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

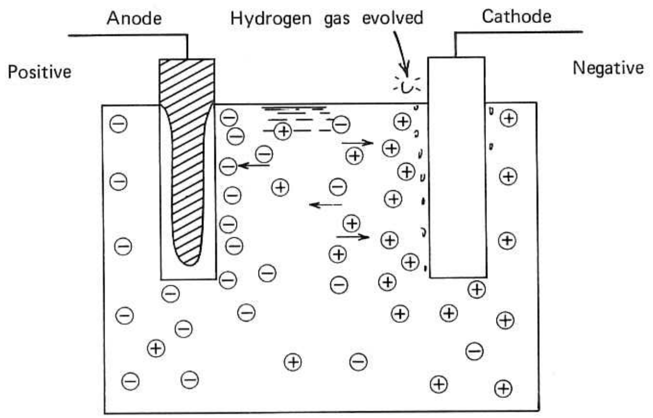

Figure 2.1 Simple electrolytic cell showing movement of ions.

2.1. The circles represent the distribution of the ions under the influence of an applied electric field. The intense potential gradient between the concentration of positive ions and the adjacent cathode surface causes electrolysis of the water. In this reaction the water molecule gains electrons from the cathode so that it separates into free hydrogen gas and hydroxyl ions.

$$2H_2O + 2e \rightarrow H_2 + 2OH^-$$

The introduction of hydroxyl negative ions is electrically balanced by positive metal ions entering the electrolyte as the anode dissolves.

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

Metal ions do not remain in solution when neutral electrolytes are used, but combine with the hydroxyl ions to form the metal hydroxide. Since this is insoluble in water it appears as a solid precipitate and no longer affects the electrochemical reactions.

$$Fe^{2+} + 2H_2O \rightarrow Fe(OH)_2 + 2H^+$$

This process is another aspect of electrochemistry, as explained more fully in numerous other books, stemming out of the original work by Faraday and obeying his famous laws of electrolysis.* Electrolysis has been successfully put to work in industry in such familiar fields as electroplating, electroforming, and electropolishing. The interest in the first

* The amount of chemical change produced by an electric current, that is, the amount of any substance deposited or dissolved is proportional to the quantity of current passed.

two is in the reaction which occurs at the cathode surface where metallic ions become captive and thus form a skin of new metal. The first is for decorative or corrosion protection purposes (car bumpers, table ware, etc.), while, in the second, the original cathode is dissolved away so that the plated shell of metal forms the final article. In the last process, electropolishing, it is the dissolution of metal from the anode surface that is of interest and which, if properly controlled, leaves a bright smooth surface on the anode. This process has most in common with ECM, since controlled metal removal is the important feature, but falls very far short of ECM in both rate and control of the metal removal.

All these well-used processes, based on electrolysis, are operated using widely spaced electrodes in tanks of almost static electrolyte. Electrolytes are also of a specialized nature; small currents are used [only a few amperes per square inch (psi) of electrode surface]; and metal removal or deposition is correspondingly small. In Figure 2.2 the lines joining the remotely spaced electrodes indicate the distribution of current flow. While there is preferential metal removal from the anode surface facing the cathode, metal removal also occurs on its other surface.

Consider, however, what happens if the two electrodes, instead of being remote from one another, are placed very close at about 0.020-in. separation, and a potential of 20 V (volts) is applied between them. The ions in the electrolyte will migrate towards the electrodes. Positively charged ions are attracted to the negatively charged cathode and negatively charged ions are attracted to the positively charged anode electrode. The rate at which they can arrive at their respective electrodes is dependent upon the applied voltage which provides the motivating

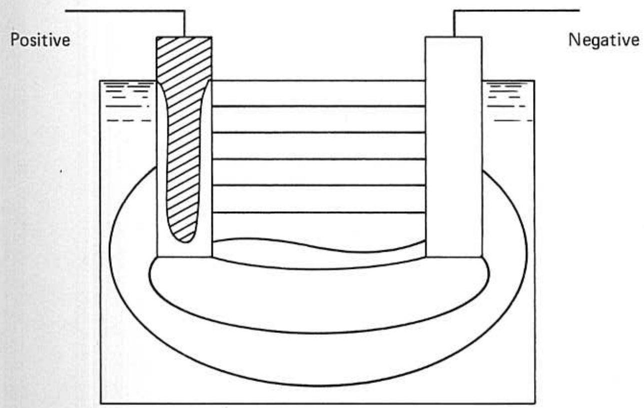

Figure 2.2 Simple electrolytic cell showing distribution of current flow.

force; the number of ions present which increase with the concentration of the electrolyte solution; and the length of the path that the ions must follow to reach the electrode. The motivating force is more precisely determined by the voltage gradient rather than just the applied voltage. So that the smaller the distance between the electrodes, the greater the voltage gradient, hence the motivating forces. In the very small gap spacing under consideration the potential gradient will be very high and migration of the ions proportionately fast. The correspondingly high current will be 100 to 1000 A/in.^{2} and metal removal from the anode surface 0.010 to 0.100 in./min.

Electrodes in close proximity are shown in Figure 2.3. The density and direction of current flow is indicated by lines joining the electrodes. The smaller the gap, the greater will be the current flow and rate of metal removal from the anode. The dotted line shows the shape of the anode after a period of ECM. It can be seen that, even with stationary electrodes, the shape produced resembles that of the cathode.

The high current density promotes rapid generation of hydroxide solids and gas bubbles in the small spacing between the electrodes. These become a barrier to the electrolyzing current after a few seconds. To maintain continuous rather than transient high current densities and high rates of metal removal, these products of the machining process must be continuously and rigorously removed. This is achieved by circulating

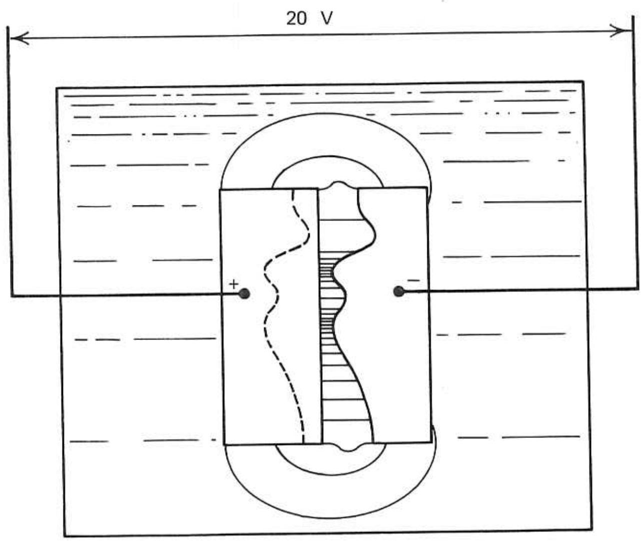

Figure 2.3 Distribution of current flow between closely spaced electrodes.

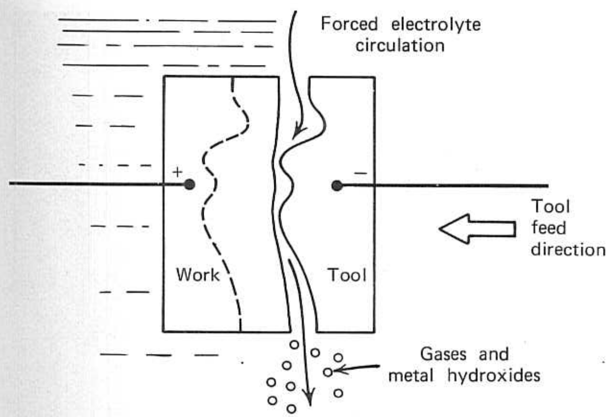

Figure 2.4 Fundamental elements of ECM.

electrolyte at a high velocity through the gap between the electrodes. In practice the electrolyte is channeled into the gap at supply pressures of 25 to 500 psi to achieve suitable flow velocities.

The forced circulation of the electrolyte permits continued fast metal removal from the anode. The original gap increases in size rapidly at first but then at a progressively decreasing rate. This is because the current falls as the gap, hence its electrical resistance, increases. An additional variable is required to maintain the current density at its initial high value. If the cathode is moved towards the anode at the same rate at which the metal is being dissolved, then the gap spacing will remain constant and current and metal removal rate will remain high. This is shown in Figure 2.4. As the cathode advances the anode progressively attains a shape that is almost an exact replica of the cathode.

Thus the two new concepts that make high metal removal rate possible are forced high velocity circulation of the electrolyte and controlled movement of one electrode towards the other. They form the basic concept of ECM.

At this point it is appropriate to consider the mechanism that permits ECM to machine a component accurately in addition to its capability of high metal removal rate. Current is conducted from all surfaces of the cathode electrode surface to all surfaces of the anode electrode. The smaller the gap spacing at various points between confronting surfaces of the electrodes, the higher will be the current density and greater the rate of metal removal. It is evident that, with progressive movement of the cathode towards the anode, ultimately the two surfaces will closely

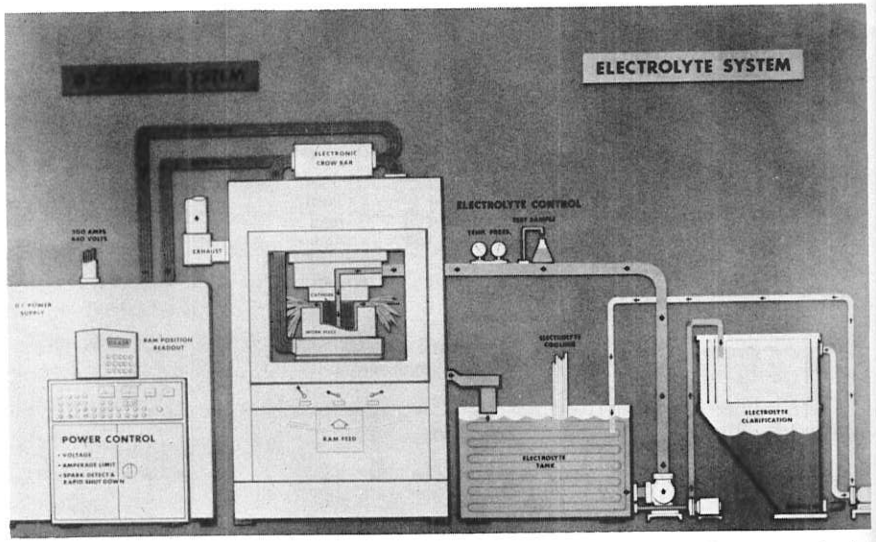

Figure 2.5 Electrochemical machine and auxiliary systems. (Courtesy of the Anocut Engineering Company.)

correspond. In fact, for reasons which will be explained more fully later, the surfaces differ by a small predictable amount that can be corrected by adjusting the cathode shape. What is important is that repeatable shapes are produced.

The process is really a very simple one, but requires specially engineered equipment for its use as a manufacturing tool. In broad categories, an EC machine consists of an electrolyte system which provides high velocity electrolyte flow between the electrodes; an electrical power system which supplies the electrolyzing current to the electrodes; and a mechanical structure which locates and provides movement of the electrodes. These systems are shown diagramatically in Figure 2.5. Aspects of their engineering, and the way in which these relate to the fundamental principles of ECM, will be discussed in the following sections.

2.1 THE ELECTROLYTE SYSTEM

High velocity electrolyte flow over the electrode surfaces is one of the key factors that separates ECM from other electrolytic processes. The high velocity limits ion concentration at the electrode surfaces and, in turn, permits passage of higher machining currents; an important

factor is dilution of the electrochemical reaction products, including heat dissipated by passage of the electrolyzing current. Velocities required are 100 to 200 ft/sec and so high pressures, 80 to 400 psi, are needed to force the electrolyte through the small machining gaps. Flow rates are dependent on the size of components to be machined, and so, pump capacities of 300 gal/min are not uncommon for machining components larger, for example, than a 12-in.-dia. turbine wheel. The electrolyte is circulated from the pump through the tooling, to exhaust into the work enclosure of the machine and then return, by gravity, to a storage tank.

The machining gap is small to obtain high rates of metal removal and to control accuracy. This gap must always remain clear, however, to allow smooth passage of the electrolyte. Any blockage will reduce locally the flow velocity, a condition not conducive to smooth dissolution of the work. Such blockages in the gap are caused by nonmetallic particles carried by the electrolyte. Another problem occurs when metallic particles short circuit the electrolyzing current between the electrodes. The local heating and sparking that results can produce serious damage to both the tool and work surfaces. Thus electrolyte cleanliness is imperative. A wire mesh filter, placed in the supply pipe, prevents these unwanted particles from reaching the tooling and therefore, is another vital feature of an EC machine. The filter prevents passage of particles greater than one third the machining gap size. A 75-μ (micron) (approximately 0.0035 in.) filter, adequate for operation at gap sizes down to 0.010 in., is suitable for performing most work. The best are those of a single weave of stainless steel (type 316) or monel wire. These are corrosion resistant, and because of the short flow path through the mesh, do not readily become clogged with metal hydroxides. Filter media of any appreciable depth are not suitable, because they rapidly become clogged and restrict the flow of electrolyte to the tooling.

Electrolyte properties also influence the size of the machining gap that, together with the tool shape, determine the geometry of the finally machined component. Variation of the electrolyte parameters—composition, concentration, pH (degree of alkalinity or acidity), temperature, and concentration of solids—will affect the accuracy of machining. Therefore, these are closely controlled. While a small quantity of metal hydroxides, introduced during machining, does not significantly affect the process, large proportions, if permitted to accumulate, do reduce efficiency and ultimately lead to process failure. Hydroxide in the electrolyte is limited by continuous removal using large settling tanks or centrifuges. Control of composition, concentration, and pH is achieved by adding either water or chemicals to the electrolyte, following periodic analysis of check samples. These properties are important because they affect either the conductivity of the electrolyte, hence the electrical resistance within the machining gap, or the electrochemical reactions taking place at the electrode surfaces.

The electrolyte is also temperature controlled. The temperature affects the chemical activity and the electrical resistivity of the electrolyte. Both are factors in determining the machining gap, hence the final work contour.

The Electrical Power System

Very large, direct currents are used in ECM. Current densities of 100 to 1500 A/in.^{2} on the electrode surfaces are typical for industrial applications of the process, although much higher values, about 5000 A/in.^{2}, are sometimes used.* Experimentally, currents of 50,000 A/in.^{2} have been achieved. In terms of metal removal, 1 in.^{3} is removed by 10,000 A/min. This convenient relationship is surprisingly accurate for most metals. Potentials of 5 to 25 V, applied across the tool and work electrodes, are required to circulate these currents through the resistive machining gap. Voltage must also be closely controlled, since it is a factor in determining the size of the machining gap, hence the accuracy of the work contour.

Electrical power systems have DC outputs up to 40,000 A, but 10,000 A units are the popular size. These transform and rectify standard high voltage, 3-phase, AC supply to a smooth DC output at closely regulated voltage. The output may be set to any voltage, within the range of the machine, to suit a particular machining operation. Heavy cables or copper bus bars are used to carry the large machining current from the power unit to the work enclosure of the machine. The power system also includes protective devices to switch the power off in the event of process malfunction, and the electrical control circuits for all the equipment comprising the machine.

Strength and rigidity of ECM fixtures, tooling, and machines are comparative with machines used for mechanical metal removal. This is because high pressures are necessary to force the large volume flow of electrolyte through the small gap between the tool and work surfaces. Containment of the electrolyte, over the large working areas of tools, produces high separating forces. At a pressure of 300 psi, acting over 30 in.^{2} (this is a typical area which might be machined on a 10,000-A machine), the separating force is 9000 lb. Also, other nonoperative areas of the tooling may be subject to high electrolyte pressures. Even larger forces occur with tool vibration. This is because the momentary reduction in the machining gap throttles the flow, causing a large surge in pressure. This effect, often known as water hammer, produces self-excited vibration of the tooling. This leads to loss of process control and, more often, complete process failure. Strength and rigidity in the equipment best ensure against such a problem.

* The amounts of different substances deposited or dissolved by the same quantity of electricity are proportional to their chemical equivalent weights.

Smooth tool movement towards the work is also a requirement to maintain a stable machining gap. The process is slow to adjust following a sudden change in any of the controlling parameters, so that sudden or jerky movements of the tool cause sudden changes in the machining gap. Perhaps 10 sec or so will elapse while the gap adjusts back to its steady-state value. If a sudden movement closes the machining gap too much, process failure occurs.

For these reasons, EC machines are substantially constructed and have robust precision tool feed systems.

2.2 SUMMARY

The ECM facility comprises a rigid machine structure with means for smoothly moving the tools, DC power supply unit, electrolyte tanks, pump, filters, and electrolyte cleaning equipment. These are only the necessary pieces of equipment; their close control of the machining parameters, together with good tooling, and overall process planning, makes ECM an effective manufacturing process.