement of the negatively charged anions will always be away from the cathode whereas the negatively charged cations will always show movement towards the cathode.

Electrolytic solution is an electrically conducting solution on dissolution of the electrolyte in a polar solvent. Cations and anions are produced when the electrolyte dissolves into the polar solvent uniformly. During the process of electropolishing the cations are drawn towards the electrode with abundance of electrons whereas the electrode with deficiency of electrons will attract the anions. Current is generated due to the movement of the anions and cations.

A viscous layer is formed onto the work surface which has a non-uniform thickness across the work surface. This in turn results in different ohmic resistance at the anode and the cathode. The difference in ohmic resistance from anode to cathode leads to greater dissolution of the protruded part in comparison to the depressed part. The thickness of the layer is smaller for the protrusion part in comparison to the valleys. The electrochemical process thus produces a uniform surface profile.

The protruded part therefore has a larger value of limiting current in comparison to that of the valleys and thereby the surface levels out as the electrochemical process proceeds.

7.4.4 Parameters Governing the Performance

Voltage range and the range of current density are the two main parameters which are related to the voltage-current curve. The key parameters that are related to the electrolyte are temperature, the age and convection of the electrolytic bath and the time duration of the entire electropolishing process.

The electropolishing process has a large number of parameter set which depends on with the electropolishing setups. The electrode-electrolyte system is required to be specified first. The type of the anodic metal used determines the choice of electrolyte. On identification of the electrolyte-electrode system, the parameters of the electropolishing process are optimized with respect to the given current-voltage relationship.

7.4.5 Applications

The electropolishing process is employed by the industries to reduce the surface irregularities which otherwise would serve as nucleation site resulting in corrosion and hence cracks. Further, the electropolishing process is employed by the food, biomedical, beverage and pharmaceutical industries as the process reduces the attachment of the bacteria. Therefore, the electropolishing surface lands itself into a wide range of applications (Brown 1998) which are discussed below:

- **Piping and tubing** The electropolishing surface is utilized to provide finish for the inner and outer pipe or tube diameters. The process is required to produce anti-fouling, non-particulating and non-contaminating surfaces. The main industries benefiting from the electropolishing of pipes and tubes are nuclear, petrochemical, semi-conductor, beverage and pharmaceutical industries.
- **Food and beverage processing** The electropolishing process has the potential to produce smooth and cosmetically pleasing surfaces with added sanitary and non-contamination qualities. Therefore the process is used to produce corrosion resistant components for use in kitchen, dairy equipments, automatic food processing equipments and containers for food and beverages.
- **Medical applications** All the surgical and medical components used in the hospitals such as clamps, scalpels, prosthetic devices, bone and joint implants requires electropolishing to achieve high levels of non-contamination.
- **Machined parts** All the machined parts such as screws, washers, bolts, valves etc., are the beneficiaries of the electropolishing process. A number of advantages is associated with the electropolishing surface such as deburring, stress relieving of the surface, non-contaminating, non-stick and non-particulating finish, etc.
- **Nuclear applications** The electropolishing process provides for critical finish for the nuclear industry. The process is used to decontaminate the radioactive metallic surfaces. Electropolishing is also used to polishing recirculation pipes

in nuclear plants and to relieve the internal surfaces of the stresses generated as a result of mechanical polishing.

7.4.6 Advantages and Limitations

7.4.6.1 Advantages

- The electropolishing process produces surface free from burrs, surface irregularities and cervices.
- The flow characteristics of the pipes or tubing are enhanced.
- The heat transfer efficiency of the heat exchanger is increased.
- The friction between the moving parts is reduced.
- Increases the corrosion resistance of the surface.
- The surface stresses are reduced.

7.4.6.2 Limitations

- The process can be troublesome for metals containing high percentage of lead, silicon and sulfur.
- The rough scratches on surfaces cannot be removed even by considerate amount of electropolishing.
- The electropolishing process is affected by the base metal condition.
- Poor electropolished surface can result from non-metallic inclusions, over-pickling, large grain size and improper annealing.

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Chapter 8
Electrochemical Processes

8.1 Introduction

An electrochemical process takes place in the presence of electrical current. It is a chemical process involving the oxidation-reduction reactions. The result of the oxidation-reduction reaction is the formation of atoms or molecules due to the loosing or gaining of electrons by the charged ions. There are a number of natural phenomenons that involves the electrochemical processes such as the ability to produce electric field by some of the sea creatures, the corrosion of metal etc.

The electrochemical processes have landed themselves for a wide range of industrial applications such as electrochemical deposition and electrical power storage batteries.

The following chapter summarizes the different electrochemical processes used in modern manufacturing world. The processes discussed in this chapter are: Electrochemical Machining (ECM) process, Electrochemical Drilling (EDD), Shaped Tube Electrolytic Machining (STEM), Electrostream Drilling, Electrochemical Jet Drilling and Electrochemical Deburring.

8.2 Electrochemical Machining

8.2.1 Introduction

Electrochemical machining is a non-conventional machining process where the material removal process takes place during electrolytic process by the anodic dissolution. Faraday's law governs the rate of dissolution of the anodic surface. The rate of dissolution also depends on the metals' electrochemical properties, properties of the electrolyte, current/voltage of the electric supply. An approximate mirror image of the tool is generated on the workpiece surface.

K. Kumar et al., *Advanced Machining and Manufacturing Processes*,
Materials Forming, Machining and Tribology,
https://doi.org/10.1007/978-3-319-76075-9_8

The process capability of the electrochemical process to produce components with complex geometry that are stress-free and crack free and other advantages such as higher material removal rate, no tool wear, bright and smooth surface lends itself to be preferred over other conventional machining processes. Therefore the ECM process has umpteen numbers of industrial applications such as turbine blades, cages for bearings, engine castings and surgical implants. ECM is more suitable for producing components on large scale.

ECM process and its other hybrid variants are capable enough to address the emerging industrial applications. For instance, pulse electrochemical machining (PECM) is one of the variations for ECM which instead of employing DC current, employs pulsed current. The PCM process provides for better stability, suitability for control and higher accuracy. The other industry where ECM finds applications includes aerospace, tribology, biomedical, automotive and deburring industries.

8.2.2 Theoretical Background

The ECM process works on the basis of Faraday's laws of electrolysis. Therefore, the process of electrolysis needs to be understood first before going through the other details related to the ECM process.

Electrolysis is the process that takes place on passing the electric current between two conductors dipped in electrically conducting solution. The solution is known as electrolyte and the conductors are known as the electrodes. The system of electrodes (cathode and anode) and the electrolytic solution constitutes electrolytic cell. The chemical reactions are taking place at the cathode and anode is known respectively as cathodic and anodic reactions.

An electrolyte differs from a conductor in the sense that the current carriers are ions and not the electrons. The ions with positive charge moves through the electrolyte towards the cathode and are the cations whereas the negatively charged ions traveling towards the anode are the anions. The flow of electrons is accompanied by the ionic movement. The movements are a result of applied potential difference that is voltage from an electric source.

A cation on reaching the cathode is neutralized or discharged by the electrons at the cathode. As a result of the neutralization process, deposition of metal atoms takes place at the cathode. To maintain the neutralization process at the cathode (cathodic reaction) the electrons are required to pass around the external circuit. The anode is the source of metal atoms which becomes positively charged cations when passed through the electrolytic solution. The reaction taking place is opposite of the cathodic reaction.

The electrolytic solution is required to be neutral meaning equal number of cations and anions to be present in it and hence the equal amount of reactions at the electrodes. Examples of such reactions are as follow, the electrolysis of copper sulphate results in the following reactions at the electrodes:

At anode, the ionizing reaction is,

$$Cu \rightarrow Cu^{2+}(aq) + 2e^{-}$$

At cathode,

$$Cu^{2+}(aq) + 2e^{-} \rightarrow Cu$$

The amount of reaction occurring is governed by the Farady's laws of electrolysis:

- The amount of metal quantities deposited or dissolved is directly proportional to the amount of electricity flowing.
- The amount of different metal quantities deposited or dissolved for a given current value is directly proportional to their chemical equivalent weights.

8.2.3 Working Principle of ECM

Figure 8.1 outlines the working principle of the electrochemical machining process. Cathode and anode of the electrolytic cell are the tools. A constant potential difference is applied across the two electrodes. An electrolytic solution is chosen suitably so that there is no change in shape of the cathode during the electrolysis process. For removal of the machining remains and minimize the unwanted remains of the electrical heating and cathodic gas generation, the electrolytic solution is pumped at certain rate which ranges between 3 and 30 m/s. the rate of metal atom removal from the anode varies inversely with the distance between the electrodes.

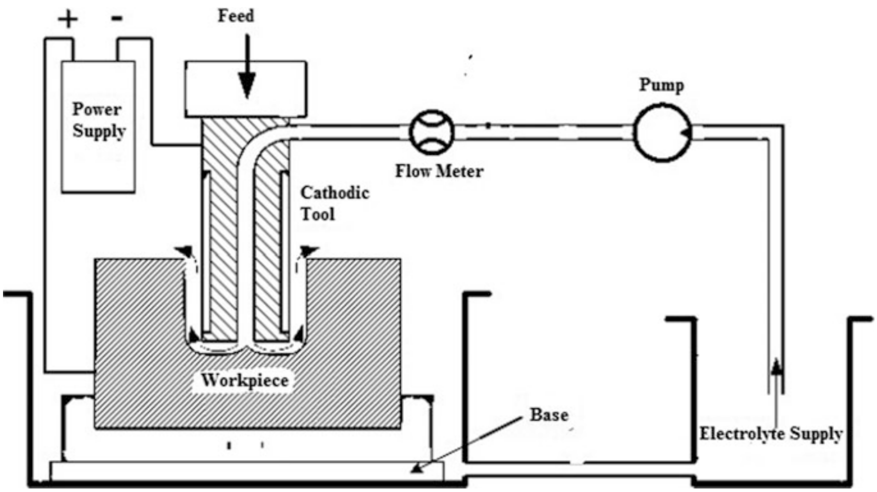


Fig. 8.1 ECM process

Thus with the initiation of the machining process the cathode starts to move towards the anode at a typical rate and then the gap width will tend to a steady state value. Under the steady state condition, the shape on the cathode will be approximately produced on the anode.

8.2.4 Machining Equipments of ECM

The main components of the ECM discussed in this section. The components include: electrolyte supply system, feed control system, holding device for workpiece and the power supply unit. The machining current which is direct current is driven by the power supply system. The tool is fed at a constant rate and controlled by the feed control system. The electrolyte supply system controls the rate, temperature and pressure of supplying the electrolyte solution. The ECM machine has the facilities for the filtration of electrolytic solution and also for the removal of sludge.

8.2.4.1 Electrolytes

The type of material to be machined determines the type of electrolyte to be used. Various types of electrolytes are being used in the ECM process. The surface characteristics of the workpiece material undergoing ECM process are also affected by the type of electrolyte being used. However, the toxic fumes generated by the use of electrolytic solution are a major environmental concern for the industries employing the ECM process. This puts a limitation on the widespread use of the ECM process. With the recent advancements in the type of electrolyte being used, non-toxic electrolytes such as citric acid and water are being used by the micro-ECM processes.

Some of the major functions served by the electrolytes used in the ECM process are as follows:

- It promotes the anodic reaction and hence the workpiece dissolution.
- Pumping of electrolyte across the machining gap helps in the removal of the debris.
- Acts as a coolant to remove the heat generated during the process.
- Helps in maintaining a constant temperature in the region of machining.

Some of the main characteristics that an electrolytic solution is required to possess are:

- Should be capable enough to avoid the formation of passive film at the electrode.
- Should not change the cathode shape by depositing on its surface.
- Should be non-toxic and safe to use.

- Should possess low viscosity.
- Should be electrically conductive.
- Should be stable and be able to maintain its pH value.
- Be easily available and inexpensive.

8.2.4.2 Tools

The tools used in ECM process can be categorized into: shaped and unshaped tools. ECM sinking under steady state process is the first variation in which the 3D negative image of the required surface profile forms the profile of the tool. The tool in this variation of ECM is allowed to sink into the workpiece until the required shape is produced onto the surface of the workpiece. The tool follows a specified path to produce the required shape onto the workpiece surface.

Higher thermal and electrical conductivity are the major requirements for the tool to be used in the ECM process. The other requirements include corrosion resistance and rigidity. Some of the commonly used materials for a tool are tungsten, titanium, platinum copper and tungsten carbide.

For the shaped tool ECM process, tool design is one of the major parts for the modeling of the ECM. The cathodes are produced at a cheaper and faster rate by employing the computer integrated manufacturing process. The tool is designed using computer aided design systems. CNC machines are then employed and programmed using the CAD designs to produce the cathodic tool. The shape produced by this tool is measured by the coordinate measuring machine which then sends the feedback data back to the CAD-CAM units for further analysis.

The taper produced during the ECM drilling can be minimized by using a wide range of tool designs such as insulated tools, dual pole tools and shaped tools. Machining rates and corrosion resistance improves with the nickel coating on the tungsten micro tools. Insulated tools can be achieved by simple spraying or dipping process. Some of the commonly used tools coating materials are urethane, Teflon, epoxy and phenol.

8.2.5 Characteristics of ECM

8.2.5.1 Material Removal Rate

The rate of material removal can be described by the Faraday's law of electrolysis. Equation (8.1) gives the specific material removal rate for pure metals and is given by Kaczmarek (1976).

$$q_c = \frac{60\varepsilon}{96{,}500\rho} \tag{8.1}$$

where, ε is the chemical equivalent weight and ρ is the density of anode material in g/mm^3.

The volumetric removal rate Q_v (mm^3/min) is given by the Eq. 8.2,

$$Q_v = q_c I \tag{8.2}$$

where, I_c is the machining current.

The effectiveness of the machining current in the material removal process is determined by the specific material removal rate. A higher value of current density implies a higher metal removal rate per unit ampere. The exact determination of the material removal rate is however difficult. This may be attributed to the fact that metals dissolves at different valences. For instance, nickel at low potential difference dissolves in divalent state which shifts to trivalent state at higher potential difference.

Choosing of electrolytic solution with proper current density and chemical composition is essential for better ECM indices, better surface finish and higher accuracy. It is usually recommended to utilize multi-component electrolyte. This is because each element of the alloy can be addressed with the required component present in the electrolytic solution. Improper selection of the electrolytic solution may lead to a thin layer of oxide film on the anodic surface which is difficult to remove. This may result in an increase in the polarization resistance.

The rate of material removal is also dependent on the electrolytic flow rate. The current efficiency is reduced with the decreasing flow rate of the electrolytic solution. This is because of the accumulation of the machining products within the electrode gap and thereby impeding the further dissolution of the metal. Further, the machining process can be terminated because of the gases generated at the cathode surface. The gap resistance and the machining current is affected by the concentration of the electrolytic solution. The heating of the electrolytic solution increase its specific conductivity and hence results in enhanced material removal rate and hence the machining performance. Temperature regulators are however employed to keep the electrolytic temperature in check.

8.2.5.2 Surface Finish

The surface finish obtained using the ECM process depends on the type of electrolytes used for the machining. Some electrolytes leave etched finish on the workpiece material. For instance, an electrolytic solution of sodium chloride produces etched finish with nickel and steel alloys. Therefore considerable variations occur in surface finish due to machining conditions and the workpiece characteristics. Peaks and valleys at the microscopic levels are observed due to the irregular current density distribution. The irregular distribution of the current density mainly results from the crystallographic irregularities such as dislocations, grain boundaries and voids. The presence of crystals with different orientations and different local composition of the alloy are some of the other factors for the irregular distribution of the current density. The different elements of the alloy have different machining rates and also the gap width. However, higher feed rate decreases the surface roughness and therefore better surface finish is obtained with the increased feed rate.

In the frontal gap area, the surface roughness ranges between 0.3 and 1.9 μm for a machined part, whereas the roughness in the side gap area can be as high as 5 μm. If the current density is high then simple salt solutions can be used for polishing some metals. Selective dissolution of certain components of alloy results in microscopic defects such as intergranular attack. However, proper selection of machining parameters and electrolyte can avoid intergranular attack. Metals Handbook (1989) summarizes the following ECM effects:

- Roughness of the workpiece surface is more with large grains in comparison to fine grains.
- Roughness and machining problems increases with the presence of insoluble inclusions such as graphite or cast iron.
- Difference in machining rates is inevitable in case of variations in composition of the workpiece such as in hardened steel.
- Serious intergranular attack results with the presence of intermetaalic compounds at the grain boundaries.

The quality of surface as reported by Masuzawa and Kimura (1991) is found to increase with the reduction in the electrolytic concentration and the increase of the temperature of the electrolytic solution. A protective layer is formed in the case of passivating systems with low electrolytic concentration and increased temperature of the electrolytic solution. The protective layer leads to the deterioration of the workpiece surface. A smoother surface is produced as the current density is increased which breaks the protective layer. For instance, in case of Nimonic 80 using NaCl solution, the surface roughness was observed to be 0.9–1.4 μm at current density of 15.5 A/cm^2 and electrolytic flow rate of 28 m/s. The surface roughness reduced to 0.2 μm with the same electrolytic flow rates and increased current density of 46.5 A/cm^2. McGenough (1988) observed marks of partial passivation in case of 0.78% C quenched and tempered steel for electrolytic velocity of 16.5 m/s. however, with the increase in velocity from 29 to 45 m/s, the marks were observed to be broken.

8.2.5.3 Accuracy of ECM

Higher process accuracy can be obtained with the smaller gap width. The current density affects the accuracy of the workpiece surface obtained by the ECM process. The current density is affected by the following:

- Gap voltage and the chemical equivalence of the material.
- Phenomenon occurring at the gap including passivation and also the feed rate.
- Properties of the electrolytic solution such as its flow rate, temperature, concentration, velocity, type and pH.

Narrow machining gaps are recommended for obtaining higher process accuracy. The machining conditions required to achieve this includes the following:

- Use of higher feed rates.
- Electrolytes with higher thermal conductivity.
- Electrolytes such as $NaNO_3$ that are passivating and possesses low throwing power.
- Use of insulated tools that will aid in limiting the side machining action.

Fine dimensional control can be obtained by using electrolytes with low throwing power such as sodium chlorate. Addition of passivating agents can reduce the throwing power of the electrolytic solution. For instance, the throwing power of NaCl solution is reduced with the addition of benzotriazol and potassium dichromate. Addition of passivating agents produces a passive film over the machined surface that improves the dimensional control of the machined parts.

Current density and the electrolytic flow rates are some of the other factors affecting the rate of film formation. The rate of film formation increases with the increase in current density whereas the electrolytic flow rate decreases the rate of film formation.

For the frontal gap, the typical dimensional tolerances are ±0.13 mm and it is ±0.25 mm for the side gap. Narrow tolerances of ±0.025 mm can be obtained with the proper control of the machining parameters. Depending on the cathodic tool, corner radii of 2.5 mm, overcut of 0.5 mm and taper of 0.001 mm/mm is possible using the ECM process (Metals Handbook 1989).

8.2.6 Applications

Some of the typical applications of ECM are discussed below.

8.2.6.1 Smoothing of Rough Surfaces

One of the most common and simplest applications of ECM process is smoothing or deburring of surfaces. The cathodic tool is placed opposite to the rough workpiece surface having peaks and valleys. The current densities differ for the peaks and valleys being higher for the peak than that for the valleys. Therefore, the peaks are removed from the surface making it smooth.

The simplicity and ease of performing the electrochemical deburring process makes it suitable to produce a large number of components for a wide range of industries. Therefore deburring of surfaces is another typical application of the ECM process.

8.2.6.2 Drilling of Holes

Drilling of holes in workpiece surface is yet another application of the ECM process. The cathodic tool used for drilling holes is a tubular electrode. The bore of the tubular electrode receives the pumped electrolytic solution. The electrolytic solution moves down the tubular electrode, then flows across the machining gap, and moves out through the side gap that is formed between the wall of the tubular tool and the hole.

The drilling operation is carried out in the gap between the base of the hole and the leading edge of the drill tool. The material removal process takes place laterally between component and the side walls of the cathodic tool where the current density is lower in comparison to that at the leading edge of the tool. The rate of material removal is low at the sidegap in comparison to that at the leading edge of the advancing cathodic tool. This is because of the progressive increasing width of the lateral gap. The phenomenon occurring at the sidegap increases the diameter of the hole. However, the drilling process results in the hole diameter greater than the external radius of the cathodic tool. This is known as overcut which can be reduced by several methods. One of the common methods is to use insulated tool i.e., using tool with the external insulation and thereby inhibiting flow of electrical current. Using of electrolyte with high current efficiency at the higher current densities is another way to avoid the overcut. The high densities occur between the workpiece base and the tools leading edge.

ECM is capable of drilling holes with the diameter ranging between 0.05 and 75 mm. The drilling depth of up to 110 mm has been achieved for the holes of 0.5–1 mm diameter.

8.2.6.3 Full-Form Shaping

The full-form shaping process makes use of the constant interelectrode gap. The tool moves with a constant rate towards the workpiece to produce the desired shape. The current density as high as 100 A/cm^2 is used and it remain to be high across the entire workpiece surface. The electrolytic flow is to be maintained across the entire workpiece surface. Since the process involves larger areas of electrodes, comparatively higher pumping rates are employed for the electrolytic solution.

8.2.7 Advantages and Disadvantages of ECM

8.2.7.1 Advantages

- No tool wear takes place since there is no contact between the workpiece and the tool.
- The material removal rate is high.
- Dimensional control is high.
- Single operation suffices to easily machine the complicated profile.
- There is no thermal damage to the workpiece structure.
- Requirement of labor is low.
- High surface finish.

8.2.7.2 Disadvantages

- Energy requirement is too high.
- Only electrically conductive material can be machined.
- The disposal of the hydrogen gas generated during the machining operation is a difficult task.
- Cleaning and oiling of the workpiece is required immediately after machining.
- The side machining effect makes it difficult to accurately duplicate the shape of the tool onto the workpiece surface.
- Production of sharp external and internal edges is a major process restriction.
- Large forces are produced on the tool and workpiece as a result of pumping of high-pressure electrolytic solution.

8.3 Electrochemical Drilling

Small holes with high aspect ratio can be machined by employing the electrochemical drilling machining process on hard-to-machine materials such as titanium, molybdenum and nickel based alloys. The electrochemical drilling, shown in Fig. 8.2, produces holes with good machining surface and relatively higher material removal rate irrespective of the properties such as elasticity, brittleness and hardness. The electrochemical drilling makes use of tubular cathodic tool. The electrolytic solution is pumped through the bore of the cathodic tool and ultimately reaches the machining area. The workpiece starts to dissolve once the machining power is turned on. The workpiece continues to dissolve while the cathodic tool is fed towards the workpiece surface. As the machining process continues the hole

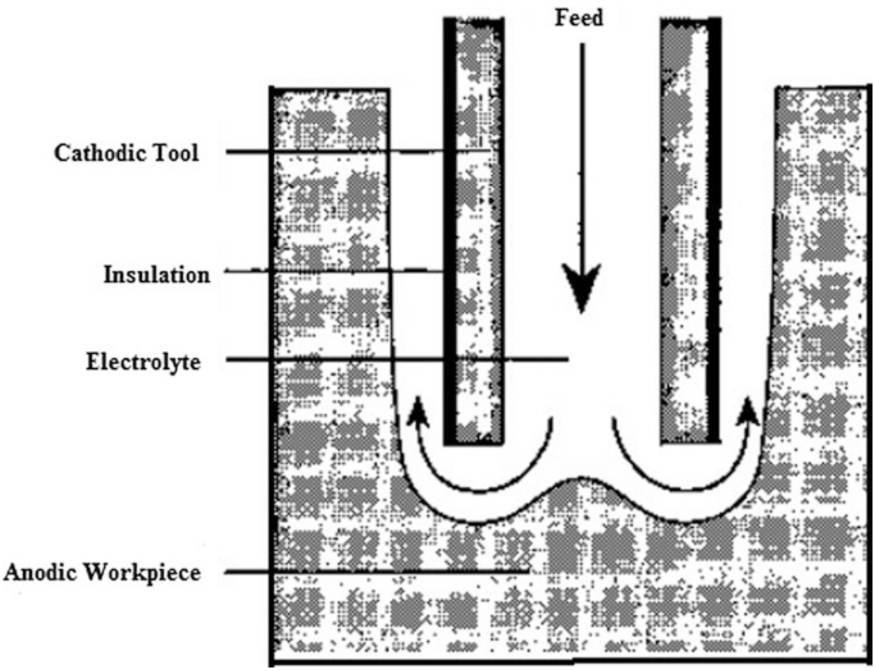


Fig. 8.2 Electrochemical drilling

with the shape similar to the cathode is produced. However, the diameter of the drilled hole is greater than the external diameter of the tubular cathodic tool. This is known as overcut. Therefore, high feed rates are preferred in order to avoid the oversized holes.

The method of pumping the electrolytic solution also affects the overcut. The overcut can be reduced also by the reverse electrolytic flow mode at a back pressure ranging 0.2–2 MPa. The products of electrolysis are therefore flushed and avoided to reach the side gap thereby eliminating the overcut. However, the size of the hydrogen gas bubbles thereby raising the electrical conductivity of the electrolytic solution (Rumyantsev and Davydov 1989). This in turn increases the process of dissolution. Tooling cost and the increase in hydraulic forces are some of the major disadvantages of the reverse electrolytic flow mode.

Efforts have been made by the researchers to improve the flow condition of the electrolytic solution in the inter-electrode gap. Attempts have also been made to reduce the cavitations phenomenon. For instance, the orbital motion to the cathodic tool enhances the stability of the process (Rajurkar and Zhu 1999). The electrolytic flow is distributed more uniformly on orbital motion to the cathodic tool and thereby increasing the process stability. The spikes of the blind holes are also eliminated by the orbital cathodic tool (Hewidy et al. 2001). Machining accuracy has been reported to increase by the use of dual pole electrode by (Zhu and Xu

2002). The dual pole electrode has a bimetallic bush outside the insulation of the cathodic tool. This arrangement weakens the electric filed at the side gap, but is infeasible for production of micro holes.

The machining stability is increased by applying a low frequency vibration to the cathodic tool. Further, the supply of pulsed current also results in the enhanced machining stability.

In electrochemical drilling process acidic electrolytes are commonly preferred so that the waste products formed goes into the solution and thereby avoiding the formation of the precipitates. However, it is costly and unfriendly to dispose the waste acidic electrolytic solution. Therefore, researchers have reported the use of neutral salt electrolytes that causes less harm to the environment. The neutral electrolytic solution can be reused indefinitely (Neergat and Weisbrod 2011). The use of neutral electrolytic solution results in the formation of precipitates which are difficult to be swept away from the machining area. Therefore, the flow of electrolyte will be blocked as the machining depth is increased which will lead to accumulation of joule heat in the machining area. This will deteriorate the flow field and eventually the process will be stopped because of the short circuit. Therefore to produce large sized holes with high aspect ratio the electrolyte refreshment rate should be high. The constant rate of refreshment can be maintained with constant electrolytic flow rates.

8.4 Shaped Tube Electrolytic Machining

Cooling channel holes having smaller diameter and high aspect ratio are required to be produced on the nozzle guide vanes and turbine blades. Some of the processes such as electron beam machining; conventional drilling and laser beam machining are not suitable to produce holes with large aspect ratios. One of the most suitable machining processes is shaped tube electrolytic machining (STEM), shown in the Fig. 8.3. The process doesn't produces residual stresses and no slender tool experiences any cutting forces.

Jackson and Olson (1969) are credited with the STEM process. They made use of acidic electrolytic solution to dissolve the removed anodic materials. The knowledge on the STEM process was further disseminated by Bellows (1982) of the General Electric Company through practical examples, the tolerances and the material removal rates achieved using the STEM process. The understanding on the STEM process was further extended by Cox who concluded that the surface finish on the drilled holes is affected by the duration of the reverse and forward voltages. However with the reverse voltage, the tool is required to be redressed periodically.

The STEM process is based on the dissolution process which takes place on applying electric potential between the cathodic tool and the anodic tool. The anodic surface is removed under the influence of this electric field by the electrolytic solution such as sulfuric acid. The electrolytic flow then removes the

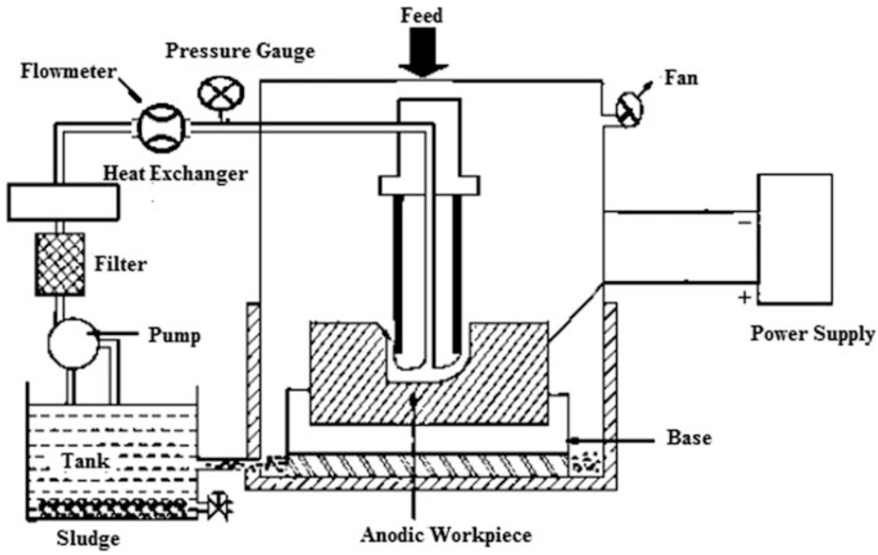


Fig. 8.3 STEM process

dissolved metal ions. The cathodic tool is a cylindrical insulated tool that moves at a specific feed rate while the voltage is applied across the machining gap.

The tool is made of titanium and is insulated in order to avoid any side machining. The operating voltage ranges 8–14 V DC and the machining current reaches to a value of around 600 A.

STEM process suffers from certain types of defects:

- *Drill wander*: the cathodic tool may deviate from its path and may break out on the blade surface under extreme conditions. The stiffness of the drilling tool is dependent on the electrolytic pressure and hence at lower electrolytic pressure the tool is prone to wander.
- *Hole inaccuracy*: the hole size deviation and the hole taper are the two main type of inaccuracies. Longitudinal striations is another type of hole inaccuracy.
- *Threading*: a repetitive variation in the hole diameter may occur at high pressure of the electrolytic solution.
- *Bulrushing*: the sudden increase in the hole diameter results in bulrushing. Low feed rates and high electrolytic pressure are the main reasons of this kind of defect.

As the STEM process uses acidic solution, the process is limited to drill holes in corrosion resistant materials such as stainless steel. The other process limitations of the STEM process are as follows:

- For drilling of single holes the process is slow.
- Handling of acidic electrolytic solution is difficult and hence suitable environmental conditions must be ensured.
- The process generates waste that is hazardous.
- The tooling and machining system required is too complex.

The process has certain advantages which are discussed as below:

- The process is capable to drill a large number of holes in the same run.
- Blind and non-parallel holes can be drilled by the process.
- The process is free from any metallurgical defects and recast layer.
- Slots and curved holes can be machined.

8.5 Electro Stream (Capillary) Drilling

The electro stream drilling process is used for drilling of holes that are too small to be produced by STEM and too deep for the electrical discharge machining. A glass capillary tube is the drill tube through which the electrolytic solution flows. The pressure for the electrolytic flow ranges 3–20 bar. A platinum wire is the cathodic tool which is sized to match the fine tube bore. To ensure the flow of the electrolytic solution in the direction of the tip and hence its integrity, the platinum wire is positioned at a small distance (around 2 mm) back from the tube tip. The longer path of the electrolytic flow results in the resistive path for the current flow which can be overcome by the higher operating voltage. Figure 8.4 shows the electro stream drilling process.

The platinum wire passing through the glass tube serves to conduct the machining current through the acidic electrolytic solution in the inter electrode gap. The common electrolytic solutions are nitric acid, sulfuric acid and HCl with concentration ranging 12–20 wt%. The condition of the workpiece dictates the selection of suitable electrolyte. For instance, for aluminum and its alloys the electrolytic solution used is the hydrochloric acid while for hastelloy, stainless steel, sulfuric acid is the electrolytic solution.

The electrolytic solution used should be carefully monitored for the temperature, pressure, flow rate and concentration in order to achieve satisfactory machining. The electrolytic temperature is 40 °C for sulfuric acid, while for rest it is 20 °C. the gap voltage is 10 times to that of the normal ECM and ranges 70–150 V. The machining time for an alloy can be calculated using the following equation (RamaRao and Mishra 1984):

$$t = \frac{F\rho_m\rho_S d^2}{8000IY}\sum_{i=1}^{M}\frac{n_i x_i}{N_i}\left(y^2 + 2Yy\right) \tag{8.3}$$

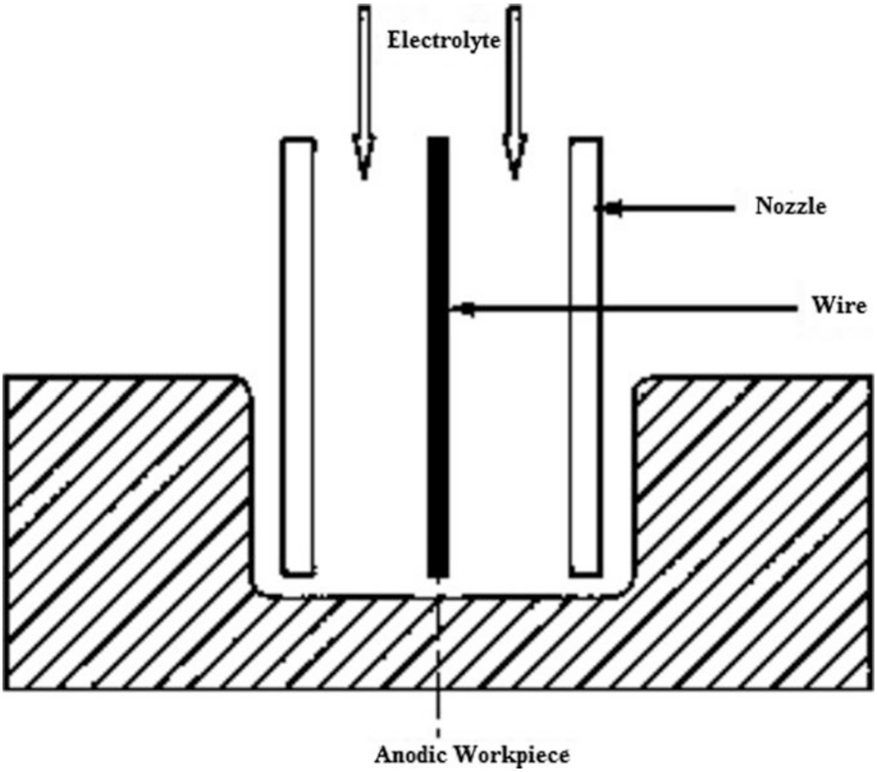


Fig. 8.4 Electro stream drilling process

Electro stream drilling process has the following *advantages*:

- Machining of holes with high ratios of depth to diameter is possible.
- Simultaneous drilling of holes together.
- Machining of intersecting and blind holes is possible.
- The process is free from metallurgical defects.
- Holes produced are free from burr.

Besides the above advantages the electro stream drilling process have some *limitations* which are as under:

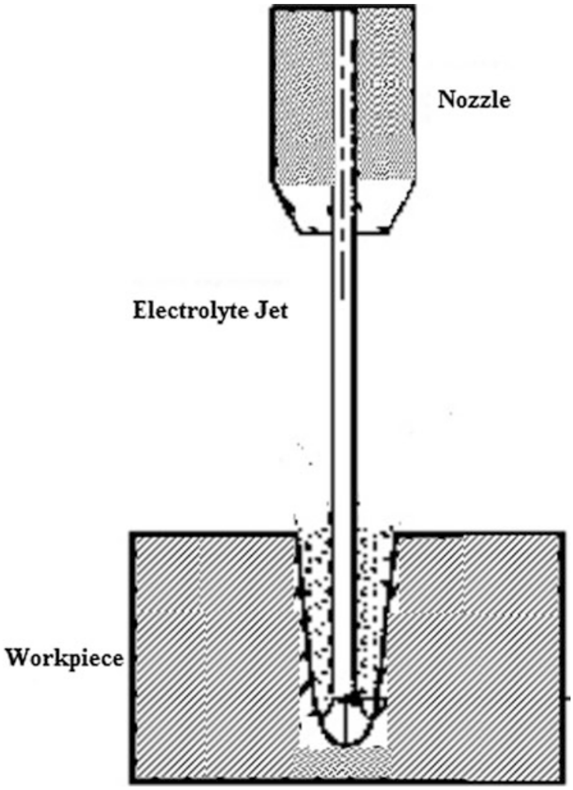
- Only corrosion resistant material can be machined.
- Generation of hazardous waste.
- Drilling of single hole is time consuming.
- Special precautions and environmental conditions are required for handling of acid.
- Oblique holes are difficult to be machined.

8.6 Electrochemical Jet Drilling

The process of electrochemical jet drilling (EJD) doesn't make use of nozzle to machine a hole. The process is also referred to as dwell drilling. The anodic dissolution is achieved by impinging a jet of electrolyte under pressure ranging 10–60 bar. The cathodic tool is therefore the nozzle through which the pressurized electrolytic fluid exits while the anode is the workpiece. A number of factors such as electrolytic pressure, diameter of nozzle and overcut influence the diameter of the machined hole. The interelectrode gap is maintained between 2 and 4 mm. for adequate removal of stock, a high current density is required which can be achieved by using electrolyte of high conductivity and high machining voltage ranging 400 and 800 V.

The EJD process, shown in the Fig. 8.5, is used for drilling holes with diameter to depth ratios 1:12, lower than that drilled by the STEM process. The diameter of the drilled hole is generally about four times the diameter of the electrolytic jet used.

Fig. 8.5 EJD process



8.7 Electrochemical Deburring

Machining operations such as forging, trimming, machining etc. produces thin ridges that are triangular in shape along the workpiece known as burrs. Burrs in workpiece can result in unsafe and noisy operation, wear and tear in the parts under relative motion; reduce the fatigue life of the component and leakages in case of hydro-pneumatic systems. Further, burrs can be safety hazard for personnel because of their sharpness. Presence of burrs in parts with relative motion can produce vibration and noise.

There are numerous conventional processes for removal of burrs with different shapes, size and properties. These processes are mainly manual and therefore require time and labor cost. Removals of internal burrs which have complicated shapes are difficult to be treated manually. The only way out to increase the efficiency of the process is automation of the deburring processes.

Electrochemical deburring (ECD) process, shown in Fig. 8.6, is one of the non-conventional processes that aids in the removal of burrs that are difficult to be accessed by the manual processes. For instance, in case of hydraulic valve bodies which serve to direct the fluid flow via a number of drilled passages, often burrs are produced which can be removed using the ECD technology.

In ECD process, the part to be deburred is made the anode and is kept in a fixture. The pressurized electrolytic solution is supplied to the interelectrode gap (Cathodic tool and burr). The burr dissolves under the influence of machining current thereby producing a controlled radius. The ECD process can be used for mechanical equipments such as spline shafts, milled components, gears and hydraulic systems.

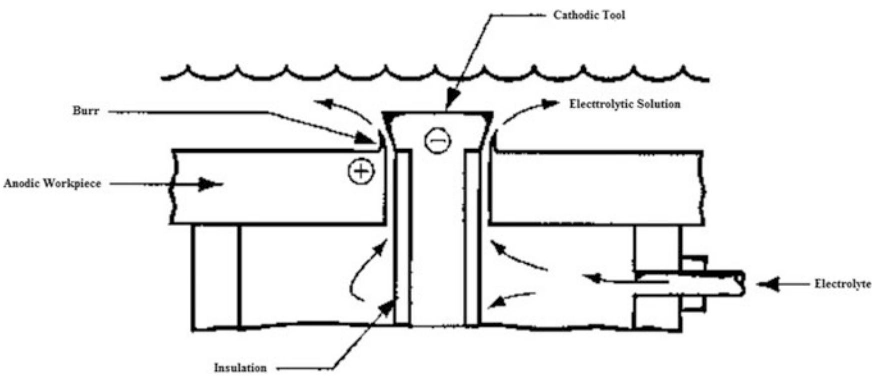


Fig. 8.6 EJD process

8.7.1 Working Mechanism of ECD

The material removal in case of ECD process is based on Faraday's law of electrolysis. The deburring speed ranges between 400 and 500 mm/min. The effectiveness of the deburring process can be enhanced by creating turbulence in the inter electrode gap by using rotating electrode tool. The turbulence of the electrolytic solution is increased by reversal of the spindle rotation.

The tool used for the ECD process must have a number of working areas so that several intersections can be deburred simultaneously. Proper tool insulation will guarantee the current flow in the vicinity of the burr. Further, the contour of the deburring tool must be similar to that of the work part thereby leaving inter electrode gap between 0.1 and 0.3 mm.

8.7.2 Advantages

- ECD process eliminates the costly hand deburring process.
- The reliability and the quality of the product are enhanced.
- The burrs are removed with the required uniformity, accuracy, clean edge and proper radius.
- The labor and personnel cost involved is less.
- Higher productivity can be achieved by automation of the ECD process.

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Chapter 9
Thermal Processes

9.1 Introduction

The thermal machining processes of material removal employs source of heat to remove material from the workpiece surface. Since the thermal processes don't entails the use of mechanical methods to remove materials, the different types of thermal processes fall into the category of non-conventional machining process. The heat source melts and vaporizes the workpiece material and thereby aiding in material removal process.

A wide range of heat sources are used by the different thermal processes. The different heat sources can be categorized into four basic types: gas combustion, thermal sources, plasma, radiation and electric arcs. The type of heat source used determines the manner in which the energy is transferred between workpiece and the source.

The following chapter discusses the different thermal processes: Electrodischarge Machining, Laser Beam Machining, Electron Beam Machining, Plasma Beam Machining and Ion Beam Machining.

9.2 Electrodischarge Machining

9.2.1 Introduction

The invention of relaxation circuit (RC) by N. I. Lazarenko and B. R. Lazarenko laid the foundation for the electrodischarge machining (EDM) process. The EDM technology was made more profitable by employing a simple servo controller which aided in maintaining the required gap between the workpiece and the tool and in minimization of arcing. The die sinking by EDM has been improved since 1940 by

K. Kumar et al., *Advanced Machining and Manufacturing Processes*,
Materials Forming, Machining and Tribology,
https://doi.org/10.1007/978-3-319-76075-9_9

employing techniques of orbital and planetary motion, pulse generators, adaptive systems for control and the computer numerical control systems (CNC).

The progress in EDM was made during the 1960s and with the continuing advancements wire EDM was born in the 1970s with the evolution of powerful generators, improved machine intelligence and new wire electrodes as a tools. The recent advancements have led to increase in machining speed by up to 20 times and the machining cost has decreased by at least 30%.

EDM can precisely machine a large number of semi conductive and conductive materials. EDM has the process capacity to drill circular and non-circular holes and produce macro and micro sized dies with complex shapes. The schematic of the EDM process is shown in the Fig. 9.1.

9.2.2 Process Mechanism

The material removal from the conductive or semi conductive workpiece material in the EDM process takes place because of a series of electric discharges taking place between the electrode and the workpiece. The tool and the workpiece remain immersed in the electrolytic medium during the material removal process. The series of electrical discharges also known as sparks results in generation of high temperature thereby melting and evaporating the two electrodes. The dielectric medium serves to provide the optimal condition for spark generation as well as also flushes out the debris in the spark gap. A small crater is produced on both the

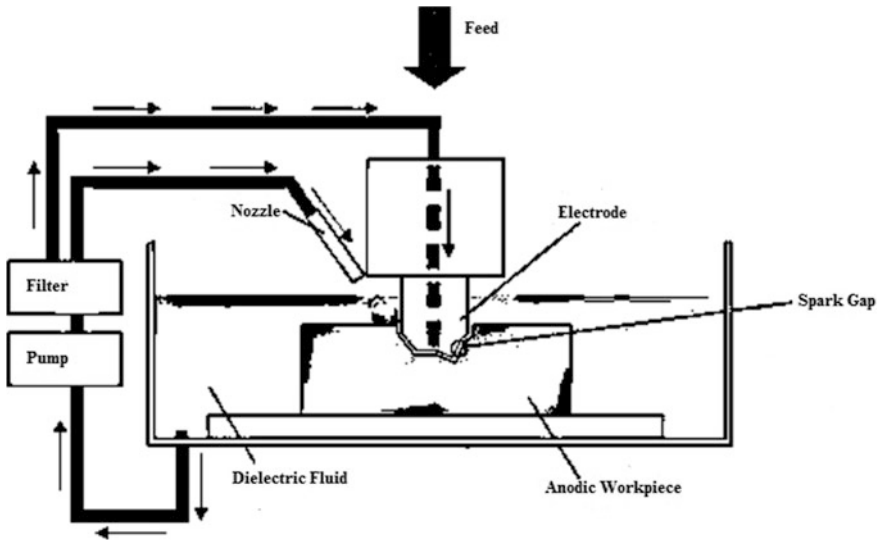

Fig. 9.1 EDM process

electrodes i.e., the tool and the workpiece as a result of each electrical discharge. Many physical processes are involved in the material removal mechanism for the EDM process and therefore material removal is a complex phenomenon.

The acceleration of the electron emitted by the cathode as well as that of the electrons in the dielectric medium towards the anodic workpiece surface results in electrical breakdown. Positive ions and more electrons are obtained when the electrons collides with the neutral atoms present in the electrolytic solution. The generated electrons are also accelerated towards the anodic surface.

On reaching the anodic and the cathodic surface, the kinetic energy of the electrons is converted to heat energy. Temperatures ranging between 8000 and 12,000 °C are generated and the heat flux of the order of 10^{17} W/m^2 are attained. Such a high temperature and heat flux can be achieved with short duration sparks ranging 0.1–2000 μs. Temperature generated is sufficient enough for the anodic surface to reach its normal boiling point. The evaporation of the dielectric medium under the influence of such a high temperature results in rising of pressure on the plasma channel which is as high as 200 atmospheres. The evaporation of the superheated metal is avoided as a result of this high temperature.

However, there is a sudden drop in pressure at the end of the pulse leading to evaporation of the superheated metal and thereby removal of metal takes place.

The dielectric fluid rushes into clear the debris produced during the EDM process. This also serves as a quenching medium for the workpiece surface. A recast layer is generated as a result of the solidification of the unexpelled molten metal. The removed molten metal solidifies to form tiny spheres which remains dispersed into the flushed dielectric. Sufficient off time must be provided to avoid the collection of debris which may otherwise make the spark unstable. The unstable spark creates an arc that has damaging effect on the electrode and the workpiece. The total contribution of the positive ions and the electrons towards the current flow determines the material removal relationship between the anode and the cathode. The anodic erosion will be relatively higher in comparison to the cathodic erosion because of the dominating tendency of electron current which may in turn attributed to difference in mass of the positive ions and the electrons the former being heavier than the latter by an order of 10^4. The width of the plasma channel increases whereas there is decrease in the current density at the end of the EDM process. Therefore, there is rise in positive ion contribution towards the current flow and hence more material removal takes place from the cathode. A servo-mechanism controls the position of the electrode thereby the gap between the electrodes is maintained. The servo-mechanism therefore aids in increased machining efficiency through the active discharges.

The shape of the current pulses determines the performance measures of EDM action such as electrode tool wear, surface finish and material removal rate. The electrical pulses can be distinguished into four different categories depending on the condition existing in the electrode gap: arcs, sparks, short circuits and open circuit pulses. The four variants can be distinguished on the time duration of discharge voltage or current. Further, the material removal rate as well the tool wear in each of the four variants differs from one another. A large distance between the two electrodes results in open gap voltages resulting in neither the material removal process nor the tool wear. Micro-short circuit occurs when the tool makes sudden contact with the workpiece surface. The micro-short circuits also don't contribute to the process of material removal. A practical working where actual discharges take place is formed between these two extreme cases. The actual discharges taking place in the actual working area are the sparks and arcs. The arcs may cause severe damage to the workpiece and the tool. When the plasma channel is not fully deionized for the previous pulse and the same current flow path is followed by the next pulse, then electric arc results. It is the sparks that contributes towards the material removal process.

9.2.3 The Machining System

One of the main components of EDM process is the servo-mechanism that controls the tool feed and maintains a constant distance between the workpiece surface and the tool for the active discharges to take place between the electrodes. The pulse is generated by the power supply unit which controls the pulse's voltage, current, off time and on time. The dielectric fluid for removing the debris and quenching the workpiece is supplied by dielectric circulation system to the inter electrode gap.

9.2.4 Power Supply

The relaxation circuit used initially in the EDM process has been replaced with the power transistor circuit which has improved response characteristics and large current handling capacity. However, the finishing processes still employ the relaxation circuit for the pulse generation as it is difficult to obtain short pulses of constant energy with the power transistor circuits (Kunieda et al. 2005). Further, fine surface finish has been reported with the use of anti electrolysis pulse circuit based on CPLD (Yan and Lai 2007).

9.2.5 Electrodes

Material: the materials chosen for tools to be used in EDM process should possess good electrical conductivity and high melting point. The most common electrode material used in the EDM process is the graphite. Graphite can be machined easily and has fine wear characteristics. Further, flush holes of small sizes can be easily drilled into graphite. Copper too has better conductivity and wear characteristics. For making deep slots in tungsten carbides under poor conditions of flushing, silver tungsten and tungsten carbides are mainly used. For cross-sectional electrodes copper graphite is preferred. Copper graphite has higher conductivity in comparison to the graphite electrode. However, the corner wear is relatively high than the graphite. For drilling of small holes, brass is usually a preferred material providing stable sparking conditions.

ZrB_2-Cu composite tools have been developed having higher material removal rate and less tool wear in comparison to the copper electrode (Khanra et al. 2009). However, the composite electrode tool has disadvantage of over-cut and average surface finish. Peeling electrode tools have been proposed by the research community to take care of the tool damage for instance electroplating of zinc over tungsten (Tanabe et al. 2011). Another development is the use of bundled electrode which is fabricated by bunching together a number of hollow celled electrodes. The bunched electrode can work with high peak current and thereby higher MRR can be achieved (Gu et al. 2010, 2012).

Movements: the electrode tool may have orbiting or rotary motion in addition to the feed. The rotation of the electrode tool aids in the flushing problem encountered while machining small holes using EDM. The cutting speed achieved is higher than the stationary electrodes while maintaining the quality of holes drilled. The shape of the cavities produced is similar to that of the electrode when using the electrodes with orbiting motion. The size of the cavities is determined by the radius of the orbit and the size of the electrode. The flushing is enhanced by the orbiting electrode motion.

9.2.6 Dielectric Fluids

Dielectric fluids dielectric serves the following functions in EDM process:

- To flush away the machining remains from the electrode gap.
- To provide for the insulation between the tool and the workpiece.
- Quench the workpiece after completion of the machining process.

The dielectric fluid used in the EDM process must possess properties such as adequate viscosity, oxidation stability, high flashing point, low cost, higher electrical efficiency and minimum odor. Kerosene has been the most preferred dielectric fluid. Certain additives are added to kerosene to prevent de-odoring and gas bubbles. Excellent results have been obtained with silicon fluids and their mixture with the petroleum oils. Deionized water is used for wire-EDM. Water and air as dielectric medium has been used for air assisted water EDM. Mixture of air and water as dielectric medium helps in controlling the environmental pollution. Improvements in surface finish with higher material removal rates for the dies have been reported with the use of powdered mixed dielectrics. For instance, a three phase dielectric consisting of gas, powder and liquid have been used for powder mixed near dry EDM. High speed gas jet has been used for the dry EDM used for machining carbon nano fibres. Other dielectrics with excellent results include ethylene glycol, distilled water and water in emulsions.

To achieve close machining tolerances with high surface quality, adequate flushing must be ensured by the dielectrics. Increased production time, arcing and reduced tool life are some of the fallouts of inadequate flushing. There are four methods by which the dielectrics can be introduced into the machining gap: normal flow, reverse flow, jet flushing and immersion flushing.

9.2.7 Material Removal

Material is removed both from the tool as well as from the workpiece in EDM. The rate of material removal depends upon the material of the workpiece, tool electrode material, electrode polarity, pulse conditions and the machining medium. Low material removal rate is achieved in case of materials with low melting points. The material removal rate in EDM ranges between 0.1 and 400 mm^3/min. The following equation describes the volumetric material removal rate given by Kalpakjain (1997):

$$VRR = i \times T_w^{-1.23} \times (4 \times 10^{-4})$$

where, T_w is workpiece material's melting point (°C) and i is the current (A).

9.2.8 Surface Integrity

One of the most important issues in EDM is that of surface integrity. The surface integrity is typically affected by one of the important factors i.e., discharge pulse energy. The EDM process results in overlapping craters the size of which depends upon the pulse energy besides on the material properties of the material as well as on the medium of machining. The peak to value surface roughness (R_t) is determined by the depth of the craters produced. The average roughness (R_a) can be determined using the following equation:

$$R_a = 0.0225 i_p^{0.29} t_p^{0.38}$$

where, t_p is the duration of the pulse in µs and i_p is the pulse current (A).

With the increase in voltage and current the surface roughness increases too. The relation between the two is found to be linear. The surface roughness as given by Jeswani (1977) can be obtained using the following equation:

$$H_{rms} = 267\left(\frac{P_r}{f_p}\right)^{0.258}$$

where, f_p is the frequency of the pulse, P_r is the power. Increase in the discharge current and pulse-on time increased the surface roughness while machining Al_2O_3 composites (Patel et al. 2009).

An electrochemical finishing technique has been adopted by Masuzawa and Saki (1987) and the surface roughness has been reported to decrease to 8 μm from 22 μm. A mate electrode was used in the electrochemical finishing technique. In micro-EDM process, low level damage of the work surface was reported with the short duration pulses of ultra high frequency (Aspiwall et al. 2008).

The surface roughness can be reduced by the correct choice of the correct dielectric flow. The dielectrics with low viscosity have been recommended by the Machining Data Handbook (1997) for achieving smoother surfaces. A comparison analysis was conducted for the surface integrity with the use of CH- and water base dielectrics in wire EDM (Klink et al. 2011). It was concluded that the surface roughness as close to 0.1 μ was achievable.

9.2.9 Heat Affected Zone

The different layers of workpiece surface undergoing EDM experiences metallurgical changes because of the temperatures ranging 8000–12,000 °C. In addition to the metallurgical changes, a thin recast layer with thickness ranging between 1 and 25 μm is also formed. The heat affected zone can reach up to 25 μm as claimed by Levy and Maggi (1990) and Delpreti (1977). The zone just adjacent to the machined surface experiences annealing. Further, some part of the melted workpiece is only expelled into the dielectrics while the remaining part solidifies by loosing heat through conduction into the workpiece which results in hard surface. The machining power determines the depth of the annealed layer. The depth of the annealed layer ranges between 50 and 200 μm for finish cutting to high material removal rates.

The annealing effect can be minimized by choosing of electrodes producing a more stable effect. The annealed material can be removed by a finish cut. The fatigue strength of the altered surface layer of the alloy undergoing EDM is reduced. This may be attributed to the fact that the altered surface layer comprises of the recast layer which may extend to the base layer. In addition to the presence of recast layer, some metallurgical alterations such as tempered and rehardened layer, intergrannular precipitates and heat affected zones, also exists. The thickness of the altered surface layer is less than 0.125 mm for EDM roughing while for EDM finishing it is less than 0.74 mm. Therefore, highly stressed undergoing EDM is recommended to undergo post treatment for the restoration of the fatigue strength.

Several methods such as low-stress grinding and chemical machining can be followed post EDM process for the removal of recast layer.

9.2.10 Applications

EDM is one of the versatile technologies to be used by the wide range of manufacturing industries. The EDM process has the capability to produce complex shapes from hard-to-machine materials such as carbides, super-alloys and heat-resistant alloys. The shapes are produced with a high level of accuracy. The operation time for the process has been reduced by the integration of EDM with CIM systems. Some of the typical applications of EDM process includes micro-machining of slots, holes and dies; surface texturing, deposition, milling and texturing and mechanical pulsing.

9.2.10.1 Electrodischarge Drilling (EDD)

The EDD process uses a tubular electrode for machining of holes. The interior hole of the tubular electrode receives the pumped dielectric in order to flush away the debris. The machining gap is fed with the dielectrics by either injection or suction through pre drilled holes while using solid rods. The EDM process has the potential to produce curved, tapper or irregular holes. One of the typical applications of EDM process is the creation of channels for cooling in turbine blades that are made using hard alloys. Large number of holes can be located accurately with the computerized NC systems.

9.2.10.2 Electrodischarge Milling

Standard cylindrical electrodes are used as a tool for EDM milling. Successive NC sweeps to the desired shape of the cylindrical electrode results in complex cavities. The cylindrical tool rotates at high speed and follows a specified contour similar as that in the case of the conventional milling. The EDM milling is a versatile manufacturing process to produce complex-shaped electrodes for generating 3D cavities in die sinking. The high speed rotation of the cylindrical tool enhances the dielectric flushing. EDM milling has replaced the conventional techniques of producing dies. However, production of complex shaped cavities with sharp corners is one of the limitations of the EDM milling process.

9.2.10.3 Texturing

The steel sheets undergoing the process of cold rolling are applied with texturing. One of the conventional and the inexpensive processes of texturing is that of the sand blasting (SB). In SB process the surface is impacted with hard steel shots at higher velocities. This impact roughens the surface of impact. However, the SB process has certain limitation such as that of lack of consistency in texturing and the control. Protection of other parts holding the steel sheet from the high velocity impact is another limitation of the SB process. Further, as has been reported by Ahmed and Knight (1988) and Pawleski et al. (1994) the limited range of roughness and the peak counts with the increasing hardness of the steel sheet is another drawback of the SB process.

To overcome of the drawbacks of the SB process, one of the variations of the EDM process is that of the electrodischarge texturing (EDT) for texturing of steel sheets irrespective of the sheet hardness. The EDT process has low material removal rate and the subsurface modifications are low as well. The texturing is accomplished by electrical sparks of very high intensity and short durations between the tool electrode and the sheet roll (Aspinwal et al. 1991). The discharge energy of the spark melts and vaporizes the roll material and thereby creating a small crater.

Surface texture with a high level of consistency and accuracy can be generated by appropriately selecting the process variables such as duration and pause time of the electrical discharge, pulse current, polarity of the electrode, type of the dielectric used and the rotational speed of the shaft. In order to avoid the possible vibrations the sheet roll is mounted rigidly during the EDT process. The rotational speed of the spindle varies between 10 and 40 rpm. Synchronization of the roll speed is done with the axial transverse motion of the machining head. The time required for texturing and the texturing cost can be reduced with the increasing number of tools which however increase the capital cost of the machine. More energy is dissipated by the spark discharge in the plasma channel by increasing the pulse current. As a result of the increased pulse current a large number of craters are formed and the surface becomes rougher. Further, the number of peaks per unit area is decreased.

9.2.10.4 Micro EDM

The material removal in micro-EDM is based on the principle of spark erosion which is similar to that of the EDM process. However, there are significant differences between the two processes. The difference lies in the flushing technique, gap control and processing techniques (Ali 1970; Maity and Singh 2012; Prihandana et al. 2009) The discharge energy for unit material removal in micro-EDM is very low of the order ranging 10^{-6}–10^{-7}. The micro-EDM process can be categorized into five main categories depending on the application (Pradhan and Bhattacharya 2008):

- *Die-sinking*: the micro features on the electrode tool produced as a mirror image on the workpiece.
- *Micro-wire EDM*: a wire of very small diameter of around 0.02 mm is used for cutting the workpiece material.
- *Micro-EDM drilling*: micro electrodes with diameters ranging 5–10 μm are used to drill holes of micro dimensions in the workpiece.
- *Micro-EDM milling*: 3D cavities are produced using micro electrodes with diameter ranging 5–10 μm.
- *Micro-EDG*: fabricates micro electrode from an electrode thicker than the one required.

The micro features that are of particular interests for the manufacturing enterprises include micro holes, micro grooves, micro channels, micro slits and three dimensional structures. These micro features of industrial importance can be produced by the micro-EDM process with high precision level and accuracy. Micro holes are the common features that can be found on injection needles, catheters, dies, turbine blades etc. The micro-EDM process has the potential to machine both the through and blind holes of diameter ranging in micrometers with a high aspect ratio of 20. High quality micro holes were machined in tungsten carbide by Jahan et al. (2009) with better dimensional accuracy, circularity and good surface finish. Micro-EDM process was employed to obtain holes with higher aspect ratios on hardened tool steel in the presence of magnetic field by Yeo et al. (2004). Blind micro holes were produced on the plastic mould steel by Ekmekei et al. (2009) using the micro-EDM process.

Another micro feature that has landed itself for a wide range of industrial applications is the micro channel. Industrial sectors such as energy, biomedical, chemical, micro molding, micro fluidics etc., have been employing micro channels in their wide range of products. Micro channel having width of 25 μm and surface roughness value, R_a = 0.4 μm has been fabricated on titanium alloys by Murali and Yeo (2004). Micro channels on bipolar plates were produced with a high aspect ratio of 1.2 by Hung et al. (2011, 2012).

Successful micro-EDM milling was carried out for non-conductive ZrO_2 ceramics by Schubert et al. (2013). 3D structures such as micro lollipop end mills were fabricated using a novel multiprocessing micro-EDM technique (Oliaei et al. 2013).

9.2.11 *Advantages and Disadvantages of EDM*

9.2.11.1 Advantages

Some of the advantages of EDM process include the following:

- Materials that are extremely hard can be machined to very close tolerances
- Complex shapes that are too difficult to be produced by the conventional processes can be machined using the EDM process.

- Fabrication of micro featured products which could be damaged because of the tool forces and pressure if machined using conventional processes.
- No distortion or damage to the workpiece material.
- Holes with micro dimensions and high aspect ratios can be obtained using the EDM process
- Workpiece material can be machined with high surface finish.

9.2.11.2 Disadvantages

- The process is time consuming.
- Material removal rate is low.
- The use of oil dielectrics can lead to fire hazard.
- Additional cost is involved for the fabrication of electrodes.
- Power and specific power consumption is very high.
- Tool wear is excessive during the machining process.
- Non-conductive materials can be machined only with special set of machining arrangements.

9.3 Laser Beam Machining

9.3.1 Introduction

Light amplification is the key element for producing laser. The light amplification is a result of stimulated emission due to incident photons of high energy. There are three main components to any laser system: laser medium, means for exciting the laser medium to the state of excitation which is the source of energy and the optical feedback system. Some other provisions such as cooling system for the mirrors, guiding system for guiding the laser beam etc., are also equally important. The laser medium can be liquid such as die; solid as for instance neodymium doped yttrium-aluminium-garnet; gas such as CO_2, Ne, He (Majumdar and Manna 2003).

Laser light is different from the ordinary light in the manner that these are highly directional, has better focusing characteristics and has high power density. These different and unique aspects of the laser light make it suitable for processing of materials. The most commonly used lasers for laser beam machining (LBM) applications are Nd-YAG and CO_2 lasers. The wavelength of CO_2 lasers in the infrared region is 10 μm. The CO_2 laser possesses better efficiency, high beam power and good quality. These advantages lend it for cutting of sheet metal at high speeds (Tabata et al. 1996). On the other hand low average beam power is possessed by the Nd:YAG lasers, however when operating in pulse mode the high peak power enables it to machine even thicker materials. The Nd:YAG lasers have a very short wavelength in comparison to the CO_2 lasers and is therefore can machine materials that are difficult to be machined using the CO_2 lasers (Meijer 2004).

Lasers are being employed in a wide range of industrial application such as cladding, heat treatment, welding, alloying and machining. Figure 9.2 depicts the laser beam machining process.

9.3.2 Principles of LBM

The material removal mechanism in LBM technique can be categorized into different stages: melting, vaporization and chemical degradation. The high energy laser beam is absorbed by the workpiece surface in the form of thermal energy. This high thermal energy transforms the volume of the workpiece material into molten, vaporized or chemically changed state. The high pressure gas then assists in removing the molten or the vaporized material (Sundar and Joshi 2009).

The physics of the LBM is pretty complex owing to losses taking place at the workpiece material in the form of reflection and scattering. The process progresses

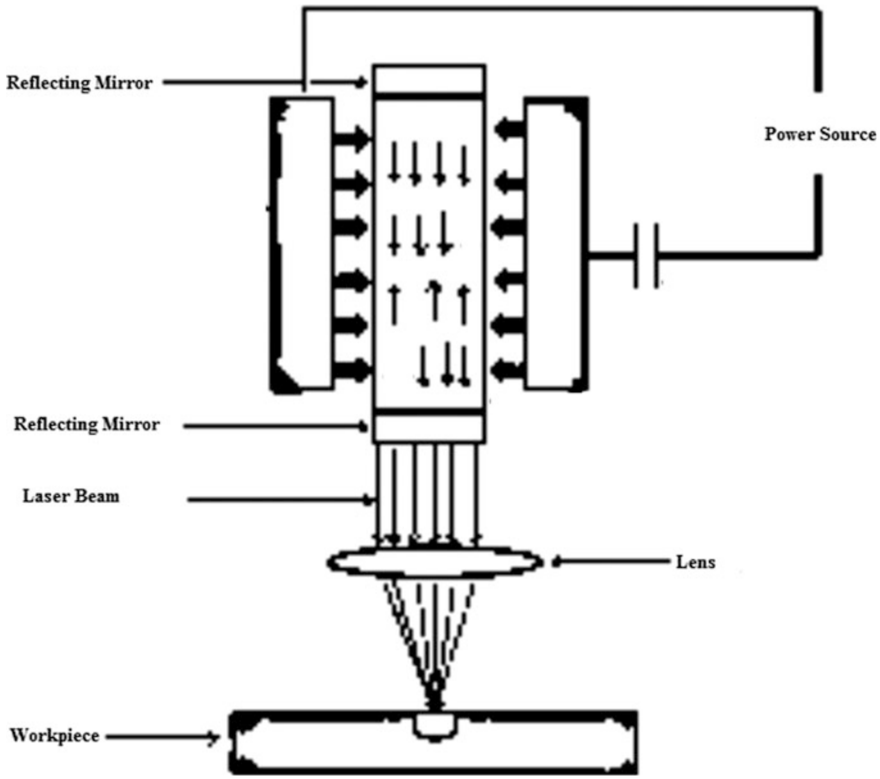

Fig. 9.2 LBM process

to melting and vaporization from the mechanism of heat absorption and conduction. Since plasma plumes are formed at the workpiece material, high intensity laser beams are not recommended. Further, the losses due to adsorption and scattering are higher with the high intensity lasers and hence there is a marked reduction in the process efficiency.

Machining by laser takes place when the power density of the laser is more than that lost by convection, conduction and radiation. Further, the radiation must penetrate the workpiece material and should be absorbed by it. The laser power density is given by the following equation:

$$P_d = \frac{4L_P}{\pi F_l^2 \alpha^2 \Delta T}$$

where,

P_d the laser power density, W/cm^2
F_l focal length of lens, cm
α beam divergence, rad
ΔT pulse duration, s
L laser power, W

The machining rate ϕ (mm/min) is given by,

$$\varphi = \frac{4C_l L_p}{\pi E_v (F_l \alpha^2) h}$$

where,

C_l material constant
E_υ vaporization energy of material, W/mm^3
h workpiece thickness, mm

The volumetric material removal rate, (mm^3/min) can be obtained using the following equation,

$$VRR = \frac{C_l L_p}{E_\upsilon h}$$

The material removal mechanism is a cumulative of several effects: reflection, absorption, conduction which is followed by melting and vaporization. The reflectivity is dependent on a number of parameters such as the properties of the material, wavelength and the surface finish of the workpiece material. The rate of material removal is lower for materials with higher reflectivity. Modifications in surface conditions can reduce the level of reflectivity and therefore enhance the material machine ability. The workpiece surface absorbs the unreflected portion of the laser light which raise the energy of the electrons to higher states. The absorbed energy is then passed rapidly to the lattice. Melting and evaporation of the workpiece starts once the workpiece is heated sufficiently. For plastics, the laser energy required to melt it, is lower than that required for metals. The materials with low thermal conductivity, melting point and diffusivity have enhanced machinability. Therefore this is one of the reasons for melting of material plastics by a low power CO_2 laser.

The non metallic materials are machined at relatively higher speeds than the metals which have higher thermal conductivity and higher reflectivity. In order to have higher speeds of machining for metals, lasers with high power densities are used. One of the major advantages of the LBM process is the smaller depth of altered layer.

9.3.3 LBM Variations

The major configurations for LBM process are: turning and milling (3-D), cutting (2-D), drilling (1-D) and micromaching. LBM is one of the versatile technologies to drill a large number of holes economically that are closely spaced. There are two variants of laser drilling: percussion and trepan. The percussion drilling on one hand punches directly through the workpiece with no relative motion between the workpiece and the laser. The trepan drilling on the other hand involves cutting around the circumference of the hole. Reduced processing time is the inherent advantage of the percussion drilling process (Chryssolouris 1991). The laser beam cutting lends itself into a variety of applications such as cutoff, punching and marking of plastics, ceramics and metals. The laser beam cutting has a number of advantages which makes it far superior than the other conventional cutting processes. Some of the advantages of the laser beam cutting processes are its material versatility, high utilization of the material, no wear of the tool, flexibility, high accuracy and edge quality (Sundar and Joshi 2009).

Laser beam milling and turning operations are used to achieve the profile desired on the specimen. Fibre optics is used to get the desired profile on the workpiece by angling the tool as desired. Parts with complex geometries are produced by laser milling without the need of expensive tooling. The most suitable application of the laser milling process is to machine parts with one-sided geometry. The process is also capable to machine complete parts but the challenge lies into reposition the work part accurately (Pham et al. 2007). Several material removal mechanisms have been proposed by the researchers for the laser milling process. Fracture technique was proposed by Tsai and Chen (2003) for laser milling of ceramics. In this technique, laser beam is used to machine the grooves on the workpiece material which is then followed by heating of machining zone by the defocused layer. Tensile stress and stress concentration is induced by the heating effect. Laser milling is also used for rapid manufacturing of micro-parts (Pham et al. 2004) and for milling of alumina ceramics (Litao et al. 2003).

Micromachining involves machining of products with dimensions below 1 mm. Laser of high frequencies and short pulses are used for such products of very low dimensions. The most commonly used lasers for medical and electronic micro products are Excimer lasers and the pulsed Nd:YAG lasers.

9.3.4 Laser-Based Cross/Hybrid/Assisted Machining

Machining of advanced materials has become possible through combination of two or more machining processes. The combination is created to exploit the advantages of the processes involved whereas minimizing the disadvantages associates with the processes in combination. The combination is usually performs better than the sum of the performances of the processes with the same setting of parameters. This is because of the fact that the interaction between the two processes also adds to the total performance (Yadava et al. 2002). In recent times, the combination of the laser and non-laser machining processes has gained a widespread popularity.

In case of laser assisted turning hybrid process, laser is focused on the unmachined portion of the workpiece. The laser energy softens the surface layer of the workpiece material resulting in ductile deformation instead of brittle while the cutting process takes place. The process results in a higher rate of removal of material with increased surface quality and dimensional accuracy. A marked reduction in the machining cost and tool wear are some of the other advantages of this hybrid laser assisted turning operation (Rozzi et al. 2000). Reduction in tool wear was observed for the laser assisted turning (LAT) of silicon nitride ceramics in comparison to the conventional turning operation (Lie et al. 2001). Further, LAT of alumina ceramic composites resulted in reduction in cutting forces and tool wear with increase in the surface quality of the specimen (Wang et al. 2002). A reduction of 17% in the thrust force was reported for steel undergoing laser-assisted micro-grooving in comparison to the conventional micro-grooving process (Singh and Melkote 2007).

Several attempts have been made to combine laser with the unconventional machining processes. Examples of such processes include ultrasonic assisted laser beam machining, laser-assisted electrochemical machining, laser-assisted electrodischarge machining and laser-assisted etching to name a few. The surface finish of the holes was found to be enhanced while using vibration assisted laser drilling in comparison to the laser drilling (Zheng and Huang 2007). Deeper holes with minimum recast layer was observed for holes drilled using the ultrasonic assisted laser drilling in comparison to the laser drilling process (Yue et al. 1996). In case of laser-assisted electrochemical machining process, the electrochemical dissolution process is accelerated through the laser radiation. The process also resulted in better accuracy and productivity as the area of machining is localized by few micron sizes (Rajurkar et al. 2006). The laser-assisted electrochemical machining process for aluminium and stainless steel resulted in an increase in material removal rate by 54 and 33% respectively (DeSilva et al. 2004). A reduction in heat affected zone and recast layer was observed in case of the chemical-assisted laser machining process in comparison to the laser machining in air (Li and Achara 2004).

LBM and EDM were applied sequentially for drilling of micro-drilling of fuel injection nozzles by Li et al. (2006). The micro-holes were drilled using laser drilling which was later rimmed by employing the EDM process. The hybrid process minimized the recast layer and the heat affected zones.

9.3.5 LBM Applications

LBM lends itself for a wide range of applications in fields such as aerospace, automotive, electronic, nuclear sector, civil structures and house hold. Advance high strength steels find application in boiler work and car industry and are machined using LBM technique (Lamikiz et al. 2005). Lasers are used to cut titanium, alloy sheets used in fabrication of compression section in jet engines for the aerospace industry (Shanjin and Yang 2006; Almeida et al. 2006; Rao et al. 2005a). Laser cutting system can be used for fabrication of slot antenna array from aluminum alloys (Wang et al. 2006). Pulsed Nd:YAG lasers are employed for cutting of complex geometries in metallic coronary stents used in medical applications (Raval et al. 2004; Kathuria 2005). Nickel based superalloys which lend it for aerospace applications are machined using LBM process (Bandyopadhyay et al. 2002; Corcoran et al. 2002; Low et al. 2003; Thawari et al. 2005; Sezer et al. 2006). Laser has also been used for machining of ceramics besides metals and alloys. The piezoceramic discs used in rainbow actuators are cut using the lasers (Juuti et al. 2004). LBM can cut into ceramic tiles and produce intricate shapes which otherwise is time consuming and expensive when produced using diamond saw or ultrasonic machining.

QFN packages, packages for semiconductors, have been successfully cut using the short pulse Nd:YAG lasers. The QFN packages are plastic encapsulated packages with copper lead frame substrates which are used in electronic industry for the packaging of semiconductors (Li et al. 2004, 2005, 2007). Laser drilling is used for formation of vertical interconnections in PCB (Kestenbaum et al. 1990; D'Ambra et al. 1992; Gan et al. 2000; Moorhouse et al. 2005) Laser is being employed for successful cutting of materials used in civil structures such as concrete, marbles etc. (Boutinguiza et al. 2002; Miranda 2004; Crouse et al. 2004; Rao et al. 2005b). Laser beam is being used for micromachining of glasses used in optoelectronics (Nikumb et al. 2005; Lee and Kang 2001; Strigin and Chudinov 1994). The medical instruments such as bone plates, temporary stents, nails and screws have been manufactured from poly-hydroxy-butyrate machined using CO_2 lasers (Lootz et al. 2001). Micro cavities in teeth and bones are recent applications of laser milling in the medical field (Werner et al. 2007).

9.3.6 Advantages and Disadvantages

9.3.6.1 Advantages

- The tool is free from wear and breakage.
- Optical laser system can easily locate holes accurately.
- Holes of very small diameters can be drilled with high aspect ratios.
- Difficult-to-machine and hard materials can be machined.
- Different entrance angles can be used to drill holes.
- High flexibility allows for automation of the process.
- Low operating cost.

9.3.6.2 Disadvantages

- Equipment cost is high.
- Drilling of holes is normally encountered with the tapers.
- It is difficult to machine blind holes with précised depth.
- Laser drilling is restricted to workpiece material thickness of 50 mm.
- Removal of adherent materials at the bore exit is required.

9.4 Electron Beam Machining

9.4.1 Introduction

Steigerwald is credited with the design of the prototype machine used for the material removal using electron beam. The electron beam machining, shown in the Fig. 9.3, was used initially in the nuclear and aerospace industries. Some of the recent applications of electron beam machining (EBM) involve that of cutting, grooving, drilling and heat treatment for the micromachining and semiconductor industries.

9.4.2 Machine Set up and Material Removal Process

The machining components in EBM are caged within a vacuum chamber with vacuum pressure of about 10^{-4} torr. Electrons are emitted by heated cathode made of tungsten filament, the temperature of which ranges 2500–3000 °C. The emission

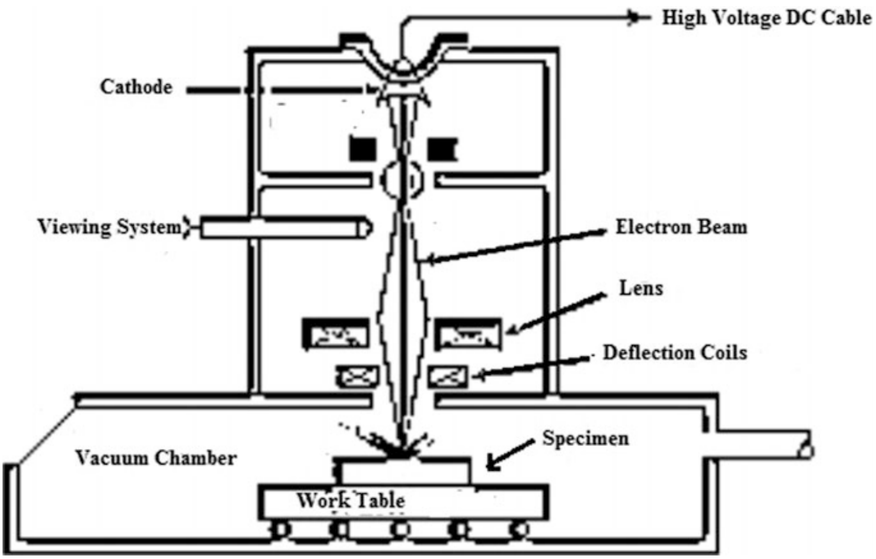

Fig. 9.3 EBM process

of electrons constitutes electric current varying between 20 and 100 mA. The current density ranges 5 and 15 A/cm^2. The current is dependent upon the material of the cathode, voltage and the temperature of the cathode. The electrons are accelerated towards the workpiece under the influence of high voltage of around 150 kV. The accelerating electrons are focused and then passed through the hole in anode. The electron beam is again focused by a system of electronic or magnetic lens to have a better control of the electron direction. The accelerating voltage imparts a very high velocity to the electrons which is maintained until the electrons strike the workpiece material.

The heating of the workpiece material takes place because of the conversion of the kinetic energy of the electron to thermal energy. The temperature of the specimen rises rapidly its boiling point and thereby leading to removal of material by evaporation. The EBM process can machine a wide range of materials because of its large power density of 1.55 MW/mm^2. Automation of EBM process is possible because of its capability to offer easy control of the beam and coupled with accurate manipulation of the workpiece.

For the removal of material from a workpiece for the creation of hole of depth g, the required number of pulses is given by the following equation:

$$n_e = \frac{g}{g_e}$$

where, g is the reuired depth of hole, (mm) and g_e is the depth of hole removed per pulse (mm)

The machining time, T_m:

$$t_m = \frac{n_e}{f_p}$$

$$f_p = \frac{1}{t_p + t_i}$$

where, f_p is the frequency of the pulse, (s^{-1}); t_i is the pulse interval, (μs); t_p is the pulse time, (μs)

The rate of drilling, Ψ (mm/min),

$$\psi = \frac{g f_p}{n_e}$$

The factors on which the drilling depth depends are the diameter of the beam, accelerating voltage and power density. The beam diameter as well the density of the material being machined determines the depth of the eroded material per pulse. With the increasing voltage, decrease in the no. of pulses for machining a hole to the desired depth has been observed. The number of pulses however increases hyperbolically with the increasing depth of the hole given that the rest of the parameters are kept constant. This means that on reaching a certain depth of the hole being machined, a very large number of pulses would be required to further deepen the hole.

The slotting time for creating a slot is given by the following equation:

$$t_m = \frac{n_e L}{f_b d_b}$$

The rate of slotting η (mm/min):

$$\eta = K d_b f_p I_e V_a$$

where, d_b is the diameter of the beam; I_e is the beam current (mA) and V_a is the accelerating voltage of beam (kV).

The machining time in slotting is therefore affected by the pulse duration, beam diameter, the number of pulses and the length of the slot.

The rate of EBM is expressed in the no. of pulses that is required to remove a given quantity of material. Therefore, to control the machining time the electron counter registering the number of pulses is adjusted. A number of material properties such as boiling and melting point, electrical and thermal conductivity determine how readily the workpiece material can be machined.

Smaller number of pulses is required for materials with lower power consumption for the removal of the same volume of material and thereby improving the machining performance of the process. The material properties i.e., the density as well as the electrical conductivity of the material jointly effect the machinability of the process. Further, the process becomes ineffective beyond a certain accelerating voltage (120 kV). The machinability index, defined in terms of the number of pulses, is dependent on the hole sinking depth. The number of pulses required is also reduced with the increasing pulse duration. The energy of the pulse as well as the nature of the material undergoing machining determines the diameter of the cavities and the hole.

The quality of surface obtained from EBM also depends on the nature of material being machined. Surface roughness as close to 1 μm is obtained for the holes and cavities. A white layer ring is often observed surrounding the hole significant of the damaged layer. The material layer is affected by the electron beams' temperature. The increasing pulse duration and the diameter of the hole increase the diameter of the damaged layer. The heat affected zone in the EBM is as much as 0.25 mm which highly impacts the surface integrity of the components under the influence of high stresses.

9.4.3 Applications

9.4.3.1 Slotting

Rectangular slots are produced in stainless steel plates in a very short duration of time. The thickness of the workpiece material determines the slotting time.

9.4.3.2 Perforations in Thin Sheets

The number of holes required for EBM process to be economically viable ranges 10^4–10^5. To achieve this economic feasibility, pulses lasting few microseconds are desired. The sheet requiring perforations are fed through the rotating drum, shifted in the direction of the axis simultaneously. The combination of the sheet feeding manner results in production of holes along helical lines. The perforations in engine components are produced as a result of manipulators capable to rotate and translate along the four axes. EBM process can be used to perforate on filters, for production of sieves and in the production of the glass fibre production.

9.4.3.3 Scaffolds for Orthopedic Applications

The use of porous structure for biomedical applications is one of the recent advancements. A number of materials are used for the fabrication of load-bearing implants such as cobalt-chromium, stainless steel and titanium alloys. A unit cell of metallic auxetic structures can be manufactured additively, and there combinations can result into load bearing implants for the biomedical applications. These combinations can be achieved using the EBM process with the stiffness as close as to that of the bone. A number of technical reports have investigated the fabrication of Ti_6Al_4V cubic structures using the EBM technique. The strength in compression and modulus of elasticity for the fabricated scaffolds have been found to be comparable to that of the cortical and the trabecular bones (Parthasarathy et al. 2010, 2011). Eldesouky et al. (2017) have fabricated and tested the Ti_6Al_4V scaffolds using the EBM process. They have recommended the use of EBM process for producing the samples with strut thickness more than 0.5 mm. the lattice structure was found to withstand a load of 71 kN without failure and thereby supporting the claim to be used in weight bearing applications.

9.4.3.4 Electron Beam Welding

The welding of two workpiece material is another application of electron beam. The thickness of materials that can be welded ranges 0.01–250 mm for steel, whereas it is 500 mm for aluminum (Klimpel 2013). The process has the potential to weld different grades of steel as well as the materials that are not weldable by other methods such as chemically active materials and the refractory materials. As such the process is a versatile technology. There can be certain complications in welding materials with different chemical composition, coefficient of thermal expansion, thermal conductivity etc. (Klimpel 2013).

A number of research reports have been presented on the electron beam welding of high and ultra-high strength steels. For instance, an investigation on the welding of 300 M was carried out for as-weld and post-weld heat treatment conditions by Zhang et al. (2013) and it was concluded that better mechanical properties can be produced with post weld heat treatment conditions. the effect of changes in electron beam welding process conditions was investigated on the micro-structural properties of carbon manganese was investigated by Elliot (1984). It was concluded that a significant effect on the micro-structural properties, especially toughness, is observed with the changing conditions. On similar track, the electron beam welding of micro-alloyed high strength steels was carried out for different energy inputs (Maurer et al. 2012) and high strength steel grades (Węglowski et al. 2016, 2017).

9.4.4 Advantages and Disadvantages

9.4.4.1 Advantages

- High rate drilling is possible.
- No difficulty while machining acute angles.
- The process is flexible with regard to the parameters.

- Material hardness, ductility and reflectivity don't impose any restriction on the process.
- The workpiece material is free from any mechanical distortions.
- High accuracy.
- Surface finish obtained is the best in comparison to the other machining processes.
- The overall cost involved is low in comparison to other machining processes of producing holes.

9.4.4.2 Disadvantages

- High cost of equipment.
- Long production time.
- Auxiliary backing material is required.
- The process results in the formation of thin recast layer.

9.5 Plasma Beam Machining

9.5.1 Introduction

The gaseous molecules are dissociated into atoms on raising the temperature of gas to about 2000 °C. The ionization of the atoms takes place at a temperature of around 3000 °C. this state of gas is referred to as *plasma*. During its earlier days of inception, the plasma gas for machining was adopted as a replacement for oxy-flame cutting of stainless steel, aluminium and other nonferrous metals. With the advancements, the process capability was extended to metallic and non-conductive materials. The plasma beam machining (PBM) process works faster for stainless steels in comparison to the mild steel.

9.5.2 The Machining System

The PBM process is based on the continuous arc generated between water-cooled copper anode and the tungsten cathode. Gas flows through the anode after being introduced at the cathode. A high temperature plasma arc is generated as a result of temperature in the narrow region of cathode reaching to about 28,000 °C. The material under the influence of such a high temperature is melted rapidly and is vaporized rapidly. The machining debris is then flushed away by the stream of ionized gas. The material removal rate in the PBM process is very much higher in comparison to other conventional processes such as turning. The machining system of PBM consists of the following components: plasma jet, plasma arc, air plasma and shielded plasma.

9.5.2.1 Plasma Arc

The arc is struck at the rear electrode of the plasma torch. The stricken arc then progresses to the conductive specimen. Temperatures of about 33,300 °C are produced. Damage to the electrode and the workpiece material takes place because of the double arcing effect which takes place between the workpiece and the nozzle. The transfer of heat from anode to the workpiece results in high heat transfer rates. The PBM process is used for the machining of metals because of its greater efficiency. The PBM is not dependent on the chemical reaction taking place between the work metal and the gas. The PBM process is also suitable for all the electrical conductive materials and cannot be machined using oxy-fuel gas cutting.

9.5.2.2 Plasma Jet

The ionized gas known as plasma is emitted by the plasma torch. The jet has a very high temperature of around 1600 °C. The emitted jet is known as plasma jet. Cooling water is used to cool down the torch which is the anode. Water extracts a large amount of heat from the anodic plasma torch and is therefore doesn't participate effectively in the material removal process. The plasma jet system is capable to handle non conductive materials difficult to be machined using the traditional methods.

9.5.2.3 Air Plasma

Machining gas used in the PBM process is compressed air. The air breaks down into its constituents under the influence of high temperature of the plasma arc. The machining rates are enhanced because of the reactive nature of oxygen with the ferrous material. Heavy oxidization of the surface is the major drawback of the PBM process. The material used for electrodes are hafnium copper or hafnium zirconium as an alternative to tungsten. The air plasma has the potential to machine electrically conductive materials such as aluminium, stainless steel and copper.

9.5.2.4 Shielded Plasma

Water shielded plasma: water replaces the shield gas in this case. A radial jacket is formed by water around the plasma torch. The quality of cut and the width of the cutting zone are reduced by the cooling effect offered by water. However, the cutting rates are not improved.

Gas-shielded plasma: to achieve cuts of desired quality when machining different materials, assisting gases are required. To protect the assisting gases from the atmosphere, an outer shield gas such as nitrogen or argon is added around the nozzle. The type of shielding gas used depends on the material being machined. Hydrogen is used often when machining aluminium, stainless steel or other non ferrous metals. Air or oxygen may be used in case of mild steel.

9.5.3 Material Removal Rate

The removal of material is a result of the absorbed heat energy by the workpiece surface from the plasma jet. The evaporated and molten metal is blown away by the plasma torch. The type of workpiece material being machined is a deciding factor for the machinability of the process. Further, the transfer rate of maximum temperature is dependent on the type of shield and machining gases used in the process which in turn determines the machinability of the process. With the increasing thickness of metal the machining speed decreases. An increased gas flow rate is required with the increased power to remove the molten metal away from the machining zone.

9.5.4 Applications

- PBM is one of the most attractive turning of materials that are difficult to be machined using the conventional machining processes.
- Profile cutting of metals is possible with the advent of the computer numerical controlled PBM process.
- The PBM process is recommended for workpiece material with subsequent welding.
- The tubes of thickness up to 50 mm can be cut using the plasma arc cutting process.
- The PBM process can cut deep grooves in stainless steel at a very high machining rate which is ten times higher in comparison to grinding and chipping methods.

9.5.5 Advantages and Disadvantages

9.5.5.1 Advantages

- The process is free from any chemical complications and maintenance.
- The process is considered to be clean which eliminates the need for grit blasting, ultrasonic cleaning and solvent wiping.
- The exposure to hazardous chemicals is totally eliminated.
- Less energy is required to operate.

9.5.5.2 Disadvantages

- The process produces heat that effects and spoils the workpiece surface.
- Toxic fumes are produced.
- Large power is required for very thick plates of mild steel.

9.6 Ion Beam Machining (IBM)

9.6.1 Introduction

In ion beam machining process, the ions emitted from ion source are accelerated towards the workpiece using accelerating voltage. The process takes place in a vacuum chamber. The IBM process is also known as ion milling, ion etching or ion polishing. A sufficiently energy intensive ion beam is produced by an ion source which on striking the workpiece surface removes the atoms from the surface of the workpiece. The electrons are emitted from hot tungsten filament (cathode) and are accelerated towards the anode using an accelerating voltage. An interaction takes place between the emitted electrons and the argon atoms present in the plasma source. This interaction results in production of the argon ions:

$$Ar + e^{-} \rightarrow Ar^{+} + 2e$$

The electron flow path is made spiral because of the presence of magnetic field between the anode and the cathode. Therefore, the ionization process increases as a result of increased interaction of electron with the argon atoms due to the increase in length of the electron travel. The argon ions then moves toward the specimen supported by a water-cooled table. The machining variables such as angle of incidence, flux and voltage are controlled independently.

9.6.2 Material Removal Rate

The atoms are ejected as a result of primary collision if the ions strike the workpiece surface obliquely. Therefore, the ejection process will be greatly affected by the incident moment vector. For the oblique incidence, the number of atoms ejected per ion beam, also known as sputtering yields, is greater in comparison to the normal incidence of the beam. Thus the momentum transfer to the atoms on the workpiece from the ion beam forms the basis of material removal process in IBM. The energy required to effect the atom removal process should be greater than the binding energies. A cascading effect may result at higher energies. The sputtering yield can be calculated using the following equation:

$$V(\theta) = \frac{S(\theta) \times (9.6 \times 10^{25}) \times \cos(\theta)}{n}$$

where, V(θ) is the etch rate measured in atoms per min/(mA/cm^2); S(θ) is the yield, atoms per ion and n is the density of the target material in atoms/cm^3.

The reduced current densities for the cases other than that of normal incidence is taken care of by the cos (θ) component. The binding energy of the atoms of the workpiece material determines the yield and hence the rate of machining which are the machinability indices in the IBM process. The machining rate for metallic materials is greater than that of the non metallic materials.

9.6.3 Accuracy and Surface Effects

IBM process has the potential to produce dimensions as small as 10 to 100 nm. The ion beams' angle of incidence is one of the major parameters that effects the slope of the sidewalls for the workpiece. The quality of surface finish obtained is too dependent on the beam incidence angle. The process produces surfaces with accuracy levels of ±1.0%. The surface finish less than 1 μm is possible with IBM.

9.6.4 Applications

- The laser mirrors are smoothened and undergo reduction in thickness using the IBM process. The surface finish also remains unaffected while the laser mirrors undergo the machining process.
- Samples for transmission electron microscopy can be produced using the two opposing beams.
- Closely packed textured cones can be produced by the IBM process in a wide range of materials such as copper, gold, silver, stainless steel and nickel.

- The IBM process results in atomically cleaned surfaces which find application in adhesion of the gold films to aluminium and silicon substrate.

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Chapter 10
Hybrid Electrochemical Process

10.1 Introduction

The material removal process in case of hybrid electrochemical processes take place either through electro-chemical dissolution (ECD) or chemical dissolution (CD). The material removal rate is enhanced either by the use of thermal assistance or action of mechanical machining. The combination also results in the improved quality of surface.

A use of laser in case of thermally assisted processes results in hybrid processes such as laser-assisted chemical etching (LAE), laser-assisted chemical machining (ECML) etc. In case of the LAE process, the dissolution rate is enhanced with the local heating of the inter-electrode gap. In ECML, the dissolution phase becomes more intensive due to rise in the current density and thereby increasing the productivity of the process.

In case of hybrid process involving mechanical machining action, the dissolution phase and hence the material removal process is enhanced by changing the inter-electrode gap conditions. The mechanical assisted electrochemical process also lead to depassivation of the machined surface by the mechanical action i.e., the removal of thin layers of oxides is ensured from the anode surface. Therefore, the surface obtained is with higher degree of smoothness.

Many hybrid processes results due to the combination of mechanical abrasion with the electrochemical machining. The examples include electrochemical superfinishing (ECS), electrochemical honing (ECH) and electrochemical grinding (ECG).

The material removal rate and the flushing are enhanced by the use of ultrasonic with the electrochemical discharge process. The combination results in ultrasonic assisted chemical machining (USMEC). In the electrochemical buffing (ECB) the mechanical action of the fluid jet enhances the chemical deposition process.

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10.2 Electrochemical Grinding

10.2.1 Introduction

In the electrochemical grinding (ECG) process the workpiece is positively charged while the grinding wheel is negatively charged. The process is performed in the presence of an electrolytic solution. Figure 10.1 shows the ECG process. The process is similar to that of the electrochemical machining (ECM) process with the difference of the cathodic tool used. The cathodic tool used is a grinding wheel in case of ECG whereas in case of ECM process a shaped tool with the desired contour to be made on the workpiece is the cathodic tool. The conductive bonding material of the grinding wheel comprises of the insulating abrasive particles. The insulating abrasive particles serve as a spacer between the workpiece (anode) and the grinding wheel (cathode). A constant inter electrode gap is maintained the size of which depends on the grain size of the particles. The electrolytic solution can be flushed through this inter electrode gap. Typically sodium nitrate and sodium chloride are used as an electrolytic solution (Bhattacharyya 1973; Bennedict 1987; Jain 2002).

The abrasive action of the non-conducting abrasive particles continuously removes material from the workpiece surface. The cathodic tool rotates at a speed ranging 20–35 m/s. The current ratings are maintained 50–300 A.

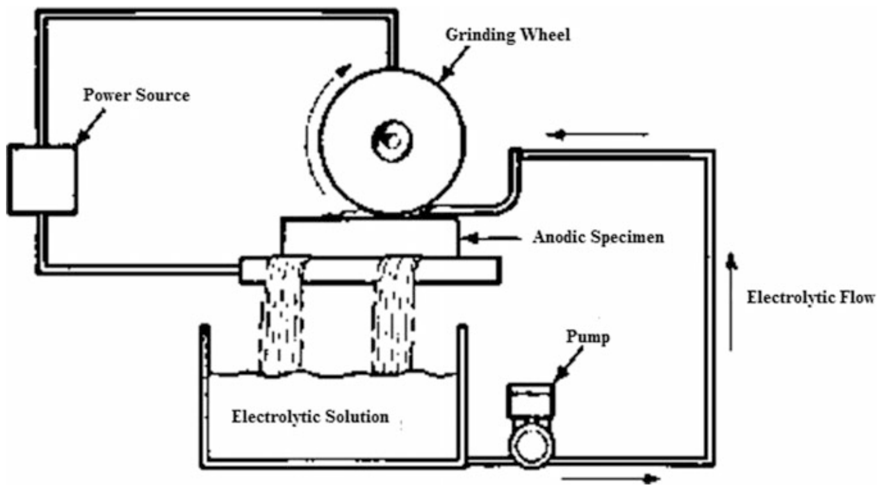


Fig. 10.1 ECG process

10.2.2 Material Removal Rate

A current density ranging 120–240 A/cm^2 is created on the application of gap voltage ranging 4–40 V between the anodic workpiece and the cathodic grinding wheel. The factors determining the current density are gap width, materials being machined and applied voltage. The material removal occurs through the combined action of the electrochemical discharge (ECD) process and the mechanical action (MA) of the abrasive grits. However, the material removal process takes place through the ECD process whereas the abrasive grit accounts for additional 5–10% of the total material removal.

In comparison to the conventional grinding process the material removal rate is four times faster for the ECG process. Further, the ECG process produces parts that are free from burrs and residual stresses. The optimum material removal rate can be achieved with the large grinding area which will in turn draw greater machining current. Following equation can be used to arrive at the volumetric removal rate (mm^3/min):

$$VRR = \frac{\varepsilon I}{F\rho}$$

where, I is the machining current, (A); F is the faraday's constant, (C); ε is the equivalent weight, (g) and ρ is the density of the material (kg/m^3).

Since ECG is a hybrid process combining MA and ECD, there is many fold increase in the machining rate and there is reduction in tool wear and consumption of energy as well. Further, the surfaces obtained are with enhanced properties. The ECD phase is governed by the Faraday's law while the MA of the abrasive grains is dependent on the conditions existing in the inter electrode gap. The conditions such as transport of electrolyte, electric filed and the hydrodynamic effects determine the MA of the abrasive grain particles.

The mechanical depolarization action is performed by the abrasive grains which progresses by abrasion of the insoluble films from the surface of the workpiece (anode). The insoluble films are formed in the case of cemented carbides and many metals. Therefore, depassivation of the workpiece is the major function of the abrasive grains. The simultaneous action of the ECD and MA process takes place in the machining area where the gap width is lesser than the height of the grain part projecting over the binder. The pure ECD process exists at the entry and exit of the wheel in which case the abrasive grains do not touch the surface of the workpiece.

The contribution of the MA component towards material removal increases with the speed of the wheel and the longitudinal feed rate and decrease in the voltage. On the other hand the contribution of ECD component increases with the decrease in feed rate and cutting forces. The electrical parameters, grinding wheel features and the machinability in the electrolyte are the factors on which the contribution of the MA approaching zero depends. Wider tolerances, larger overcut and poor surface finish are produced with slower feed rates. With the increasing feed rates the wear of the grinding wheel too increases. The saving of the machining costs are higher with the use of diamond grinding wheels that considerably reduces the grinding forces and hence the wear of the wheel. The productivity of the process, surface integrity and dimensional accuracy are increased with the MA phase.

The material removal rate for the electrolytic dissolution part depends on variables such as electrolyte, material type and the current density. The highest current density yields the optimum material removal rates. However, the current density is restricted by the rate of anode dissolution and the boiling point of the electrolytic solution. Higher current density can be achieved by increasing the wheel pressure for the material removal process. The increased wheel pressure reduces the machining gap and hence allows for higher current density. While on the other hand the lower current density is the result of increased abrasive grain size that increases the machining gap.

10.2.3 Accuracy and Surface Quality

Tolerances of ±0.003 mm are achievable with the traditional grinding process which also results in heat and stresses. However, the tolerances of ±0.025 mm are achievable with the ECG process. There are a number of factors on which the closer tolerances can be achieved. Some of which are electrolyte flow, current, metallurgical properties of the workpiece and the feed rate. Accuracies of about ±0.025 mm are achievable with the ECG process. The grinding action produces the final cut to result in closer dimensional tolerances and good surface finish. For achieving closer tolerances, sharp edges, reduced overcut and bright surface finish, use of lower voltages are recommended. The ECG process can machine very thin material of about 1.02 mm thickness which otherwise warps under the pressure if machined using any of the conventional machining processes. This may be attributed to the fact that a very little contact occurs between the workpiece and the wheel. However, the process lacks accuracy while grinding the inside corners. The electric filed effect seldom leads to achieving radii better than 0.25 mm.

10.2.4 Applications

The following are the applications of the ECG process:

- The parts produced from difficult to machine materials can be machined using the ECG process.
- Production of cutting tools from tungsten carbide and tubes with thin walls.
- Production of specimens for tensile tests and metal fatigue.
- Production of holes at the end of fatigue cracks in steel structures.

- Machining of high strength alloys and carbides.

The process is however not suitable for die-making industries.

10.2.5 Advantages and Disadvantages

10.2.5.1 Advantages

- Free from burrs.
- No distortion of thermosensitive and fragile parts.
- Good quality of surface.
- Narrow tolerances are achievable.
- Wheel life is longer.
- No work hardening.

10.2.5.2 Disadvantages

- The capital cost in comparison to conventional process is higher.
- Only electrically conductive materials can be machined.
- Corrosive nature of electrolytic solution.
- Disposal of electrolyte is problematic.
- Requires disposal.

10.3 Electrochemical Honing

10.3.1 Introduction

The high rate of material removal for the ECD and the MA processes are combined to give rise to another hybrid material removal process known as electrochemical honing. The electrochemical honing (ECH) process as shown in the Fig. 10.2, results in a comparatively higher rate of material removal in comparison to the other conventional honing process. The cathodic tool in ECH is similar to that used in the conventional machining process. The cathodic tool possess a number of small holes so that the electrolyte can be introduced into the inter electrode gap directly. The electrolytic solution serves to provide electrons through the ionization process. Further it also functions as coolant and also flushes the debris away that is produced as a result of shearing off by MA. The metal sludge resulting from the ECD action

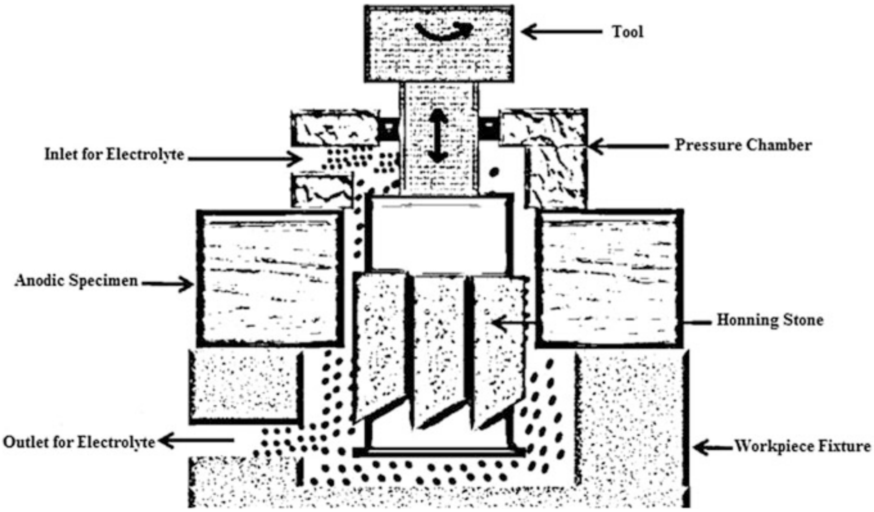


Fig. 10.2 ECH process

is too flushed away by the electrolytic solution. The ECD phase is responsible for the maximum material removal while the MA action is sufficient enough to generate straight, round and geometrically true cylinder. The oxides formed on the workpiece surface as a result of the ECD action are removed by the MA action. The ECD phase is thus enhanced by the MA action as the abrasion presents a fresh surface for further dissolution. The electrolytic solution used is sodium nitrate solution instead of more acidic solutions such as sodium chloride. DC current is usually employed by ECH process. The gap voltage ranging 6–30 V results in a current density of 465 A/cm^2 (Randlett et al. 1968). Geometrical errors in the machined bore are bound to occur because of the poor distribution of the electrolytic solution in the machining gap.

10.3.2 Process Characteristics

In the ECH process the abrasive stone with metallic bond is carried on the spindle. This is the cathodic tool and has the reciprocating motion. The rapidly flowing electrolytic solution separates the reciprocating cathodic tool from the workpiece. A gap size ranging 0.076–0.250 mm is maintained by the abrasive stones. The ECD phase depassivates the machining surface. In another arrangement of the ECH machining system, the honing sticks used are nonconductive and forms the cathodic tool responsible for the MA process. The reciprocating and the rotary motion of the machine spindle are responsible for the ECD process.

The ECH process removes material that is three to five times faster in comparison to the conventional machining process and around four times faster when compared to the internal cylinder grinding. The ECH process is capable to produce tolerances in the range of ±0.003 mm, whereas the range of surface roughness is between 0.2 and 0.8 μm. The surface roughness is controlled by allowing the MA action to continue even after turning off the current. However, light residual stresses of compressive nature remains in the surface. A conventional cross-hatched surface is produced by the ECH process that is used for load-bearing and sealing surfaces.

10.3.3 Applications

The errors in roundness are decreased as a result of rotating motions. Further, the taper and the waviness nature are reduced through the reciprocating motion of the tool. The heat distortion is also minimized as a result of light stone pressure. The process is made burr free due to the presence of ECD phase that results in no residual stresses. Therefore, hard and conductive materials can be machined using the ECH process. The ECH process is capable of tackling pinion gears of high alloy steels. The holes can in the cast tool steel components can be machined by the ECH process. One of the important applications of the ECH process is the hone forming process (HF) in which case the abrasion process as well as the metal deposition process proceeds simultaneously. The HF process is used for parts that have become out-of tolerance and also for reconditioning of the worn surfaces.

10.3.3.1 Finishing of Gears by ECH

The machining chamber used for finishing of the gears by ECH process is the distinguishing feature that differentiates between the components used for the internal finishing of the cylinders. Machining chambers have been developed by Naik et al. (2008) and Misra et al. (2010) for machining of *helical gears*. For the ECM action to take place, the anodic gear specimen must mesh perfectly with the specially designed cathodic tool. Simultaneously the anodic gear must mesh with the honing gear for the mechanical honing to take place. The three gears involved in the machining process must have the same module and involute profile.

Shaikh et al. (2013) developed the concept of *twin complementary cathode gear* to solve the machining problem for the bevel gears which restricts the reciprocating motion of the workpiece gear required for the finishing operation. However the use of pulsed power supply during ECH (PECH) by Pathak et al. (2015) showed an improvement of 50% in local errors over twin complementary cathode gear arrangement. A simultaneous improvement in micro-geometry and the surface finish for the bevel gears was also reported by using the PECH process.

10.3.4 Advantages and Limitations

10.3.4.1 Advantages

ECH process offers a number of advantages which are as under:

- Material with any hardness can be machined. However, the material should be electrically conducting.
- The surface finish produced is cross-hatch lay pattern that is beneficial for oil retention.
- The ECH process has the ability to correct errors related to the geometrical shape, form errors and location errors.
- The ECH process is relatively fast in comparison to the ECM and mechanical honing.
- The abrasive sticks used have increased life due to the limited contribution of mechanical honing.

10.3.4.2 Disadvantages

- Only electrically conductive materials can be machined.
- The ECH process is more costly.
- Machining of blind holes is a major limitation of the ECH process.
- Errors such as location of holes and its perpendicularity cannot be taken care by the ECH process (Jain et al. 2009).

10.4 Electrochemical Superfinishing

10.4.1 Introduction

The conventional superfinishing process removes the micro-irregularities from the workpiece surface with the aid of reciprocating honing sticks moving along the length of the workpiece. The honing sticks also undergo rotary motion simultaneously with the reciprocating motion. However the process suffers from disadvantage in the form of surface irregularities such as out of roundness and waviness.

The disadvantages of the conventional superfinishing operation have been done with the electrochemical superfinishing (ECS) operation which is combination of ECD and mechanical scrubbing (MS). The electrochemical superfinishing is therefore an improvement over the conventional superfinishing operations. The MS action of chip removal is further enhanced by the small stock removal offered by the dissolution process of the ECD component. Therefore, the ES process has the potential of high stock removal by using either a separate cathodic tool electrode or diamond abrasive stick with a metallic bond.

Therefore, the merit of the ECS is the high stock removal with the ability to produce close tolerances and is therefore used as one of the major machining operations by different industries. The grinding process that is required initially in case of conventional superfinishing is eliminated in case of the ECS process. The ECS process can be used in cases where the high stock removal rate is not possible with the conventional machining processes. Further, the process is well suited for difficult to machine alloys and other metals.

Since in ECS, the bulk material removal proceeds electrochemically in an electrolyte cooled atmosphere, the process is suitable for the parts that are susceptible to heat and distortion. The ECS process produces components that are free from burrs.

10.4.2 Material Removal Process

The ECS process produces oxide film on the workpiece surface. The high spots on the workpiece surface that are aberration to the regular surface are scrubbed away by the MS action. Such surface irregularities will be dealt by the ECD phase heavily in comparison to the areas still covered with the protective oxide film. The protective film aids in correcting the geometrical accuracies such as roundness and cylindricality.

The type of electrolyte used determines the power of the oxide film. There are certain electrolytes with strong power which reduces the ECD with their protective film. The others have strong power too, but in order to build up the film the electric charge required is too small. A decrease in the current by about 10–20% has been observed in case of the ECD process without the mechanical scrubbing action. This is attributed to the presence of dark visible film. Therefore, as a result of decreasing current, the material removal rate too decreases (EI-Lawendy 1977). Hence the MS phase should proceed alternatively with the ECD phase.

Use of light stone pressure is recommended after the ECM phase in order to take care of the metallurgical damage resulting due to MS. The action therefore results in a bright surface finish; straightness and roundness of less than 0.007 mm and diameter with tolerances ±0.013 mm. High instantaneous current densities are possible with the use of pulsating voltage (Datta and Landolt 1983). This is possible because of the relaxation time of zero current following each current pulse. The relaxation time allows for the removal of heat generated by the Joule effect and the reaction product.

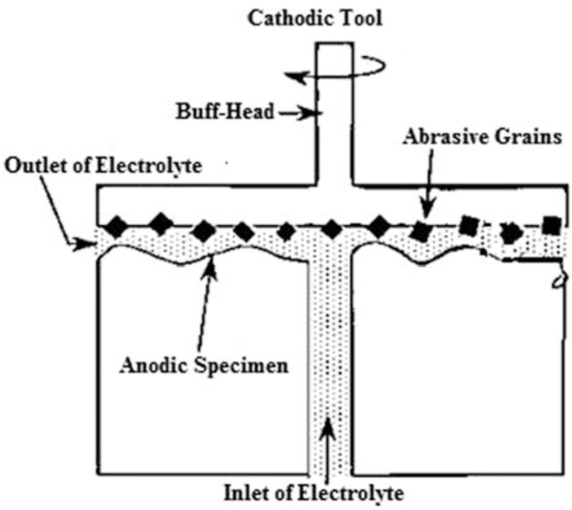
The process parameters involved in the ECS process are that similar to ECM process such as electrolyte type, gap voltage, temperature and concentration. The process parameters for the MS phase involve stone pressure, oscillation amplitude and frequency and the abrasive grain size. Higher current densities result in higher material removal rate associated with the ECD phase. With the high current densities, the availability of the energy for the dissolution phase to continue increases. Increase in material removal rate can be had with the increasing scrubbing speed, duty cycle and voltage. The oxide film removal process too increases with the consequent increase in the high energy. With the increasing scrubbing speed the percentage contribution of MA phase increases.

10.5 Electrochemical Buffing

10.5.1 Introduction

The electrochemical buffing (ECB) as shown in the Fig. 10.3 is one of the finishing processes known for producing mirror like and bright surfaces. However, the electrochemical buffing process is a slow process. Further, the working environmental conditions are unsuitable since the process is carried out under dry conditions resulting in dust. A carbon fiber cloth is utilized in the ECB process that rubs the workpiece specimen against the revolving cathode fiber buff. A suitable pump is used to supply the electrolytic solution. The electrolytic solutions used typically are NaCl or $NaNO_3$. The machining current flows to through the carbon cloth to the cathode from the workpiece specimen. The current density ranges 0.1 to 7 A/cm^2 whereas the buffing speed between 1 and 6 m/s (Hoshino and Ogawa 1995).

Fig. 10.3 ECB process



10.5.2 Material Removal Process

The ECD process occurs on the surface of the anodic workpiece. The surface of the anodic specimen is rubbed by the carbon cloth buff. The polishing speed is controlled by the parameters such as the type of electrolytic solution, the current density and the type of workpiece material. NaCl can be used as electrolytic solution to ensure high current densities and hence higher polishing speed. The material removal rate is increased with the addition of Al_2O_3 abrasives to the machining medium. However, there is a decrease in surface brightness and smoothness. During the ECB process, the surface of the workpiece specimen is deposited with a passive oxide film. The surface is made smoother with the removal of the oxide films by the MA action which enhances the dissolution phase to prevail in the high irregularities region.

10.6 Ultrasonic-Assisted ECM

10.6.1 Introduction

There is an increasing need in the industries to machine hard and ductile materials in many applications. The parts with better surface quality are obtained using the ultrasonic machining process (USM). However the USM has the demerit of lower material removal rate and machining productivity. The better surface quality rates and higher machining rate are possible with the ECM process. However the ECM process is suitable for machining conductive materials only whereas hard and brittle materials can be machined using the USM process. The machining of composites containing metallic and non-metallic phases cannot be machined by using either the USM or ECM process.

The combination of the two machining processes will aid in using the advantages of both the process in combination to machine composite materials. The combination of USM and ECM yields ultrasonic assisted electrochemical machining (USMEC), shown in the Fig. 10.4. The USMEC system employs the normal USM process replacing water with abrasive carrier fluid as an electrolytic solution. The USMEC process uses voltage ranging 3–15 V DC and the current densities ranging 5–30 A/cm^2. The dissolution process proceeds in tandem with the vibration of the machine head and hence the cathodic tool at ultrasonic frequencies of 20 kHz and amplitude of 8–30 μm. The process parameters of the USMEC process are similar to that of the USM and the ECM process.

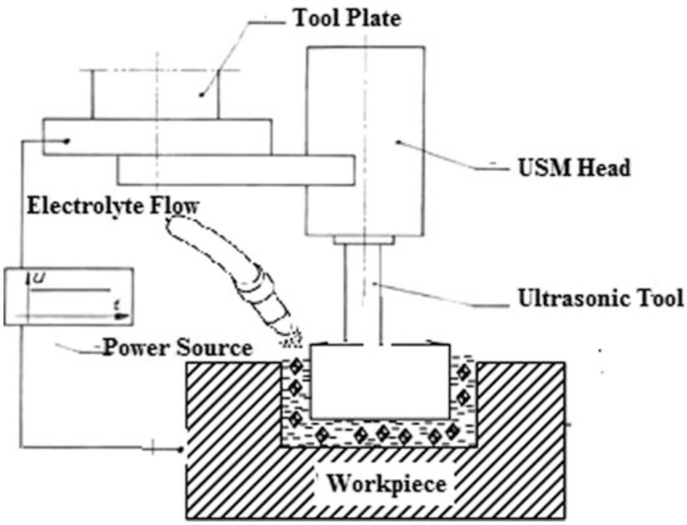


Fig. 10.4 USMEC process

10.6.2 Material Removal Process

The relative position of the tool with respect to the workpiece is one of the major factors in determining the intensity of the dissolution phase in the USMEC process. The dissolution phase reaches its optimum efficiency for the machining gap size equivalent to that of the size of the statistically pressed abrasive grains. A minimum interelectrode gap is achieved under this condition by the non conductive abrasive grains. To maintain an efficient ECD process, the pulsed voltage when replaced with the DC should be synchronous with the oscillation of the tool. The synchronization also helps in avoiding the formation of the spark discharge across the inter electrode gap.

The MA phase in the USMEC process occurs by the impact of the ultrasonic abrasive grains at the workpiece surface. The MA phase and the dissolution phase occur simultaneously. The MA action of the abrasive grains should be directed towards the oxide film formed as a result of the dissolution phase and not on the material of the anodic specimen. The mechanical depassivation of the workpiece surface enhances the dissolution process. Therefore, the USMEC process has higher machining speed and lower rate of tool wear in comparison to the normal USM process. Further, the enhanced surface quality is achieved because of the conditioning of the chipping marks by the dissolution phase.

The machining performance in terms of productivity is increased with the increasing current densities. However, the side-machining effect reduces the workpiece accuracy.

10.7 Laser-Assisted ECM

The ECM phase is carried out in temperature ranging 20–80 °C. ECM is the dissolution phase that occurs in the machined surface. Increasing the temperature in the inter electrode gap can aid in accelerating the rate of dissolution phase. One of the sources of increasing the temperature is the laser beam. The laser beam in combination with the ECM process results in another hybrid ECM process referred to as laser-assisted ECM process (ECML). The electrolytic layer should be as thin as possible and the laser wavelength should be chosen such that minimum energy is absorbed by the electrolyte layer. Occurrence of many physical and chemical phenomenons takes place on the workpiece surface as well as at the subsurface layers because of the laser heat.

The rate of electrochemical reaction is affected by the laser radiations through several mechanisms. Changes in the steady state potential occur owing to the laser heating of the surface area being machined. The rate of reaction increases as result of the localized heating of the surface layer. Further, the mass transfer rate is accelerated, metal passivity degree is decreased, current efficiency is changed and finally the concentration of the current carrier is increased. However, the effect of the laser radiation is not well understood for the current efficiency of the anodic dissolution. The degree of localization will be more pronounced with the increasing current efficiency with the temperature. However, the laser may become impenetrable for the decreased current efficiency with the increasing current. There

The current density and the dissolution intensity showed an increase from 0.6 to 1.8 mm^3/(min A) when the temperature increases from 20 to 40 °C (Zybura-Skrabalak and Rusraj 2000). The material removal rate of the ECM process is enhanced by up to ten times through the laser assistance and therefore can be applied for the various micromachining applications. The laser serves to locally dissolve the anodic workpiece specimen. Employing pulse radiation is another way to increase the localized dissolving effect of the laser beam. Similar effect can be obtained using the increased electrolytic flow. The ECML process lends itself in electronic and space industries to shape small elements (5–500 μm) with higher accuracy of (1–10 μm). The ECML process is of particular interest for the electronic industries where the products are fabricated using the difficult-to-machine materials such as ceramics, composites and alloys. The precision and the efficiency of the small holes have been reported to increase using the laser-assisted jet ECM (LAJECM) by Pajak and coworkers (2004).

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Part III
Virtual Manufacturing

Chapter 11
Introduction to Virtual Manufacturing

11.1 Introduction

There has been a shift in paradigm in manufacturing from real to virtual. This has led to a rapid surge in the research interest for scientific community to explore more to this paradigm shift. The environment of physical manufacturing is now being simulated using the computers. The understanding of behavior of different components of physical manufacturing and then emulating the same on the computer has lead to reduction in amount of tests and tests before actual production. Further, the emulation leads to reduced wastage of material and interruptions to the actual machine (Owen 1997; Radharamanan 2002). The safety related issues too are minimized. The management of data for the actual manufacturing and the product-life cycle management can be easily documented. A number of virtual systems have been developed given the advantages associated with such systems. Some of the examples of virtual systems are: Virtual Manufacturing, Virtual Machine Tool, Virtual Machining, Virtual Tooling, Virtual Assembly and Virtual Prototyping.

A focused research on Virtual Manufacturing has led to the development of e-manufacturing or a Digital Factory. The Virtual Manufacturing environment has led to modeling of shop floor capabilities, devices and even the whole enterprise. This has increased the decision making capabilities for the different manufacturing processes (Iwata et al. 1997; Lee and Noh 1997; Wang et al. 2004). There has been an equal interest in the field of Virtual Machine Tool systems as well. Much of the research in this regard has been on the design of machine tools and on the simulation of the models of machine tools. The modeling was done either for all the different operating modes of a machine tool or for application specific mode of a machine tool (Wang et al. 2008). There has been an expansion in the capabilities of Virtual Manufacturing and Virtual Machine Tool from simple simulation such as straightforward tool-path generation, verification of NC-code etc., to complex predictions such as analysis of tool life, surface topography, predictions of

K. Kumar et al., *Advanced Machining and Manufacturing Processes*,
Materials Forming, Machining and Tribology,
https://doi.org/10.1007/978-3-319-76075-9_11

machining error, vibration, temperature etc. Other field of research besides Virtual Manufacturing and Virtual Machine tool has been in Virtual Assembly (Wang et al. 2006), Virtual Tooling (Ko et al. 2005) and Virtual Prototype (Tsen et al. 1998).

The present chapter aims to provide for deeper insight into virtual systems. A discussion on the Taxonomy of Virtual Manufacturing and Virtual Machine Tool systems has been carried in the chapter. Better understanding of the topic has been attempted through classification of the subsequent topics into Virtual reality, Web-Based, mathematical modeling and hardware interaction simulation. The chapter ends with the concluding remarks.

11.2 Taxonomy for Virtual Manufacturing and Virtual Machine Tool

A number of definitions and technologies have been used for the virtual manufacturing systems for their definition and classification. Many researchers have recognized the need to classify Virtual Manufacturing technologies. A classification based on matrix of manufacturing sub systems was proposed by Onosoto and Iwata (1993). The sub-systems can be divided into 'real' comprising of Real and Physical System and Real and Informational System or into 'virtual' systems defined by Virtual and Physical Systems and Virtual and Informational System. Lawrence Associates Inc. has categorized the Virtual Manufacturing systems into three sub-categories: product-oriented systems, production-oriented systems and control-oriented systems. The product-oriented systems define the processes related to design of a product. The evaluation of machining processes is done through production-oriented systems. The control-oriented systems focus on the dynamic controlling of the production processes. Another classification system as proposed by Lee et al. categorizes the virtual manufacturing systems into type of system integration, functional usage of the system and design for process and the product. A more detailed classification scheme has been proposed by Marinov and Seetharamu (2004) through the concept of using small building blocks.

The virtual environment can be subdivided into Sub-system, Functionality and Sub-Functionality. Sub-system layer is made of different virtual systems such as Virtual Tools and Virtual Manufacturing. The possible functionalities are constituted by the Functionality layer. The Functionality layer may be subdivided into Sub-Functionalities. Depending on the target domain, each sub system has its own functionality. All the functionalities of a parent system are inherited by the sub systems. The domain of Virtual Tool consists of simulation analysis considering the entire machine tool into its scope. The domain of Virtual Manufacturing on the other hand consists of analysis of manufacturing processes such as milling, turning etc. The scope of analysis consists of optimization of the manufacturing process numerical analysis and the prediction of parameters such as material removal rate, machining time, temperature etc. For instance, the Virtual Machine Tool systems perform a wide range of functions such as virtual training, virtual monitoring and control, machine tool design etc. The system also has the capability to perform other functionalities within the scope of Virtual Manufacturing such as simulation for material removal rate, analysis of tool wear etc. In this way an environment for Virtual Manufacturing is created by extending and linking the capabilities of the different sub systems.

11.3 Virtual Reality Based Systems

The general perception towards virtual reality is the usage of complicated devices such as headsets, computers and communication with the virtual world through the use of interactive gloves. Therefore it is a common perception that virtual reality is an expensive process for the manufacturing environment. The virtual reality (VR) systems can be categorized into desktop VR and immersion VR. The visualization capabilities can be enhanced using the desktop type virtual reality systems. However, the immersion type virtual reality systems are more affordable than the desktop type because of the easy availability of virtual equipment sets.

Lin and Fu (2006) developed the Virtual Machine tool Structural Modeler (VMSM) which is capable to provide interface for modeling of machine tools in an environment of virtual reality. Several modules such as component module, library for module shape, combination rule and structure, makes up the architecture of the VMSM system. The VMSM system provides the capability to select the structure of machine tool, modify the structure and control it. It also provides to simulate the machining process.

A system known as VR CNC has been developed by Kao et al. (2006) providing support for virtual training. The system has two modules: VR CNC controller and the VR CNC structure. The structure module of VR CNC includes machine table, driving system, feedback system and the servomotor. The controller is made of HMI, NC code parser and interpolation algorithm. The functions such as Cycle Start, Cycle Stop, Emergency stop, Tool exchange and Feed rate.

Products Virtual Analysis System (PVAS) is a system that incorporates both the immersion VR and the desktop VR. The three main functions employed were: VR display, analysis and optimization of kinematics of a product, virtual manufacturing and the assembly process through dynamical and virtual interactive environment. Sun et al. (2008) have developed a similar system wherein the human-machine interaction was achieved using 3D mouse, high-level graphics accelerator card, VR projectors and 3D optical equipment. To provide for real sense to the operator a wireless USB virtual NC panel was also used.

A deeper insight into the machining process can be obtained with the aid of virtual training systems. The various technical aspects such as cutting power, the force of cutting, obtainable surface quality, material removal rate as well as the economical aspects can be analyzed well in advance. Recording of data related to the processing time such as the machining time and the set-up time of the machine was made possible by incorporating a functional timer in a virtual machine shop. On the basis of the timer it was possible to calculate the data related to time and hence the economic characteristics such as cost of labor, and material costs. The virtual shop enables the simulation of repair and maintenance.

The behavior of the tool movement could be analyzed using simulation for real time cutting developed by Luo et al. (2010). Besides the analysis of tool movement, the clamping of the workpiece, its alignment and adjustment of tool have also been made possible using the virtual systems.

The researchers have focused on to bring the different virtual systems to life by enhancing the visual effects. This has been achieved through the use of different virtual systems. The constant research activity in the field of virtual reality has made it possible several basic functionalities such as interpretation of code and simulation of material removal rate. Thus the clear advantage of the different virtual systems is to provide for more realistic and intuitive environment. However, the complex functions such as prediction of the different process parameters and the analysis of the surface finish are still major limitations of the different virtual systems. This may be due to the limitation of the present hardware and software to cope up with the animation speed when incorporating for analysis of data into the different virtual systems.

11.4 Web Based Systems

The virtual manufacturing environment has also been supported via the different web-based technologies. A number of web based virtual systems have been developed to assist in design of machine tools, simulating the performance of machine tool and the manufacturing process and controlling the same through the web network.

The web based manufacturing environment is made of structure configuration of machine tools, geometrical configuration of the mechanical component and the kinematics between the different mechanical components. Division of mechanical components of a machine into nine different units and several combinational patterns was proposed by Shinno and Ito (1986). The representation of the kinematic chains for the mechanical units was done through a connectivity graph which also reflects the combination of the mechanical units. To maintain the display between the related components a scene graph was used.

A Web-based CAM subsystem (Seo et al. 2006) of web based virtual manufacturing was developed for the animation of the different manufacturing process. The animation was developed to reflect the real time manufacturing process by distributing the load data to a middleware, Common Object Request Broker Architecture (COBRA) and translator.

There are two primitives: IndexFaceSet and ElevationGrid nodes, to define the dynamics of the geometry when simulating the material removal process using the Virtual Reality Modeling Process. The set of grids constitutes the ElevationGrid wherein by changing the xDimension and Zdimension values the grid size can be changed. The grid also consists of intersecting points with their individual heights. The neighbouring intersecting points result in the formation of a small surface. On the other hand in case of IndexFaceSet, several facets define the surface formed by the interconnection of different vertices. The movement of vertices changes the shape of the IndexFaceSet.

A simulated modeling platform in 3D for the distributed manufacturing has been developed by Qin et al. (2004). The developed system provides for control features through internet in addition to the modeling of the modeling of the machine tools. Concept of drag-and-drop assembly methods was adopted by the developed system. A model-component based module system was used to implement the developed system. The system is made of a hierarchical geometric modeler, two assemblers and a behavioral editor. The basic modeled primitives can be combined with the general extrusions and the designers also have the leverage to integrate the different CAD models into simulation models. A Virtual Reality Modeling Language browser aids in visualization of simulation component model. The resemblance to the actual machining process can be enhanced with ElevationGrid of small grid spacing value and large dimensions. The large dimension of the ElevetionGrid is however expensive as it involves the interactions amongst the different sub layers such as Java Applets, the Virtual Reality Modeling Language (VRML) browser and a web browser.

The HTML approach was adopted by Hanwu and Yueming (2009). This approach integrates the different plug-ins such as JavaScript, VRML and Java Applets. The 2D display area for human machine interaction was done using the JavaScript and Java Applets, whereas the virtual manufacturing environment was created using the VRML plug-in. The different components of the interface for the developed system includes interfacing for the main operation, removal screen, reference tool addition, visualization interface for material removal, the simulation interface showing the machining results and the interface for G-code editor. The G-codes can be entered or exported manually by the user using the G-code editor.

A system known as HVMS-II (Xu et al. 2006) carries out physical and geometrical simulations simultaneously. This is one of the systems that aids in the study of machining parameters and their prediction and also on the output responses such as material removal rate through internet. It is a hybrid system that predicts surface topography, cutting forces and vibrations of cutter. Another such system is the Virtual Machining and Measuring Cell (VMMC) which was developed by Yao et al. (2002). The system is capable of predicting cycle time of the machining process and the cost of the process.

A two-tier client architecture based system was developed by Qiu et al. (2001). The system provides for the update of the workpiece geometry dynamically. The dynamic updating of the workpiece geometry is also performed under the VRML scene. The Web server forms the server part and the relaying of the data between the different clients is done using the Java application. A client is a Java applet consisting of External Client Interface (ECI), Graphical User Interface (GUI), External Authoring Interface (EAI), NC core, shell and the components that are serves to update the geometry of the workpiece during the machining process. The applet can be either single or multi-user mode. In case of multi-user mode, one of the users is made the 'master' client whereas the other users serve as 'slaves'. The user through the GUI gives command to the master client which is then passed onto the slave ECI via messenger. The shell then interprets the commands received from the master and the slave clients. The G-code is analyzed by the NC interpreter which is then sent to the shape updating algorithm. A full collaborative system can be established in between the clients.

A web based CNC milling system was developed by Ong et al. (2002). The system comprises of three databases: a virtual machining database which has been modeled using VRML, a virtual workpiece database and a database for the virtual cutting tool. The different databases can be accessed online through the Common Gateway Interface (CGI). These are integrated with HTML through Java Applets and VRML plug-ins. The system simulates the material removal process, interprets the NC codes, predicts different machining parameters and detects collisions. Script node is used for the representation of the real time simulation of the material removal process. ElevationGrid node is used for modeling of the workpiece surface. The system incorporates a time-control module for maintaining the simulation speeds. The module reads the time of the computer's system through the G-code interpreter. It also calculates the total elapsed time, the cutter position required and feedbacks the outcome to the VRML scene. The virtual cutter is then forced to reach the required position in time. Thus the module aids in ensuring that the material removal process is completed in time with the desired feed-rate.

An internet based virtual manufacturing system was developed by Luo et al. (2002) that integrates the with the VR scene. The system does so by the combination of model-based rendering method (MBRM) and image-based rendering method (IBRM). The image quality is enhanced producing realistic effects because of the incorporation of the IBRM in the system. The IBRM system makes use of the image mosaic technology. However, due to the lack of interactivity between the operator and the virtual scene, the IBRM system alone cannot provide the users with the immersive feelings. The better interactivity is provided by the MBRM system. A detailed algorithm is used for the purpose that simulates material removal process. Therefore, good rendering capability as well as real-time simulation of the machining process can be obtained with the integration of IBRM and MBRM systems. In the developed system, the ElevationGrid node too represents the workpiece dynamics for the machining operation.

The intensive research in the field of web-based systems for virtual manufacturing has led to its popularity. However, it still remains a challenge for simulating basic outputs such as dynamic simulation of the material removal process. A wide range of simulation algorithms such as Java and VRML have been developed. Further, it has also been a challenge to the scientific community to obtain the real time capabilities between a virtual system and a real machine tool.

11.5 Mathematical Modeling

A more scientific approach towards the simulation of the real behavior of the machine tools and the manufacturing process can be had with the mathematical modeling and numerical analysis. The mathematical modeling can provide for a more accurate prediction of the machining process.

The modeling of the real CNC behavior was done via a virtual system known as Virtual CNC (VCNC). The system incorporates empirical models assisting in the development of structure for the virtual machine tool. The developed system integrates the dynamics of the feed drive, trajectory generation and algorithm for axis tracking (Erkorkmaz et al. 2006).

A Cutter Location (CL) file is fed to the system for the tool-path geometry. The CL file comprises of circular, linear and spline segments. The trajectory generation algorithm receives the dimension of the cutter, coordinates of the tool tip and feed from the different segments. The noise parameters are determined using the real time interpolation parameters such as feed-rate, displacement, jerk or acceleration. The servo sensor detects the position errors that are used to predict the errors in contouring at each interval. The control level aspects can be then used in the extrapolation of the quality characteristics of the work specimen undergoing material removal process (Susanu and Dumur 2004).

Altintas and Merdol (2007), developed a system which simulates the outputs such as cutting errors, torque demand and form errors. These are then compared with the results from experimentation. This was implemented with the CNC process to obtain the Virtual CNC process. The Virtual CN system was able to predict and analyze the accuracy of tool path contours, tracking of sharp corners and auto tuning of servo controllers for feed drive.

An algorithm for prediction of error on machined surface, cutting force, feed drive system and thermal behavior was jointly developed by Yun et al. (2002, 2003). A model for end-mill with multiple flutes which was an approximation of the size effect model was developed for the prediction of the cutting forces. The model was also capable of predicting machining errors under the changing cutting action. The prediction of the diamond turning process was made possible using the Virtual Manufacturing and Inspection System (VMIS). The proposed system incorporates Virtual Manufacturing, Virtual Machine Tool and capabilities of inspection. The main objective of the developed system is to evaluate, simulate and therefore optimize the machining process. The development of the VMIS system has been supported through a number of works such as the algorithm for inspection of surface topography, the optimization algorithm for the NC program under virtual manufacturing environment and modeling of workpiece for simulation of the material removal process.

Different models for the prediction of temperature and vibrations of machining process have also been developed. Sui et al. (2010) developed a mathematical model for the prediction of surface temperature and thermal deformation of the cutter. A model for the prediction of milling temperature was developed using the combination of exponential fitting with the least square method. The system predicted the temperature with the variation in depth, width, feed rate and speed of cutting. Zhu et al. (2007) proposed a model for the prediction of temperature of cutting and vibration for a turn-mill machining centre. The developed model was based on the analysis of the differential equation derived using the mass, stiffness and damping of the machine tool.

The main research in the field of mathematical modeling has been aimed at prediction of the machining parameters in the virtual manufacturing environment. Expensive experimental methods are often required to validate the different proposed model. There is lack of reports on the empirical models for the prediction of surface profiles.

11.6 Hardware Interaction

A machine tool is a complex control and mechanical system and therefore it is not a trivial task to understand and model accurately the individual component. A lot of research work has been carried out in this field and have led to the incorporation of hardware and Programmable Logic Controller (PLC) for the different simulation systems.

The PLC codes may be generated by the PLC based simulation systems for the verification purpose. These may be then downloaded for the real PLC on the shop floor. One of the key elements during the early design stages of a machine tool is the simulation aided validation and optimization of the machine control. The requirement demands the simulation tools to allow the verification of the software and therefore commissioning with a virtual model of the machine tool. The hardware and software of the PLC system are hierarchically structured. Each component of the system is connected with each other and has defined inputs and outputs. The connection is in accordance with the flow of information, energy and material between the sub-systems of the PLC system. A defined behavior can be assigned to each of the sub-system.

The systems are hardware and dependent on the machine tool. A prototype integrating the isolated systems within a common platform was developed that overcame the challenge of dependency. The developed prototype was based on Distributed Machining Simulation (Dimas) which is open and distributed server/ client architecture. The control manufacturers verify the different functionalities of the CNC through test procedures being carried out manually requiring tremendous amount of time. Hardware-in-loop (HiL) simulation was designed as a new strategy that integrates the software environment and the machine tool of a control system. Different control devices such as PLC, NC and Human Machine Interface are linked and are used for operating the HiL simulation system. The different systems are linked on a simulation board within PC. The HiL simulation system enables for the real control, PLC, CNC and a real time virtual machine tool that is capable of interacting with one another through the regular communication interfaces such as filed and drive buses. The main goals of the HiL system are to enhance the quality of the developed software, allow for concurrent engineering between software and the hardware environment, optimization of the mechatronic system and finally to provide training on the basis of virtual machine tools.

The testing and verification of the complete functional chain of a machining process in a real time manner can be done through the capabilities of the HiL systems. This allows for the depiction of real time conditions. This has aided the research in the direction aiming the development of real time deterministic models that have the capabilities to compute the dynamics of the machining process in real time. A virtual model by the name VML 150 was developed by Butala et al. (2008) that incorporates the aforementioned principle. The system integrates the real CNC controller to the virtual objects. The VML 150 system works either on the basis of manual commands set directly on the CNC controller or through the G-codes. The VML 150 system simulates the similar kinematic behavior as that of the real machine tool. The capabilities of the HiL simulations have been expanded to cover a wide range of applications such as virtual start-up, machine diagnostics, planning of maintenance schedule and optimization of control software. This has been achieved by coupling the HiL systems with the other technologies. Röck and Pritschow (2007) is one such example that simulates the flexible machine components via Finite Element Method (FEM).

The research in the direction of hardware interaction based simulations is very scarce. The main objective of the systems has been to virtually control the machine tool design. This aids in testing and verification of the machine tool before it is actually built. The different simulation systems also aid in strategically planning for the labor and material costs. However, virtual systems with real-time software and hardware capabilities are a requirement for porting of real data to the virtual systems. Software-in-the-loop (SiL) approach has been adopted for this purpose. Often inaccurate results may be obtained by the simulation of the machine tool in a non-real-environment. The CNC vendor doesn't provide for all the virtual models at the early stages of development and those that are available are pretty expensive.

Further, to have a more accurate and intelligent simulation environment, there is still a lack of efficient way in which the shop-floor data can be incorporated into the system. Integration of algorithm for the prediction of parameters on the basis of data from shop floor is one of the possible solutions to address the above lacuna.

Overall, the HiL approach is useful for validation of the PLC based programs and in addition to this it also serves to integrate the control and design environment. The HiL approach however lacks portability. The approach requires further enhancement and improvements before it is widely adopted for other applications.

11.7 Conclusion

A number of virtual manufacturing systems have been developed over the years. For the development of virtual manufacturing environment a number of techniques, algorithms and integrated tools have been developed. One of the main issues for the different systems is the lack of integration capability of one system with another system. This lack in capability leads to less flexible systems. Virtual Reality is one of the enhanced and improvised ways of providing a real feel of the real machining environment. However, the different Virtual Reality systems lack data input and output functions. This signifies that the Virtual Reality systems alone are not sufficient to produce complex simulations. Augmented reality and Distributed reality approaches are the future trends to aid in complex simulations.

A number of benefits are offered by the Web-Based systems over the non-based systems. The Web-Based system offers for the collaborative manufacturing environment by allowing simultaneously the access by multiple users remotely. The different components of a web-based system are modeled using the client-server and multi-tier architecture. However, it still remains a challenge to simulate the real machining processes using the Web-Based systems.

Development of a virtual manufacturing is a multi-disciplinary activity requiring and employing different types of approaches in the system. The capable virtual system must have the following characteristics: neutral data for the interoperability, visualization of realistic processes, using hardware interaction incorporation of the shop floor information, support to multidirectional flow of data, empirical modeling with generalization and assistance in collaborative manufacturing environment.

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Chapter 12
Virtual Manufacturing of Transmission Elements: A Case Study with Gears

12.1 Introduction

The manufacturing of some of the mechanical components is a complicated task even with the technical know-how of the component. One such mechanical component is gear. The complication is further aggravated with the representation of the drawing in 2D sketches as it becomes difficult to comprehend the complex profiles and the arrangements for manufacturing using the 2D drawings. The problem of comprehending the 2D drawings for the geometrical aspects can be done away with the 3D solid models. However, understanding of the manufacturing process of gear remains to be a challenge until and unless the gear generation process is animated to represent the motion of gear cutter and the gear blank. The problem can be addressed using the technology of virtual manufacturing.

There has been an increasing trend to explore the potentiality of the Virtual Reality (VR) systems for a wide range of applications. The VR system simulates the real environment on a screen. The application of the VR systems can be more meaningful if applied with appropriate knowledge base and expertise.

Number of literature has been reported on the simulation of the real manufacturing processes into virtual environment. Work in the area of rapid prototyping under virtual environment has been reported by Tesic and Banerjee (1999). The enhanced 3D visualization of the object was provided by Balyliss et al. (1993) using the VR technology. They reported the visualization of various automotive components using the different virtual manufacturing tools such as 3D-STUDIO MAX and Virtual Reality Manufacturing Language (VRML). Kimura (1993) further enhances the work by representing the process and product modeling as a kernel for the environment of virtual manufacturing. Modeling issues such as representation language, standardization etc., were addressed by in the work of Kimura. The production processes were simulated using the platforms such of VRML and MAYA by Arangarasan and Gadh (2000). Research work regarding the simulation of the manufacturing process was done using AUTOCAD and 3D Studio Max

K. Kumar et al., *Advanced Machining and Manufacturing Processes*,
Materials Forming, Machining and Tribology,
https://doi.org/10.1007/978-3-319-76075-9_12

(Pattanayak et al. 2003; Roy et al. 2003; Pohit 2006). However, the literature does not report on the mechanism of chip formation.

Therefore the main focus for the research community in the manufacturing filed has been on the mechanisms of chip formation and chip breaking. The first major work on this regard was the Merchant model of chip formation developed in 1945. There have been studies on the cutting tools with same geometry and cutting parameters along the tools' cutting edge (Kahng and Koegler 1997; Sakurai et al. 1998). However, there is scarcity of literature on tools with varying geometry and parameters of cutting along the cutting edge of the tool. Example of such tools is that of complex shaped gear. The present chapter is an attempt to simulate the gear manufacturing process with much of the emphasis on the formation of the chip during the manufacturing process. The chip formation process has been depicted using the disc type form cutter.

12.2 Methodology Adopted

There are number of gear cutting methods. The selection of a suitable gear manufacturing process depends on the type of gear being manufactured. The present chapter aims to simulate the chip formation process and therefore the gear milling process has been selected. The chapter highlights the steps in manufacturing helical and spur gears in the VR environment.

12.2.1 Generation of Spur Gear

The spur gear has been generated using the disc type cutter. A special purpose milling machine is used for this purpose. The automation of the cutting cycle was adopted including the fast return of tool and the blank indexation. The automation process includes all the processes until the production of all the teeth on the gear blank. The adjustment of the axis of the gear blank and that of the cutter produces the gear teeth with the desired depth.

The desired depth is produced in a number of cuts as specified in the input data by the user. The blank rotates on completion of a gear tooth and the entire process then repeats again. The procedural steps are followed repeatedly until all the teeth have been produced on the gear blank.

12.2.2 Generation of Helical Gears

The generation of the helical gears takes under the similar arrangements as used for the generation of spur gears. However, the cutting plane of the gear cutter was kept at certain inclination to the vertical plane. Therefore the disc type cutter is inclined while performing the gear generation process. The cutting action of the disc type cutter is inclined equivalent to that of helix angle which is to be specified by the user.

12.3 Process of Chip Formation

The process of chip formation includes several factors and is therefore a complex process. The factors are: path of the chip movement, contraction of chip, chip curling and the type of chip.

12.3.1 Type of Chip

The type of chip formed depends on the material of the gear blank (Khanna 1981; Arshinov and Alekseev 1976). The type of chip can be categorized into: continuous, segmental and continuous with inhomogeneous chip.

The cutting of brittle materials with low speeds leads to the formation of segmental chips. The formation of segmental chips is the result of fracture mechanism. The continuous chips are formed on cutting ductile materials under steady state conditions. The high friction between the rake face of the tool and the chip leads to increased temperature. This increased temperature results in welding of the chip to the face of the tool. Such a formation is known as continuous chips with Built-Up-Edge. These are generated with low cutting speeds. The cutting operation of stainless steel and titanium alloys results in inhomogeneous chips. These are generated under high speed cutting conditions.

12.3.2 Path of Chip Movement

The deformation of the material in the front of the cutting edge of the tool takes place owing to the shearing action of the tool. This is the principle for the formation of the chips. The direction of the chip movement and the chip formation is depicted in the Fig. 12.1.

12.3.3 Chip Thickness and Chip Curling

The chip curling process is shown in the Fig. 12.2. The chip curling takes place as the thickness of the layer increase and a wedge shape is acquired by the layer.

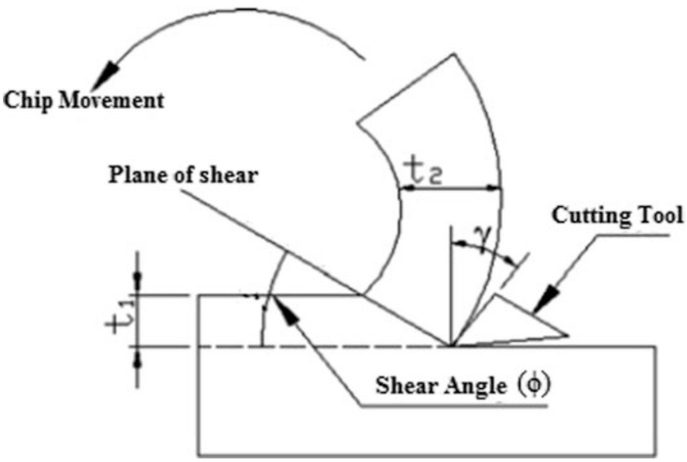


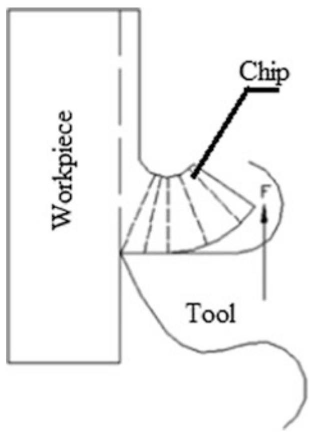
Fig. 12.1 Chip generation and the direction of chip movement

Cutting angle, uncut chip thickness, type of cutting fluid, speed of cutting etc., are some of the factors for the curling of chip (Khanna 1981; Arshinov and Alekseev 1976). The shape of the curl can be either flat spiral or helix depending on the conditions of machining process. The condition for the formation of flat spirals is: $\gamma = 0$ and $\phi = 90°$. However in case of fabrication of gears $\phi \neq 90°$ and $\gamma \neq 0$ and therefore the chip will curl in the form of helix. The present example, it has been assumed that the chip formation takes place in the form of spline (Arshinov and Alekseev 1976). Equation 12.1 was used for the creation of spline:

$$\varphi = (\pi/2 - \gamma) \tag{12.1}$$

The thickness of the chip was calculated using Eq. 12.2:

Fig. 12.2 Chip curling



$$\begin{aligned}[(Addendum\,Circle\,diameter) - (Dedendum\,Circle\,dia)]/n \\ = [(D_a) - (2.188\,m + 0.05 - D_a)]/n \\ = [0.188\,m + 0.05]/n\end{aligned} \tag{12.2}$$

where, D_a is the diameter of the addendum circle, n is the number of cuts and m is the module of the gear.

12.3.4 Contraction of Chip

The length of the chip formed (L) is less than the length of the part cut (L_0) by the cutting edge of the tool. The plastic compression of the layer is the main reason for the difference in length. The phenomenon of shortened chip length is known as longitudinal shortening (Khanna 1981). Coefficient of cutting characterizes the longitudinal shortening phenomenon and is given by,

$$k = \frac{L_0}{L} \tag{12.3}$$

Typically the value of k lies between 5 and 8.

The phenomenon of longitudinal phenomenon was also considered for the simulation of the chip formation process to provide a more realistic feel.

12.4 Software

The animation environment has been depicted via complete software. The software has been built on one of the virtual tools platform known as 3D-SUDIO-MAX. The prototype software has been built using Max-script, an object contained programming language. The Max-script language allows for the parametric variation.

The entire software written in max script guides the users throughout the gear generation process. The step-wise process helps at each and every step from creating the 3D model of the gear cutter, gear blank, input of the various parameters of cutting to the final output which is either in the form of frames or a movie clip. The final output helps the user to visualize the fabrication of gear and also the chip formation process. The entire software module has been divided into the following modules: Start, Input, Special, Virtual Manufacturing module.

Following assumptions have been made for the developed software:

- Continuous chips with built up edge has been considered.
- Width of the chip is equal to the width of cut.
- Constant thickness has been assumed.
- The value of k has been taken as 7.

12.4.1 Start Module

All the files of the program are written in Max-script and contained in the start module of the software. Resetting of the 3D Max studio is the first operation for the software. The start module will reset the software and make it ready for the user to start any operation afresh. The software proceeds to the next module known as Input module on instructions of the user.

12.4.2 Input Module

The design parameters are entered by the user through the input dialogue box. These design parameters are evaluated first before the data obtained is input. The dialogue window is created using the Max script language. The software developed is a user friendly model as it adopts to the suitable values even if there is no prior knowledge regarding the different cutting parameters. To aid the users in this regard, predefined values of upper and lower bounds for the various input parameters are provided by the software. The software will also not proceed further in case the user provides erroneous data. The software gives a warning message in this situation.

The essential parameters that a user is required to furnish the software are: gear module, gear speed, power to be transmitted, transmission ratio, pressure angle, helix angle, material of gear blank and cutter and selection of form cutter if simulating for bevel and helical gears.

Some of the optional input parameters include: number of cut, depth of cut, precision of the gear etc. The program can be recalled in case the user is required to modify any of the input parameters. The required changes once made will result in automatic up gradation of the product. The modification step is impossible in actual process thereby saving cost and time.

In the present case study, the material for cutter has been kept as cast steel, the number of teeth of cutter is set to 8, module of gear as 7, radial feed of the cutter as 2 and linear velocity of cutter as 4. These are entered in the input stage for the cutter. Figure 12.3 depicts the INPUT STAGE FOR CUTTER graphical user interface. The Max script for the same is depicted in the Fig. 12.4.

The values entered in the “GENERAL PARAMETERS” window, shown in the Fig. 12.5, are pressure angle as 20°. Full-Depth, transmission ratio as 3, stress fatigue factor value as 600, helix angle of gear as 5 degrees, deformation factor as 76. Figure 12.6 shows the code for the generation of “General parameters” interface.

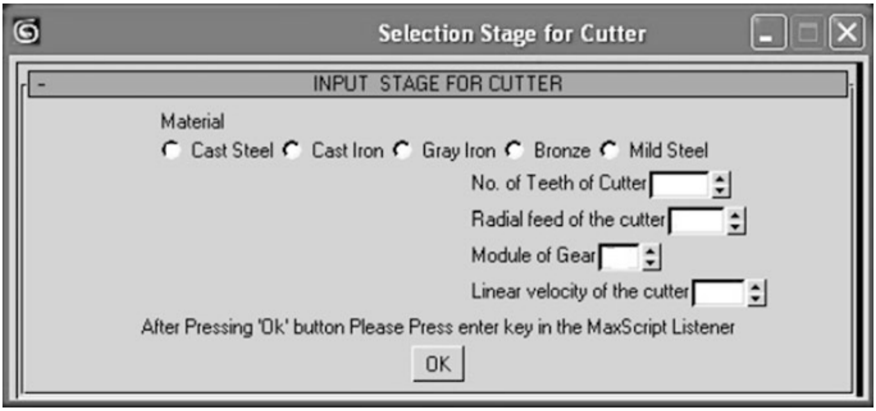


Fig. 12.3 Input stage for cutter

```
clearlistener()
resetmaxfile()

rollout sel_gear "INPUT  STAGE FOR CUTTER"
(
    radiobuttons matrl1 "Material"
            labels:#("Cast Steel","Cast Iron","Gray Iron","Bronze","Mild Steel")

spinner no_teeth "No. of Teeth of Cutter" range:[5,10,8] type:#integer width:70 align:#left offset:[250,0]
spinner rdl_feed "Radial feed of the cutter" range:[1,8,3] type:#integer width:70 align:#left offset:[250,0]
spinner mod "Module of Gear" range:[0.0,20.0,7.0] type:#float width:50 align:#left offset:[250,0]
spinner spd "Linear velocity of the cutter" range:[2,8,4] type:#integer width:70 align:#left offset:[250,0]
label lab1 "After Pressing 'Ok' button Please Press enter key in the MaxScript Listener"


        button o1 "OK"
        on o1 pressed do
        (
                Tc=no_teeth.value
                m=mod.value

            closerolloutfloater floater1
```

Fig. 12.4 Max script code for “Input stage for cutter”

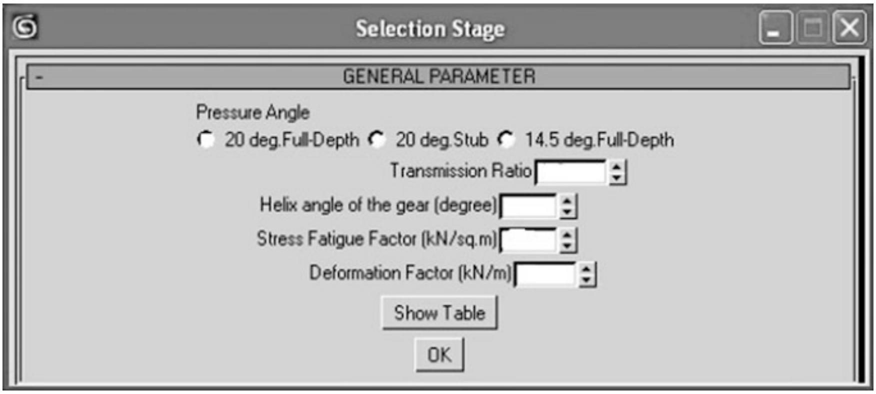


Fig. 12.5 General parameters for the case study

```
rollout sel_general "GENERAL PARAMETER"
(
                radiobuttons prangle "Pressure Angle"
                        labels:#("20 deg.Full-Depth","20 deg.Stub","14.5 deg.Full-Depth") align:#middle
        spinner tr_ratio "Transmission Ratio" range:[0,100,3] width:80 type:#float
        --spinner pow "          Power (KW)" range:[0,5000,9] width:80 type:#float
        spinner hex_angle " Helix angle of the gear (degree)" range:[0,20,4] width:80 type:#integer
        spinner str_ftg_factr "Stress Fatigue Factor (kN/sq.m)" range:[0,5000,600] width:80 type:#integer
        spinner def_factr "Deformation Factor (kN/m)" range:[0,5000,76] width:80 type:#integer

        button table "Show Table"
        button oke "OK"

        on prangle changed state do
        (
        case prangle.state of
                (
                        1:      phi_flag=1
                        2:      phi_flag=2
                        3:      phi_flag=3
                )
        )
        on oke pressed do
                (
--                      Np=spd.value
--                      Tp=no_teeth.value
                        tr=tr_ratio.value
                        P=kw
                        k=str_ftg_factr.value
                        c=def_factr.value

----fileIn "design_3.ms" --mode:"r"
closerolloutfloater floater1
fileIn "gear_generationh.ms"


                )
        on table pressed do
                (
                        shellLaunch "d:\\table\\def.exe" " "
                        shellLaunch "e:\\table\\def.exe" " "
                        shellLaunch "f:\\table\\def.exe" " "
                        shellLaunch "g:\\table\\def.exe" " "
                        shellLaunch "h:\\table\\def.exe" " "
                        shellLaunch "i:\\table\\def.exe" " "
                )

)
floater1=newrolloutfloater "                                              Selection Stage" 533 480
addrollout sel_general floater1
```

Fig. 12.6 Code for “GENERAL PARAMETER” rollout

Fig. 12.7 “SELECTION” user window

The type of gear selected for the present case study was spur gear. The “SELECTION” graphical user interface is shown in the Fig. 12.7.

Similarly, the other inputs are entered in the INPUTS user interface as depicted in the Fig. 12.8. The code for the same is represented in the Fig. 12.9. Figure 12.10 depicts the code for the “Pinion properties” interface and the code for “GEAR and PINION input data” is depicted in Fig. 12.11.

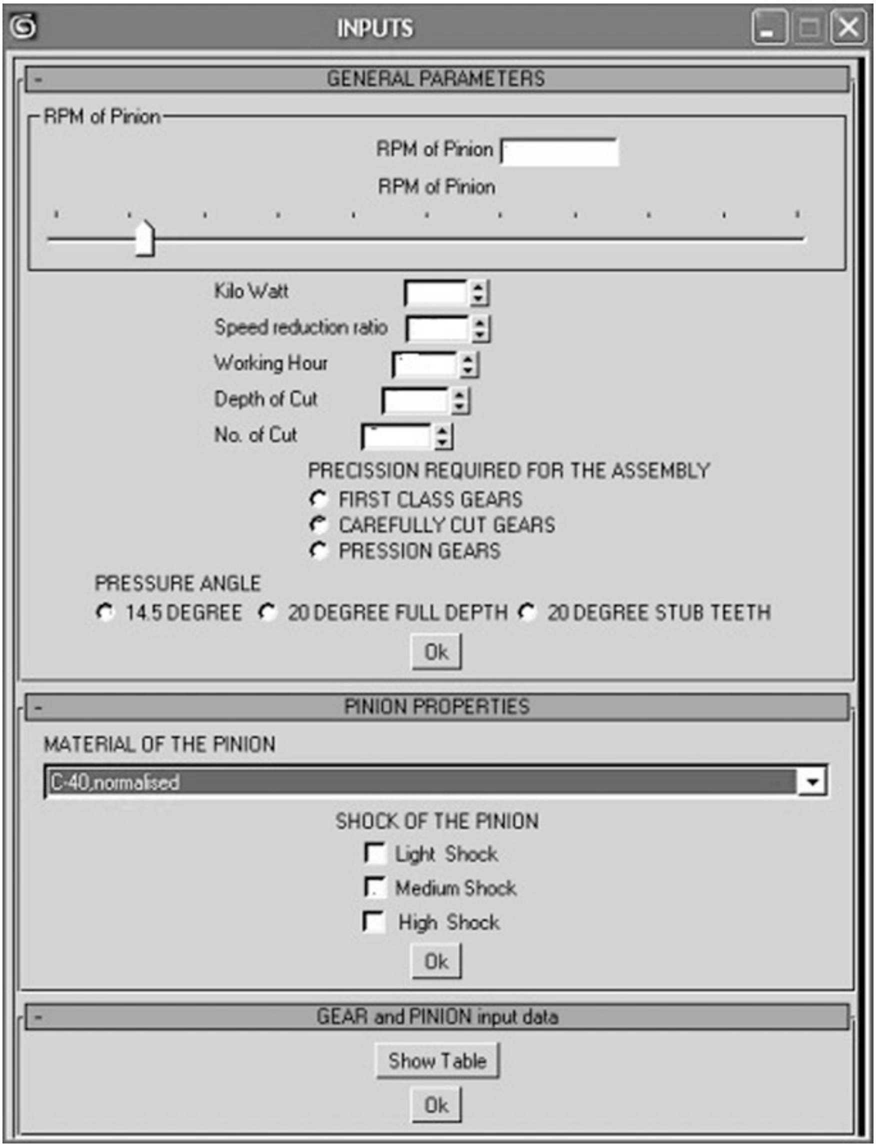


Fig. 12.8 "INPUTS" interface of the software

12.4.3 Cutter Generation Module

The creation of cutter is first task after the input module of the software. It is only after the creation of cutter that the cutting operation of the gear blank can be simulated. Corresponding cutter is created depending on the type of cutting process.

```
ClearListener()
rollout g_p  "GENERAL PARAMETERS"
                (
                        group   "RPM of Pinion"
        (
                edittext rpm2 "                                    RPM of Pinion" fieldwidth:70 fieldHeight:50 bold:true
              slider rpm1 "                                 RPM of Pinion" orient:#horizontal ticks:10 range:[0,10000,1000]
        )
        on rpm1 changed val do
        (
        rpm2.text = val as string
                  )
         on rpm2 changed text do
        (
         val = rpm2.text
         rpm1.value = rpm2.text as float
          )
        spinner kw1 "Kilo Watt                    " range:[0,200,9] type:#integer width:75  align:#left offset:[100,0]
        spinner ratio "Speed reduction ratio   " range:[0,5.0,3.0] type:#float width:75 align:#left offset:[100,0]
        spinner WH "Working Hour              " range:[0,24,10] type:#integer width:75 align:#left offset:[100,0]
         radiobuttons prssn "PRECISSION REQUIRED FOR THE ASSEMBLY"  columns: 1 default:1
        labels:#("FIRST CLASS GEARS","CAREFULLY CUT GEARS","PRESSION GEARS")
                on prssn changed state do
                   (
                    case prssn.state of
                        (
                                1: gr=1
                                2: gr=2
                                3: gr=3
                        )
                   )
         radiobuttons prssn1 "PRESSURE ANGLE"   default:1
        labels:#("14.5 DEGREE ","20 DEGREE FULL DEPTH","20 DEGREE STUB TEETH")
                on prssn1 changed state do
                   (
                    case prssn1.state of
                        (
                                1: p=1
                                2: p=2
                                3: p=3
                        )
                   )

                button ol "Ok"
              on ol pressed do
                (
                   kw=kw1.value
                   rpm=rpm1.value
                   r=ratio.value
                   hour=WH.value
                if kw==0 or rpm ==0 or r==0 or hour ==0 or p==0 or gr==0 then
                   (
                   if kw==0 then querybox"PUT THE VALUE OF KILO WATT CORRECTLY(EXCEPT ZERO)" title:"CHECK INPUT DATA(KW)"
           if gr==0 then querybox"CHOOSE THE PRECISION CORRECTLY" title:"CHECK INPUT DATA(precision)"
                   if p==0 then querybox"PUT THE VALUE OF PRESSURE ANGLE CORRECTLY" title:"CHECK INPUT DATA(pressure angle)"
        if rpm==0 then querybox"PUT THE VALUE OF RPM CORRECTLY(EXCEPT ZERO)" title:"CHECK INPUT DATA(RPM)"
        if r==0 then querybox"PUT THE VALUE OF SPEED RATIO CORRECTLY(EXCEPT ZERO)" title:"CHECK INPUT DATA(SPEED RATIO)"
        if hour==0 then querybox"PUT THE VALUE OF HOUR CORRECTLY(EXCEPT ZERO)" title:"CHECK INPUT DATA(HOUR)"
```

Fig. 12.9 Code for generation of “GENERAL PARAMETER” interface

```
        rollout pinion "PINION PROPERTIES"
        (

                dropdownlist material_p "MATERIAL OF THE PINION"
                items:#("click and choose any material ","Malleable CI","CI,grade 25","C-30 Steel,normalised","C-30 Steel,hardened","C-40,normalised","C-
40,hardened","Ni-C Steel","Cast Steel","Mo-Cr Steel","Mn-Mo Steel","Surface hardened Steel")
                on material_p selected i do
                        (
                   fb_p=bs[i]
                      Ep = young[i]
                      bhn_p = hbn[i]
                        )
                label lab1 "SHOCK OF THE PINION"
             checkbox light  "Light  Shock" align:#center
       checkbox medium "Medium Shock" align:#center offset:[5,0]
          checkbox high   " High  Shock" align:#center
                on light changed state do
                (
                     medium.checked = false
         high.checked = false
         sf11=1.0
                 )
           on medium changed state do
                (
                 light.checked = false
                 high.checked = false
                 sf11=2.0
        )
      on high changed state do
                (
                 light.checked = false
       medium.checked = false
       sf11=3.0
        )
      button ok_p "Ok"
             on ok_p pressed do
                (
               if fb_p == 0 or Ep == 0 or bhn_p ==0 or sf11 == 0 then
                  (
                  if fb_p ==0 or Ep == 0 or bhn_p == 0 then (querybox"SELECT AT LEAST ONE OF THE MATERIAL(NOT click and choose me)" title:"CHECK INPUT DATA
(click and choose me")
         else querybox"SELECT SHOCK OF THE PINION(LIGHT/MEDIUM/HIGH)" title:"CHECK INPUT DATA(shock of the pinion)"
                  )
                  else removeRollout pinion ff
                )
```

Fig. 12.10 Code for generation of “PINION PROPERTIES” interface

12.4.3.1 Disc Type Form Milling Cutter

The disc type form cutter is created in this module. The path of the profile of the cutter is given by Eq. 12.4:

```
rollout gear_pinion "GEAR and PINION input data"
(

                    button tbl "Show Table"
                    on tbl pressed do
                           (
                    shellLaunch "d:\\table\\def.exe" " "
                    shellLaunch "e:\\table\\def.exe" " "
                    shellLaunch "f:\\table\\def.exe" " "
                    shellLaunch "g:\\table\\def.exe" " "
                    shellLaunch "h:\\table\\def.exe" " "
                    shellLaunch "i:\\table\\def.exe" " "
                           )
             button ok_1 "Ok"
                  on ok_1 pressed do
                        (
              closerolloutfloater ff
           fileIn "global_1ah.ms"

                           )

)
ff = newrolloutfloater "                                    INPUTS " 500 800 300 10
addrollout g_p ff
addrollout pinion ff
addrollout gear_pinion ff
```

Fig. 12.11 Code for generation of "Gear and PINION input data" interface

$$x = -r\sin\theta;\ y = r\cos\theta - R_d \tag{12.4}$$

Value of θ is defined using the values of module, number of teeth, and the pressure angle of the gear. R_d is the radius of the dedendum circle and r is the radius of curvature of the tooth profile. After receiving the required input values, the software creates the core of the cutter body. The solid model of the tooth is then created that consist of NURBS sweep surfaces and few planar surface patches.

12.4.4 Gear Generation Module

To position the cutter, it is given a radial feed. The operation then starts by feeding the cutter in the vertical direction. The cutter is retracted to the original position on completion of a tooth. The cutter undergoes the rotational motion all through the gear creation process. The cutter is along the inclined direction in case of the helical gear cutting process. The gear blank is given one rotation to prepare for the creation of the next tooth. The procedural steps are continued until all the teeth are cut.

Three types of chips are formed during the cutting of tooth on the gear blank by one tooth of the cutter. One type of the chip formed is known as the bottom chip whereas the other two types are known as the flank chips. Further, the assumption has been made that the chips don't interfere with one another during the chip formation process.

Boolean operations are used to generate chips. Let Set A represent the gear blank and Set B represent the portion of the tooth form cutter that is involved in the removal process of the material from the gear material. The amount of material removed can be represented using Set C [= (Set(A-B)]. The chip formed follows the curl along the spline as given by Eq. 12.1. Equation 12.2 is used for the calculation of the chip thickness. The longitudinal shortening is considered as per the Eq. 12.3.

12.4.5 Virtual Manufacturing Module

The backbone of the virtual manufacturing is the animation in which the different components are simulated dynamically. A series of still pictures results in creating the animation effect. An impression of moving objet is produced on displaying the pictures sequentially at successive intervals. The still picture is known as frame. The time interval between the frames is an important factor for the animation. It is at 12 frames per second (fps) that the illusion of continuous motion begins to break down for the human eye. Also the human eye can perceive frame rate between 60 and 10 fps. Therefore it is standardized to keep frame rate at 24 fps. The animator is also required to decide whether to shoot each frame once or twice. The terminology to represent this is “on ones” or “on twos”. It is always better to shoot “on twos” and thereby making the frame rate of 12 fps effectively. Different positions are occupied by the gear blank and the cutter in each frame which depends upon the kinematics of the cutting process. The frames are stored as rendered views in the hard disk which then can be run effectively with the help of Windows media player.

12.4.6 Special Module

The software consists of some special modules that aids in providing for a realistic view of the cutting process. These modules are: camera, material, animation, render and light. Each of these sections is discussed in the subsequent sections.

12.4.6.1 Material

One of the simplest material properties is the color since it is easiest to identify. To control the different aspects of the object in relation to color, the “Material Editor” module of the software consists of several effects and color swatches. The material editor consists of a number of options such as Ambient. Diffuse, Self-illumination, Reflect, Opacity and transparency, Reflection and refraction to provide a realistic view of the object in scene.

12.4.6.2 Camera

The software consists of two types of camera: Free camera and Target camera. A cone is included for both types of camera showing where the camera is pointing. The free camera offers to capture the view of the area which is directly in front of the camera. A Target Distance needs to be specified which is the only parameter for the Free camera option. The Target camera on the other hand points to a controllable target point which at a certain distance from the camera. Target camera is particularly useful in situations where the camera won’t move.

12.4.6.3 Light

Lighting is another important factor playing a vital role in the manufacturing environment. Appropriate lighting can result in enhanced feeling and mood of the scene. There are two main options of lighting: natural and artificial. To provide enhanced rendering effects, the software consist of one key light source and several secondary lights. A spotlight is the key light source and is positioned in front and above the gear cutting arrangement. The spotlight serves to cast the shadow. The secondary lights on the other hand fill the holes and the gaps. These are positioned on the floor and also on each side of the gear cutting arrangement.

12.4.6.4 Animation

The Animation dialogue box can be used to set the frame rate. The connection between number of frames and time is provided by the frame rate which is measured in frames per second (fps). The options available includes: PAL (Phase Alternate Line), Film and NTSC (National Television Standards Committee). The software has the option to input the frame rate as per their choice. The time can be set on the Time Slider option in the Time Display section of the software.

12.4.6.5 Render

The final output is adjusted using the rendering option. The Render dialogue box consists of the following section:

- Render Scene where the frame to render can be specified. The final image size an also be specified.
- Environment dialog box where the user can define the different environmental settings such as background color, settings for global lighting, Volume lights and atmospheric effects.
- Rendering Effects box that includes options such as Blurr, Color Balance and Lens Effects.
- Advanced Lighting panel that includes the setting for Radiosity, Light Tracer, Lighting Analysis tool and Exposure Control.

Once the above settings are completed, the operation of gear creation can be viewed frame by frame. A rendered movie clip is created and can be saved by the user.

The gear blank undergoes up and down movement with the forward motion. The movement of the gear blank together with the rotating cutter creates the impression of cutting of tooth on the gear blank. The different stages of the gear creation process are depicted via a large number of frames that have been generated by the software. The cutting stroke is the upward movement of the gear blank and the idle stroke is the downward motion of the gear blank. The depth of cut is illustrated by the positioning of the cutter under the blank.

12.5 Conclusion

The case study is an example of manufacturing environment under the virtual environment. The software example in this chapter delineates the chip formation process during the gear cutting operation. A large number of frames captured give a realistic feel of the gear cutting process. The virtual manufacturing environment therefore aids in the better understanding of the different complex manufacturing processes which are otherwise difficult to comprehend.

The designers can change design using the virtual manufacturing environment by changing the relevant parameters. Virtual manufacturing environment saves both the cost and the time. Such a virtual manufacturing environment can be a learning tool for those involved in the complex manufacturing environment.

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Chapter 13
Virtual Manufacturing: Scope, Socio-economic Aspects and Future Trends

13.1 Introduction

Manufacturing environment encompasses a wide range of activities such as product, resources, process and plant and is an indispensable part of any economy. However, the requirement of flexible manufacturing system has been increasing rapidly because of the increasing complexity of the products and processes that have become highly sophisticated. Further, the different enterprises are distributed geographically and are dependent on materials, information and flow of knowledge. It is also become a necessity for the manufacturers in this competitive environment to have a prior knowledge about their processes before they apply them at the shop floor to save cost and time. The above mentioned challenges can be well addressed through the virtual manufacturing environment providing a computer based environment for simulation of the different complex manufacturing processes. The virtual manufacturing environment has led to saving of cost, optimization of quality of product and time drivers.

The present chapter therefore aims to discuss the scope of the virtual manufacturing environment. The chapter also discusses on the socio-economic aspects of the virtual manufacturing technology. Finally the chapter discusses on the economic benefits of virtual manufacturing technology (VM). Chapter concludes with the discussion on the future trends in machine tool industry, automotive and aerospace industries.

13.2 Scope of Virtual Manufacturing

The scope of the VM is the definition of processes, products and resources within the different constraints of cost, weight, time, quality and investment. The three main paradigms of VM according to Lin et al. (1995) are:

K. Kumar et al., *Advanced Machining and Manufacturing Processes*,
Materials Forming, Machining and Tribology,
https://doi.org/10.1007/978-3-319-76075-9_13

13.2.1 Design-Centered VM

The information to the designer related to the manufacturing activities is provided during the design phase of the product development. In this scenario, VM is the optimization of product and the related processes to achieve the desired manufacturing goal such as flexibility, quality etc., using the simulated manufacturing processes. It is also to use the simulations to evaluate the production processes at different levels and to keep the designer informed of the product and process results.

13.2.2 Production Centered VM

From this scenario point of view, VM aims to allow for inexpensive and fast evaluations of the alternatives of manufacturing processes using the simulation potential and capability of modeling the different manufacturing processes. Therefore, VM in this case is the converse of Integrated Product Process Development (IPPD).

13.2.3 Control Centered VM

VM in this case aims to simulate the different control models and manufacturing processes resulting in simulation of the actual production cycle for its optimization and seamless product development.

Marinov (2000) has proposed another paradigm of the VM process. As described by Marinov, the scope of Virtual Production System manufacturing activities includes design, planning, quality assurance, marketing and management. The objective of VM is limited to activities that results in changing the attributes of the product such as mechanical properties, physical and geometrical characteristics and attributes related to process such as cost, agility and quality.

A 3D matrix was proposed (Bowyer et al. 1996), to provide for the scope, objectives and domains concerned with the VM environment. The vertical plans are Logistics, Production and Assembly. These three aspects are the main aspects of the manufacturing environment and cover all the aspects related to the manufacturing processes. The different levels in a factory are represented by the horizontal planes. VM deals with the operation on a unit at the microscopic level. This unit operation includes the behavior of the material and its properties, the different models for the cutting tool, machine tool, workpiece and fixture. The cells are then formed by encapsulation of these models that inherits the lower levels characteristics in addition to new objects such as virtual robot. The relevant subsystems derive the macroscopic level i.e., the factory level. The methods used in achieving the VM systems deal are dealt with the one of the axis. The vertical axis represents the level whereas the horizontal axis represents the application.

13.3 Economics and Socio-economic Aspects of VM

VM environment can help in saving cost and time and instill confidence in manufacturers that the products can be delivered in time and within the constraint of the cost. The manufacturers are also able to ensure the quality of goods and services. There are numerous benefits offered by the VM environment:

- It results in reduction in time-to market the product, enhances the quality of the product and also reduces the number of physical prototypes required. The VM environment helps simulate the different available manufacturing alternatives and thereby aiding in the early design phase. The optimization of the design of product and the manufacturing process is possible with the VM environment while simultaneously achieving the specific goals.
- The VM leads to reduction in wastage of material, cost of tooling, manufacturing cost and enhanced user confidence. VM thus optimizes the manufacturing process through the simulations in the production phase of the product development. The behavior of the tool and the parts geometrical and physical analysis can be done by the VM tools and technologies. The analysis of the manufacturing processes and the related sub-systems aids in the production phase aids in enhanced confidence particularly in case where the manufacturing process is new and complex in nature.
- The VM tools aids in the prototyping phase in which it is referred to as virtual prototyping. The prototypes can be analyzed before it is physically prototyped and thereby saving cost and time.

Besides the above mentioned benefits of VM in the different phases of product development, the VM technology also has certain exclusive general benefits. These are:

- **Quality**: VM aids in design for Manufacturing by making available the high quality tools and the instructions required to support production.
- **Producibility**: optimization being one of the objectives of the VM technology, aids to optimize the manufacturing processes, in tandem with the design of the product. This produces products of high quality that are free from defects and involving less rework with the requirements being met.
- **Shorter cycle time**: the product can go directly to the production phase ensuring that the production is free from any false start.
- **Flexibility**: any changes in the production phases can be easily adopted under the VM environment. The production line can be tuned to produce products of different mixes.
- **Customer relations**: the customers can participate with increased opportunities within the integrated product and process development environment.
- **Responsiveness**: the VM environment aids to respond appropriately to the customers about the different funding and delivery schedules related to the products and services.

13.4 Economic Aspects

As far as the research community is concerned, the focus while developing the VM environment lies into check whether the developed simulations are working properly i.e., if there are any errors in the developed simulations. Further, they verify and validate the results obtained to ensure the application for the industrial use. However, from the industrial pint of view, the focus is mainly on the reliability of the developed technology, the integration aspects of the technology as to whether it can be integrated with other manufacturing sub-systems of the manufacturing environment and also on the economic aspects of the developed tools and technology.

The VM technology was a topic of academic interest, however, given the wide scope and the economic benefits of the VM environment, the technology can be exploited to the benefit of industrial applications. The 3D geometries for the aerospace industries are now created using the CAD software which was not at all accepted by the aerospace industries. With the advancements in software and hardware technologies, the VM environment new software tools have been developed by the research community to simulate the complex manufacturing processes and the same are being explored for the industrial benefits.

Researchers have classified the industrial applications of VM tools and technologies into three main classes: the techniques that are used regularly in the industries, mature technologies that are not widespread in their scope but are mature and some that are still under the development phase.

The ever changing perspective of the society to have technologically advanced products to meet their requirements and to cope up with the fast demand of the society, industries have begin to focus on technologies that reduces the marketing time of the product and at the same time produces quality products. The industries are now doing away with the old models where the activities of the manufacturing domain were “real” thereby leading to wastage of time, money and resources.

In the present environment of global competitiveness, the working style has been undergoing a transformation from “real” to “virtual”. The shareholders are the main stakeholders in any company and they only invest if the organization reaps economic benefits for them. The VM environment is optimizing the manufacturing processes resulting in improved profit margins for the organization. The improved profit margins keep the shareholders to remain interested in such an organization for a longer period of time. It has become possible for the manufacturing industries to produce diversified goods and services at mass level. Further, the web based VM systems have enabled to take care of the geographical barriers across the industries. The physical movements of the employees, labor and material resources in the organization has been reduced and converted to the digital movements.

The organizations can set up virtual manufacturing units with the aid of VM tools and technologies. Companies with virtual environment can concentrate on the core business and the secondary activities can be outsourced. This has resulted in cost efficiency and release of resources for more essential projects.

However, balancing of different activities in VM environment still remains a challenging task. The technical know-how of the different interfaces of the VM environment is quintessential to from the security aspect as well as to reap the economic benefits of the VM environment technology.

Further, the VM tools and technologies are expensive and therefore the small scale enterprises with small budgets are reluctant to adopt such capital intensive tools and technologies. However, the small and medium sized industries are the backbone of economics for any country. Therefore, the policies of the government must be positive to allow such enterprises to remove the investment barriers and vouch for the quality of their products through optimization of the different processes at the early design and manufacturing phase.

13.5 Trends and Exploitable Results

13.5.1 Machine Tool

There has been research and development in the field of "Virtual Machine Tools." The objective of the research community in this regard has been to develop prototypes that are characterized by comprehensive digital geometric designs. The cost and time has are being saved with the development of simulations for stationary behavior of machine structure, the change of sate variables and signals in case of the electronic circuits, the dynamic behavior of the parts that are in motion during the machining process and the simulation of the complex manufacturing process as a whole. The simulation leads to analysis of results such as stresses, Eigen frequencies, temperature distribution, cutting forces, chatter, vibrations etc.

The simulations for different results can be combined together that aids in reflecting various interdependencies such as elaboration of the frequency response with Finite element analysis. The industries have been exploiting results from the forming processes and other cutting processes. The simulations have been developed to reflect on the realistic behavior of the machine tool.

13.5.2 Automotive

The VM environment for the automotive sector has been to use Digital Product Creation Process that aims to design and visualize the simulations for the three main domains: product, process and resources. The different automotive companies focus on "big M" manufacturing concepts that encompasses not only the fabrication, logistics and assembly processes but also the product realization process that incepts from the needs of the customer to delivery of the goods and services to the customer.

The domain of product constitute of designing the individual component of the vehicle that encompasses all the data which are necessary for designing the product to sustain through its entire life cycle. The domain of process on the other hand comprises of the detailed planning of how the manufacturing processes must be performed. This domain includes the assignment of resources and simulation of the manufacturing process to optimize the workflow. The simulations are done for the ware houses and factories, the kinetics of manufacturing systems and robots. This also constitutes the FEA of different components of automobile.

There has been a lot of research in the field of VM environment for the automotive industries which has resulted into application of Virtual and Augmented Reality technologies on a wider sale for the automotive components. Some of the standard Virtual Reality Technologies for product design are stereoscopic visualization via CAVE and stereoscopic visualization via Powerwall software. The different technologies are used for different areas such as painting with robots. The developments and advancements have led to the increased focus on co-operative tele-work that aids the developers at different geographical sites to manipulate the virtual workpiece. The head mounted displays are used to visualize the virtual work-piece.

13.5.3 Aerospace

The parts used in the aerospace industry are designed and optimized using VM tools and technologies. FEA simulations are used to optimize the weight of frames, the 3D kinematics simulations are used to program the machine used for riveting and tools of augmented reality to support the complex assemblies.

The virtual workpiece and the simulation for various manufacturing processes allows for planning the maintenance, assembly and training activities for the workforce in the aerospace industries. This aids in enhanced quality of products that is a vital element for the success of the aerospace industry. The simulations can aid in taking into account the constraints of ergonomics such as visibility tasks.

13.6 Future Scope of VM

Given the number of advantages the VM environment has for the manufacturing enterprise, the VM tools and technologies still remains concentrated to large with the large manufacturing enterprises. These tools are not prevalent with the small manufacturing enterprises because of the capital intensity involved. The availability of large number of simulation models at each level is another hindrance to the wider adoption of the VM tools. At each level a new model is required to be built even if it has already been developed for earlier activities. The third reason of not being so prevalent with the small manufacturing enterprises is the high dependency of the VM technologies on the effectiveness of the hardware and the software.

The above drawbacks can act as a source of future for the VM tools and technologies. These are discussed below:

- **Automatic generation of simulation models**: the data of the CAD environment needs to be manipulated so that it can be used effectively for the simulation models. The future lies into develop CAD models that can automatically create ready-to-run simulations. This will eliminate the need to develop new models.
- **Integration of simulation systems**: the developed simulations should be able to integrate themselves with the different planning and design tools. This will aid the designers and the planners to be benefited from the simulations at the cost of minimum effort.
- **Hybrid simulation**: the combination of simulated and the real hardware in the development of the machine tool and the manufacturing systems is another scope for the VM technologies. The simulated models will be directly linked to the machine controller to dynamically test the behavior of the machine.
- **Virtual prototyping**: one of the important objectives of the manufacturing enterprises remains to obtain a virtual prototype of the different parts so that near realistic behavior can be achieved for the static and dynamic conditions.
- **Human computer interface**: the development of user friendly interfaces is another key element to the success of VM environment. It's a requirement now to develop not only good interfaces that meets the graphical requirements but also enables for clarity in voice and speech recognition.

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