Keynote Papers

Presented at the Scientific Technical Committee Paper Discussion Sessions

Present Situation and Future Trends in Modelling of Machining Operations Progress Report of the CIRP Working Group 'Modelling of Machining Operations'

C. A. van Luttervelt – TU Delft; T. H. C. Childs – U Leeds; I. S. Jawahir – U Kentucky; F. Klocke – RWTH Aachen; P. K. Venuvinod – City U Hong Kong
With contributions from: Y. Altintas – U British Columbia; E. Armarego – U Melbourne; D. Dornfeld – U Berkeley; I. Grabec – U Ljubljana; J. Leopold – GFE Chemnitz; B. Lindstrom – KTH Stockholm; D. Lucca – Oklahoma State U; T. Obikawa – Tokyo IT; Shirakashi – Denki U; H. Sato – Chuo U

Abstract

In 1995 CIRP STC "Cutting" started a working group "Modelling of Machining Operations" with the aim of stimulating the development of models capable of predicting quantitatively the performance of metal cutting operations which will be better adapted to the needs of the metal cutting industry in the future. This paper has the character of a progress report. It presents the aims of the working group and the results obtained up to now. The aim is not to review extensively what has been done in the past. It is basically a critical assessment of the present state-of-the-art of the wide and complex field of modelling and simulation of metal cutting operations based on information obtained from the members of the working group, from consultation in industry, study of relevant literature and discussions at meetings of the working group whit the aim to stimulate and pilot future developments. For this purpose much attention is given to a discussion of desirable and possible future developments and planned new activities.

keywords: cutting, modelling, co-operative work

1. The CIRP working group "Modelling of Machining Operations"

Manufacturing in the future will require much more powerful strategies for control of processes in a highly automated manufacturing environment. Effective utilisation of the newest manufacturing equipment depends heavily on applications of information technology. Accurate predictions of the results of manufacturing operations are required. This includes prediction of the accuracy of shape and dimensions and the surface roughness and properties of the subsurface layer of the parts produced, the machining times required and the costs of the operation. The amount of scrap should be minimised. Existing methods for control of manufacturing operations mainly based on the craftsmanship of the machinists are becoming obsolete and have to be replaced by science-based methods. These are the main reasons for the development and introduction of Computer Aided Process Planning or CAPP-systems to support process planning in the low volume, high variety production of high quality goods with tight tolerances by a large variety of machining operations [ElMa 93]. Those CAPP-systems require reliable models and simulation methods of all involved manufacturing processes. This is extremely difficult to achieve for metal cutting operations due to the great number of different machining operations each with its only partially understood relations between input and output variables. No research institute in the world can hope to develop the final solution on its own. Only a concentrated effort of many researchers working closely together can hope to achieve significant progress.

During this century a wealth of knowledge in metal cutting has been obtained through scientific research in many laboratories scattered all over the world that is documented in thousands of publications of all kinds. Unfortunately much of this knowledge can not be used by computers because it is not properly formalised, does not cover recent developments in metal cutting technology or is not even known outside a small circle of experts. Nobody has a complete overview of what knowledge is available for practical applications in industry. Even for those few cases for which models are known to technicians in the workshop these can not be used due to lack of reliable numerical data or the models are misused because the boundaries of the application area are not known well enough.

During the meeting of CIRP STC "Cutting" in January 1995 it was realised that a speedy and significant leap forward in the field of modelling and simulation of metal cutting operations by a co-operative action is required. Following a proposal by Professor B. Lindstrom (KTH Stockholm), the president at that time, a special working group was formed. Professor C.A. van Luttervelt (TU Delft) was elected chairman of this working group "Modelling of machining operations".

The mission of the working group "Modelling of Machining Operations" was defined as:

1 to promote the development of models of chip removal operations by defined cutting edges with the aim of quantitatively predicting the performance of such operations.
2 to promote the use of such models in industry

Three subgroups were formed to deal with certain aspects in more detail. Much information was collected by the leaders of those subgroups and by the secretary:

1. Professor F. Klocke (TH Aachen), subgroup "applications of models"
2. Professor I.S. Jawahir (U Kentucky), subgroup "fundamentals of modelling"
3. Professor T.H.C. Childs (U Leeds), subgroup "computational mechanics"
4. Professor Patri K. Venuvinod (City U Hong Kong), secretary and organiser of a literature database

The working group started its activities following the pattern of earlier similar projects within STC "Cutting" notably those of the working group "chip control" [Jawa 93, Lutt 93] and the working group "monitoring of metal cutting operations" [Byrn 95, Anom 95]. Over 60 researchers and R&D engineers took part in the activities of the working group. Most of them are members of CIRP, but from the beginning, other researchers on modelling of machining operations were invited to participate [Lutt 97] and
some "outsiders" gave valuable contributions. During the entire existence of the working group, discussions on the aims and the ways how to proceed took place. This gave rise to many discussion papers such as [Arma 95] and a number of internal progress reports by the chairman and by the leaders of the subgroups which were mainly intended to steer the activities in a certain direction. This keynote paper, which is in fact the first external progress report, reflects the major results of the activities thusfar.
The working group organised the "CIRP International Workshop on Modelling of Machining Operations" on 19 May 1998 in Atlanta, USA where several important topics, including a preliminary version of this report were discussed with an audience of nearly 80 participants.

2. Classification of models and unified terminology

The field of modelling of machining operations is extremely large. Models may be required for different purposes. There are many different machining operations. For each operation, different aspects can be modelled and many different techniques for modelling can be used. Consequently there exists a wide variety of models dealing in one way or another with machining operations. Also there are many different opinions on various aspects of modelling.
In order to establish a good understanding a unified classification of models was developed. Models are classified according to six characteristics: type of operation, aspect, element, modelling technique, nature and capability.
Concerning the terminology, the working group adheres to the usual rules in CIRP: ISO terminology is used whenever possible. In the case of machining this concerns in the first place ISO 3002 "Basic quantities in cutting and grinding". Additional terminology can be found in the CIRP Unified Terminology. Work on special unified terminology in relation to modelling is still in its infancy and is not worth reporting here.

The working group decided to focus on operation models able to predict quantitatively all the technical performance measures for operations belonging to turning, milling and holemaking i.e. chip types and chip forms, cutting forces, tooldamage and toollife, surface roughness and integrity and workpiece precision.
However the main effort will be the rather unexplored field of prediction of workpiece precision which is of high practical importance and which requires the development of a suitable set of models of the whole machining system. Machining system models should be constructed by using suitable models for each of the relevant elements.

3. Fundamental Aspects of Modelling

3.1 Introduction

The primary objective of modelling of machining operations is to develop a predictive capability for machining performance in order to facilitate effective planning of machining operations to achieve optimum productivity, quality and cost.
Machining performance can be divided into two categories:

a. *technical aspects* such as accuracy of shape and dimensions and surface roughness and properties of the subsurface layer of the workpiece
b. *commercial aspects*, useful for management such as machining time and cost, throughput time, the fraction of rejects, etc.

Difficulties in modelling machining processes are largely attributed to two main factors:

a. Lack of fundamental understanding of the basic mechanisms and the interactions of cutting tool and work material even in the most simple case of orthogonal cutting with a single straight cutting edge without corner radius or inclination angle and a straight primary motion.
b. The different purposes and the great variety and complexity of real machining operations

While significant effort has been made towards understanding the complex interactions in the basic mechanism, the validity and completeness of such models and the means of transforming these models into practical models for the much more complex practical machining operations remain highly questionable.

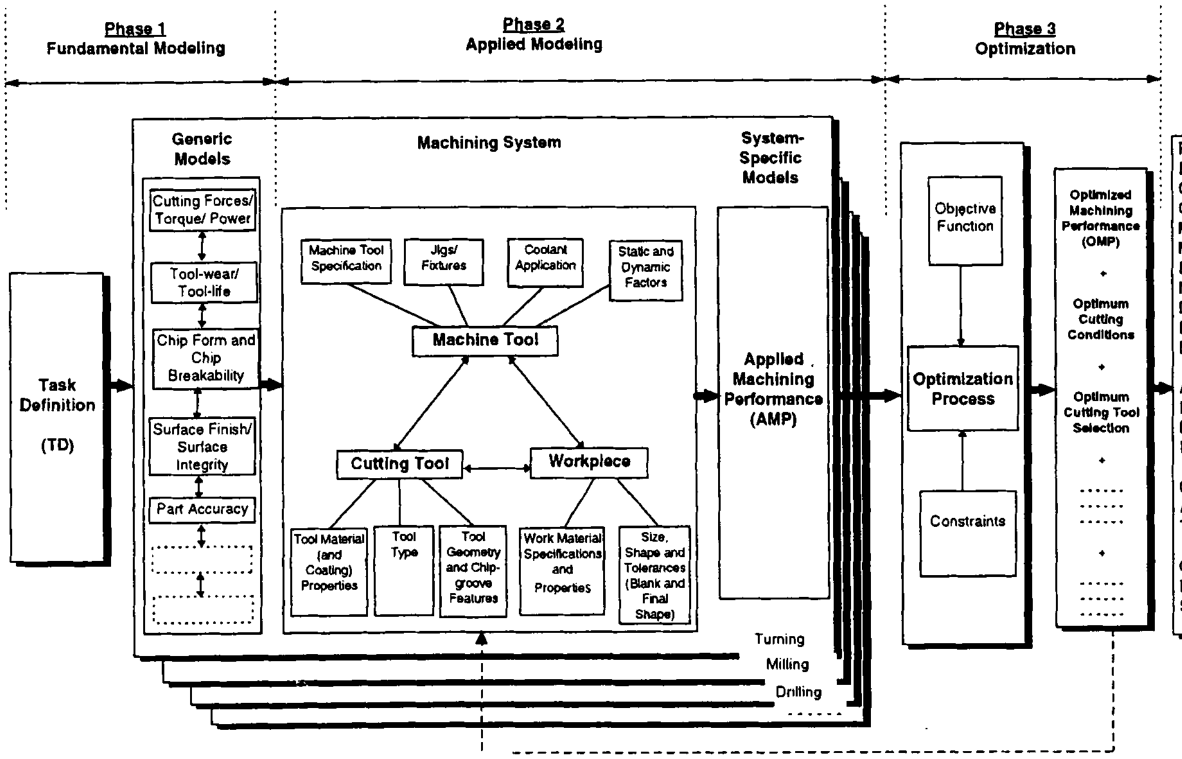


Fig.1 Predictive models for machining operations for practical applications.

A vast majority of past efforts deals with developing analytical models with very limited experimental validation of the models under only a few selected cutting conditions, tool geometries and work materials. Quantitative analysis of such models seems to suffer from the lack of adequately acceptable methodologies for applications under a wide range of conditions.

Moreover, the inaccuracies involved in the use of the thermal and mechanical property variations of the work and tool materials at high cutting temperatures characterised by large strains and strain-rates are compounded by the limitations of the modelling techniques. The same kind of limitations occur also with the newer numerical and computational models and even with AI-based models.

Analytical, numerical and AI-based methods are among the most commonly used techniques for predictive modelling which has the need for experimental validation. In recent years, significant activities are being reported on establishing combinations of these methods and other less-commonly used methods such as probabilistic/stochastic modelling. This leads to the development of hybrid modelling techniques by using combinations of these methods.

Predictive modelling for machining operations for practical applications would consist of two phases: (fig 1):

Phase 1:The development of models for machining variables; and

Phase 2:The development of models of machining performance.

In the actual application a third phase may follow in order to determine optimal conditions.

According to the defined task a proper set of generic models is selected. These are then "filled" with the appropriate set of data for the case at hand.
Typical input conditions include cutting conditions, tool geometry, chip-groove parameters, tool and work material properties, machine tool dynamics, etc.
In the opinion of scientists today the output should be produced in two stages:
In stage 1, some basic phenomena in the chip formation process such as the stresses, strains, strain-rates, temperatures, friction, tool-chip contact length, chip flow, etc. are predicted.
In stage 2, one or more of the common machining performance measures such as, cutting forces, torque, power, tool-wear/tool-life, chip-form/chip breakability, surface roughness/integrity and part accuracy, relevant for the case at hand, are predicted.
The major challenge in this two stage predictive modelling is the transformation of the outputs from stage 1 to stage 2. A vast majority of the research groups continue to develop newer and newer models for improving the outputs of stage 1. Here the modelling is very much restricted to simple orthogonal cutting.

Stage 2 requires the development of predictive capability for machining performance measures in operations such as turning, milling, drilling, etc., which brings in complexities.

3.2 Purposes of modelling of machining operations and two different schools of modelling

3.2.1 Purposes of modelling

There are many different reasons why models of metal cutting operations may be required. The most well known examples are:

1 design of processes
2 optimisation of processes
3 control of processes
4 simulation of processes
5 design of equipment

For **design or planning of processes,**in principle, only rather simple models would be needed to enable the selection of the proper type of operation (turning, face milling, end milling etc.), the type and main dimensions of the cutting tool and the class of toolmaterial (e.g. carbide end mill 10 mm dia for high speed milling of hardened steel). However a major point of concern will be whether the intended operation can actually be performed without disturbances. To answer this question it is necessary to investigate the boundary conditions for safe machining. This would require a degree of finesse of modelling which is usually not possible at this state. The best available "models" at this state are certain rules, e.g. on the stiffness in order to prevent too large deflections and vibrations.

For the purpose of **optimisation of processes** more complicated models are required. Some of those models take only technical aspects into account (e.g. a model to calculate the maximum feed for an allowable value of the cutting force). Some other well known models also consider economical aspects (e.g. to calculate the economical cutting speed).

The purpose of **control of processes** has not attracted much attention in the application of models for metal cutting operations. This is strange since better use of appropriate models could help by decreasing scatter of results of machining operations significantly and thus prevent rejects. If the effects of the input variables could be predicted with better accuracy it should in principle be clear what tolerances on the input variables should be maintained if certain tolerances on the output variables are required. This approach has seldom been used in metal cutting.

Simulation of machining processes is still in its infancy. Recently the finite element method is used for simulation by computer of the basic chip formation process but it is still a long way before we will be able to simulate practical machining operations with an acceptable degree of accuracy and reliability and an acceptable amount of effort for daily use.

Relatively good use has been made of models for the purpose of **design of equipment**. There are sufficient simple models to estimate expected values of cutting forces, torque, power and spindle speeds needed to specify machine-tools for certain operations to be performed on a given workmaterial. There are even models available to study the elastic and thermal deformations and the dynamic behaviour of machine-tools.

Models required for the design of jigs and fixtures and cutting tools are much less well developed.

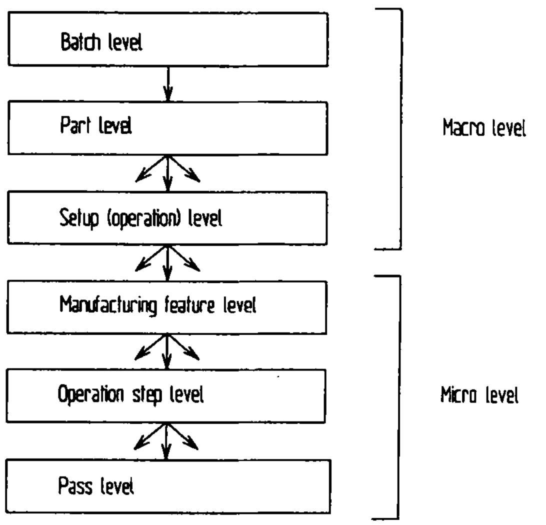


Fig 2. Levels of abstraction of machining operations.

One can consider machining operations at the six levels of abstraction indicated in fig. 2 [Jasp 95]. The planning of each level requires its special activities and thus appropriate models.

At the **batch level,** information about a batch of parts is dealt with. Relevant information includes the number of parts to be produced, all operations to be performed, required machining time, cutting tools, fixtures etc.

At the **part level,** all information required to machine one specific part is considered. Relevant information includes type of workmaterial, shape of raw material, sequence of setups to be performed, etc.

At the **setup level,** the number of operations to be carried out on one part while it is retained in its fixture is considered. Relevant information includes the sequence of operations to be performed and for instance the minimization of the number of the required tools may become important.

At the **operation step level** (operation steps are unit operations such as centring, drilling, reaming, tapping etc.), the details of each operation are defined. Relevant information includes the specification of the cutting tool and the number of passes by each tool. Often the sequence of operations on each specific shape element of the workpiece has to be considered.

At the **pass level** (a pass is one uninterrupted tool movement through the workpiece material), the kinematical quantities depth of cut, cutting speed, feed have to be selected.

Up to now the working group considered only modelling at the operation step and pass level. Models to support decision making at higher levels will not be dealt with in this progress report. These levels should be considered later. Suitable models for the lower levels form a good basis for modelling of the higher levels.
It should be realised that the techniques for simulation sometimes applied at the higher levels for the purpose of plant layout or production planning are completely different from those addressed in this report.

When developing new models it is useful to keep the various purposes and levels in mind and to make the models as simple as possible for the intended purpose. The CIRP working group will attempt to "construct" a "house of models" consisting of separate building blocks but with an efficient flow of information between the blocks. Modern developments in information technology e.g. those pursued by ISO/TC184 Factory Automation should be taken into account.

3.2.2 Confrontation of two different traditional schools in modelling of machining: science and engineering

Two basically different schools in the field of modelling of machining operations can be distinguished:

1 Modelling as an engineering necessity
2 Modelling as a scientific challenge

Taylor [Tayl 02], the earliest well known name in the field of modelling of machining operations.He aimed to provide as simple as possible guidelines for use in the daily life of machine shops. His guidelines were based on engineering practice and were supported by systematic experimentation in the machine shop. Some of these guidelines could be presented in the form of mathematical expressions like the well known Taylor formula which relates tool life to cutting speed in turning of carbon steel with high speed steel tools. Later this formula proved to be extremely versatile. It could be adapted to many other combinations of one operation, one workmaterial and one tool material and even the effect of other variables could be included. His train of thought was followed by many industry oriented research organisations.

Merchant [Merc 45] took modelling of metal cutting as a scientific challenge. He started from the basic mechanism of chip formation. He was the "father of the shear plane theory". He pointed to the importance of studying the behaviour of the workmaterial and friction between tool and chip. Also this school of thoughts got many followers, this time mainly in universities. They focused mainly on the very simple basic quasi static cutting process.
One of the important questions in this area of research is the position of the shear plane, which is an abstraction of the zone of transition between workpiece and chip. At present, more than fifty shear angle relationships are known and none is really satisfying. Later it became clear that in fact a shear zone of certain dimensions should be studied. Different techniques, known from plasticity of materials were applied for this purpose. There are hundreds of publications in this field, among which are several books, Among the authors are several well known members of CIRP. One of the latest is P.L.B. Oxley's book "MECHANICS OF MACHINING, An Analytical Approach to Assessing Machinability" of 1989 [Oxle 89].

3.2.3 Classical schools unable to serve industry

None of the two classical schools could serve the needs of industry in a satisfactory manner. Reasons for this are:

1 The "engineering school" was never able to predict the influence of work material or tool material on the values of the constants in the empirical equations.
2 The "scientific school" was never able to predict what type of chip formation would occur at specified conditions or even in the case of a continuous type of chip formation process; also they were never able to predict the actual behaviour in the chip formation zone accurately enough.
3 The "scientific school" could never bridge the gap between the simplified fundamental case studied and actual three-dimensional cutting operations nor could the "engineering school" bridge the gap between pure empirical and fundamental scientific quantities.
4 The fast introduction of new tool materials and new tool designs, including indexable inserts with chip forming geometries which cause new phenomena, which were unknown before.
5 The introduction of an ever widening spectrum of work materials including refractory materials and hardened steels with similar effects.
6 The introduction of new machining methods such as circular milling, high speed machining, dry machining, which bring in new problems needed to be addressed but in which knowledge obtained earlier did not apply.
7 The shifting interests of the metal cutting industry; in many cases workpiece accuracy and surface quality became more important than tool wear and cutting force. Later, protection of workers health and environment were added.

In the early days of metal cutting, tool wear was the predominant mode of tool damage, which was initially considered to be mainly a mechanical process governed by the dependence of the influence of temperature on the ratio of hardness of the tool to hardness of the workmaterial and the influence of cutting conditions on the local temperature at tool faces. The determination of the optimal cutting speed on the basis of a techno-economical optimisation process later became a point of major concern.

With increasing capabilities of the cutting tools the capabilities of the machine-tools became of concern and the attention shifted to the prediction of the main cutting force and the related cutting torque and power. In this era several well known models for the prediction of the cutting force were developed. Here a difference between the "European school" and the "American industrial school" can be detected. In Europe, the specific cutting force method became the standard. The concept was originally developed by Kienzle. In an overview paper Victor reviewed and compared the results obtained by a number of researchers and brought these into a common framework [Vict 71]. In the American industrial school, the unit material removal rate per horsepower became the standard for the calculations. It can be shown that the specific cutting force and the material removal rate per horsepower are reciprocal values neglecting some constant which originates from the different systems of units used. So, in principle those two schools are very similar. In contrast was the "American scientific school". Their method of calculation was based on the rather accurate assumption of a constant value for the shear stress in the shear zone to be determined experimentally for each workmaterial and a prediction of the area of the shear surface. Consequently, there was much greater need to predict the shear angle in the USA than in Europe. Therefore, the majority of shear angle relations are of American origin.

The point of major concern today in the majority of cutting operations is to predict the resultant accuracy and surface characteristics of the workpiece. Especially in small batch manufacturing of precision parts, it is desirable to be able to select the machining methods, the cutting tools and the cutting conditions in such a way that a very high level of certainty that a workpiece that meets all ever more rigid accuracy requirements is produced. This shift in attention causes two fundamental changes in the requirements of modelling of metal cutting:

a the dynamic character of the chip formation process becomes important
b the error motions become important

For the purpose of modelling of the action of chip formation, the chip types, chip forms and chip disposal, cutting forces and tool wear, it was sufficient to consider only the interaction of the cutting tool with the workpiece caused by the ideal relative motions provided by the machine-tool neglecting all error motions and even in this case the workpiece-tool interaction had to be simplified very much. In all models for tool wear and cutting force, and even in models for the prediction of chip shapes, the true mechanism of chip formation was neglected. Even today no reliable model is available to predict the chip type.
When surface integrity is of importance, it is essential to be able to predict which mechanism of chip formation, as signalled by the chip type, will occur. Consequently, the least that is required is to be able to predict under what conditions the following chip types will be produced:

a quasi static continuous chips
b continuous chip with built up edge
c segmented chips in which the chip consists of strongly connected segments caused by a fluctuating shearing process
d wavy chips, semi-continuous chips in which the thickness of the chip varies periodically
e elemental chips in which the subsequent fragments are not connected at all or in which the connection is very fragile

It would be desirable that more details could be predicted such as the thickness of the chip, the frequency of the periodical variations of the chip formation process and especially the magnitudes of the cyclic variations of the cutting force components caused by those dynamic chip formation processes.

When the accuracy and surface roughness of the workpiece are considered, the error motions are important which means that the machine-tool and all other elements that determine the mechanical and thermal behaviour of the machining system should be included in some way in the model of the cutting operation. Here only partial solutions are proposed for certain aspects, but up to now, these could not be brought into a common framework.
A special problem domain is the prediction of chatter since this is caused by the mutual interaction of the dynamic properties of the mechanical system and the self-excitation by the cutting process.

Tool life is still a limiting factor even today in a great number of cases but the reason is often quite different from that in the past. New modes of tool damage have become predominant. One is tool fracture which is related to the more frequent use of modern hard and brittle tool materials. Here the traditional deterministic empirical models for tool wear, mainly based on the predominant effect of temperature do not apply. The brittle modes of tool failure are of a completely different nature. Other effects should be taken into account and the stochastic nature should be reflected in the model.
However, before complex stochastic models are considered, it is wise to study the causes of brittle tool failure. After many years of debate researchers at TU Delft succeeded in confirming that unfavourable exit conditions when the cutting edge leaves the workpiece are the origin of tool fracture rather than the entrance conditions when the cutting edge enters the workpiece. Thus, the frequent failure of carbide cutters in face milling of steel workpieces could be explained and rules could be formulated to avoid this kind of tool failure [Lutt 84, Peke 84].
Another important aspect of tool wear is the influence of even minor changes of the tool shape due to wear which have an immediate effect on workpiece dimen-

sions or surface roughness and the integrity of the subsurface layer. The various modes of tool damage of completely different nature can not be modelled up to now in a way useful to industry.
The consequence of these arguments is that much more attention should be given to other aspects of tool damage and tool life than the classical flank wear.

3.2.4 The third approach: the machining data base
In the seventies it became clear that the two traditional schools of modelling of metal cutting could not solve the problems industry was facing. The engineers could not explain the many disturbing effects which occurred when applying the relations obtained experimentally to new situations and the scientists did not know how to bridge the gap between theory and practice.
Therefore a third way out was attempted the machining database [Kahl 87]. Typically one organisation per country tried to collect as many sets of machining data which had proved to give satisfying results in industry in computer databases and put those data at the disposal of the members. The number of stored data increased very rapidly but application to new situations proved to be difficult. Often it was not clear at all why a certain set of data was successful in one situation while it showed to be inapplicable to a seemingly similar situation. The database people tried to check the reliability of incoming data carefully,by applying cross-checking of data of various origins and worked on the development of more accurate models but did not succeed to improve the quality of their data very much and the interest in those general machining databases diminished.

In the mean time due to the increased use of NC-machine-tools, especially in small batch production, much attention was given to computer aided process planning CAPP. In the scientific literature of the eighties and the nineties hundreds of publications appeared in this domain [Elma 93, Anom 97]. Universities developed many new principles to develop the field of process planning from the traditional experience-based methods into a field of much more systematically science-based methods. Implementation of CAPP systems in industry proved to be much more difficult. A major reason, but not the only one, was the lack of reliable cutting data.
Industry can not work without reliable machining data and has to find practical solutions which at least can solve the problems of today as well as possible with the available means. Many metal cutting companies started to make their own machining data bases. Frequently they underestimated the problem and did not properly identify the factors to be taken into account to classify the data.
Some manufacturers of cutting tools provide their customers with machining data on CD's which give more opportunities to give much more detailed data than is possible on paper. But, they too do not know how to take into account the influence of the machine-tool, and consequently, their information on expected workpiece accuracy is also superficial and imprecise.

3.2.5 A new school in the future?
It is high time to consider how the problems in industry can be solved better. There is no single way out. No single method is better than the others. All possible means should be used. Some basically different approaches are possible. These include:
a detailed prediction of the boundary conditions for stable machining
b accurate prediction of the influence of discontinuous chip formation and error motions
c minimisation of error motions

From the above it has become clear that the two factors which cause the most nuisances are the discontinuous processes of chip formation and the error motions. One can try to develop models for both these effects. Then the next step required would be to develop models which could predict the influences of both effects on tool life and workpiece precision and roughness. In this way it would in principle be possible to develop models which would assist in the selection of the variables of any machining operation but it would be a long and uncertain way to go. Thus approach (b) does not seem very promising.
Actually machining operations show the best performances if dynamic chip formation and error motions can be avoided. Consequently, it seems much simpler to concentrate on the development of models, and possible also on other means, which would signal that a certain set of selected cutting variables would result in a non-desirable cutting process and thus should be avoided. In principle it should be much easier to develop models for the boundary conditions where a non-quasi static process of chip formation or error motions beyond a certain limit are likely to occur. Within these boundaries, machining can be performed with a relatively high rate of success especially when the cutting conditions are selected as far away from the boundary conditions in the middle of the resulting process window. This would mean that the models for the prediction do not need to be very accurate. This has two effects:
a the models could be rather simple and only the most significant effects have to be taken into account.
b no great precision of the data in the models is required
This makes it desirable to develop approach (a).
In the past much effort has already been made to minimise error motions. For this reason, machine-tools are designed and manufactured with great care for the static geometric accuracy and it has always been attempted to reduce the effects of forces and temperatures on the geometry as much as possible. Similar considerations apply also to the tool holders and the workpiece fixtures. We are close to the boundaries of what can be achieved by mechanical means.
Much can be expected from software compensation of

geometric inaccuracies. This software compensation requires in itself suitable models but these do not seem too difficult to develop [Sart 95, Weck 95].

3.3 The complexity and uncertainties of modelling machining operations

Comprehensive and reliable models of machining operations are dificult to be realised owing to a variety of issues that need further consideration.

3.3.1 Large variety of machining .

There exists a large variety of machining operations, each requiring a tailor-made model. Turning is a continuous operation so that a steady state model suffices. In contrast, milling is an intermittent operation where the steady state is never reached owing to the continuous change in the thickness of cut. Unlike in turning and milling, the geometry of the cutting wedge is continuously varying along each cutting edge in drilling so that it becomes necessary to integrate the effects along the edge. Even within one group of operations noticable variants occur. For example there is a variety of drilling tools for various purposes with variations in the number of cutting edges, geometry of the cutting edges, the mode of guidance of the drill in the hole, length/diameter ratio, etc. Such variations within one group require adapted models.

3.3.2 Large variety of input variables

In each machining operation, there is a large number of input variables. These can be grouped into several categories:

Fixed variables are those variables which are fixed for a certain operation such as the machine-tool, the workpiece, the cutting tool, the fixture, the tool holding device and the cutting fluid.

Free variables are those variables whose values can be selected freely for a certain operation; these are also often called setting conditions; the kinematical quantities speed, feed, depth of cut, width of cut, thickness of cut, etc. certainly belong in this category.

3.3.3 Large variety of internal variables

In modelling the chip formation process, for instance with the aim to predict forces by using the shear plane approach, one needs to know the mean shear stress on the shear plane which, in turn depends on the combination of shear strain, strain rate and temperature at the shear plane. Hence, models for these internal variables are required. Further, there appears to be a natural order of variables in the sense that the preceding variable is needed in the prediction of the following one. An example is:

> chip dimensions -> forces -> temperatures -> wear rate -> tool life -> economic performance measures
>
> [Venu 96].

Thus often, a series of models for specific sets of internal variables need to be woven together in order to predict the desired output variable(s).

3.3.4 Large variety of output variables

Machining is an economic activity. This means that both the technical and economic aspects of the result are of importance. Recently other aspects are added like working conditions for the operators (noise, smell, health and safety) and the environment. The importance of the various performance indicators vary significantly with the case at hand.

3.3.5 Work material properties are difficult to determine

The work material has significant effects on the results of machining operations. In the literature on modelling most attention is given to the influence of the mechanical properties on the chip formation process and cutting forces. In the practical situation the very significant influence of the work material on tool damage and tool life, and thus on the selection of cutting tools and cutting conditions is often even more important. Although much attention has been given to explain the influence of the work material on tool life by physical and chemical processes, the only practical method is purely empirical in which work materials are grouped in machinability classes with comparable behaviour (see e.g. VDI 3323 Information on applicability of hard cutting materials for machining by chip removal) and for which the constants in the tool life equations are determined experimentally.

The magnitudes of strain, strain rate and temperature involved in machining are several orders higher than those that can be handled in current material test equipment. Added to this is the fact that the variety of work materials to be addressed by modellers of machining operations is several orders larger than that facing modellers of other metal processing operations. A way out of this problem is to recognise machining itself as a material test as advocated by Armarego [Arma 83], Venuvinod [Venu 96], etc. Armarego's school has been particularly successful in predicting cutting forces in a number of practical machining operations (turning [Arma 70], end milling [Arma 91], face milling [Arma 95a], and a variety of drilling operations [Arma 85] [Arma 96]) from a common data base of machining properties work materials (shear angle, chip flow angle, edge forces, shear stress, and tool-chip friction coefficient amongst others) obtained from simple single edge oblique cutting tests on each work material. A related problem is that the relation between the designation of workmaterials, whether these are designations defined in standards or commercial designations used by material suppliers and the actual properties that are relevant for machining is very weak. Different batches of the same nominal material may result in a wide scatter of thermal/mechanical behaviour and in the results of cutting tests like cutting force, surface finish and tool life.

Similar problems occur with tool materials and cutting fluids.

3.3.6 Complex tool/work material interface

Friction and wear on the tool rake face and flanks are extremely important in metal cutting. Here the situation is still more complex. The phenomena occurring on machining proporties of the tool faces depend on the local conditions of stresses, velocities and temperatures and the local properties of tool and work material and the cutting fluid. At the extreme conditions of pressures and temperatures, chemical and physical reactions between the three partners may occur which may change the known properties of the partner materials significantly.

A most mysterious partner is the cutting fluid. Often the composition and fundamental properties of the cutting fluid are completely unknown to the user. Also modern tool coatings cause complications. To consider the tool/work material interface as a classical two-body problem is an unacceptable simplification for basic studies.

3.3.7 Machining is a small scale operation

The volume of material undergoing machining is much smaller than in most other metal forming operations. The size, shape and dispersion of grains and metallurgical phases (as influenced by heat treatment) have significant influence on the nature of chip formation. An implication is that the concepts of continuum plasticity may not be adequate and one may have to consider meso-plasticity. The small dimensions of the cut also require us to recognise the size-effect [Back 52] and the influence of dislocations [Turk 67]. In some cases the thickness of the cut is comparable to the cutting edge roundness (lack of edge sharpness) so that the influence of stagnant zone and "ploughing" effects at the rounded cutting edge on cutting forces can be large [Albr 60]. Inspite many attempts, no satisfactory models for these edge effects have so far been developed so that most cutting force models have had to make the unrealistic assumption that the cutting edge is perfectly sharp.

3.3.8 The process of chip formation is not uniquely defined

The situation in machining is quite different from metal forming operations. In forming there are basically two different situations:

a The output geometry of the workpiece is fully determined by the tool geometry such as in extrusion; the internal distribution of stress and strain and the required force is determined by the material behaviour and friction on the tool-workpiece interfaces.

b The input force or energy is determined by the machine and the resultant deformation is determined by the resistance of the material against deformation and friction.

In machining none of these two cases exists. The chip can assume any thickness and also the cutting force can assume any value. There is much evidence that this often depends on the state of initial tool-work contact. In other words, the machining process is inherently not uniquely defined [Dewh 78].

In addition to this non-uniqueness of the deformation process it should be noted that a cutting system is in a sense an "open" system. There is an interaction between the chip formation process and the "driver" of the relative motions between workpiece and tool due to the finite stiffness of the machine-tool. Depending on circumstances the resulting static and/or dynamic elastic deformations may cause inacceptable results of machining operations. The prediction of the behaviour of open systems is still in its infancy. Some more details are mentioned in sections 6.4 *vibrations in cutting* and 7 *workpiece precision*.

3.3.9 Large variety of chip types and chip forms

The chips produced can exhibit a variety of types as was already mentioned in section 3.2.3. This results from different processes in the zone where the process of chip formation takes place. These are often called "regimes of chip formation". The origin of the different regimes is in the various responses to the complex exposures to high levels of strains and strain rates, stresses and stress rates, temperatures and temperature rates together with the friction on the tool-workpiece-chip interfaces. The boundaries between those regimes are unclear and it can not be predicted with any great accuracy which regime can be expected in a particular situation.

In addition, there is an influence of the geometry of the tool face of indexable inserts, separate chip formers, external obstacles encountered by the chip, etc. which cause a variety of chip forms.

The modelling approach required for each chip type and each chip form tends to be quite distinct. Hence it becomes necessary to predict the state of chip formation so that the appropriate model for predicting the desired output can be invoked. These aspects were extensively studied by an earlier working group of STC "Cutting" [Jawa 93, Lutt 93]. Since then significant new results have been obtained by Jawahir's group.

3.3.10 Large machining data bases are needed

As a result of the large variety of machining operations, work materials, internal variables, and states of chip formation to be addressed, machining operation modelling has required the support of large machining databases. We have already noted the database used by Armarego for instance. However, the creation of these databases is an expensive activity requiring extensive off-line experimentation. This feature has been a major hurdle in transferring models validated at the laboratory level to shop floor practice.

3.4 Literature Database

A literature database which includes information on a variety of papers of interest to modellers of machining operations has been created. Data entry is done through a specially designed Visual Basic software. Data access, querying, and report generation can be done through Microsoft Access. The software may be accessed by CIRP members from an FTP site located at City University of Hong Kong [Venu 98].

As of March 1998, the database had over 3500 records. Each record in the database includes the standard bibliographic information (title, author names, journal, page numbers, etc.) There are facilities to include an abstract, key words and comments. The most important special feature of the database is the inclusion of labels. Labels are descriptors of the paper from a specified point of view. Over 180 labels have been decided upon by the Working Group after careful thought. Each paper in the database has been labelled according to this agreed list. The labels enable the literature to be analysed from different points of view. The collection of literature is relatively sparse on publications in a language other than English. Future efforts would be directed towards correcting this imbalance.

3.5 Survey of recent research on modelling

A comprehensive survey conducted by the CIRP's Working Group on Modelling of Machining Operations during the 1996-97 period identified over 55 major research groups as currently active in modelling efforts. This survey covered over 15 topics related to modelling of machining operations and this survey has made an attempt to establish the most common tools and techniques used by these research groups worldwide. The operational classification includes six major groups: single straight edge orthogonal, single straight edge oblique, turning, milling, drilling and form-tool machining.

A broad grouping of the results indicates that over 43% of the research groups were active in experimental- /empirical modelling followed by 32% involved in analytical modelling. Among the 18% of the research groups that are active in numerical modelling, finite element modelling (FEM) techniques were found to be the most dominant tool while only a small number of groups were involved in boundary element methods (BEM) and finite difference methods (FDM). A growing number of groups were also found to be active in modelling of machining operations using A.I. techniques.

Also, the survey results show that over 31% of the modelling efforts deal with turning followed by milling with 24%. Single straight edge orthogonal cutting, drilling and single straight edge oblique cutting account for 20%, 13% and 9% respectively.

Large groups of researchers are actively involved in developing newer models and/or modifying the existing models for improved performance. In the subsequent paragraphs of this paper, a summary analysis of the most common types of models is presented.

3.6 Semi-empirical models.

Taylor, who has been acknowledged as the father of metal cutting science, adopted the empirical approach in proposing his well known Taylors equation, $vT^n=C$ where v is cutting speed, T is tool life, and n and C are constants [Tayl 07]. This equation has since been extended to include other cutting conditions like feed and depth of cut [Kron 66]. The Taylor equation and its extended versions are extensively used even today in assessing machinability and machining economics. Tool materials continue to be compared on the basis of the Taylor index and Taylor constant. The machining databases that the industry uses are dominated by Taylor parameters.

The power-law form of the extended Taylor equation has subsequently been applied to include simple work material properties, and tool geometry parameters [Woxe 32]. Kronenberg [Kron 66], Colding [Cold 59, Cold 91] and others have used similar forms of equations for predicting cutting forces and temperatures. Rubenstein et al have provided a rationale for the extended Taylor equation by utilising a power-law expression for cutting temperature while modelling crater wear and flank wear based on the assumption of adhesion and diffusion wear effects [Rube 78].

Semi-empirical models are simple and easy to apply. However, apart from not providing a deep understanding of the cutting process, extensive new experimentation is needed each time a new cutting variable is added to the power-law relationship and, the entire process needs to be repeated afresh each time a new tool-work material combination is encountered. This is extremely unsatisfactory in the context of CNC shops where the variety of tools and work materials tend to be very large. The main flaw in the semi-empirical approach is that it does not provide any mechanism to learn from previous machining experiences. This statement is also true, albeit to a much lesser extent, with computational modelling. In contrast, analytical modellers look for patterns of behaviour at a higher level by invoking known relationships borrowed from Physics, Mechanics, Material Science, etc. Relationships which have worked well in previous instances and basic parameters are apparent in Armarego's suite of analytical models covering a fairly large range of practical machining operations [Arma 83, 85]. More recently, he has stated simulation results from his analytical models in the power law form covering a large range of tool geometry and cutting variables. However, the experimental data he utilises is several orders smaller than what would have been required if a similar relationship were to be developed purely empirically, i.e. without the benefit of the higher level insights provided by analytical modelling.

3.7 Analytical Models

Analytical models come with varying degrees of "fineness" (i.e., brush type, according to [Arma 96]) concerning accuracy and applicability. For instance [Kald 97] addresses macro-level issues of preliminary tool selection before the cutting conditions have been selected. Shear plane theories aim at only mean conditions at the shear and tool-chip contact planes. They may be said to be medium-coarse brush. Shear zone theories provide insights into spatial distributions of stresses, strains, etc. Therefore, they are of finer brush.

Analytical models can be purely deterministic or augmented by probabilistic or stochastic considerations. Sometimes, the results of such models are statistically fitted.

3.7.1 Mechanistic force modelling

Mechanistic force models can be defined as force models based on the mechanics of the cutting process; however, they are not purely analytical and depend heavily on empirical cutting data for their modelling capability. These models are commonly computer-based and draw heavily on the mechanics of oblique single-edge cutting. Simply put, these models are a blended combination of analytical and experimental modelling techniques. This approach avoids the complications of requiring basic mechanics parameters such as shear angle, dynamic stress, friction angle, etc. by using empirical cutting force data. The geometric features of the specific operation are then combined with the empirical cutting data to produce specific mechanistic models for different machining operations.

Mechanistic modelling techniques are based on some of the early fundamental relationships between the chip load (i.e. the undeformed area of cut) and the cutting forces, cutting tool geometry, cutting conditions, workpiece geometry and type of operation. Martellotti, Koenigsberger and Sabberwal [Mart 41, Koen 61, Sabb 61] and others analysed the end milling process by using the following basic emperical relationship for cutting force as commonly used in Europe:

$$F_c = k_c . b . h \qquad (1)$$

Where k_c is the specific cutting force and a function of the cutting parameters such as thickness of the cut, rake angle, inclination angle, etc.; b is the width of cut and h is the thickness of the cut. Kline et al. [Kline 92] presented a mechanistic model for predicting the cutting forces in end milling including the effects of tool runout and tool deflection on the part accuracy. An improvement to this model was performed by Sutherland and DeVor [Suth 86] by accounting for the system deflections on the cutting parameters (e.g. chip load).

Mechanistic modelling techniques have also been used by Elbestawi et al.[Elbe 94] and Altintas et al.[Alti 96]. Sutherland et al. [Suth 88] used cylinder boring and turning operations to model the prediction of cutting forces. The detailed effect of tool geometry and cutting parameters on the cutting forces has been discussed. The experimental work was used to calibrate and validate the proposed model. Endres et al. [Endr 95] used the mechanistic modelling technique to predict the machining forces including the ploughing mechanism due to the rounded cutting edge. A calibration algorithm was used to fit the empirical models. Recently, Chandrasekharan et al. [Chan 97] used mechanistic methods to develop a predictive model for cutting forces in drilling operations.

3.7.2 Shear plane models

Notwithstanding the physical impossibility of a shear plane and many theoretical objections raised since its original formulation by Merchant [Merc 45], shear plane modelling has stood the test of time. Although much of the earlier work focused on classical operations, the method has been applied quite successfully in the prediction of forces in several practical machining operations in recent times. Armarego has modelled turning, [Arma 70], milling [Arma 95a], drilling [Arma 96], etc. Altintas [Alti 95] has achieved particular success in the field of milling, see also section 6.4.3.

Forces

Merchant's pioneering paper on single edge orthogonal cutting [Merc 45] has established two cardinal principles:

(i) Chip Equilibrium (the chip can be considered as a rigid body in translational equilibrium under the external forces acting on it), and
(ii) Force-Velocity Collinearity (the shear and friction forces at the shear plane and the tool-chip contact face are collinear and opposite to the shear and sliding velocities at the two faces respectively).

Merchant, Shaw [Shaw 52], Zorev [Zore 66], etc. later extended the shear plane approach to single edge orthogonal cutting. Venuvinod recently used the concepts of twin-shear plane and chip segment interaction force to solve the problem of force partition in two edge oblique cutting [Venu 96].

Shear angle solutions

Force prediction using the shear plane approach requires *a priori* knowledge of the shear angle and tool-chip friction coefficient. While no robust models are as yet available for estimating the latter, the apparently never ending search for the ideal shear angle solution has continued to today. Merchant was one of the first to start this chase when he proposed his solution based on the principle of minimum energy. This solution is now accepted as the upper bound provided the work material can be considered to be perfectly plastic. The lower bound was subsequently determined by Lee and Shaffer using the slip line field approach [Lee 51]. Lindstrom has recently reviewed relevant literature and identified 52 shear angle solutions [Lind 97]. Most of the solutions are however restricted to single edge cutting (mostly orthogonal cutting). Armarego however has demonstrated that the cutting forces in practical machining operations can still be predicted from a shear angle database derived from single edge operations [Arma 85]. In order to achieve this, he defines an equivalent cutting edge which is defined as the line joining the two end-points on the active cutting edge (which may include the rounded nose in turning). Armarego established a unified (and generalised) mechanics of cutting approach for classical oblique cutting and applied this in his work on modelling of operations such as turning, milling and drilling. His basic models include the effects of cutting edge forces [Arma 95]. The ongoing research program at the University of Melbourne also includes the basic investigation of classical rotary tool processes [Arma 96].

A major problem with the shear plane approach is regarding the uncertain magnitude of tool-chip friction coefficient and the shear stress at the shear plane. Connally and Rubenstein developed a model based on the lower boundary of the shear zone to address these problems [Conn 68]. The solution did not require tool-chip friction to be known and the shear stress utilised was that at the lower boundary of the shear zone which could not be influenced by the strains and strain rates in the shear zone. This model has repeatedly shown excellent correlation with experimental results on the power component of the cutting force. However, uncertainties remained with regard to other force components. This approach has been recently extended to oblique cutting with one and two cutting edges [Venu 96].

Temperatures

Analytical models for the estimation of mean shear plane and tool-chip interface temperatures were developed by Loewen and Shaw [Loew 54], Chao and Trigger [Chao 50, Chao 55], etc. The basic assumptions were that the rake and flank contacts were continuous. Carslaw and Jaeger's solutions for stationary and orthogonally moving rectangular heat sources have played a crucial role in these models [Cars 50]. The moving heat source solution was subsequently extended to oblique motion [Sast 81] which enabled a model for rake temperatures arising in single edge oblique cutting [Venu 86]. Recently, Stephenson has assessed a number of rake face temperature models against infrared and thermocouple measurements and concluded that the models due to Loewen and Shaw, and Venuvinod had exhibited the best correlation [Step 91]. Rake face temperatures are important in modelling crater wear whereas flank temperatures are important in flank wear modelling. However, the assumption of continuous flank contact is questionable when, as is many times the case, flank wear is dominated by adhesion wear. Adhesion wear assumes partial contact in the vicinity of contact asperities. Venuvinod therefore modified Trigger and Chao's model to take into account the thermal constriction resistance at the tool flank [Venu 90]. This model has resolved many uncertainties involved in linking flank temperature to flank wear. In particular it has highlighted the link between wear and work surface hardening.

General Comments on Shear Plane Solutions

All shear plane solutions provide only limited qualitative agreement with experimental results particularly with various work materials. In shear plane models the work material flow stress is assumed to be constant during deformation. No account can therefore be taken with this model of variations in flow stress with strain, strain-rate and temperature, thus virtually ruling out consideration of the influence of cutting speed. Allowing for the variation of the flow stress, for a work hardening material, Christopherson et al [Chris 58] modified Hencky's equation for stress equilibrium. This analysis clearly showed that the velocity discontinuities such as the shear plane conditions are no longer admissible, as they involve infinite gradients, and must open up to form finite plastic zones.

3.7.3 Curved shear surface models

Chips are usually curved, upwards- away from the tool face- or sidewards- parallel to the tool face. Both effects can not be explained by a flat shear surface. Also, in all cases in which a tool corner is present, a flat shear plane cannot exist. In all those case a three dimensional curved shear surface should be present. The geometry of this shear surface can be completely calculated from the primary motion (often a rotation of workpiece or tool), the geometry of the cutting edge and the motion of the chip and the thickness of the chip [Spaa 71],[Lutt 76]. In earlier publications the presence of a curved shear surface was seen as the reason why curved chips are produced. Van Luttervelt showed that there are several reasons why chips with a certain curvature can be produced [Lutt 76]. The consequence is that a curved shear surface should be present. A remarkable result of these studies is that the shear surface in most cases passes not through the cutting edge but passes a little bit above the rake face. This slightly more complex model is able to explain certain phenomena in cutting much better than the simple flat shear plane. An example is the presence of a boundary layer between tool and chip. A dynamic model is even able to explain chip segmentation [Lutt 77]. Models with curved shear surfaces are not often used in models for other purposes than studying chip forms such as cutting force, temperatures, etc. due to the complexities involved.

3.7.4 Shear zone models

Palmer and Oxley [Palm 59], in their early work, observed the chip formation process using a cine-filming technique. This work showed that the shear zone in which the chip was formed was of substantial width. In analysing the stresses in this zone it was shown that account had to be taken of variations in shear flow stress in order to obtain good agreement between predicted and experimental forces. A subsequent investigation of the flow along the tool-chip interface was made by Enaharo and Oxley [Enah 66]. They constructed a slip-line field and the corresponding hodograph for a given set of conditions. The comparison of streamlines which were constructed from the hodographs, with the experimental streamlines which were obtained by them for the flow around the rounded cutting edge clearly showed the applicability of the slip-line field models.

Roth and Oxley [Roth 72], in a later work, constructed a slip-line field from the measured velocities of flow. This model gave the distribution of hydrostatic stress along the boundary slip-lines. Velocity conditions are all approximately satisfied with the boundary velocities. Cutting force equilibrium conditions were shown to hold valid for this model.

3.7.5 Predictive machining theory

Oxley's [Oxle 89] continuing research led to the development of a comprehensive predictive machining theory which is based on the classical orthogonal cutting operations. This model assumes a thin shear zone, chip equilibrium and a uniform shear stress in the secondary deformation zone at the tool-chip interface. The minimum energy principles are applied. The model allows for the variation of flow stress properties in terms of the strain, strain-rate and temperature. A 'velocity-modified temperature' approach was used for finding solutions in the model. The thermal properties of the work and tool materials are used as functions of temperatures and the heat partitioning factors as a function of the thermal number.

The input variables are the cutting speed, width of cut, undeformed chip thickness, tool geometry and the work material chemical composition. The predictive model gives the shear angle, cutting forces, primary zone strain, strain-rate, velocity-modified temperature, flow stress, interface shear stress, chip thickness, interface temperature, tool-chip contact length, shear flow stress, etc. Further work conducted by Oxley and his co-workers include extensions of this initial predictive model to oblique machining and to operations such as turning and milling where the chip flow effects are taken into account with the use of tool inserts having a nose radius and the varying cutting edge angle [Youn 97].

3.7.6 Models for chip back flow

A large domain of research work completed by various researchers during the last few years primarily deals with the chip forms and the evacuation of chips from the machining zone. An extensive review of this is presented by Jawahir and van Luttervelt in a CIRP keynote paper in 1993 [Jawa 93].

One aspect is the chip backflow effect which means that the chip flows into a pit in the toolface if this is close enough to the cutting edge. The study of restricted contact tools is important in relation with machining with grooved tools having a toolface land. By following the early work involving the slip-line field solutions of Johnson [John 62], and Usui et al [Usui 63], Jawahir and Oxley showed a quantitative relationship for predicting the chip back-flow angle [Jawa 88]. The validity of the centred fan slip-line field for a wide range of cutting conditions were also shown through a series of models to take account of the rounded cutting edge and the flank wear [Jawa 86]. The use of the predictive machining theory for predicting the cutting forces in machining with restricted contact tools was shown in a very recent work by Arsecularatne and Oxley [Arsc 97].

3.7.7 Models for chip forms

In all traditionally known shear plane models, the chip velocity is assumed constant across the chip thickness and the chip is straight. This conflicts with the experimental observation that the chip is usually curled. Kudo [Kudo 65] and Dewhurst [Dewh 79] presented several admissible slip-line field solutions to account for this. In their models they introduced a curved shear plane to give the required velocity gradient across the chip. More recent work by Shi and Ramalingam [Shi 91] provides a model with a kinematically admissible slip-line field for machining with a cutting tool having a flank wear land.

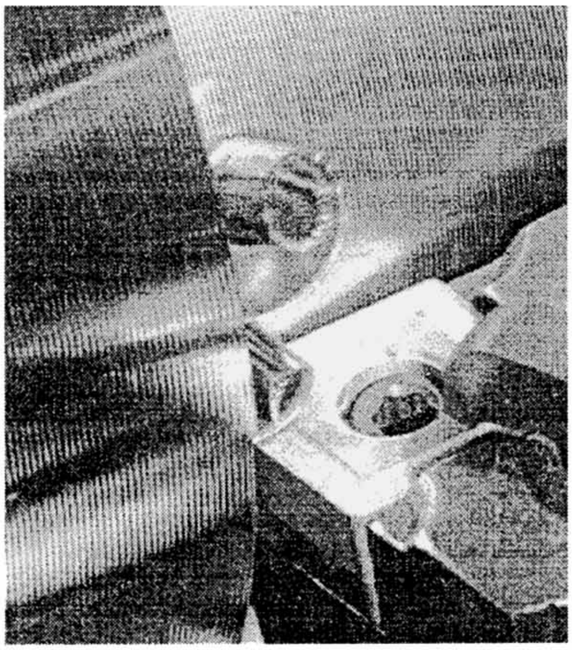
An analysis of chip curvature was made using an obstruction chip former. This work was subsequently extended to include the chip curl in machining with a grooved tool [Shi 93]. The cyclic nature of chip curl in machining and its effects have recently been established by Fang and Jawahir [Fang 96] and Ganapathy and Jawahir [Gana 93, Gana 98]. All of these works essentially deal with chip up-curl only. The most commonly observed chip side-curling effect was initially explained as the geometric effects by Pekelharing [Peke 63]. Van Luttervelt [Lutt 78] subsequently showed this effect as resulting from (a) the non-straight cutting edge; (b) non-linear primary motion of cutting; (c) non-perpendicularity of cutting edge to the primary motion; and (d) variation of chip compression rate along the chip width. A most recent work by Balaji and Jawahir [Bala 98] attempts to correlate the cutting force patterns with the chip side-curl in bar turning.

3.7.8 Comments on future development of models for chip formation

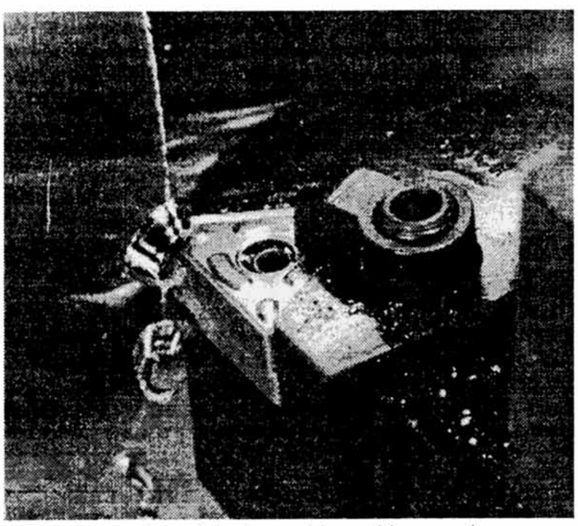
No significant progress is anticipated in the future in shear plane and shear zone models although these models have made a significant impact in the past. The need for further studies in the areas of friction-/tribology is emphasised due to the recent industrial trends where advanced tool materials and tool coating techniques, and a wide range of chip-groove designs have emerged during the last decade or so. Establishing the actual tool-chip contact length for machining with a grooved tool is a very complex task, particularly when the contact within the chip-groove is variable and very heavily depends on the chip-groove utilisation which in turn is a highly variable factor within a chip breaking cycle. Fig 3a shows the experimental situation studied with a simple grooved tool in quasi 2-D machining. Figure 4 shows a method proposed to identify the varying tool-chip contact regions in this case. The challenge is characterising the levels of contact in these regions when machining with a complex grooved tool under 3-D cutting conditions (Figure 3b). Developing a quick and reliable machine-tool-based testing/measuring method for obtaining on a routine basis the material behaviour under large strains and high temperatures will be another challenge where an analysis of varying work-tool material properties for new tool and work materials could be more readily represented.

3.7.9 Need for predictive modelling of effective cyclic chip breaking

Predictive modelling of cyclic chip breaking is a very interesting area where the experimentally observed cyclic chip formation patterns (see Figure 5 for 2-D machining) can be extended to modelling 3-D cutting conditions. Developing such models is not only likely to contribute to the cutting tool design, but also to provide an insight into the actual cutting process and its direct variables that could be controlled for effective machining performance.



a 2-D formation of broken chips with simple groove geometry



b 3-D formation of broken chips with complex groove geometry

Fig. 3 Modes of chip formation and chip breaking

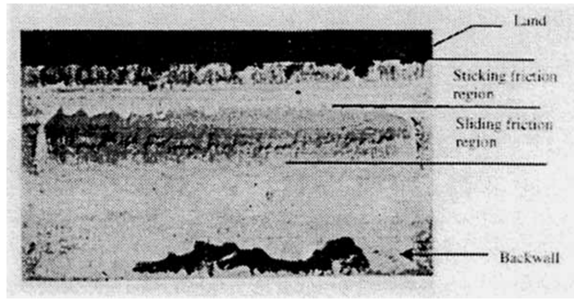


Fig. 4 Contact regions on the toolface.

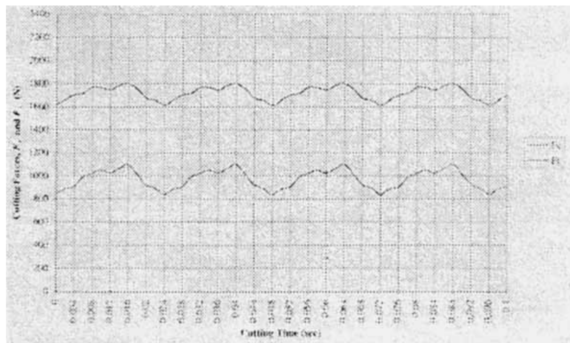


Fig. 5 Dynamic cutting force variation.

3.7.10 Need for modelling the effects of a rounded cutting edge

The need for modelling of machining with rounded finite cutting edge radii is another possible direction in which the effects of such cutting edge radii on all common machining performance measures can be clearly demonstrated.

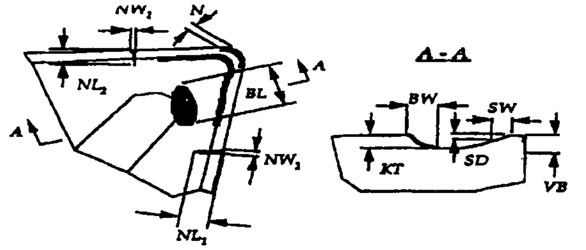
3.7.11 Need for modelling the effects of chip breaking geometries and for standardised test procedures to quantify those effects

Today, a great variety of indexable inserts and even solid cutting tools are provided with all kinds of "so called chip breaking geometries". The aim is to produce chips that are broken in small pieces and are easier to evacuate from the cutting zone. Two main types can be distinguished:

a Chip splitting, wide chips are split into several more narrow ones; examples are found especially in drilling and end milling tools; with those tools the thickness of the cut along the cutting edge is not constant; how this affects the cutting process can not be modelled up to now.

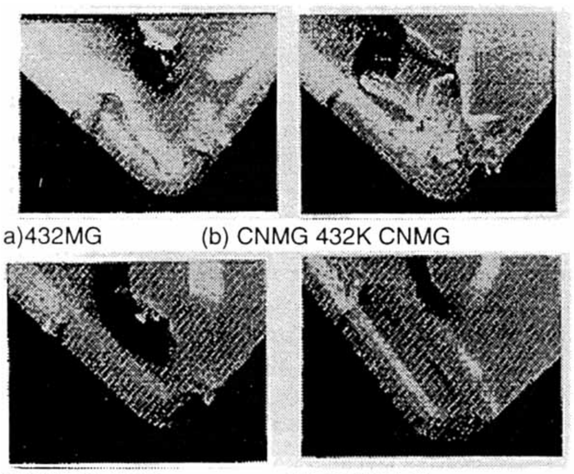
b Chip curling, the rake face of the tool is provided with features to cause tighter upcurling (or sometimes sidecurling) of the chips; the aim is to obtain cyclic chip breaking

Those special features have more significant effects on all common machining performance measures like cutting force, tool life and surface finish than is usually considered. The main reason is that these effects are often neglected in modelling and testing.



VB	flank wear
BW	width of groove backwall wear
BL	length of groove backwall wear
KT	depth of groove backwall wear
SW	width of secundary face wear
SD	depth of secundary face wear
N	nose wear
NL_1	notch wear length on main cutting edge
NW_1	notch wear width on main cutting edge
NL_2	notch wear length on secundary cutting edge
NW_2	notch wear width on secundary cutting edge

a) Measurable toolwear quantities on grooved tools



a)432MG (b) CNMG 432K CNMG

© CNMG 432P (d) CNMG 43

f = 0.43 mm.rev. a = 2.54 mm
Toolcoatng = KC850
Cutting time = 2 min. V = 274 m/min.
Workmaterial = 1037M steel

b) Concurrently occuring multiple wear patterns on four different grooved tools.

Fig. 6 Wear of grooved tools.

The deficiency of all currently available standards for tool-life testing (e.g., ISO 3685 (turning), ISO 8688 (milling) and ASME 85) on this point has been noted several times earlier. The need for establishing new standards for concurrently occurring multiple tool-wear types in machining with grooved tools has been urged in recent times (Figure 6). However it is not likely that ISO will draft revisions of these standards unless specific proposals are presented by a body with sufficient authority.

Empirical modelling of tool-life relationships for machining with grooved tools have recently been updated with the additional effects of a tool coating factor and a chip-groove effect factor [Jawa 95]. Analytical prediction of tool-wear in terms of one or more of the machining variables such as the cutting temperature and/or the tool-chip interfacial friction is a meaningful avenue to pursue. Establishing a truly predictive model for surface roughness, and the corresponding residual stress variations, without involving the traditionally known geometry relationship is a step in the right direction. Also, from the part specification point of view, the accuracy of parts needs to be predicted and/or established through a validated model incorporating the machine tool dynamics and stability.

3.7.12 Need for modelling of chip types

In section 3.2.3 the importance of prediction of the regime of chip formation and the resultant chip types was mentioned. This requires a unified detailed identification of the various chip types and appropriate models for the formation of the various chip types and perhaps even more important models to predict the boundaries between the various chip types. Most models are based on consideration of the stress-strain-temperature relation of the work material exposed to intensive shear in the primary shear zone. A recent overview was given by Professor M.C. Shaw [Shaw 97].
After careful examination of movie pictures taken of a cutting processes under a microscope, van Luttervelt was able to construct a dynamic system of four shear planes and a kinematically dead zone to represent the stagnant zone between chip and tool face [Lutt 77]. This system made it possible to explain and kinematically simulate the formation of segmented chips. These movies also clearly showed that the segmentation started in front of the stagnant zone, close to the cutting edge and not in the primary shear zone, a fact which has been neglected in all subsequent research.
Up to now no agreement has been reached on this very basic aspect of chip formation. It is hoped that computational mechanics will be of help here.

4. Applications of computational mechanics in cutting

4.1 The goal of computational mechanics

The goal of computational mechanics in cutting is to quantitatively predict by computer simulation all variables which can not be predicted by other means with acceptable accuracy. Examples are the flow of a chip, including the associated stresses and temperatures in the workpiece, the chip and the cutting tool in the vicinity of the chip formation zone. Up to now it is not possible to use computational methods for the prediction of tool damage and workpiece precision.
The starting point of all studies on simulation of chip

formation is the work material's constitutive behaviour, the friction law between the chip and tool, physical properties such as work and tool thermal characteristics, and the shape of the tool.

The last point differentiates metal cutting from most other metal plastic flow processes: the tool shape does not by itself completely determine the chip geometry. Especially with flat tool faces the process of chip formation is not uniquely defined as was mentioned in section 3.3.8. This leads to un-predictable variations of tool-chip contact length, chip thickness and chip curling and sometimes even of chip types which also cause variations in cutting force. One of the aims of designing inserts with sintered in chip breaking geometries is to reduce the influence of the properties of the work materials and of this non-uniqueness on chip geometry [Lutt 83] and thus to improve the predictability of results. Several researchers suggest that this aim has been reached with several of the recently introduced chip breaking geometries but if this is really true is still doubtful. However it should be realised that the application of computational mechanics to modelling of the effects of chip breaking geometries is still in its infancy.

4.2 Problems in simulation

Lack of uniqueness between chip form or cutting forces on the one hand and simple property descriptions on the other, such as average friction coefficient between chip and tool or shear stress on the primary shear plane, has been common knowledge since the 1950's [Koba 59]. The bounding work by Hill [Hill 54] and the slip-line field work of Dewhurst [Dewh 78] have shown how non-uniqueness can arise. These works have forced researchers to focus their attention on a more detailed consideration of the variation of flow stress of a workmaterial with strain, strain rate and temperature, and on better friction modelling too, as a necessary part of successfully predicting chip flow.

Much early progress was made by Oxley and his co-workers [Oxle 89], but the potential for major advances has come with the development of numerical, finite element methods. Usui et al.[Usui 82] have developed an updated Lagrangian elastic-plastic scheme for steady state prediction by an iterative convergence method (ICM). Others have developed Eulerian rigid plastic schemes for the steady state [Iwat 84], or have used commercial software for non-steady conditions [Carr 88]. Recently arbitrary Lagrangian Eulerian and adaptive remeshing codes have been applied to machining [Rako 93, Maru 95, Cere 96]. However there has never been any cutting benchmark against which to test these numerical models other than the early attempt by Stenkowski [Sten 85].

Another problem which is crucial in finite element modelling is the selection of the chip separation criterion. As noted by Ceretti and Altan [Cere 98], uncertainties exist with regard to the use of limit strain and limit energy approaches.

4.3 Round robin on FEM simulation

Over the last two years, the CIRP Working Group has developed an open round robin exercise that could become such a benchmark. Collaborators have been invited to model the steady state orthogonal finish turning of a low carbon resulphurised free cutting steel (wt% 0.09 C, 1.01 Mn, 0.33 S) by a zero rake angle carbide tool, at feed $f = 0.1$ mm, depth of cut $a = 1$ mm and cutting speed v = 150 m/min. Output has been requested of cutting force F_c, thrust force F_T, shear plane angle Φ, chip/tool contact length l_c and of the distribution of temperature, friction and normal stress along the contact length. This choice was made because a yield criterion and friction input data and experimental results existed for it. Also it was expected to be a relatively simple situation, with low friction, for a cutting test. Equation (2) gives the yield dependence on strain, strain rate up to 2000 s^{-1} and temperature T up to 700 °C obtained by a rapid heating Hopkinson bar method (Usui 82). (At f = 0.1mm, v = 150 m/min the maximum cutting temperature 600 °C).

$$\bar{\sigma} = A\left(\dot{\bar{\varepsilon}}/\dot{\bar{\varepsilon}}_0\right)^M \bar{\varepsilon}^N, \quad \text{with} \quad \dot{\bar{\varepsilon}}_0 = 1{,}000, \quad M = 0.018 + 0.000038T,$$
$$A = 910\exp(-0.0011T) + 120\exp\left(-0.00004(T-280)^2\right) +$$
$$+50\exp\left(-0.00001(T-600)^2\right), N = 0.16\exp(-0.0017T) +$$
$$+0.09\exp\left(-0.00003(T-370)^2\right) \tag{2}$$

Friction on the rake face was measured by a split tool method [Usui 82]. The results in figure 9 could, at low normal stress, be fitted to a Coulomb friction law with μ = 1.0. At high normal stress friction stress saturated at 360 MPa, which was 0.82 times the shear stress measured on the primary shear plane. Both the yield and friction data were obtained by T. Kitagawa of Kitami Institute of Technology. Other input data for modelling were the tool thermal conductivity of 46 W/mK and work thermal conductivity, W/mK and specific heat, J/kgK, respectively 62 - 0.044T and 450 + 0.38T.

Participants in the round robin have used a range of finite element techniques. The bracketed numerals in the following list match the codes in figure 7. Elastic-plastic modelling has been carried out by the ICM method {Obikawa - Tokyo Institute of Technology (1), Childs - Leeds University (2)} and by a non-steady state method {Ueda - Kobe University (3)}. Three researchers have used the same adaptive meshing rigid plastic code {Altan - Ohio State University (1), Barcelona - Palermo University (2), Ceretti - Brescia University (4,5)} while two have used other rigid plastic methods {Ueda (3) and Leopold - Chemnitz (6)}. Figure 7a to c compares predictions with experiment. F_c and F_T predictions (figure 7a) cluster round the experimental result, with more spread in F_c than in F_T and little to choose between elastic and rigid plastic methods. An average friction coefficient F_T/F_c = 0.5 can be seen. Contact length and shear plane angle predictions (figure 7b) do discriminate between elastic and rigid plastic. Elastic plastic methods predict longer contacts and lower shear plane angles, closer to reality, than do the rigid plastic methods. Rigid plastic methods also show much more variability in rake face temperature prediction (figure 7c) than do the elastic methods which also cluster closer to the experimental results.

Self-consistency tests can be performed on the model results. The resultant tool force projected on to the primary shear plane area and divided by that area should be the shear flow stress in the primary zone region. Table 1 gives the experimentally measured values (values deduced from equation 1 are 480 - 510 MPa depending on strain and temperature assumptions). Many of the model results are larger than this. A second test is to compare to the observed rake face friction behaviour the predicted variation of rake face friction with normal stress (figure 9d). Most predictions (but not all) tend to the observed behaviour at low and high normal stress, but hardly any follow the observed transition behaviour at intermediate stresses.

Table 1. Observed and computed shear stress on the primary shear plane in [MPa]

Experiment	Elastic-plastic			Rigid plastic				
	1	2	3	1	2	4	5	6
445	635	485	551	792	570	737	724	490

Figure 7 demonstrates that some finite element methods are able to predict the behaviour in cutting. An explanation of Table 1 is that many software packages currently have difficulty in controlling internal equilibrium, probably the hydrostatic pressure component. The round robin exercise has shown this to be an important issue. It has also shown the modelling of friction to be an area that needs development: the average friction coefficient of 0.5 in the example here hides a variation from 1.0 to conditions where friction stress is independent of normal stress. Of course, obtaining yield data at high enough strains, strain rates and temperatures also needs attention.

4.4 Recent progress in computational mechanics of machining and some difficulties

4.4.1 Basic equation of metal machining

The first goal of metal machining research is to develop an analytical system which would enable us to predict machining performance without any cutting experiment, for the selection of cutting conditions. However machining operations are very complicated and many phenomena are interrelated as shown in fig. 8.

In these relations the chip formation process is the main problem, because tool failures will depend on the magnitudes and variations of temperature and stress. The quality of the machined surface will also depend on the chip formation process.

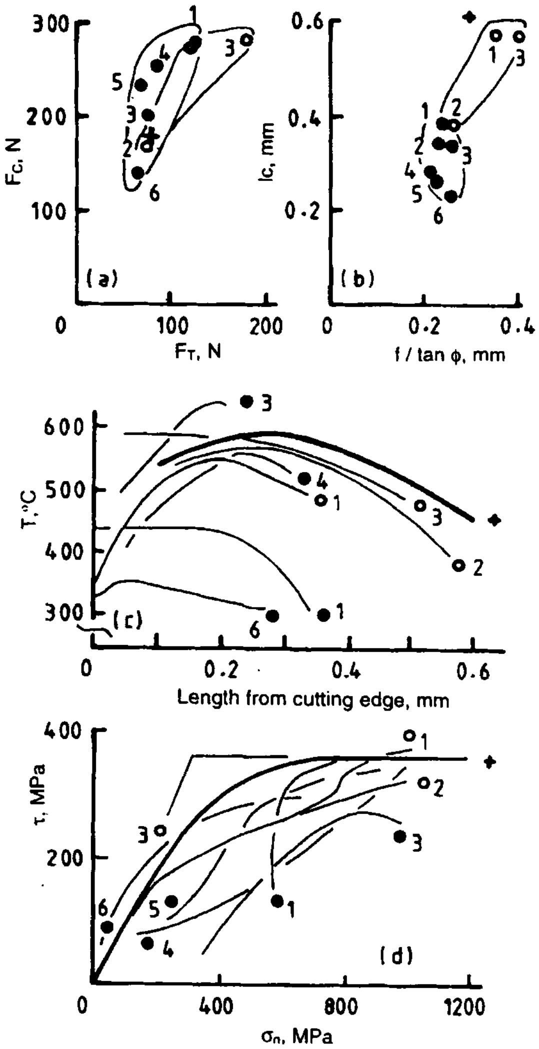


Fig. 7 Experimental (+) and predicted (rigid-plastic •, elastic-plastic o) variations of (a) F_c with F_T, (b) l_c with $f/\tan\Phi$, (c) temperature with distance along rake face and (d) friction stress with normal stress on the rake face.

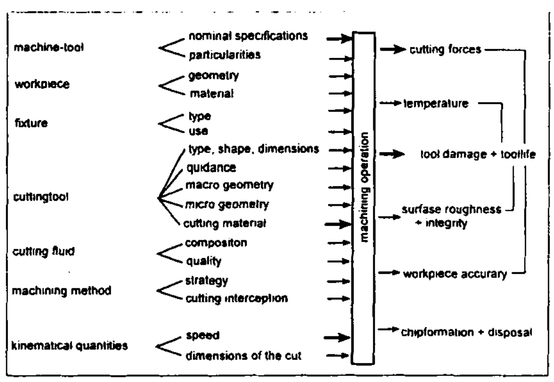


Fig. 8 important factors in cutting performance

The recent dramatic progress in computer hardware and software shows the possibility to predict those difficult phenomena by simulation with a finite element method. As the chip formation process deals with large plastic deformations and fracture coupled with high temperatures and high strain rates, the analysis of the process should be based on the plastic deformation theory combined with temperature analyses. As in the theory wherein the stress-strain relation is shown in an incremental manner, the chip formation process should be traced from its beginning except for the special case of a steady state continuous chip formation process.

For large plastic deformations the finite element formulation based on the updated Lagrangean method with Euler's stress-strain relation is proposed as shown in equation (3) after [Nagt 74], in which the geometrical non-linearity due to the change of shape is introduced and over constraint of incompressibility on deformation region is also relaxed.

$$\{\dot{F}\}+\{F_t\}=\{[K_M]+[K_G]+[K_F]\}\{\upsilon\} \tag{3}$$

where $\{ \dot{F} \}$, $\{ v \}$ are nodal force rate and velocity respectively. $[K_m]$ is an ordinal stiffness matrix, $[K_G]$ is a geometrical stiffness matrix and $[K_F]$ is a correction matrix for load respectively, $\{Ft\}$ is the nodal force rate caused by thermal volumetric change. The temperature distribution can be easily calculated simultaneously through FEM.

4.4.2 Some difficulties in simulation

In the cutting process the work material is parted at the front of the tool edge. In order to simulate the cutting process, a criterion for these phenomena must be introduced, such as maximum stress/strain or a geometrical criterion. The latter seems preferable since in practical cutting the work material is parted inevitably at the tool edge and this does not depend on the machinability of work material. Therefore at the present stage the geometrical separation method shown in fig. 9 is considered to be the most effective for ductile materials [Obik 96].

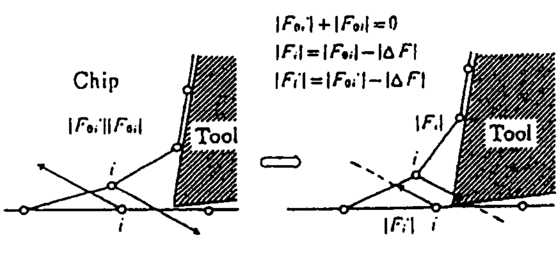


Fig. 9 Geometrical parting criteria

Good physical property data are essential inputs to the analysis. Since a material in cutting comprises large plastic deformations coupled with high temperatures at high rates of strain and temperature variations, the flow stress characteristics should be determined under those conditions. Equation (4) shows flow characteristics obtained by Hopkinson bar tests [Shir 70].

$$\sigma=\sigma\left(\dot{\varepsilon},\theta,\int(\dot{\varepsilon},\theta)d\varepsilon\right) \tag{4}$$

where $\int(\dot{\varepsilon},\theta)d\varepsilon$ is the effect of strain rate and temperature in straining.

Friction conditions between a chip and the tool face are essential boundary conditions for determining chip formation. The conditions vary from heavy loading near the cutting edge to light loading where the chip leaves the tool and the conditions are well known not to follow Coulomb's law. Equation (5) shows an example of non-linear friction characteristics.

$$\tau_t / k = 1-\exp(\mu\sigma_t / k) \tag{5}$$

where τ and σ_t are the frictional and the normal stress on the tool face. k is the shear flow stress of the chip material and μ is the material constant [Shir 73]. When a fracture criterion of the chip material is introduced, a shear type or a saw-tooth type chip generation can be realised as shown in fig. 10 [Obik 97]. However it should be realised that this is not the type of chip that occurs in real machining. The fundamentals of the simulation should be adapted to the real mechanism of chip formation as described in eg.[Lutt 77, Shaw 97].

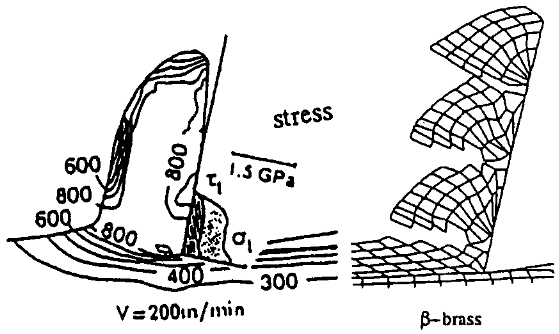


Fig. 10 A simulated segmented chip

Estimation of tool life caused by wear and fracture is essential for the selection of cutting conditions or planning a production system. In terms of wear of cemented carbide tools used to turn steels, crater wear is, and flank wear may be, thermally activated. It has been proposed that the wear volume per unit sliding distance and unit area, dW/dL depends on the temperature θ and also on the stress σ_t

$$dW / dL = C_1\sigma_t \exp(-C_2 / \theta) \tag{6}$$

where $C1$, $C2$ are characteristic constants, and θ is the absolute temperature .

Since most cutting tools used in modern production sites are made of a brittle material, brittle fracture with a stochastical behaviour may occur. A macroscopic brittle fracture stress criterion under triaxial stress state has been proposed by B. Paul et al. and the Weibull's probability distribution has been also superposed as shown in fig. 11 [Paul 76, Usui 79]. The threshold of fracture stress will be greatly affected by temperature, stress and service duration [Shir 87]. Tool life under the selected conditions may now be estimated based on the above characteristics (eq. (6) and fig. 11) of tool materials using the obtained distributions of stress and temperature on the cutting tool in the simulation.

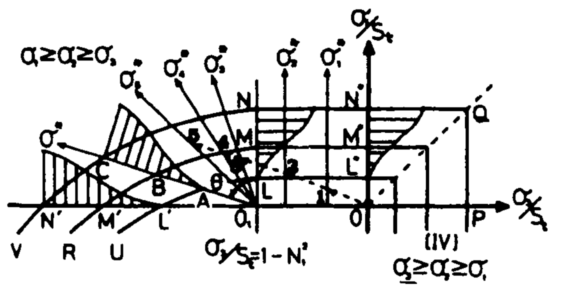


Fig. 11 Statistical brittle fracture criteria

4.4.3 The future of computational mechanics of the machining system

The extention of simulation systems of cutting processes from two dimensions to three dimensions will be performed in the near future with the progress of computer hardware, because the algorithm required for the simulation has almost been developed. From a practical point of view, the most significant problem for the simulation on real materials is to obtain information concerning their physical properties under the conditions occurring in the chip formation zone, such as flow stress, fracture characteristics under high strain rate/temperature and effect of their histories, and reliable wear/fracture criteria of tool materials etc.
When the value of simulation for practical applications has been established and its reliability has been confirmed, a virtual machining system may be emerging. There might be three application levels for virtual machining: machine shop, design of cutting tools and machine tool industry.
Two main purposes of virtual machining in machine shops are to educate new production technicians or to re-educate the engineers and verification of process plans and NC-programs with a higher level than is presently the case with verification software which only checks the programmed geometry but is not able to evaluate the selected technology
For manufacturers of cutting tools the design of optimum shapes of high performance cutting tools is of major concern.

The requirements of new advanced machine tools such as those for ultra high speed cutting can also be defined more accurately by a virtual machining system.

4.5 Modelling studies of machining at nanometer scale

Machining is performed at an ever reducing scale. A quite recent addition is nanometer scale cutting. Further understanding of the effects which govern the ultraprecision machining process is driven by the desire to create surfaces of exceptional accuracy and quality. The generation of the surface topography and sub-surface structure has been an important and long standing research issue in cutting research.

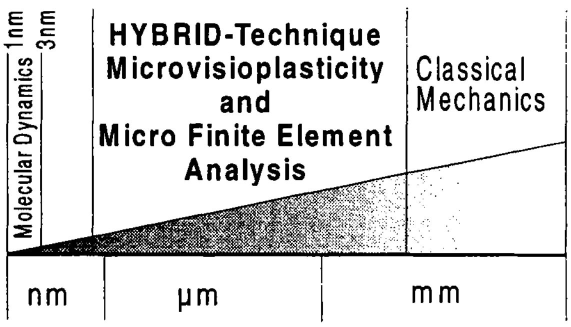


Fig. 12 Application areas of different analysing methods in machining

Pioneering work has been done in the fifties by Shaw, who concentrated on studies of the built up edge, and Pekelharing, who concentrated on the grooving wear in the minor cutting edge in turning. These aspects were an important factor in the CIRP-OECD co-operative research project [OECD 96]. At that time typical feeds in finish turning were around 0.1 mm/rev. Later researchers, e.g. [Daut 89] focused on precision machining with smaller cuts with typical feeds around 0.01 mm/rev or even superprecision machining with feeds around 0.001 mm/rev. The latest research work focuses on even smaller feeds of 0.0001 mm/rev or less.
The research of machining at the nanometer scale was mainly focused on modelling. For the latter purpose the molecular dynamics approach was conducted by several research groups e.g. [Bela 93, Koma 97, Shim 95, Rens 95]. Significant progress has been made in dealing with the computational challenges but there still is a lack of experimental studies. At such small thicknesses of cut the microgeometry of the cutting edge has a very important effect. Therefore much attention should be given to the characterisation of the cutting edges and to the phenomena taking place in the immediate vicinity of the cutting edge. Only then the significant differences in the cutting forces and in the subsurface layer can be understood. This was studied for a variety of workmaterials [Bela 93 , Lucc 98]. Such experiments will help to validate

the molecular dynamics models.

4.6 Hybrid-technique: visioplasticity and finite element method

The application area of the proposed HYBRID-Technique, based on a new Micro-VISIOPLASTICITY-Method and a special Micro-Finite Element Method, is given in Fig. 12. For investigations near the surface of machined parts, e.g. in a sublayer-depth less than 3nm, the molecular dynamics approach may be applied. If the investigations are in the range of mm, classical mechanics is used in several fields of mechanics and production engineering with success. The proposed Hybrid Technique is well suited for the range of some nm up to mm.

4.6.1 Visioplasticity

The method of Visioplasticity is based on studies in the early Fifties [Thom 54,Farm 76]. In the past a wide range of applications has been published. Main topics in the field of use are problems of metal cutting and metal forming processes. Visioplasticity has proven to be a powerful tool to analyze plastic flow of engineering materials. There is a distinction to common grid techniques due to the combination of a pure geometrical displacement measurement with fundamental mechanical and thermodynamic rules.
The method is based on a grid structure application onto a plane surface of the workpiece which suffers the same deformation as the workpiece itself. The most suitable are point or orthogonal line structures. The use of Visioplasticity assumes the grid surface to remain in a plane state and the deformed material to be incompressible. In a symmetric workpiece the grid may be applicable in an inner plane of symmetry.
Such planes are free of shear stresses which would violate the plane strain condition. Only compressive stresses have to occur vertical to the plane of symmetry to guarantee that the divided workpiece deforms in the same manner as a undivided one. The path of each grid crossing point along a so-called streamline during deformation can be investigated by in situ observation or step by step deformation. For a good approximation of such streamlines by numerical equations, the differences between two successive deformation steps has to be small. This is mostly important in regions where large gradients of velocity occur. Typical applications are given in the figures 13 to 16

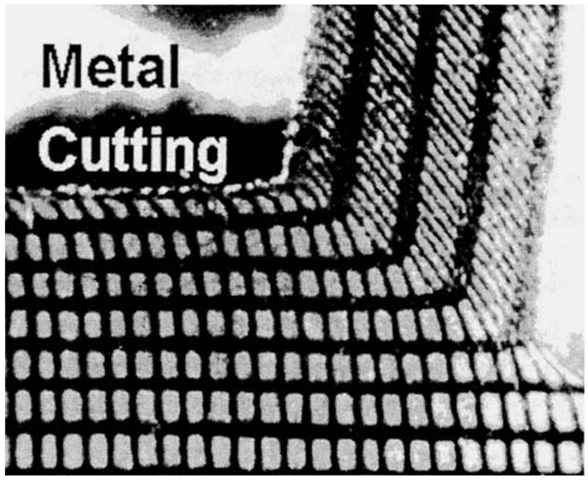


Fig. 13 Stationary Metal Cutting

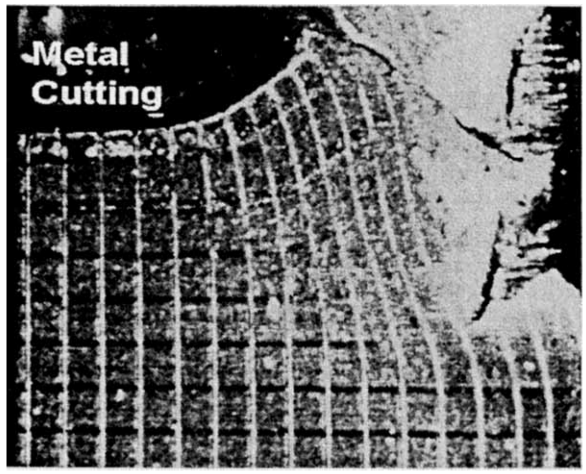


Fig. 14 Interrupted Metal Cutting

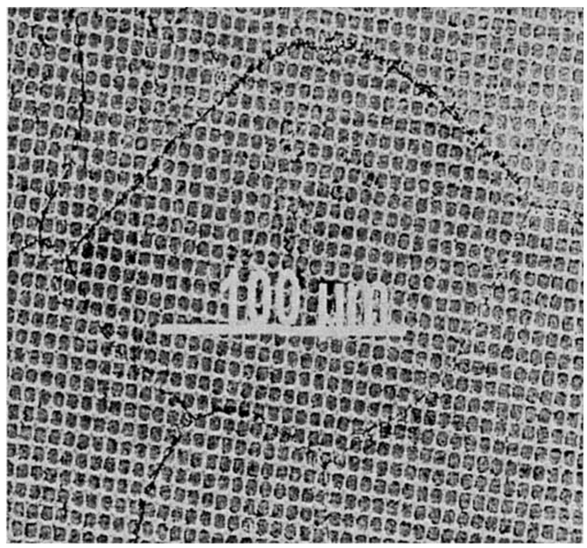


Fig. 15 Microgrid (100µm)

4.6.2 Hybrid Technique VISIO-FEM: HTVF

The basic concept of the hybrid technique [Leop 91,95,95a] is given in fig. 17.
By means of the coupling of the visioplasticity and FEM methods into a hybrid technique VISIO-FEM, as illustrated in fig. 17 the disadvantages of each of the individual methods can be removed or considerably reduced.

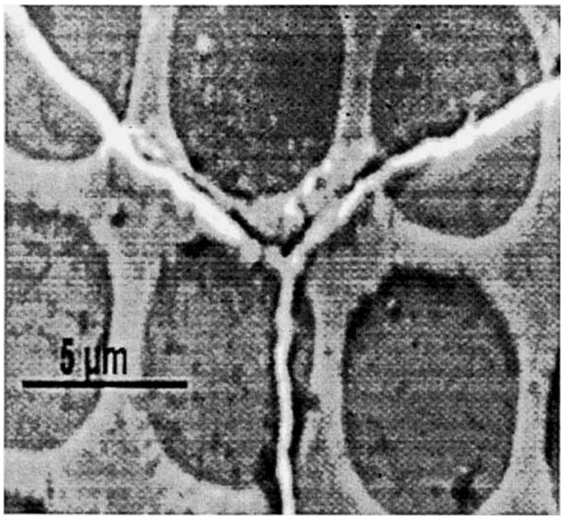


Fig. 16 Microgrid (5,0 µm)

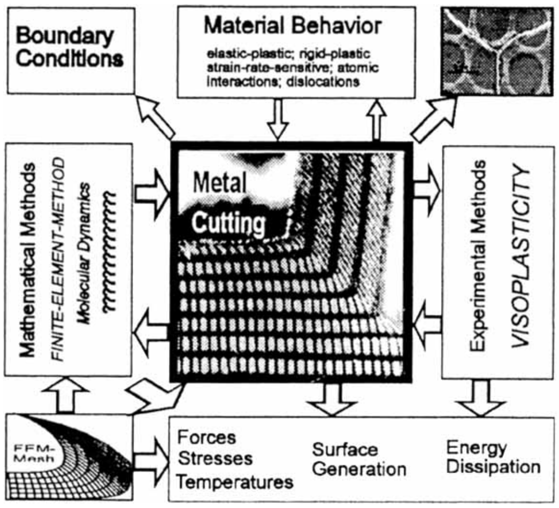


Fig. 17 Concept of the hybrid method of visioplasticity and the Finite Element Method.

The Finite Element code FEPAS realizes this coupling [Leop 97]. FEPAS may be applied for thermomechanical coupled viscoplastic problems in the Eulerian flow formulation and includes contact problems with friction as well as problems with free boundaries. The coupling of VISIO and FEM is possible in two ways, see also fig 17:

A directly by

- taking the deformed VISIO grid like a part of the FEM mesh,
- FE mesing outsides the VISIO domain,
- taking the calculated velocities by VISIO like boundary conditions in the FEM

B indirectly by full FE modelling and feedback to the measured geometry and calculating by VISIO velocities for parameter fitting of the theoretical model.

4.7 Survey of computational mechanics

Independently from the CIRP WG "Modelling of machining operations", Professor K. Ueda from Kobe University undertook a detailed survey of current research computational on mechanics and simulation of cutting [Ueda 98]. He identified a total number of 90 publications from research groups. These publications could be grouped into the following main groups: cutting state studied, type of computational model, included effects on stress-strain relation, mechanism of chip separation and comparison with experiments. In addition over 80 special features are distinguished.

4.8 Conclusions concerning computational mechanics

Metal machining is a key technology in manufacturing, in which demands for high productivity and high accuracy are increasing greatly. Virtual manufacturing will be one of the answers to meet with these requirements, for which computer simulation technologies based on elasticity, plasticity, heat transfer and material science create a powerful tool. There is no doubt that advancements in computing capability and graphical visualization technologies will bring a further development in the field of the simulation.

5 Industrial aplications of models

5.1 Questionnaire

The aim of the subgroup "Applications of models" is to stimulate the development of models that suit the needs of the metal cutting industry and to promote the use of such models in industry.

Models should be developed for a well defined purpose. An important aim of the WG is the development of models that are better adapted to industrial needs and to stimulate the use of such models in the metal cutting industry. The subgroup „Applications of models“ undertook the following activities:

- To make an inventory of the characteristics of existing models that are actually applied in industry to predict the results of machining operations and to derive future needs for models to be developed in the field of machining
- To identify the most promising fields to develop models fit for industrial application
- To collect industrial ideas and trends in the field of modeling
- To stimulate industrial involvement in the activities of the working group

Researchers and industries were contacted by a questionnaire with the following questions:

1 Which parameters do you model and for what kind of cutting operation?
How do you model the described parameters?

2 Which parameters do you think should be modeled and for what kind of cutting operation in the near future?

Which approach/method do you think is the most promising?

3 Which applications do current/ should future models aim at?

4 Researchers were asked to indicate topics on which they would be interested in cooperation with other collegues.

5 Industrialists were asked whether they were interested in a contribution to the working group e.g. by forming a user group or to assist at presentations.

In order to facilitate the answering and analysis of the questionnaire a standard format was provided.
The most important results of this exercise are:

- The addressed industrial companies are highly interested in the use of reliable and industrially applicable models for process layout. A strong need for tools to estimate and evaluate the results of machining processes prior to actual machining was observed.
- The addressed companies hesitate to get more involved in research activities related with modeling for the following reasons:
  + models on cutting provided by research are seldom commercially available
  + models focus on certain aspects of the cutting process but are not valid for a broad range of applications or for complex manufacturing systems
  + models are often complex to handle; only experts can use them
  + models in the field of cutting do not focus on the workpiece

5.2 Suggestions for future developments

After this enquiry, we have thought about the question as to how the interest of industry can be increased, with the following results.
The interest of the manufacturing industry for the activities of the working group can only be raised if we succeed in showing worthwhile results. In fact the best stimulus for more intensive application of models in industry is the development of models which better fulfil the needs of industry. Therefore emphasis will be given to the following categories of research items with significance for practical application:

Refinement of models for the following aspects of classical operations:
- control of workpiece geometry including shape
- control of surface roughness and surface integrity
- prevention and minimisation of burr formation
- prediction of chatter
- control of chip forms and chip evacuation

Modelling of new cutting operations:
- high speed machining
- (ultra) precision machining
- micromachining
- workpiece precision in dry machining
- machining of hardened steel and of other classes of unusual metallic and non-metallic work materials as eg. plastics

Modelling of less frequently studied operations:
- screw cutting operations including tapping
- new variants of milling

Modeling of the machine-tool
In most of the work on modeling of cutting the machine-tool is considered to be ideal with infinite stifness and no error motions. In reality this is not true. Models which predict chatter and workpiece precision should contain a certain amount of information about the mechanical system consisting of machine-tool, workpiece, fixture, cutting tool and toolholder in a very efficient way. It has to be decided what minimum information is required for a specified application and how that information can be obtained effectively.

Increase the reproducability of machining operations
The ability to control machining operations depends on two factors:
- the ability to obtain results within a required allowable maximum amount of scatter
- the ability to predict the limits between which the average of the results is expected with a specified level of confidence

Much attention is given to the accuracy with which models can predict the average. Only little attention is given to methods to minimise the scatter of cutting operations. This means that the accuracy of the predictions by models can never be tested properly. Many unfavourable opinions about models are in fact based on the impossibility to define the test conditions exactly. It is not useful to try and increase the accuracy of predictions if the reproducibility is not improved at the same time.

Efficient methods to determine the numerical values in generic models
Fundamental modeling entails generic predictive models for all required machining performance measures (cutting forces/tool wear&life/chip forms&disposal/surface roughness&integrity/part precision) for the whole range of machining operations. Applied modeling involves application of generic models to a specified operation on a specified machining system taking into account the characteristics of all relevant components such as machine, cutting tool, workpiece, etc. This means the model has to be "filled" with all required information in the form of data and knowledge, see fig 1. Only then the model can be used for its intended purpose to predict the results of an operation in order to assist in the search for optimal parameters. The need for predicting the

complete set of Applied Machining Performance Indicators AMP of a machining system followed by its optimization has been discussed in detail in a recent keynote paper [Jawa 97]. It is practically impossible to measure all required data for each case at hand. A prerequisite for succesfull application of the new generic models to be developed is that simultaneously efficient methods will be developed to estimate the required model parameters.

Modelling software construction box
There is a large number of models available for the various process state variables such as cutting force and temperature or the performance measures such as surface finish and tool wear. There also exists a large number of models for the different elements of the machining system such as the process to be performed, the cutting tool and the machine tool. But these can only be used on their own. There is hardly any connection between all these models. As soon as one tries to apply a number of models to one particular case differences in structure, assumptions and required data appear which make it impossible to use them as components in a construction box to design new models for more complex situations such as the levels indicated in fig 1.
Models will be used in the form of software. This means that components of the construction box have to be designed as software modules with properly defined functions, inputs, outputs and interfaces.
It is a challenge for the working group to design this modeling software construction box.

Verification of models
The reliability of models has to be tested, the accuracy of models has to be determined. In the past many different models were proposed for the same or a very similar purpose. Models will not be widely applied if the reliability has not been proven. It is a serious problem how to do this. A neutral organisation such as CIRP could do significant work here.

This is a long list of research items. Small groups of research institutes should work together on a particular research item and inform the working group about the progress made. Other groups might test the results and use some of them to speed up progress with their own research agenda. The overall effect will be a faster development of models with a higher reliability and better suitability for practical application. The WG is not very well equiped to indicate any priority for the activities by its members. The actual selection of a subject in a laboratory depends mainly on local circumstances. Nevertheless, there should be an attempt to stimulate concerted efforts. It will also be attemped more intensively to get the input from various kinds of industries: the metal cutting industry, the machine-tool industry, the cutting tool industry and software bussiness. We will invite selected persons from each of those branches to contribute to defined research items and to steer them in the right direction.

6 New developments in modelling of machining operations

During the last decade several new techniques for modelling of processes have emerged. Some of them have already been applied in metal cutting. Some examples will be presented in this section.

6.1 AI-based modelling

Artificial intelligence (AI) based modelling is a new trend which is still in its infancy (note that the literature database has revealed less than 1% contribution). Most of this work is related to process monitoring through sensor fusion or predicting one or more outputs from sensory data, while some recent works utilized AI techniques for machinability predictions and cutting tool design [Jawa 93, Fang 94]. The dominant AI approach utilized is the artificial neural network (ANN). Unlike analytical models which provide explicit models with deep physical understanding, artificial neural nets (ANN) provide implicit models captured within the weight matrices of the net. They are certainly effective at pattern recognition and facilitating quantitative prediction. They facilitate learning from prior experimental data but, not yet, from prior analytical insights. In other words it cannot be taken as an analytical process model. Its utility however might lie in helping to obtain synergy amongst modelling, sensing, and learning. This aspect is worth studying more intensively by the community of metal cutting scientists. The next section discusses some possible approaches.

6.1.1 AI-techniques

As in many other areas of manufacturing, it is believed that proper application of AI methods can solve many of the problems encountered in modeling with conventional techniques. Several good examples can be found in recent volumes of the Annals of the CIRP. Application of one of the various AI-techniques to represent one of the aspects of the great variety of metal cutting operations was the subject of many recent publications. It is high time to have a better understanding of what kind of technique can best be used for a particular type of problem.
One significant experience is that those techniques are also not capable of predicting the results of a new operation if no sufficient data on a number of similar operations is available. The amount of data required for a reliable prediction is much larger than is available in most practical cases.
The working group intends to study this field more intensively in the near future. Possibly a new subgroup should be formed to strengthen activities in this area.

6.1.2 New techniques for empirical modelling of machining operations

Machining operations are very complex and do not permit pure analytical physical modeling, hence empirical modelling appears as the only remaining option. Empirical modeling can either be based on qualitative or quantitative information about the machining process. Qualitative information is usually represented as expert knowledge and can be cast into a model by various methods of artificial intelligence (AI) which have been formulated for the development of expert systems. Applications of AI methods in the field of manufacturing engineering have already been thoroughly elaborated within CIRP [Dimi 96].
Quantitative information is usually represented by measured data about process variables and parameters, and a model represents a relation between these data. Most frequently, measurements are influenced by various stochastic disturbances, therefore quantitative empirical modeling has to be supported by statistical methods. These can either be parametric or non-parametric.

In the case of parametric modelling, a proper model is first defined based upon some physical arguments and then the parameters of the model are adapted to the operation under consideration by some statistical error minimization technique. The emerging regression relation then represents the empirical law that corresponds to a specific case. Although, this approach can be very accurate and applicable in specific cases, its weakness is in the formulation of the proper model, which requires profound understanding of the phenomenon under modelling. There appears a question of how to formulate a parametric model that could be generally applicable. For this purpose the modeling of relations by perceptrons that was developed in the field of artificial neural networks appears to be very promising [Hyki 94]. The number of cases related to modelling of machining operations by perceptrons is steadily growing and an extensive literature on this subject is already available [Huan 94].
Although perceptrons appear quite generally applicable for on-line automatic modelling of non-linear empirical relations, some engineers hesitate to use them for the following reasons:

1. the method does not provide explanation of the adapted parameters,
2. it is often not known how many terms must be utilized in the model,
3. the adaptation is sometimes slow and it is not known if the adapted model really corresponds to a globally minimal statistical estimation error.
4. the method can not be used for predictive models

These topics are still the subject of intensive explorations in the field of artificial neural networks.

Some of the above mentioned deficiencies can be avoided by utilizing non-parametric modeling. It is based on the empirical estimation of joint probability distribution from given samples of a set of measured variables [Grab 97]. It is characteristic that in this case, the form of the corresponding physical law needs not be specified in advance in terms of parameters and therefore the non-parametric approach is very convenient for automatic statistical modeling of natural laws. The corresponding mathematical formulation is simple, general, and requires only the specification of variables.

Application of parametric or non-parametric empirical models generally requires two phases that correspond to adaptation and application of the model. In the first one, the complete data must be provided by measurements and the model must be adapted to them. In the second phase, only partial data are given while the remaining complementary data are estimated from the model. The properties of an empirical model are presented to a computer either as model parameters or as a set of joint multivariate data. In the phase of adaptation, the measuring device can provide unlimited number of joint samples which cannot all be stored in the computer memory. Therefore, when utilizing non-parametric modeling one has to specify a finite set of prototype joint data. For this purpose a self-organized adaptation of prototype data was developed in which the empirical information is optimally preserved in the model [Grab 97]. A stored prototype sample can generally be interpreted as a content of a memory cell or an artificial neuron. The adaptation of prototype data corresponds to self-organized learning of an artificial neural network, while the estimation of unknown data from given partial ones corresponds to a recall of missing information from a trained network.
For the purpose of the estimation by the conditional average estimator, the prototype data must be properly connected in the sample space. There are some proven techniques for this purpose. Artificial neural networks, either perceptrons or RBFNN, are optimal statistical estimators of relations between data. Consequently they are generally applicable for on-line modeling of machining operations based upon quantitative data obtained from measurements. Quite often the quantitative data are obtained by pre-processing of signals from various sensors. The purpose of the pre-processing is usually to compress the information into some characteristics, and thereby obtaining faster operation, time-invariant presentation of data, etc. Most frequently various statistical moments, correlation functions, spectral densities, chaotic characteristics, etc are utilized.

Problems met in modelling of machining operations stem from the areas of kinematics, dynamics, rheology, planning, monitoring, diagnosis, control and quality assurance [Huan 94, Grab 97]. Several of these problems have already been successfully solved by application of AI and neural networks. The literature on these subjects is quickly expanding and many examples were already presented in recent volumes of the Annals of the CIRP.

Among various applications, utilization of NN for on-line monitoring and diagnosis appears most promising because it can further lead to optimization and intelligent control of manufacturing processes. [Whit 92]

6.1.3 Non linear dynamics

Since the late 1970's revolutionary ideas of non-linear science have led to vastly improved understanding of extremely complex and non-linear physical systems in a wide range of diverse applications. CIRP has recommended wide-ranging studies of non-linear dynamical systems as a framework for solving complicated problems in manufacturing. The time is now ripe for the application of non-linear dynamics to understand, control and optimise mechanical manufacturing processes such as cutting, grinding and forming. Also in cutting we could learn much from interdisciplinary work with physicists and mathematicians. In order to support this the European Union started the new COST Action P4 "Non-linear dynamics in mechanical processing" in April 1998 with the main objective to create specific and mutually beneficial opportunities for cooperation between physicists and mechanical engineers in the area of non-linear dynamics and its application to understand, control and optimise mechanical manufacturing processes. The duration of the action is four years. This action enables researchers within the European Union to obtain additional funds for contacts with fellow researchers for accepted projects. Our colleque professor I.Grabec from the University of Ljubljana is chairman of the COST Action P4 Management comittee.

6.2 Minimisation of error motions

Error motions are a nuisance in machining because they have an immediate negative effect on the workpiece precision and surface roughness. Error motions can not be predicted accurately by pre-process models. In addition it is difficult to relate error motions exactly to the geometry of the finished workpiece. Consequently reliable prediction of workpiece precision is nearly impossible. The geometric precision of the workpieces can only be improved significantly by reduction of error motions. There are various sources of error motions:

1 geometric errors of the machine-tool: the classical deviations of straightness, parallellism, squarness etc due to imperfections in the manufacturing of the machine or wear.
2 control errors caused by the machine controller.
3 load errors errors due to deformations caused by forces and temperatures occuring during the use of a machine.

In the past, much emphasis was given to reducing all three classes of error motions by better design and manufacture of machine-tools i.e. a mechanical engineering approach. In addition to this, other approaches are proposed:

A To reduce the load errors by controlled limitation of the allowable force level and heat input; this requires models to determine the limiting values for the case in hand as well as models to predict forces and heat input.
B Compensation of error motions. This approach already has a long history. Compensation of static geometric errors by mechanical means is nearly a century old. Later came compensation by the machine controller. Also, compensation of control errors is possible. Even compensation of the load errors by the use of signals of force and temperature in the machine controller was attempted. Not all NC-units are suitable for this approach.

It is also possible to take predicted error motions into account in making the NC-program. This posibility was pursued succesfully by a Dutch consultancy firm recently. A special software module SmartAct is added to the Smartcam NC-programming system which takes into account all error motions of a machine determined by one or two days of measurements and programming. The result is a reduction of resulting error motions down to much less than 20% of the original values in most cases. The system is now in use in several companies.

6.3 Modeling of vibrations in cutting

When considering vibrations in cutting operations two aspects have to be considered: forced vibrations and self-excited vibrations. For both cases the cutting stiffness, the structural stiffness, and the cutting mechanism are the principal characteristics to be observed. From the manufacturers point of view efficiency and surface finish are the most significant terms of evaluation. The following is mainly based on [Sato96].

6.3.1 Forced vibrations

The dynamic characteristics of the cutting stiffness were studied by using a high speed measurement apparatus of the workpiece profile to identify the transfer function between depth of cut and the surface profile during cutting. With the use of this equipment it was verified that the cutting stiffness is constant at least up to 200 Hz for appropriate cutting conditions. It was confirmed by experiments that structural vibrations between workpiece and tool are directly transferred to the surface profile i.e. the surface roughness. In other words, this revealed the missing link between the structural vibration and the surface finish.

Study of the principal structural frequency components related with the surface finish made it obvious that the following frequency components are of importance: rotational speed of the work, major structural natural frequencies of the machine tool, natural frequencies of workpiece and spindle system and excitation frequency components within the machine tool like noise due to gear trains, electro-magnetic frequencies for driving motor and others. These factors were adopted to develop design principles for the development of machine-tools capable for ultra precision machining.

6.3.2 Self-excited vibrations

Four aspects will be considered:

Cutting stiffness during self-excited vibrations
A number of scholars such as Tobias, Tlusty, Merritt and others have identified the conditions under which self-excited chatter starts. In their investigations the cutting stiffness was kept constant. In their opinion the phase shift was the cause for self-excited vibrations. However, it is obvious that self-excited vibrations can be caused also without phase shift when the cutting stiffness is constant. Experiments conducted with respect to forced vibrations showed that the cutting stiffness does not accompany the phase shift.

The behavior after the onset self-excited vibrations
It is interesting to identify both the limit where vibrations start and the mechanism how the vibration lasts with finite amplitude. There have been cases that cutting was performed succesfully even when vibrations occurred like in rough cutting of rolls and other hard materials. Almost all investigations were only interested in the limit where the vibration starts, since after the onset of vibrations, it is meaningless to ponder on the behavior from the machining point of view. However, the identification of the mechanism while self-excited vibrations are present makes it possible to decide whether the cutting can be allowed to continue.
The existence of the multiple regenerative effect
It was pointed out that the multiple regenerative effect is important after the onset of the self-excited vibration. The regenerative effect was indicated as one term of the mechanism which causes the vibration. It means that in turning, the thickness of the cut is affected by the relative motion between tool and workpiece during the preceeding revolution. If the vibration amplitude grows after the onset of vibrations the trajectory of the vibration immediately crosses that of the preceeding revolution. This denotes that the regenerative effect takes place not only one revolution earlier, but even two or more revolutions earlier. This is called the multiple regenerative effect. The importance of this effect for the analysis in the time domain was pointed out.

Phenomena due to the multiple regenerative effect
Due to the multiple regenerative effect, the tool is detached from the work and the tool trajectory of one revolution earlier is left on the work, which means that the cutting mechanism is non-linear, even if the cutting stiffness is constant. The chips are separated by the effect even under adequate cutting conditions. This phenomenon was ingeniously utilized by Prof. T. Nakagawa to manufacture metal fibres for composite materials. Characteristic marks of the vibration are left on the workpiece and sometimes these have been misunderstood with respect to the mechanism of the vibration, however, it can be theoretically correlated with the behavior by introduction of the multiple regenerative effect.
The conclusion of this section should be that although some progress has been made in understanding vibrations in cutting the basic attitude should be that vibrations should be avoided whenever possible. The consequence is that we should concentrate on the prediction of the vibration limits so that vibration-free machining can be assured.

6.4 Chaos theory based modeling

It has recently been discovered that metal cutting exhibits low dimensional chaos [Bukk 95]. This realization is having a significant impact on the classical views concerning the dynamics of metal cutting. The groups led by Kumara (Penn State U) and Grabec (U of Lubljana) are active in this area. However, no explicit models of the cutting process based on chaos theory has been developed as yet. The theory however has led to new applications of fractals and wavelets in monitoring and diagnostics of cutting processes.

6.5 Mechanics and dynamics of milling

Mechanics and dynamics of milling have been studied extensively by several researchers such as Armarego [Arma 91]. Later Altintas followed this track. His research group designed an orthogonal cutting data base for use in oblique milling operations in cooperation with Armarego [Buda 96]. The orthogonal cutting data base is based on a thin shear zone model and consists of shear stress, average friction coefficient on the rake face and shear angle as a function of cutting speed, rake angle and thickness of cut. Using oblique transformation, cutting forces are predicted for any milling cutter with sharp edges [Lee 96]. By integration in the time domain milling force, torque, power,surface roughness and chatter vibration can be predicted and analytical chatter stability models can be obtained with a parametric cutter geometry design [Alti 95]. The generalized milling model is able to handle any milling cutter geometry for process analysis and optimization [Alti 96].

7. Prediction of workpiece precision

7.1 Complexity of models for workpiece precision

Models capable of predicting the precision of workpieces manufactured by machining operations should include all factors which might influence the precision of workpieces in machining significantly in one way or the other. Groups of influencing factors are:

1 the geometrical product specification GPS
2 the geometry of the part before the machining operation considered takes place

3 the work material
4 the machine-tool in operational condition
5 the position of the workpiece on the machine-tool
6 the clamping device of the workpiece
7 the machining method
8 the cutting tool
9 the cutting conditions
10 the cutting fluid
11 the location of the tool-workpiece interaction

In each group a large number of influencing factors can be distinguished. The total number of variables in a workpiece precision model would be of the order of one hundred. Also the precision of workpieces can be described by a large number of aspects such as accuracy of size, location, shape, etc. On each workpiece each of these aspects should in principle be studied for all geometric elements. To describe the precision of one workpiece may easily require the order of one thousand element/aspect combinations or precision units.

If the complexity of models is defined as the product of the number of influencing factors times the number of output variables this would mean that the order of complexity of workpiece accuracy models is 10^2*10^3=10^5.

For practical reasons the complexity should be reduced at least three orders of magnitude. Even models with a complexity over 10 are already difficult to handle by traditional means. The complexity of models can be reduced in two ways:

By reduction of the number of influencing factors included in the model.

This can be realised by:

1 by leaving out influencing factors of minor significance
2 by combining several independent influencing factors into new combined influencing factors.
We should strive for models with a maximum of about 10 influencing factors.

By reduction of the number of output variables.

In the case of workpiece precision this can be done easily since not all precision aspects are of importance for each geometric element. Many elements may be neglected completely because the precision is not critical. Certain precision aspects of a number of related geometric elements may be grouped together. An example is the roundness deviation of various steps on a turned shaft. The roundness deviation on each of those steps is caused by the same origin.

In this way the number of precision aspects included in a model can be reduced to a maximum of about 10 in most cases without becoming unrealistically simple. Reduction of the complexity is an important step in modelling. It seems possible to accomodate many situations of industrial importance in models for workpiece precision with acceptable complexity. Which influencing factors and precision aspects should be included in a certain model depends on the aim and the application area of that model. Therefore the aim and the application area of models should always be clearly defined.

Co-operative work on the significance of the influencing factors on workpiece precision in particular situations seems worthwhile and could form a good basis for the development of realistic models.

7.2 Available models for workpiece precision

The few available models for workpiece precision can be dievided into the following types:

Models for deflection of the machine, workpiece and tool due to the cutting force

These models consider a nominal value of the cutting force component in the sensitive direction and calculate the resulting displacements and the effects on workpiece shape and dimensions.

Models for error transmission

Deviations of the nominal shape and dimensions of the blank cause a variation of the depth of cut and thus a variation of the cutting force. Due to the finite stifness of the system, deflections occur which cause smaller variations of the workpiece shape and dimensions than those of the blank. The transmission function depends on stifness and cutting conditions.

Models for thermal deformations

The complex temperature fields in the machine, tool and workpiece cause thermal deflections which can be calculated and even compensated to a certain extent once the actual temperatures in certain points are known. More advanced models also calculate temperature distributions especially in the workpiece once the heat input at the chip formation zone is known. These simulations of workpiece deformations by FEM resulting from the heat generated at the tool workpiece interface become more important in dry machining and precision machining of hardened steel and refractory materials [Warn 97].

Models for the prediction of chatter

In most models, only static components of the cutting force are considered. The dynamic force component may give rise to chatter which spoils the machined surface and causes other nuisances in machining. Predicting chatter in order to be able to select condiditions which avoid chatter is a great challenge and has been attempted already a long time. In principle the theory to predict chatter is available. The main problem is that the actual data about the many variables which are important are nearly never available with sufficient accuracy because they are difficult to determine. Two categories of data should be distinguished:

1 the dynamic properties of the system which depend on the machine tool, the workpiece and the cutting tool and which varies with the position and direction of the relevant cutting force vector
2 the dynamic behaviour of the relevant cutting force

vector which changes with the work material, type of operation, tool shape and material, cutting conditions and type and amount of toolwear

models for fixturing errors
Geometric deviations of workpieces are also caused by fixturing due to positional errors of the locating surfaces of the fixture, uneven surfaces on the rough workpiece, workpiece surfaces not in contact with locating surfaces of fixture and deformation of the workpiece and the fixture by clamping forces. Only few models exist to quantify the influence of those effects on the final workpiece geometry. Some recent examples are [Hurt 98, Li 98, Liao 98, Sali 98]. In addition the location and orientation of the workpiece-fixture contact surfaces may influence the deformations caused by the cutting force and thermal expensions [Acun 98].

Models for the prediction of surface finish
Surface finish includes roughness and modifications of the surface layer. The number of models available for prediction of surface finish is very limited. The main reason is that these models can not be based on engineering principles like those for elastic deformations. Most knowledge about surface roughness and integrity is empirical, and based on experiments in the laboratory. Up to now, very few relationships in a mathematical form which relate surface parameters to cutting conditions are available. A basic model is that of the kinematical roughness determined by the the tool profile and the pattern of motions of the tool relative to the workpiece. The

actual roughness may be more than five times higher due to error motions, effects of unstable built-up-edge and a changing tool profile due to wear. It is difficult to model each of those effects. Also there are strong interactions. Most knowledge is available for turning, much less for other operations. In addition it is very difficult in practice in many cases to keep all factors under such tight control as is required to obtain reproducable results. Repeatability is a prerequisite for effective modelling.

7.3 Models for burr formation

In many cases parts produced by machining can not be used immediately due to the presence of burrs. Burrs are caused by the action of the cutting tool on relatively tough work material under most cutting conditions. The removal of burrs takes additional costly operations. Consequently, where possible precautions should be taken to avoid the formation burrs completely or, at least, to minimize or control the size and location of burrs which may not need to be removed. This is possible by the selection of appropriate tools (and geometries), machining conditions, tool paths and, to some extent, part design.

There has not been much detailed study of burr formation in comparison to the study of, for example, chip formation. Early models, used either empirical representations of process mechanics, for example [Gill 76], which used a simplified analytical model based on plasticity or were residual results from research addressing other effects (for example, Pekelharing's classic study [Peke 78] of "foot formation" in the exit of interrupted cut tooling, using FEM, yields great insight to the burr formation process and the influence of process conditions.). Others, for example Nakayama and Arai [Naka 84], define the critical terms in burr formation and present experimental evidence to substantiate the observations of formation mechanisms. Finally, others used microscopes and SEM technology to observe the detailed deformation of material during the tool exit stage in orthogonal machining that creates a burr [Iwat 82]. Ko and Dornfeld [Ko 98] developed a model for burr formation in materials exhibiting ductile and brittle behavior, and evaluated the model at slow machining speeds. This was originally done using plasticine material as the workpiece. Although not exhibiting strain hardening, plasticine "kinematically" behaves like conventional materials for burr formation. Later, Chern and Dornfeld [Cher 96] continued the development of burr formation models and extended Ko's model with more realistic machining operations and conditions. They also included a study of edge breakout phenomenon as well.

In general, closed form solution analytical solutions for general problems of elastic-plastic large deformation such as chip and burr formation processes are very difficult to obtain. Thus, as reviewed elsewhere in the paper, finite element method techniques are fruitfully applied. One of the first analyses was done for oblique machining a ductile metal using a commercial FEM package, ABAQUS Standard [Park 98a]. Based on the change in geometry at the edge of the workpiece and a series of stress and strain contours, the fundamental burr formation mechanism was found and divided into four stages as the tool approaches the work edge. The influence of work edge geometry could also be determined. These stages are initiation, initial burr development, pivoting point and final development. Park continued this study by employing ABAQUS Explicit code which allows for a more detailed and mechanistically correct analysis of burr formation. This code has the advantage of using a ductile failure model for chip separation rather than a parting line approach. In addition, an adiabatic heating model is adopted to simulate the heat generation effects of the plastic work. The results were also compared qualitatively with experiments. Hashimura *et al* [Hashi 95] analyzed the three dimensional burr formation in oblique machining and verified the results in slow speed *in situ* SEM machining . This study showed the effects of the tool inclination angle and proposed a burr formation mechanism consistent with earlier studies. Fig. 18 shows a schematic representation of the stages of burr formation in both ductile and brittle metals, as observed in the SEM machining.

As a result of these basic studies and other published research, the analysis can be extended to the predic-

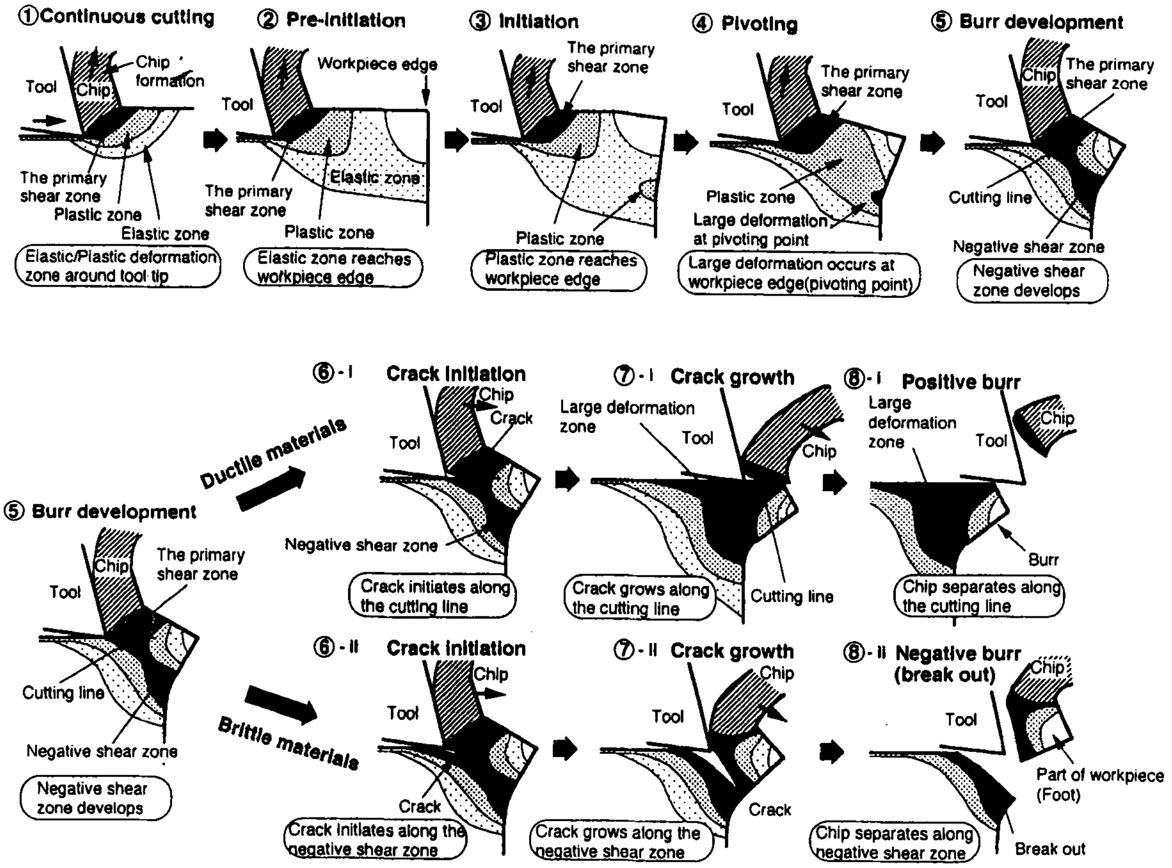


Fig. 18 Schematic representation of burr formation.

ion of burr size and location in more conventional machining processes [Nara 95, Hashi 98]. This offers the potential for burr minimization based on tool design, tool path and process parameter planning. And. although much more complicated, the analysis of burr formation in drilling is underway. Many of the same early researchers addressed burrs in drilling but no comprehensive analytical studies existed. Stein has looked extensively at burr formation in precision holes with special emphasis on through hole geometry effects and the influence of feed rates and other process parameters [Stein 95, Stein 97]. The influence of intersection geometries on burr size and shape, specially for non-axially intersecting holes, was quantified.

8 Augmenting modelling through synergistic interactions with sensing and learning

8.1 Developments in sensoring, monitoring and supervision

The literature database has revealed that about 8% of metal cutting literature has been devoted to sensing and monitoring. Much of this work has occurred in the last decade and half. Many new techniques for processing sensor signals have been developed.

Recent overviews were produced by another CIRP working group [Byrn 95,Anom 95]. The reliability of prediction is being increased through sensor fusion and the implicit modelling abilities of ANN. Yet, the worlds of sensing and modelling have so far remained completely apart. It is time these two communities come together in a complementary fashion.

The need to conduct extensive off-line experiments to compile the machining databases that support the calibration of model parameters has been the major hurdle in the extensive utilization of even models that have been rigorously validated under laboratory conditions. Sensing is likely to provide a way out in this regard. Sensing can augment modelling in two principal ways.

Firstly, recall that the aim of modelling is to predict the magnitude or trend of the desired performance measure. This performance measure depends on the process inputs and current state of the process. Until the general current state has been identified (e.g. a stable built-up-edge might or might not be present) , one cannot select the applicable model. A sensed signal from a cutting process, is however a result of the same cutting state. Hence, with a proper selection of the sensor(s) and signal processing methods, it should be possible to identify the current state.

Secondly, as noted already, calibration of the model coefficients is the main reason one is forced to rely on expensive and, often, unreliable machining databases to day. Figure 19 schematically illustrates a method of overcoming this problem by augmenting modelling with sensing and learning. machining databases.

$\{O_p\}$ and $\{O_s\}$ are the desired performance measures and sensed outputs respectively from the

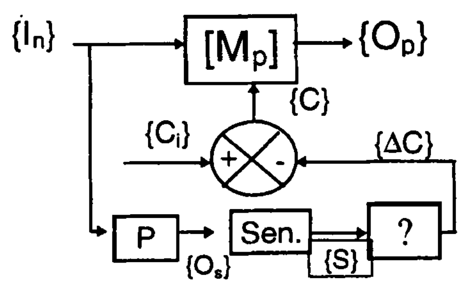


Fig. 19 Calibrating A Predictive Model by Using Sensed Output

very same process [P] as the latter manifests in real time. Hence, $\{O_s\}$ should contain much information concerning the way [P] behaves for the nominal input $\{I_n\}$. All we need to do is find a way of utilizing this insight towards determining the corrections {ΔC} that need to be made to the model coefficients $\{C_i\}$ set initially through a static machining database.
Figure 20 shows another possible method of combining the powers of sensing and modelling by taking advantage of a learning system, L, such as an ANN.

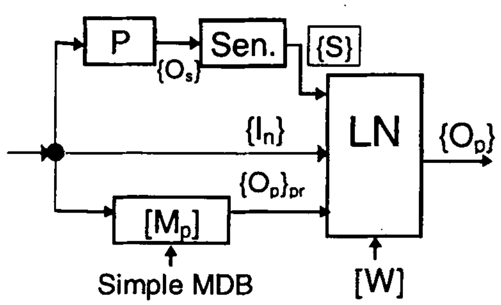


Fig. 20 Augmenting Learning Through Modelling as well as Sensing

8.2 Sensor enhanced modeling

Whatever the technique used models require a tremendous amount of data if they are used to predict the results in small batch manufacturing with a variety of operations, cutting tools and work materials. It will never be possible to obtain all the required data from public sources or properly designed experiments. Accurate and reliable data can only be obtained from own experience in the workshop. However a workshop is no laboratory and production people are not trained to perform experiments and to carry out the necessary measurements. The only reasonable solution seems to equip machine-tools with sensors and other information input equipment to collect the desired information. The first run of actual production operations are performed with starting cutting conditions as found in public domain machining data collections e.g. those provided by cutting tool manufacturers. The actual process state and output values are captured and fed into the primitive model which is based on estimated constants based on published data. The primitive model can be improved on the basis of the captured information. The next operation can be performed with improved cutting data calculated from the improved model. This cycle should be repeated as often as possible. In this way the models learn from experience. This approach was advocated in [Peng 97, Peng 97a, Venu 97, Lutt 98].

8.3 Throwing everything together

The majority of the current applications of ANN in machining utilize either the nominal process inputs, {In}, or sensor signal features, {S}, or both as inputs. A disadvantage of this method is that each learning exercise is an individual episode. By complementing this scheme with model predictions one may be able to accelerate the learning process as well as improve the robustness of the learning system.
Variations of the above schemes are being pursued at City University of Hong Kong and Technical University of Delft in predicting and compensating workpiece dimensional errors in machining.
In doing so the best elements of recent research will be brought together in one system which will serve to a certain extend as a test bed for some of the ideas formulated in this paper or in one of the recent conferences mentioned in 9.3. The main aim is to investigate how recent developments in AI technology and sensoring techniques can enhance workpiece accuracy.

9. Guidelines for future research

9.1 Changes in the development of models for machining

Work on modelling of machining operations is carried out by laboratories all over the world. Not all of them are represented in CIRP. In the past much work was carried out in Europe, especially Germany. Especially during the last few decades, significant contributions came from Australia. In this decade many activities can be observed in the USA.
In the past most work was done by individuals or small groups. Typical examples are Prof Shaw in the USA, Prof Pekelharing in the Netherlands, Prof Oxley and Prof Armarego in Australia. These workers had to restrict themselves to certain aspects of modeling and often dealt only with the basic process of chip formation or the ideal processes of turning, milling and drilling neglecting the influence of all elements of the machining system other than the workpiece and cutting tool. In principle new models had to be developed for each process. Armarego tried to bring these attempts together into a general machining theory [Arma 70-96].
Nowadays it seems that a significant part of the work on modeling of machining operations is carried out as planned work by research teams, financed by agencies. Typical examples are Jawahir's group at the University of Kentucky and the Virtual Machine-Tool group at the University of Illinois at Urbana-

Champaign. Both groups are executing an overall plan to model all aspects of the most important machining operations taking into account all elements of the machining system.

As long as CIRP STC "Cutting" has existed it has been active in one way or another to collect and evaluate information on modelling. This has led to some noteworthy results:

1 An extensive program of cooperative research in which a well coordinated series of experiments was carried out by a number of laboratories in nearly all OECD countries at that time. The main results are documented in the final report [OECD 66].
2 Less succesfull was the endeavour of the working group "Application of Machining Research to Industry AMRI", founded by the STC"C" chairman of that time, Prof Colding, to write a book containing all knowledge about machining relevant to industry. Practical applicable models would have been an essential part of it. The AMRI group never succeeded in writing that book. Some of the information collected might still be available but most of it is not suited to the needs in industry of today.
3 The working group "chip formation" collected all available knowledge on chip formation and chip evacuation. Modelling is an essential part of this area [Jawa 93, Lutt 93].

9.2 the CIRP International Workshop on Modelling of Machining Operations held on 19 May 1998 in Atlanta USA

The aims of the workshop were to discuss problems and possible solutions in the future development of models for machining operations aimed for practical application in the metal cutting industry. The gap between engineering necessity and scientific challenge should be closed by coordinated action of all persons concerned. There were nearly eighty participants, among which were many persons, not usually involved in CIRP activities.
Dr M.E. Merchant spoke about "An interpretive look at 20th century research on modelling of machining". His conclusions were: In computer integrated manufacturing, machine tools are required to run ever more autonomously and must be able to avoid or correct processing errors or failures. The key to the advancement of such capacity is to increase the accuracy and realism of machining process models by effective utilisation of a proper mix of fundamental, empirical and science based knowledge in such a way that the models can be integrated within the overall system of manufacturing.
Professor P.L.B. Oxley reviewed "The development and application of a predictive machining theory". He showed how the results of over fourty years of research have enabled to predict cutting forces and temperatures depending on work material properties and cutting conditions and how these predictions can be used to selecting cutting conditions. He signalled the main weaknesses of his work: The work was maily limited to plain carbon steels and should be extended to other workmaterials. Efficient tests should be developed to obtain the required workmaterial properties. The chip formation model should be extended to include rounded or chamfered cutting edges, chip breaking geometries, 3D-cutting, interrupted cutting as in milling and various modes of chip formation. Several of these aspects have already been studied by other researchers but could up to now not be integreted in the predictive machining theory.
A large number of wishes was presented by representatives from the automotive, aerospace, heavy equipment and cutting tool industries.
Some thirty papers were presented in four parallel sessions: Analytical modelling,Computational Modelling, Experimental/ Emperical Modelling and Integration of Modelling.
After lunch group discussions took place on these four areas with the aim to asses the current status but especially to define the most promising prospects for future directions of research. Each group prepared a list of maximal six items for presentation at the plenary session. The most striking results of this are as follows:

The first issue is **fragmentation**. In experimental data this arises from the multiplicity of materials, cutting tools and cutting conditions available to investigators which leads to large volumes of data which cannot be directly compared with or integrated with the data of others. This lack of a coherent data set makes model-experiment comparisons difficult and impedes progress in developing and refining our understanding of the physical processes which control machining response. In simulation this arises because the "global" machining problem is so broad that individual researchers and research groups, rather than developing a "global" simulation focus on individual elements of the overall problem. In the creative stage of simulation development this is desirable. However, solving the overall problem requires incorporating these individual simulations in a comprehensive code, and solving practical machining problems requires incorporating the 'best' individual simulations in a comprehensive code. Unfortunately there is no procedure for identifying the 'best' solution and the software is not written in a modular fashion so that integrating individual simulations is difficult. Also, this is compounded by the difficulty to characterize the machine tool performance which significantly affects the overall machining performance of a machining system consisting of workpiece, cutting tool and machine tool including jigs and fixtures. Modeling and simulation activities need to be based on the relevant machining system rather than from the analysis of simple orthogonal type processes.

The second issue is **multiple communities**. There are three groups with an active interest in working to develop a global machining simulation: the modelers developing the simulation, the experimentalists generating data to guide and validate model development and the users who seek a rapid, low-cost solution to their immediate machining problems. There are concerns that experimentalists and modelers are not interacting as effectively as they could be and that there is poor model coordination of modeling and experiments. There is also concern that there has been inadequate interactions between the future users of the technology and researchers. Thus, some key capabilities desired by the user community, for example coordination with CAD/CAM systems, the need for models which address real machining conditions and real tool geometries including chip breakers, are not receiving the attention they deserve. Cooperative efforts on modeling of machining performance parameters such as tool-wear/tool-life, chip-form/chip breakability or surface roughness are considered a significant step in the right direction.

The third issue is the **knowledge base** on which the models and simulation are based. Numerous concerns were raised regarding the perceived inadequacy of the physical models on which the simulations were based including: the quality of material flow stress data relevant to the machining regime; the tribological aspects of machining; tool wear; and surface roughness. Additional advances in these areas are essential to ensure robust and reliable predictive models for use in simulation. In this regard, the use of advanced tools and techniques for generating and sustaining the required knowledge base with no loss of accuracy and reliability of predictions is highly encouraged.

9.3 modelling of machining in 1998

Modelling of machining operations is a continuing story which seems to be more vivid this year than ever before. Over 40 papers on various new aspects of modelling of machining operations were presented this year at CIRP sponsered conferences.

Most of these recent research efforts deal with possible new ways to obtain a better control of machining operations in general but remarkably much emphasis is given to workpiece accuracy and the application of new techniques. Thus it seems we are on the right track as far as the subject is concerned. What is still missing is a common framework..

9.4 Future work by the CIRP working group on modelling of machining operations

The working group is still far away from reaching its original aims. After three years of reconnaissance of the problem area more effective methods should be developed to speed up progress.
One serious handicap is that up to now no funding could be obtained for such CIRP activities. Institutes are only able to contribute when their financed research activities fit into a programmed CIRP activity.
The aims of this working group are very ambitious. We try to make a significant step forward on the global level while most financed research is restricted to the national level or even has a more narrow purpose. Some people even consider effective modeling of manufacturing operations as a strategic asset in global competition which hampers the free exchange of knowledge.
Another handicap is that young researchers, and perhaps even more the agencies that finance research, are not very excited by new work on modelling of such classical operations as metal cutting. Work on new techniques like rapid prototyping seems to have much more glamour.
The working group intends to continue its activities. We will concentrate on a few areas:

- FEM simulations including computational techniques, material properties and friction laws
- new modeling techniques e.g. AI
- software standards for modeling and simulation
- prediction of workpiece precision
- applications to high speed machining, machining of hard materials, superalloys or other special workmaterials, dry machining
- bringing all well proven partial models together into the „house of models", fit for overall prediction of machining performanche in practical applications

There will be an effort to form small groups that work together on specific topics.

10. Conclusions

- The CIRP working group modelling of machining operations has started an ambitious project to improve the quality of modelling and simulation of metal cutting operations significantly by a joint effort of its members with the aim of enabling industry with a better control of such operations.
- A wealth of information was collected, partlally evaluated and stored in a systematic way in a literature database. This is a sound basis for further analysis and new research to develop improved models, better suited for industrial needs. New information was added recently which deserves attention.
- The field of modelling of machining operations has been scanned with an intensity as never before and the aims of the working group have been defined clearly.
- A start has been made with a classification of models and an unified terminology which enhances the quality of communication.
- This keynotepaper, which in fact is a progress report, has presented many problems and only few partial solutions. The working group intends to develop solutions for at least some of the identified problems in the near future.
- Much attention should be given to the design of a house of interrelated models for the various operations, considered at the required levels in

which the partial solutions can be placed as building blocks. CIRP could design the architecture of such a house.

- At this moment the complexity of the task is fully apparent. One may doubt whether the aims can be fully reached but it seems realistic to expect that through a joint effort of a sufficient number of participants, a significant leap forwards can be made.
- It is certain that such an ambitious undertaking needs more time than the usual three years of existence of a CIRP working group.
- In the future it will be impossible to rely completely only on automatic monitoring to improve the control of machining operations because monitoring lacks the predictive capability needed to plan operations. In addition even monitoring systems need reliable models of some sort.
- The use of sensors such as those used in monitoring systems might be useful to update the data in the applied models by some learning procedure.
- Some new research has started in participating laboratories which may lead to new results within a few years time. The working group intends to stimulate those new developments. Application of AI-techniques and computer simulation also on higher levels than the basic chip formation process seem worthwhile areas of research.
- In all activities we have to realise that industry is not interested at all in academic discussions about the type of models and the techniques used. The only thing that counts is whether a model provides acceptably good results in their situation.
- Researchers tend to try to develop generic solutions which can be applied to a wide range of different needs. Most industries use a limited number of machines, operations and materials and are generally concerned with achieving good (rather than the best) machining practices. Reliable short time solutions with little sophistication may be more productive than very sophisticated ideal solutions which may never become true.
- The working group intends to pursue its adapted aims with adapted methods. It will be operational at least for three more years.
- The working group still invites contributions from people all over the world which might fit our purpose and goals.
- An enhancement of the quality of models for and the level control of machining operations can not be achieved by STC "C" alone. Better ways of co-operation with other STC's of CIRP such as M, O, P and S should be sought.

Literature

A database with relevant literature containing over 3500 publications provided with keywords and tools for searching and analysis can be obtained from Professor Patri K. Venuvinod, City University of Hong Kong, Email: mepatri@cityu.edu.hk

References

[Acun98] D'Acunto A., Martin P., Guery M., 1998 Fixturing Effects influence on workpiece quality in milling, Proc. Int. Seminar Improving Machine Tool Performance, San Sebastian, 6-8 July 1998 vol 2 pp 575-585

[Albr 60] Albrecht, P., 1960, The ploughing process in metal cutting, Trans. ASME, Vol. 82, p. 348

[Alti 91] Altintas, H., Spence A., 1991, End milling force algorithms for CAD systems, Annals of CIRP, Vol. 40/1, pp. 31-34

[Alti 95] Altintas, Y., Budak, E., 1995, Analytical Prediction of Stability Lobes in Milling, Annals of CIRP, Vol. 44/1, pp. 357-362

[Alti 96] Altintas, Y., Lee, P., 1996, A General Mechanics and Dynamics Model for Helical End Mills, Annals of CIRP, Vol. 45/1, pp. 59-64

[Anon 95] 1995, VDI Berichte 1179, Ueberwachung von Zerspan- und Umformprozessen

[Anon 95a] 1995, Proceedings of the IVth Int. Conf. on Manufacturing, The Polish Academy of Sciences, Warsaw

[Arma 70] Armarego, E.J.A., Uthaichaya, M., 1970, A mechanics of cutting approach for force prediction in turning process, J. Eng. Production, p. 1

[Arma 83] Armarego, E.J.A., 1983, Development of a General Cutting Analysis for Machining with Plane Faced Tools, 1st Int. Metal Cutting Conference (IMCC), Guangzhou, China, p. 11

[Arma 85] Armarego, E.J.A., Whitfield, R.C., 1985, Computer based modelling of popular machining operations, Annals of CIRP, Vol. 34/1, pp. 65-69

[Arma 91] Armarego, E.J.A., Deshpande, N.P., 1991, Computerised end-milling force predictions with cutting models allowing for eccentricity and cutter deflection, Annals of CIRP, Vol. 40/1, pp. 25-29

[Arma 95] Armarego, E.J.A., Jawahir, I.S., Ostafiev, V.A., Venuvinod, P.K., 1995, Modelling of machining operations, City University of Hong Kong, December

[Arma 95a] Armarego, E.J.A., Wang, J., Deshpande, N.P., 1995, Computer-aided predictive cutting model for forces in face milling allowing for tooth run-out, Annals of CIRP, Vol. 44/1, pp. 45-48

[Arma 95b] Armarego, E.J.A., 1995, Machining performance Prediction for Modern Manufacturing, Advancement of Intelligent Production, Ed. E. Usui, JSPE Publication

Series No. 1, 7th Int. Conf. Production/Precision Eng. and 4th Int. Conf. High Technology, Chiba, Japan, Sept. 15-17, pp. K52-K61

[Arma 96] Armarego, E.J.A., Zhao, H., 1996, Predictive force models for point thinned circular centre edge twist drill designs, Annals of CIRP, Vol. 45/1, pp. 65-70

[Arse 97] Arsecularatne, J.A., Oxley, P.L.B., 1997, Prediction of Cutting Forces in Machining with Restricted Contact Tools, J. Machining Sc. and Tech., 1(1): 95-112.

[ASME] ASME Standard, Tool Life Testing with Single-Point Turning Tools, ASME, New York, USA.

[Back 52] Backer, W.R., Marshall, E.R., Shaw, M.C., 1952, The size effect in metal cutting, Trans. ASME, Series B, Vol. 74, pp. 61-72

[Bala 98] Balaji, A.K., Jawahir, I.S., 1998, Analysis of Chip Side-Curl in Turning Operations, J. Machining Sc. and Tech., (in press).

[Baeh98] Baehre D., Dollmeier R., Warnecke G.(1998) Modeling of thermo-elastic workpiece deformation for compensation of dimensional errors in turning of hard metals, Trans. NAMRI/SME vol XXVI pp 123-128

[Bela 93] Belak, J. Boercker, D.B., Stowers, I.F., 1993, Simulation of Nanometer-Scale Deformation of Metallic and Ceramic Surfaces, Mat. Res. Soc. Bul., May, pp. 55-60

[Bhat 69] Bhattacharya, A., Ham, I., 1969, Analysis of tool wear, part I Theoretical models of flank wear, J. Eng. for Industry, ASME, pp. 790-798

[Buda 96] Budak, E., Altintas, Y., Armarego, E.J.A., 1996, Prediction of Milling Force Coefficients from Orthogonal Cutting Data, Transactions of ASME, Journal of Manufacturing Science and Engineering, Vol. 118/2, pp. 216-224

[Byrn 95] Byrne, G. et all, 1995, Tool condition monitoring - TCM - the status of research and industrial applications, Annals of CIRP, Vol. 44/2, pp. 541-568

[Carr 88] Carroll, G.J.T., Strenkowski, J.S., 1988 Int. J. Mech. Sci., Vol. 30, pp. 877-886

[Cars 50] Carslaw, H.S., Jaeger, J.C., 1950, Conduction of heat in solids, Oxford U. Press, London

[Cere 96] Ceretti, J.E., Fallbehmer, P., Wu, W.T., Altan T.J., 1996, Mat. Processing Tech., Vol. 59, pp. 169-181

[Cere 98] Ceretti, J.E., Horn, T. 1998 Progress Report to STC"C"

[Chan 97] Chandrasekharan, V., Kapoor, S.G., DeVor, R.E., 1997, A Calibration Procedure for Fundamental Oblique-Cutting Model Coefficients Based on a Three-dimensional Mechanistic Drilling Force Model, Trans. NAMRI/SME, 25: 255-260.

[Chao 50] Chao, B.T., Trigger, K.J., 1950, Temperature distribution at tool-chip and tool-work interface in metal cutting, Trans. ASME, Vol. 80, pp. 311-320

[Chao 55] Chao, B.T., Trigger, K.J, 1955, Temperature distribution at tool-chip interface in metal cutting, Trans. ASME, p. 1107

[Cher96] G. L. Chern and D. A. Dornfeld (1996), "Burr/Breakout Development and Experimental Verification," Trans. ASME, J. Eng. Mats. Tech., Vol. 118, No. 2, pp. 201-206.

[Chil 97] Childs, T.H.C., aout 1997, Material property requirements for modelling metal machining, J. Phys. IV France 7 (1997) Colloque C3, suppl. au J. Phys. III, pp. XXI-XXXVI

[Chri 58] Christopherson, D.G., Oxley, P.L.B., Palmer, W.B., 1958, Orthogonal Cutting of a Work-Hardening Material, Engineering, Lond., 186: 113-???.

[Cold 59] Colding, B.N., 1959, A Three-Dimensional Tool Life Equation - Machining Economics, ASME J. Eng. for Industry, 239-250.

[Cold 91] Colding, B.N., 1991, A Tool temperature/Tool Life Relationship Covering a Wide Range of Cutting Data, Annals of CIRP, 40(1): 1991, 35-40.

[Conn 68] Connally, R., Rubenstein, C., 1968, The mechanics of continuous chip formation in orthogonal cutting, Int. J. Mach. Tool Des. Res., Vol. 8, pp. 159-187

[Dewh 78] Dewhurst, C.P., 1978, Is the machining process uniquely defined?, Annals of CIRP, Vol. 27/1, pp. 1-4

[Dewh78a] Dewhurst, C.P., 1978, Proc. Roy. Soc., A360, pp. 587-610

[Dini 96] Dini, G., 1996, Literature Database on Applications of Artificial Intelligence Methods in Manufacturing Engineering, Compiled by 26th CIRP Assembly, Como, Italy

[Elbe 94] Elbestawi, M.A., Ismail, F., Du, R, Ullagaddi, B.C., 1994, Modeling Machining Dynamics Including Damping in the Tool-Workpiece Interface, ASME J. Eng. for Industry, 116: 435-439.

[ElMa 93] ElMaraghy, H.A. et all, 1993, Evolution and future perspectives of CAPP, Annals of CIRP, Vol. 42/2, pp. 739-752

[Enah 66] Enahoro, H.E., Oxley,P.L.B. 1966 Flow along tool-chip interface in orthogonal metal cutting J. Mech.Eng.Sci 8, 36-41

[Endr 95] Endres, W.J., DeVor, R.E., Kapoor, S.G., 1995, A Dual Mechanism Approach to the Prediction of Machining Forces, Part 1: Model Development, ASME J. Eng. for Industry, 117: 526-533.

[Fang 94] Fang, X. D., Jawahir, I. S., 1994, Predicting Total Machining Performance in Finish Turning Using Integrated Fuzzy-set Models of the Machinability Parameters, Int. Journal of Prodn. Res., 32 (4): 833-849.

[Fang 96] Fang, X. D., Jawahir, I. S., 1996, An Analytical Model for Cyclic Chip Formation in 2-D Machining with Chip Breaking, Annals of CIRP, 45(1): 53-58.

[Farm 76] Farmer, L.E., Oxley, P.L.B., 1976, A Computer Aided Method for Calculating the Distributions of Strain-Rate and Strain from an Experimental Flow Field, J. of Strain

Analysis, 1, pp. 26-31

[Gana 93] Ganapathy, B.K., Jawahir, I.S., 1993, A Force Model for Chip Breaking in Orthogonal Machining, PED-Vol. 64, Manufacturing Science and Engineering, ASME, 461-474.

[Gana 97] Ganapathy, B.K., Jawahir, I.S., 1998, Modeling the Chip-Work Contact Force for Chip Breaking in Orthogonal Machining With a Flat-faced Tool, ASME J. Manuf. Sc. & Engg., 120: 49-56.

[Gill 76] Gillespie, L. K. and Blotter, P. T. (1976), "The formation and properties of machining burrs," Trans. ASME, J. Eng. Ind., 98, 1, 66-74

[Grab 97] Grabec, I., Sachse, W., 1997, Synergetics of Measurement, Prediction and Control, Springer-Verlag

[Hashi95] Hashimura, M., Ueda, K., Dornfeld, D. , and Manabe, K. (1995), "Analysis of Three Dimensional Burr Formation in Oblique Cutting," CIRP Annals, Vol. 44, No. 1, pp. 27-30.

[Hashi95b]Hashimura, M. and Dornfeld, D. (1995), "Analysis of Burr Formation Mechanism in Machining Process," Proc. First Int'l Machining and Grinding Conference, SME, Dearborn, MI.

[Hashi98] Hashimura, M., Hassamontr, J. and Dornfeld, D. A. (1998) "Effect of In-Plane Exit Angle on Burr Height and Thickness in Face Milling Operation," Trans. ASME. J. Manufacturing Science and Engineering, to appear.

[Hill 54] Hill, B.R., 1954, Mech. Phys. Solids 2, pp. 278-285

[Hurt 98] Hutado J.F, Melkote S.N., 1998 A model for the prediction of reaction forces in a 3-2-1 machining fixture, Trans. NAMRI/SME vol XXVI pp 335-340

[Huan 94] Huang, S.H., Zhang, Hong-Chao, 1994, Artificial Neural Networks in Manufacturing, Concepts, Applications, and Perspectives, IEEE Transactions on Components, Packaging, and Manufacturing Technology, A 17, No. 2, 212-228

[Hyki 94] Hykin, S., 1994, Neural Networks, McMillan, New York

[Iwat 84] Iwata, F.K., Osakada, K., Terasaka, Y., 1984, Trans ASME Jnl. Eng. Matls. Tech., Vol. 106, pp. 132-138

[Iwat 82] Iwata, K., Ueda, K. and Okuda, K. (1982) "Study of mechanism of burr formation in cutting based on direct SEM observation," J. Japan Soc. Prec. Eng., 48, 4, 510-515.

[Jasp 95] Jasperse, H.B., 1995, A macro process planning system for machining operations, Ph.D.thesis, Delft University of Technology

[Jawa 86] Jawahir, I.S., 1986, *An Experimental and Theoretical Study of the Effects of Tool Restricted Contact on Chip Breaking*, Ph.D. Thesis, University of New South Wales, Australia.

[Jawa 88] Jawahir, I.S., Oxley, P.L.B., 1988, New Developments in Chip Control Research: Moving Towards Chip Breakability Predictions for Unmanned Manufacture, Proc. Int. Conf. ASME, MI=88, Atlanta, Georgia, USA,311-320.

[Jawa 93] Jawahir, I.S., Fei, J., 1993, A Comprehensive Evaluation of Tool Inserts for Chip Control Using Fuzzy Modeling of Machinability Parameters, Trans. NAMRI, 21: 205-213.

[Jawa 93a]Jawahir, I.S., Luttervelt, C.A. van, 1993, Recent developments in chip control research and applications, Annals of CIRP, Vol. 42/2, pp. 659-694

[Jawa 95] Jawahir, I. S., Li, P. X., Ghosh, R., Exner, E. L., 1995, A New Parametric Approach for the Assessment of Comprehensive Tool-wear in Coated Grooved Tools, Annals of CIRP, 45(1): 49-54.

[Jawa 97] Jawahir, I. S., Balaji, A. K., Stevenson, R., van Luttervelt, C. A., 1997, Towards Predictive Modeling and Optimization of Machining Operations, Keynote Paper, Symp. on Predictable Modeling in Metal Cutting as Means of Bridging Gap Between Theory and Practice, Manuf. Science and Engg., ASME IMECE, Dallas, Texas, USA, MED-6-2: 3-12.

[John 62] Johnson, W., 1962, Some Slip-line Fields for Swaging or Expanding, Indenting, Extruding and Machining for Tools with Curved Dies, Int. J. Mech. Sci., 4: 323-347.

[Kahl 87] Kahles, J.F., et all, 1987, Machining data requirements for advanced machining systems, Annals of CIRP, Vol. 136/2, p. 523

[Kald 98] Kaldor, S., Venuvinod, P.K., 1997, Macro-level Optimization of Cutting Tool Geometry, J. Manufacturing Science and Engineering, ASME, Vol. 119/1, pp. 1-9

[Kita 76] Kitagawa, T., Shirakashi, T., Usui, E., 1976, Characteristics Equation of Crater Wear, J. JSPE, Vol. 42/12, p. 1178.

[Kline 82] Kline, W.A., DeVor, R.E., Lindberg, J.R., 1982, The Prediction of Cutting Forces in End Milling with Application to Cornering Cut, Int. J. Mach. Tool. Des. Res., 22: 7-22.

[Kloc 97] Klocke, F., January 1997, Progress report of subgroup "Applications of models", Aachen

[Koba 59] Kobayashi, A., Thomsen, S.E.G., 1959, Trans ASME Jnl. Eng. Ind., 81B, pp. 251-262

[Koen 61] Koenigsberger, F., Sabberwal, A.J.P., 1961, An Investigation into the Cutting Force Pulsations during Milling Operations, Int. J. Mach. Tool Des. Res., 1:15-33.

[Koen 90] Koenig, W., et all, 1990, Machining of new materials, Annals of CIRP, Vol. 39/2, pp. 673-681

[Ko 91] Ko. S. L. and Dornfeld, D. A. (1991), "A Study of Burr Formation Mechanism." Trans. ASME, J. Eng. Ind., 98, 1, pp. 66-74.

[Koma 97] Komanduri, R. Lucca, D.A., Tani, Y., 1997, Annals of CIRP, Vol. 46/2, pp. 545-596

[Kron 66] Kronenberg, M., 1966, Machining science and application, Pergamon Press
[Kudo 65] Kudo, H., 1965, Some New Slip-line Solutions for Two-dimensional Steady-State Machining, Int. J. Mech. Sci., 7: 43-55.
[Lee 51] Lee, E.H., Shaffer, B.W., 1951, The theory of plasticity applied to a problem of machining, Trans. ASME, Vol. 73, pp. 405-413
[Lee 96] Lee, P., Altintas, Y., 1996, Prediction of Ball End Milling Forces from Orthogonal Cutting Data, International Journal of Machine Tools and Manufacture, Vol. 36/9, pp.1059-1072
[Leop 91] Leopold, J., 1991, Hybrid-Method: Visioplasticity and Finite Element Method in Production Engineering, LUSAS-AMT 1991, Stratford-upon-Avon/UK
[Leop 95] Leopold, J., Schmidt, G., 1995, Software Package VISIO, Manual, Chemnitz
[Leop 95a] Leopold, J., Schulze, B., Schmidt, G., Semmler, U., 1995, Computational Modelling of Cutting and Forming Operations using Micro-Visioplasticity, 5th Int. Workshop on Computational Modelling of the Mechanical Behaviour of Materials, Aachen, November 27-29
[Leop 97] Leopold, J., Semmler, I., 1997, Finite Element Simulation on the Free Chip Formation in Two and Three Dimensions, CIRP-CNAM, January 29, Paris/France
[Liao 98] Liao Y.J., Hu S.J., Stephenson D.A., 1998 Fixture layout optimization considering workpiece-fixture contact interaction: simulation results, Trans. NAMRI/SME vol XXVI pp 341-346
[Lind 97] Lindstrom, B., 1997 Private communication.
[[Li 98] Jie Li, Weidong Ma, Yiming Rong 1998 Fixturing surface accessibility analysis for automated fixture design, Trans. NAMRI/SME vol XXVI pp 329-334
Loew 54] Loewen, E.G., Shaw, M.C., 1954, On the analysis of cutting temperature distribution, Trans. ASME, Vol. 76, pp. 217-231
[Lucc 98] Lucca, D.A., Chou, P., Hocken, R.J., 1998, Effect of Tool Edge Geometry on the Nanometric Cutting of Ge, Annals of CIRP, Vol. 47/1, *to appear*
[Lutt 73] Luttervelt, C.A. van, 1973, Quality of machined surfaces, Section 4D in draft CIRP/AMRI Textbook on Machining
[Lutt 76] Luttervelt, C.A. van, Pekelharing, A.J., 1976, Chip formation in machining operations on small diameters, Annals of CIRP, Vol. 25, p. 71
[Lutt 77] Luttervelt, C.A. van, Pekelharing, A.J., 1977, The split shearzone mechanism of chip segmentation, Annals of CIRP, Vol. 26, p. 33
[Lutt 79] Luttervelt, C.A. van, 1979, Assessment of the present situation of chip control, VDI Berichte 762 Tagungsbericht Schneidstoffe und Werkzeuge
[Lutt 84] Luttervelt, C.A. van, et all, 1984, Testing commercial cutters on the exit failure of cemented carbide face cutters, Annals of CIRP, Vol. 33/ p. 51
[Lutt 93] Luttervelt, C.A. van, 1993, New Developments in Monitoring of Chip Control, VDI Berichte, No. 988, Neue Entwicklungen in der Zerspantechniek
[Lutt 97] Luttervelt, C.A. van, 1997, A report from the CIRP working group on modelling of machining operations, Machining Science and Technology, No. 1, pp. 163-169
[Lutt 97a] Luttervelt, C.A. van, et all, 1997, An on line learning model for getting correction factors of cutting parameters, NAMRC XXV technical papers pp. 111-116
[Lutt 98] Luttervelt, C.A. van, 1998, The importance of suitable models for machining operations to improve machinetool performance, to be published in Proc. of Int. Sem. Improving Machine Tool Performance, San Sebastian, Spain, July 6-8
[Mart 41] Martellotti, M.E., 1941, An Analysis of the Milling Process, Trans. ASME, 67: 233-251.
[Maru 95] Marusich, I.T.D., Ortiz, M., 1995, Int. Jnl. Num. Methods in Eng., Vol. 38, pp. 3675-3694
[Merc 45] Merchant, M.E., 1945, Mechanics of the metal cutting process I, Orthogonal cutting and a type II chip, J. Appl. Physics, Vol. 16/5, pp. 267-276
[Nagt 74] Nagtegaal, J.C., Parks, D.M., Rice, J.R., 1974, On Numerically Accurate Finite Element Solutions in the fully Plastic Range, Com. Metli. Appl. Mech. Eng., Vol. 4, p. 153
[Naka 84] Nakayama, K. and Arai, M. (1984), "Burr formation in metal cutting," CIRP Annals, 36, 1, 33-36.
[Nara 97] Narayanaswami, R. and Dornfeld, D. (1997), "Burr Minimization in Face Milling: A Geometrical Approach," Trans. ASME, J. Engineering for Industry, Vol. 119, No. 2, pp. 170-177.
[Obik 96] Obikawa, T., Usui, E., 1996, Computational machining of Titanium Alloy, Trans. ASME, J. Manufact. Sci. Eng., Vol. 118, No. 208
[Obik 97] Obikawa, T., Sasaliara, H., Shirakashi, T., Usui, E., 1997, Application of Computational Machining Method to Discontinuous Chip Formation, Trans. ASME. J. Manufact, Sci. Eng., Vol. 119, p. 667.
[OECD 66] Anom., 1966, Proceedings of the Seminar on Metal Cutting held on August 1-2, Paris, OECD, Paris
[Oxle 89] Oxley, P.L.B., 1989, Mechanics of Machining: An Analytical Approach to Assessing Machinability, Ellis Horwood, Chichester
[Park 94] Park, I. W., Lee, S. H. and Dornfeld, D. (1994), "Modeling of Burr Formation of Orthogonal Metal Cutting," ESRC Report 93-34, University of California , Berkeley.
[Park 98] Park, I. W. and Dornfeld, D. (1998), "A Study of Burr Formation Processes using the Finite Element Method; Part I," Trans. ASME, J. Eng. Mats. and_Tech., submitted

for publication.

[Park98b] Park, I. W. and Dornfeld, D. (1998), "A Study of Burr Formation Processes using the Finite Element Method; Part II, The Influence of Exit Angle, Rake Angle, and Backup Material on Burr Formation Processes," Trans. ASME, J. Eng. Mats. and Tech., submitted for publication. [Palm 59] Palmer, W. B., Oxley, P. L. B., 1959, Mechanics of Orthogonal Machining,Proc. Instn. Mech. Engrs., 173(24): 623-638.

[Paul 76] Paul, B., Mirandy, L., 1976, An Improved Fracture Criterion for Three Dimensional Stress State, Trans. ASNffi, Vol. 98/2, p. 159.

[Peke 78] Pekelharing, A. J., (1978), "The exit failure in interrupted cutting," Annals of the CIRP vol 27/1, pp, 5-10.

[Peke 84] Pekelharing, A.J., 1984, The exit failure of cemented carbide face milling cutters, Annals of CIRP, Vol. 33, p. 47

[Rako 93] Rakotomolala, H.R., Joyot, P., Touratier, M. Comm., 1993, Num. Methods in Eng., Vol. 9, pp. 975-987

[Rens 95] Rensch, R., Inasaki, I., 1995, Investigation of Surface Integrity by Molecular Dynamics Simulation, Annals of CIRP, Vol. 44/1, pp. 295-298

[Roth 72] Roth, R.N., Oxley, P.L.B., 1972, Slip-line Field Analysis for orthogonal Machining Based Upon Experimental Flow Fields, J. Mech. Engg. Sci., 14(2): 85-96.

[Rowe 94] Rowe, W.B. et all, 1994, Applications of artificial intelligence in grinding, Annals of CIRP, Vol. 43/2, pp. 521-532

[Rube 78] Rubenstein, C., 1978, An analysis of tool life based on flank face wear, Part I, J. Eng. for Industry, ASME, pp. 221-226

[Sabb 61] Sabberwal, A.J.P., 1961, Chip Section and Cutting Force during the Milling Operation, Annals of CIRP, 10(1): 197-203.

[Sali 98] Salisbury E.J., Peters F.E. The impact of surface errors on fixtured workpiece location and orientation, Trans. NAMRI/SME vol XXVI pp 323-328

[Sart 95] Sartori, S., Zhang, G.X., 1995, Geometric error measurement and compensation of machines, Annals of CIRP, Vol. 44/2, pp. 598-610

[Sast 81] Sastry, V.V.S., Sitharama Rao, T.L.S., Venuvinod, P.K., 1981, Steady state temperatures in obliquely moving heat sources, 6th Int. Heat and Mass Transfer Conf., IIT, Madras, pp. E39-E48

[Sato 96] Sato, H., 1996, Importance of Analysis in Engineering Synthesis - Taking Vibration Themes on Machine Tools as a Case, Proc. 3rd CIRP Workshop on Design and Implementation of Intelligent Manufacturing Systems, Un. of Tokyo, June 1996, pp. 18-24

[Shaw 52] Shaw, M.C., Cook, N.H., Smith, P.A., 1952, The basic mechanics of three dimensional cutting operations, Trans. ASME, Vol. 74/6,

[Shaw 97] Shaw,M.C. 1997, Mechanik der Saegezahn-Spanbildung, lecture at the occasion of receiving the Georg-Schlesinger-Award 1997 of TU Berlin

[Shen 97] Shen, L.G., Luttervelt, C.A. van, 1997, A hybrid intelligent methodology for assessment and optimisation of machining operations in an intelligent machining system, Hong Kong August 1997

[Shi 91] Shi, T., Ramalingam, S., 1991, Slip-line Solution for Orthogonal Cutting with a Chip-breaker and Flank Wear, Int. J. Mech. Sci., 33(9): 689-704.

[Shi 93] Shi, T., Ramalingam, S., 1993, Modeling Chip Formation with Grooved Tools, Int. J. Mech. Sci., 35(9): 741-756.

[Shim 95] Shimada, S. Ikawa, N., Inamura, T., Ohmori, H., Sata, T., 1995, Brittle-Ductile Transition Phenomena in Microindentation and Micromachining, Annals of CIRP, Vol. 44/1, pp. 523-526

[Shir 70] Shirakashi, T., Usui, E., 1970, Fundamental Study of Effect of Temperature and Strain Rate on Metal Machining (Part 1), Bull. JSPE, Vol. 45/4, p. 91.

[Shir 73] Shirakashi, T., Usui, E., 1973, Friction Characteristics on Tool Face in Metal Machining, J.JSPE, Vol. 39/9, p. 966.

[Shir 87] Shirakashi, T., Ihara, T., Usui, E., 1987, Analytical Prediction of Chipping Occurrence of Carbide Tool in Interrupted Turning with Temperature Rise, J. JSPE, Vol. 53/10, p. 1589.

[Spaa 71] Spaans, C., 1971, The fundamentals of threedimensional chop curling, chip breaking and chip control, Ph.D.Thesis, Delft University of Technology

[Step 91] Stephenson, D., 1991, Assessment of steady state metal cutting temperature models based on simultaneous infrared and thermocouple data, J. Eng. For Industry, ASME, pp. 121-148

[Stein 95] Stein, J. and Dornfeld, D. A. (1995), "An Analysis of the Burrs in Drilling Precision Miniature Holes using a Fractional Factorial Design," Proc. ASME IMECE, MED-Vol. 2-1, San Francisco, November, pp. 127-148

[Stein 97] Stein, J. M. and Dornfeld, D. A. (1997)"Burr Formation in Drilling Miniature Holes," CIRP Annals, Vol. 46, No. 1, 1997, pp. 63-66.

[Suth 86] Sutherland, J.W., DeVor, R.E., 1986, An Improved Method for Cutting Force and Surface Error Prediction in Flexible End Milling Systems, ASME J. Eng. for Industry, 105: 149-154.

[Suth 88] Sutherland, J.W., Subramani, G., Kuhl, M.J., DeVor, R.E., Kapoor, S.G.,1988, An Investigation into the Effect of Tool and Cut Geometry on Cutting Force System Prediction Models, Proc. North Amer. Manuf. Res. Conf., 16: 264-272.

[Tayl 07] Taylor, F.W., 1907, On the art of cutting metals, Trans. ASME, Vol. 28, p. 31

[Teti 97] Teti, R., Kumara, S.R.T., 1997, Intelligent computing methods for manufacturing systems, Annals of CIRP, Vol. 46/2, pp, 629-652

[Thom 54] Thomson, E.G., Yang, C.T., Bierbower, J.B., 1954, An Experimental Investigation of the Mechanics of Plastic Deformation of Metals, University of California publications in Engineering, Vol. 4, pp. 89-144

[Turk 67] Turkovich, B.F. von, 1967, Dislocation theory of shear stress and strain rate in metal cutting, 8[th] Int. Mach. Tool Des. Res. Conf., pp. 531-542

[Ueda 98] Ueda, K., 1998 Survey of computational mechanics in cutting, personal communication

[Usui 63] Usui, E., Hoshi, K., 1963, Slip-line Fields in Metal Machining Which Involve Centered Fans, Proc. Int. Prod. Eng. Res. Conf. ASME, Pittsburgh, pp, 61-71.

[Usui 79] Usui, P., Uhara, T., Shirakashi, T., 1979, Probabilistic Stresscriterion of Brittle Fracture of Carbide Tool Materials, Bull. JSPE, Vol. 135/4 p. 189.

[Usui 82] Usui, E.E., Shirakashi, T., 1982, ASME Publ., PED-7, pp. 13-35

[Venu 86] Venuvinod, P.K., Lau, W.S., 1986, Estimation of rake temperatures in free oblique cutting, Int. J. Mach. Tool Des. Res., Vol. 26/1, pp. 1-14

[Venu 90] Venuvinod, P.K., Lau, W.S., Rubenstein, C., 1990, Tool Life in Oblique Cutting as a Function of Computed Flank Temperature, J. Eng. for Industry, ASME, Vol. 112, pp. 307-312

[Venu 96] Venuvinod, P.K., Jin, W.L., 1996, Three Dimensional Cutting Force Analysis Based on the Lower Boundary of the Shear Zone, Part I: Single Edge Oblique Cutting, Part II: Two Edge Oblique Cutting, Int. J. Machine Tools and Manufacture, Vol. 36/3, pp. 307-338

[Venu 97] Venuvinod, P.K., 1997, Literature Database for Modellers of Machining Operations: Progress Report, Originally presented at CIRP General Assembly, Tianjin, Updated in March 1998.

[Venu97a]Venuvinod, P.K., 1997, Prediction augmentation through reinforcing interactions amongst modelling, sensoring and learning, Meeting of the CIRP WG Modelling of machining operations, Tianjin China, August 29

[Venu 98] Database on published literature in modelling of machining, acces through email mepatri@citye.edu.hk

[Vict 71] Victor, H.,1971, Schnittkraftberechnungen fuer das Abspanen von Metallen, Werkstatt technik 59 H7 S 317-327.

[Warn 86] Warnecke, G., 1986, Metal cutting of steel Ck 45 cutting process in the microstructure influence of heat treatment, Video, 16.5 min, Inst. Fur den Wissensschaftlichen Film. Gem. GmbH

[Warn 97] Warnecke, G., Baehre, D., 1997, Modelling of thermoelastic workpiece deformation during turning of hardened steel, Prod.Engineering Vol IV/2 pp51-54

[Weck 95] Weck, M., et all, 1995, Reduction an compensation of thermal errors on machine tools, Annals of CIRP, Vol. 44/2, pp. 589-598

[Whit 92] White, D.A., Sofge, D.A. (editors), 1992, Annals of CIRP of the past decade (6) Handbook of Intelligent Control, Neural, Fuzzy and Adaptive Approaches, Van Nostrand Reinhold, New York

[Woxe 32] Woxen, R., 1932, A theory and equation for the tool life of lathe tools, IVA Handlingar, Stockholm, Vol. 119, *pp's?*

[Youn 87] Young, H.T., Mathew, P. and Oxley, P.L.B., 1987, Allowing for Nose Radius Effects in Predicting the Chip Flow Direction and Cutting Forces in Bar Turning, Proc. Inst. Mech. Eng. Part C201(C3): 213-226

[Zore 66] Zorev, N.N., 1966, Metal cutting mechanics, Pergamon Press

Models for Machining Variables	Currently Active Major Research Groups: Modeling Tools and Techniques				Summary of Present Status	Future Directions
	Analytical	*Numerical*	*Experimental*	*AI -based*		
Shear plane model (includes stresses, strains, strain-rates, temperatures, etc.)	Altintas, Armarego, Astakhov, Brinksmeier, De Chiffre, De VorDautzenberg, Le Maitre, Leopold, Ostafiev, Oxley, Patri, Srivastava	Le Maitre, Ostafiev	Brinksmeier, De Chiffre, Dautzenberg, Oxley		• Early classical work by Merchant (1938-45), Lee and Shaffer (1951). • Several researchers have applied the models.	• No significant progress anticipated due to poor applicability, although known as a good analytical model.
Shear zone model (includes stresses, strains, strain-rates, temperatures, etc.)	Armarego, Astakhov, Colding, Dautzenberg, Leopold, Li, Lindstrom, Le Maitre, Oxley, Patri, Wright	Altan, Altintas, Ceretti, Dillon, Le Maitre, Spur, Strenkowski	Colding, Dautzenberg, Lindstrom, Oxley, Wright		• Classical work by Palmer and Oxley (1959), Oxley and Welsh (1963). • Many research groups have extended the model and applied.	• Need for ascertaining whether the shear zone is curved. • No other significant progress expected.
Friction/ Tribology Models (including tool-chip contact)	Armarego, Astakhov, Bouzakis, Brinksmeier, De Chiffre, Childs, Colding, Dautzenberg, Grabec, Jawahir, Klocke, Le Maitre, Li, Oxley, Ramalingam, Shin, Shirakashi, Wright	Altan, Bouzakis, Childs, Le Maitre, Leopold, Spur	Altintas, Bouzakis, Brinksmeier, De Chiffre, Childs, Colding, Dautzenberg, Grabec, Jawahir, Klocke, Le Maitre, Leopold, Oxley, Toenshoff, van Luttervelt, Vigneau, Weinert, Wright		• Zorev's (1963) classical explanation of stresses at tool-chip interface. • Several slip-line solutions have been proposed. • Mean friction analyses dominate.	• Need for developing truly predictive models for tool-chip contact in grooved tools. • Effect of new work materials and tool coatings. • Effect of complex chip-groove geometry.
Constitutive Modeling and Work-tool Material Properties	Altintas, Astakhov, Bouzakis, Brinksmeier, Childs, Colding, Dautzenberg, Dornfeld, Jawahir, Klocke, Lindstrom, Le Maitre, Li, Oxley, Shin, Teti, Wright	Altan, Altintas, Bouzakis, Dillon, Jawahir, Leopold, Lovell, Reutsch, Spur, Toenshoff, Xie	Bouzakis, Colding, Dautzenberg, Etxeberria, Klocke, Lindstrom, Narutaki, Oxley, Ruisi, Shin, Srivastava, Teti, Toenshoff, Vigneau, Warnecke, Wright	Teti, Warnecke	• Many different experimental methods have emerged for establishing flow properties of the material. • Accuracy, speed and cost of constitutive relationships seem a major problem.	• Use of machining tests to establish realistic constitutive models. • Ascertain work-tool material properties for new work materials and tool coatings.
Chip Flow and Chip Curl Models	Armarego, Athavale, Dautzenberg, Fang, Ghosh, Jawahir, Kruth, Lenz, Nedess, Ostafiev, Oxley, Patri, Ramalingam, Redetzky, Shirakashi, Teti	Altan, Athavale, Dillon, Fang, Ghosh, Ostafiev, Shirakashi, Spur, Ueda, Weinert, Xie	Athavale, Dautzenberg, Ghosh, Jawahir, Kaldor, Klocke, Lenz, Majstdrovic, Nakayama, Rehsteiner, Teti, van Luttervelt, Warnecke, Xie	Fang, Jawahir, Li, Warnecke, Weinert	• Need for chip breaking enforces studies on chip flow and curl. • Constant chip curl radius assumed. • 2-D models are most common.	• Need for developing truly predictive models for chip curl. • Establishment of a methodology for combining individual flow and curl into a 3-D chip form. • Development of 3-D Models.

Figure A-1 (annex)

Models for Machining Performance	Currently Active Major Research Groups — Modeling Tools and Techniques: Analytical	Numerical	Experimental	AI-based	Summary of Present Status	Future Directions
Cutting Forces/ Torque/ Power	Altintas, Armarego, Astakhov, Bouzakis, Colding, Dautzenberg, De Vor, Fang, Grabec, Jawahir, Klocke, Koren, Kruth, Le Maitre, Li, Lindstrom, Novak, Ostafiev, Oxley, Patri, Ramalingam, Schulz, Shin, Srivastava, Teti	Altan, Ceretti, Childs, Koren, Le Maitre, Ostafiev, Reutsch, Schulz, Strenkowski, Ueda	Altintas, Colding, Dautzenberg, Grabec, Jawahir, Klocke, Koren, Le Maitre, Lindstrom, Nakayama, Shin, Teti, Toenshoff, van Luttervelt, Weinert	Elbestawi, Fang, Jawahir, Kumara	• This is the most widely modeled measure. • Some data bank-based modeling efforts for operations are seen most recently. • Some consideration is given for finite cutting edge radii.	• Need prediction of cutting forces for machining with complex grooved tools. • Modeling for machining with rounded finite cutting edge radii. • Work-tool combinations including tribological interactions at the interface.
Tool-life/ Tool-wear	Bouzakis, Colding, Diega, Dautzenberg, Grabec, Jawahir, Jemelniak, Klocke, Koren, Lenz, Oxley, Patri, Schulz, Teti, Ulsoy,	Altan, Altintas, Bouzakis, Ceretti, Childs, Koren, Ueda,	Bouzakis, Colding, Davies, Dautzenberg, Etxeberria, Fang, Grabec, Jawahir, Kaldor, Klocke, Koren, Kuljanic, Kumara, Lenz, Li, Lindstrom, Majstdrovic, Narutaki, Novak, Play, Ruisi, Schulz, Srivastava, Teti, Toenshoff, Ulsoy, Vigneau, Warnecke	Fang, Lenz, Leopold, Majstdrovic, Teti, Warnecke	• Extensively empirical in nature. • Still largely restricted to Taylor-type equations. • Several attempts have been made on analytical modeling.	• Need for establishing standards for concurrently occurring multiple tool-wear types in machining with complex grooved tools. • Need for implementation of a unified procedure for tool-life testing. • Analytical prediction of tool-wear rates.
Chip Form/ Chip Breakability	Armarego, Dautzenberg, Fang, Jawahir, Kruth, Lenz, Ostafiev, Patri, Teti	Altan, Ceretti, Fang, Ostafiev, Spur, Ueda, Weinert, Xie	Dautzenberg, Dornfeld, Jawahir, Kaldor, Klocke, Lenz, Majstdrovic, Nakayama, Nedess, Rehsteiner, Teti, van Luttervelt, Warnecke	Fang, Jawahir, Li, Majstdrovic, Warnecke, Weinert	• Significant contributions have been made by the CIRP international working group on chip control during 1990-93. • Predictability of chip breaking has become a requirement for advanced machining.	• Developing an analytical/ numerical capability for predicting the type of chip formation (e.g. serrated chip, smooth chip, discontinuous chip, etc.). • Prediction and quantification of chip forms. • Analytical prediction of burr formation.
Surface Roughness/ Surface Integrity	Altintas, Armarego, Bouzakis, Colding, Grabec, Klocke, Koren, Oxley, Rehsteiner	Altan, Altintas, Bouzkis, Koren, Leopold, Reutsch, Ueda	Bouzakis, Colding, Grabec, Klocke, Koren, Le Maitre, Leopold, Nakayama, Narutaki, van Luttervelt, Warnecke	Fang, Leopold, Li, Rehsteiner, Warnecke	• Very limited predictive modeling attempts. • Purely geometric relationships for surface roughness. • Complex relationship noted between surface roughness and operational parameters, work materials and chip breaker types.	• Developing predictive models. • Establishing tool-chip interactions with the cutting conditions and corresponding material flow behavior.
Part Accuracy	Ostafiev, Patri		Ostafiev, Patri, van Luttervelt	van Luttervelt	• Closely related with and dependent on other machining performance measures. • Traditional correlation with machine tool vibrations.	• Urgent need for modeling attempts on part accuracy. • Analytical modeling of a machining system for process and structural stiffness.

Figure A-2 (annex)