CHAPTER

I

Introduction

Man's steadily improving standard of living has been largely due to his ability to devise and make use of tools. His logical and constructive mind conceived readily mechanical mechanisms from the wheel and lever to complex modern industrial machinery. The mechanisms of such tools were readily observed by the human senses and thus understood and accepted. The less tangible natural phenomena, however, such as electricity, chemical reactions, and fluid dynamics, were not easy to observe or to understand. Although today these are well-developed sciences, their early progress was hindered by lack of comprehension, distrust, and even religious opposition. Lack of understanding may be the reason why electrochemical machining, which is based on these less tangible sciences, has been slow to attain the acceptance and general use that it deserves.

Shaping components by selective removal of metal has been performed traditionally by mechanically operated tools. Using the principle that a hard material will cut a softer one, the traditional machines control the movement of a hardened tool as it cuts metal from components. The more familiar include turning, boring, milling, planning, broaching, and grinding machines. All these have been in use for half a century or more. They are now of sophisticated design and use specially developed tools; tool movements are often automatically rather than manually controlled. This development of metal-cutting technology has been necessary to keep pace with the advances in engineering materials and component designs and the need for increased productivity. But these well-used, well-understood traditional tools are nearing the limits of development and are not always suitable for machining today's tough super-alloy materials and complexity shaped components.

Electrochemical machining, a new powerful tool, is one of man's latest innovations. It has farther reaching capabilities for metal removal than traditional mechanical tools, and in many ways, is a simpler, more direct, fundamental method. Metal is gently dissolved away, atom by atom, rather than mechanically "torn" away. Although very simple in its principle of operation, its reliance on electrical, chemical, and fluid flow phenomena can set imaginary barriers to its comprehension. It is a revolution in machining and so new fundamental principles must be learned.

Dissolution of the anodic electrode, during electrolysis, is the basis of electrochemical machining. (The mechanism of this dissolution and the engineering controls necessary to make it an effective metal-shaping process are discussed more fully in Chapters 2 and 13.) The general principle of anodic metal removal was one of the discoveries of Michael Farraday (1791–1867). From Farraday's work stemmed the development of electroplating, electropolishing, and so on, processes that are well established in our manufacturing industries.

Suggestions for the application of anodic metal removal as a metal-working technique were proposed by W. Gusseff, a Russian, in 1929 (see British patent No. 335,003) and again much later by C. F. Burgess in a paper for the Electrochemical Society (United States) in 1941.

But is was not until the fall of 1959 that the phenomenon of anodic metal removal was put forward in the form of commercial apparatus for regular industrial application by Anocut Engineering Company of Chicago. In the following year the Steel Improvement and Forge Company announced its commercial application of the process based upon research by the Batelle Memorial Institute.

Anocut Engineering Company of Chicago played a major role in pioneering the process and in overcoming the technical problems peculiar to the equipment used for it. Other firms entered the field, and through collaboration between users and machine tool interests, brought about the rapid development of a wide range of electrochemical machines from 1960 through the remainder of the decade. There are now several manufacturers of these machines in the United States of America, Europe and Japan.

The tough alloys and complex components, which are increasing in the modern manufacturing scene, particularly in the gas turbine industry, have tested severely and sometimes exceeded the capabilities of our well-used manufacturing processes. It is not surprising, therefore, that the introduction of electrochemical machining into manufacturing has received much impetus in recent years.

Electrochemical machining's (ECM) application in all fields of indus-

try is almost boundless; yet understanding, confidence, and willingness to make this fundamental change in approach is growing lamentably slowly in our so called space age. It has been used to a greater extent in the aeroengine industry than in any other. It would be nice to say that this industry is more progressive, but the use of ECM has often been promoted by extreme need, rather than by progressive attitudes in manufacturing. The complexity of component shapes and toughness of the high-strength, heat-resistant alloys used in gas turbine aeroengines can preclude the use of conventional mechanical methods of manufacture. Faced with extremely difficult manufacturing problems or intolerably high costs these industries have turned to ECM for relief. Unfortunately, the pioneering has, therefore, been on exceptionally difficult and exacting work—a real case of being "thrown in at the deep end." Needless to say, progress has been slow in advancing the process, since special new skills and knowledge have had to be developed, to a high degree, to electrochemically machine these "super" components. Both the time required to develop proficiency for success in application, and failures when this proficiency has been lacking have promoted a general reluctance towards full utilization of the process. Many industries today, however, have broken through this initial learning barrier, and following upon their first successes, have extended the use of the process into many aspects of manufacture. The initial "high risk" factor has been eliminated and necessarily high machinery and tooling investments made based solely on the economic and quality advantages of the process. The list of advantages offered by ECM is so impressive that those working closely with the process are frustrated continually by the effort required to gain wider confidence and acceptance for it. Its advantages fall into three groups, costs, quality, and flexibility.

1.1 ECM ADVANTAGES

Costs

In many ways ECM has similar characteristics to forging and casting. The foremost of these is the ability to produce a large complexly contoured surface in a single pass of the ECM tool. A direct saving in machining time is made compared to a mechanical milling operation, in which a small cutter has to traverse the entire contour several times. Many mechanical operations may be replaced, and finishing operations, such as deburring, blending radii, and polishing are usually avoided. Add to these capabilities

- Low scrap
- Unskilled or automatic machine operation
- No tool wear

and the potential for reducing manufacturing costs becomes apparent. The capability of a single ECM machine to perform work faster and displace several mechanical machining operations also reduces inventory expense, since there is less work in progress, and the capital investment in both the machines and the buildings they occupy is less. ECM may also be regarded, perhaps more realistically, as a process which may be used to manufacture modern technically advanced components without increasing the price of the final product, despite rapidly rising labor costs. This is frequently the reason for using the process in the aeroengine industry. Improved jet-engine performance requires the use of complexly shaped components of "super-alloy" materials. The time required to machine conventionally, for example, an engine casing has increased today several fold over the time required to produce a similarly sized part 10 years ago. Labor costs have also increased alarmingly. Component complexity or material toughness are no problem to ECM, and its capability to process parts rapidly minimizes the burden of increased labor costs.

Quality

ECM is a controlled process rather than a method of machining. Metal is dissolved away electrolytically so that surfaces are consistently produced which are free from imperfections or stress. The process naturally produces radii on corners and does not produce burrs. The stress-free electrochemically machined surface does not have the fatigue strength of surfaces produced by mechanical machining. A suitable, and very consistent, mechanically worked surface can be obtained, however, by post ECM treatment of the surface by glass ball peening or similar processes; such surfaces then display good and consistent fatigue strengths.

Accuracy is difficult to define, since it is dependent on the quality standard of the tooling and the degree of process control imposed. There is also some variation in accuracy, depending on the shapes that are to be produced. Within these limitations, general values of accuracies

are as follows:

- On contoured surfaces ±0.005, or ±0.002 in. can be obtained by special care in tool design or by developing tool contours by trial and error.
- Specific dimensions, as determined by the depth of penetration of a tool into the work, can be held to ±0.001 in.
- Care in tool design, some empirical tool development, and very close control of the machining parameters will permit tolerances of ±0.0005 in.

It should be noted that these values of accuracy are typical of values generally obtained using currently available equipment and technology. In some cases, for example, the machining of cylindrical steel rods using tapered ring-type cathodes and sodium chlorate electrolyte, much closer tolerances are achieved. The ultimate limits of dimensional quality have yet to be ascertained but undoubtedly will depend on the ruggedness and precision of machines and tooling, the close control of the machining parameters, and the selection of electrolytes.

Flexibility

A general purpose EC machine can produce a wide variety of component shapes, large or small in area, or several components at once. The diversity of the process is indicated by comparing Figures 1.1 and 1.2. The process duplicates nearly all mechanical cutting methods; hard or tough materials, complex contours, and thin sections are all readily machineable. This flexibility makes ECM a powerful production tool and

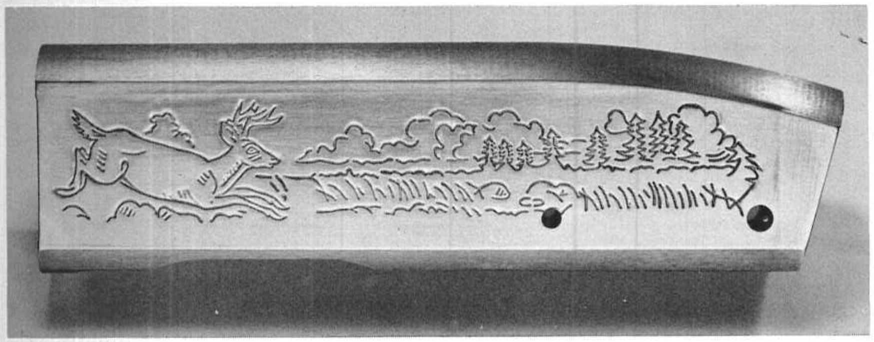

Figure 1.1 Fine definition of an EC machined motif on a rifle stock. (Courtesy of the Anocut Engineering Company.)

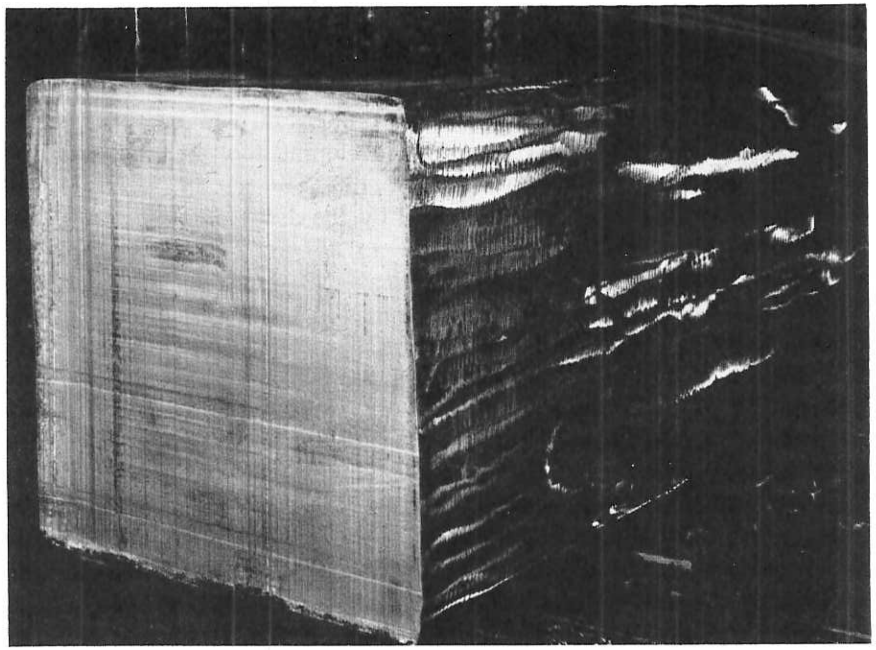

Figure 1.2 Massive billet, approximately 30 in. square, cut through with an ECM tool. (Courtesy of the Anocut Engineering Company.)

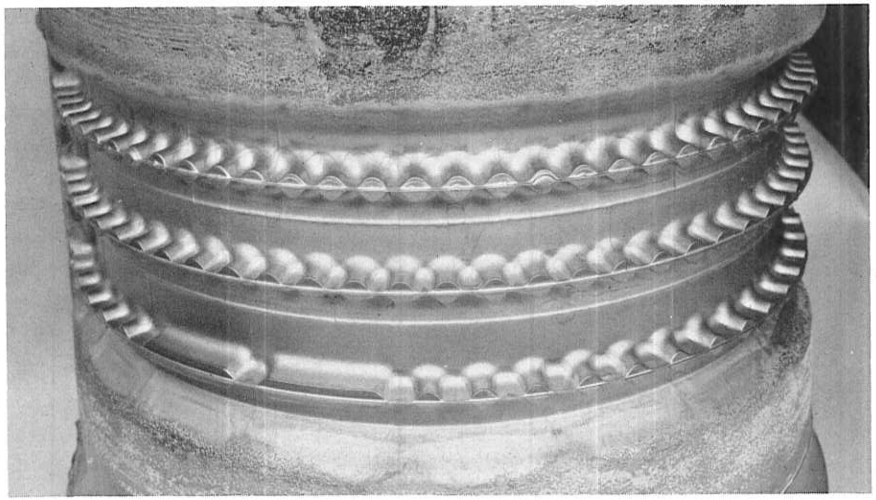

Figure 1.3 Electrochemically machined section of a 16-in.-dia. titanium aeroengine casing. Three banks of electrodes, each similar to that shown in the frontispiece, produced this excellent standard of surface finish and dimensional control in only 1½ h of machining. (Courtesy of the General Electric Company.)

permits greater latitude in component design. An excellent example of ECM work can be seen in Figure 1.3.

1.2 DISADVANTAGES

The disadvantages of ECM, apart from considering suitability to perform particular types of work, lie in the difficulty in learning to use it and justifying initial starting costs. Machines are not sold in quantities sufficient to obtain the benefits of mass production and, in addition, still reflect development costs. It is expected that the price of machines will continue to fall; but the corrosion-resistant materials used and the number of auxiliary pieces of equipment, electrical and hydraulic, which comprise the machining facility, will always make the machines expensive. Tooling also is expensive, but while this limits the process to quantity production, the equivalent conventional tooling is usually similarly priced. The initial investment in machine and tooling may be $150,000 or more, so that there must be great confidence that the tooling can be correctly designed and then operated successfully in production. Unfortunately, instruction in tool design is not readily available and even though tool design is relatively straightforward, specialized knowledge is required.

Again, operation of the ECM process is simple, but lack of proper knowledge makes even the most minor problem a major delay. Those concerned in any way with ECM must have adequate aquaintance with its principles of operation and capabilities to make sound judgments. If full use is to be made of the process, it should be well understood by management, component design, production, development, and quality control personnel; those immediately charged with the operation of ECM should have specialized skills and knowledge. Generally training is a difficult task, since few experts are available, learning by experience is long and expensive, and useful information is retained as proprietary by successful users.

There are numerous publications and patents on ECM, but these are either very repetitive in the information they provide or are so academic and specialized that only someone already knowledgeable in ECM can place the information in useful perspective.

1.3 LEARNING TO USE ECM

A good way to shorten the learning period is to have an electrochemical machine supplier build and test tooling for the first applications so that he can supply the first machine together with operational tooling. Usually a complete service is available to provide guidance in the selection of components for ECM, prove tooling, install the ECM facility, and guide in subsequent production. This sounds like the complete answer but, alas, is not. The process needs team effort within a company for lasting success. In the longer term, the machine tool supplier is too remote from the scene to fully coordinate the many facets of ECM into the complete engineering structure of a company. In addition they do not, generally, have the long-duration production experience essential to trouble-free, continuous operation of the process.

ECM jobbing shops also provide a means of getting parts made by the process without risk of failure. Certainly this is a good way to gain acceptance of the process with regard to quality and economics. It also provides a means of using the process when fewer components are to be made than justify the purchase of a full machining facility. Actual "know-how" cannot be learned in this way, however, since it is essential to operate a facility in-house and build a proficient team of ECM people, to obtain full benefits from the process.

At the time of writing there are about thirty factories in Europe and in North America that successfully operate groups of EC machines. The gas turbine industry predominates with twelve such factories, but there are also very successful facilities operated in the large electrical, forging, and automobile industries. There are eleven job shops that specialize in ECM work and about 200 machines larger than 3000-A (ampere) capacity that are in service. Most of these are of 10,000-A capacity, but machines of 40,000-A capacity are in use at several locations. There are also many smaller machines used on small components, such as turbine blades, test specimens, and so on.

It is perhaps significant to reflect on how these successful appliers of ECM first made use of the process. Usually it started with one or two creative engineers experimenting on either a home-made machine, or a small capacity machine purchased from a machine tool supplier.

Having gained experience and demonstrated a degree of process capability these engineers formed a nucleus and impetus for the growth of an ECM team. The team ideally included people knowledgeable in ECM in functions such as, tool design, tool and machine maintenance, production planning, facility engineering, and process development. The ECM team, however, only provided the capability to produce. The other vital factor which permitted the establishment of the process was in gaining the understanding, confidence, and acceptance of it by the engineers within the structure of a company who were not directly involved with ECM. These engineers were the customers and had to be convinced

before they would want the products of ECM or be prepared to finance ECM. Component designers, for example, had to be convinced their quality standards would be met; production engineers needed assurance of costs and ability to meet their schedules; managers needed proof that their investment in the process was sound, and so on. This educational role also fell on these ECM experts. They had to be first-class salesmen as well as engineers.

The situation is similar today for any company entering this field of manufacturing technology. While still difficult, the first steps a company must take are becoming progressively easier, however, because of the availability of sophisticated EC machine tools and the example of already successful users.

One aspect of ECM, that of the design and operation of the tooling, has proved to be a problem and is perhaps the single remaining object delaying its wider use.

Even today tools tend to be designed by guess work; engineers rely heavily on final empirical development of the tools on the machine. Delays occur while tooling is being reworked and adjusted before being put to work in production. The real cost of the finally developed production tool is, therefore, prohibitively high; early commitments to meet production schedules cannot be made; and the whole enterprise becomes shrouded in risk and uncertainty. Tool design, so far, has been an art rather than a technology. Faced with this lack of firm design principles, several workers have researched the process parameters but their results have been presented in too complex a form for ready use in tool drafting offices. The tendency has been to over complicate rather than simplify the process. As a result, to some it has seemed unwieldy and over academic for practical use. In fact, the process is simple, practical, and economic. There is a wealth of knowledge and experience, both practical and academic, in electrochemical machining. The expert user can now identify the basic simplicities so that he can apply the process with positive assurance. ECM tooling can be designed by an engineer knowledgeable in this field that will perform production work without need of development activity.

The main objective of this book is to set out the basic principles of tooling design and operation in the most direct way possible, to permit the reader to successfully apply ECM. The tooling is the most critical factor, and yet, it is in this area that little literature exists. The intention is to present tooling design and operation as systematic procedures, based on logical theory and practice, and, in so doing, show ECM as a working technology rather than an unpredictable art. The theories and practices, which will be discussed, are all based on actual production operations.

While these have been used by the author and others extensively, it is expected that alternative approaches may prove very successful. Indeed, it is to be hoped that many new and significant advances in ECM process technology will be made in the next decade.

Some coverage, although in less depth, will also be given to other significant aspects of the process such as its fundamental theory, machinery and its installation, economics, electrochemistry, and so on. Again, the emphasis will be on only the information necessary for proper understanding and application of the process.

There are, of course, many specialized aspects of the process, and others of purely academic interest, that could provide absorbing reading; these are not included in this book. Such information would detract from the basic process technology, essential to successful physical handling of the process, and the basis for sound business judgement as to its use.

CHAPTER II

Fundamental Principles of the Process

When a voltage is applied between two metal electrodes which are immersed in an electrolyte, current flows through the electrolyte from one electrode to the other. Unlike the conduction of an electric current in a metal, in which only the electrons move through the structure of the material, "ions," electrically charged groups of atoms, migrate physically through the electrolyte and in so doing carry the current. The transfer of electrons between the ions and electrodes completes the electrical circuit and also brings about the phenomenon of metal dissolution at the positive electrode, or "anode"; this is the basis of metal removal in the ECM process. Gases are also produced at the surfaces of the electrodes, the greatest volume being hydrogen which is evolved from the surface of the negative electrode, called the "cathode." The metal detaches from the anode surface atom by atom, and after a somewhat complex mechanism at the surface of the anode, can appear in the main body of the electrolyte as positive ions, or which is more normal in electrochemical machining, as precipitated solids of the metal hydroxide. Electrolytes may consist of acids or, more generally, of basic salts dissolved in water. In the presence of water, salt crystals split into small positively and negatively charged particles which move independently throughout the solution. These are known as "ions" and may be a single atom or a group of atoms bearing one or more units of electrical charge. The negative charges equal exactly the positive charges but the numbers of negatively and positively charged ions may not necessarily be equal.

The application of a potential between immersed electrodes sets up an electric field that cause migration of the ions as shown in Figure