The cross-sectional area of the ducts supplying the working surface of the tool must be 10 times the minimum cross-sectional area of flow in the gap. Pressure losses in the ducts are then limited to 1 or 2% of the tool operating pressure.

This 10:1 area ratio is good to use as a general rule. Sometimes, because of limited space in the electrode body itself or in some other part of the tooling, it may be necessary to reduce the area of the supply duct. In such cases, the internal contours of the duct are smoothly blended and its cross-sectional area smoothly tapered down towards its entry into the machining area of the tool. Pressure losses in the ducts, to make sure adequate pressure is available at the tool for its operation, should be carefully calculated if the area ratio is less than 5:1.

All pipes and channels, used for ducting the electrolyte, must be of strength suitable to withstand the pressure. Distortion, due to pressure loading, can also affect the accuracy of the tooling. Joints and other interspaces of the tooling are ported to atmosphere, to avoid possible pressure build-up in these areas. Disasterous results may occur if this rather small point is overlooked.

Cleanliness in the electrolyte ducts is essential. The ducts must be designed for ease of inspection against corrosion and debris, and to ensure that seal or gasket material cannot enter the system.

CHAPTER VII

Procedure for Tool Design

7.1 COMPONENT APPRAISAL

The advantages of producing a component by ECM are either financial or metallurgical. These are assessed and compared with other methods of manufacture to determine the suitability of ECM for the manufacture of a particular component. In addition, the availability of equipment and so on are taken into account.

In costing an ECM operation, the capital depreciation of the machine, cost of tooling, labor, and electrolytes are considered. Other factors, such as lack of distortion when ECM is used, will simplify or remove the necessity for other supporting conventional operations with corresponding cost reduction. A thorough examination of costs is only essential, however, in marginal cases, since if the time of an ECM method is a tenth or less of the conventional method of manufacture, and the level of capital expenditure is similar then cost savings are assured.

The time required to perform an ECM operation is determined simply by the tool feed rate and the depth of cut measured in the direction of tool feed. Within the limitations of present production machines, it is usual to estimate the maximum tool feed rate at 0.050 in./min for nickel and titanium alloys, and 0.1 in./min for ferrous alloys. With experience in handling a particular material it is possible to stipulate the process limitations more accurately. These values, however, are intended for planning purposes, since they can invariably be achieved in practice; frequently they will be exceeded. The tool feed rate is estimated at the above values or lesser values, depending on the power available from the machine upon which the work is to be performed. A useful round figure for these calculations is that *10,000 A removes 1 in.^{3} of material per minute.* If, for example, a component of 10-in.^{2}

area is to be machined at 0.050 in./min (500 A/in.^{2}), then a machine of at least 5000-A capacity will be required. A machine of 2500-A capacity would limit the tool feed rate to 0.025 in./min. The area of the work to be machined, considered in these calculations, is the plan area viewed in the direction of tool feed.

Stresses are not induced by ECM so that, provided a component is received in a stress free condition, the machining will not produce distortion. The process is often used economically to produce components that, because of their thin or intricate sections, normally require numerous conventional machining operations to avoid distortion. An excellent example of this is in the machining of sleeve ports for the sleeve valve assembly of an aeropiston engine. Previously punched and milled the ports are now produced slightly faster by ECM. Frequent grinding operations on the sleeve bore, because of distortions introduced by the punching and milling, are no longer required; this accounts for a major part of the cost saving.

Local regions of high stress, which are produced by conventional machining methods, can adversely affect the strength of a component. The thermal shock and fatigue endurance may also be reduced as a result of grain growth in high stress areas on a component operating at high temperatures. As an example of this, some gas turbine makers prefer the stress-free nature of an electrochemically machined surface for high temperature airfoils, rather than the highly stressed surface produced by conventional machining.

An important consideration, in assessing the cost of an ECM operation, is the possibility of a post treatment to improve the fatigue properties of the component. Generally, there is a reduction in fatigue strength of 10% for ferrous alloys to 40% for nickel alloys. Properties are fully regained by removal of 0.0006 in. of metal from the surface by Vibro polishing, grit blasting, or shot peening.

There will also be some work involved in removing ridges left on the electrochemically machined work surface. These correspond to electrolyte slots in the tool or occur between adjacent areas, individually machined.

7.2 DESIGN CHANGES

It usually becomes apparent, either during the initial appraisal of a component or subsequently when the configuration of the tooling is considered in more detail, that small changes in the component design can aid the process, or simplify the tooling. Even if a component has been designed specifically for ECM, the possibilities for further component improvement may only appear at the tool design stage. At this time, compromise can often be reached with the component designer on certain difficult features. As a result, improvements in the final accuracy and surface finish of the component and faster machining time or reduction in tooling costs may be realized.

Each component, of course, presents its own particular problems and each must be treated on its own merits. The following examples, however, occur frequently.

The process requires a rapid flow of electrolyte over all surfaces of the component that are to be machined. Sharp features cause areas of inadequate flow and sometimes cavitation. These lead to irregularities in the component surface and often, complete breakdown of the process.

Figures 7.1*a–c* show how a difficult component can be modified to permit the simple use of ECM. This is also illustrated in Figures 7.2*a* and *b*. Here, the two adjacent bosses give opposing flows of electrolyte, but this is overcome in the second design.

The tool shape is not the inverse shape, or a simple envelope of the component. It bears a complex relationship to the required shape of the work. The methods of tool correction will be discussed later, but what is important in the present context is that the form of the tool need not always have a complex shape. If the designer will accept the complex shape for his component, the tool can then be of a simple shape that is easy to manufacture. This principle is illustrated in Figures 7.3*a* and *b*.

Many tools carry electrolyte supply slots that leave small ridges on the finished machined surface of the component. Also, if adjacent areas are machined, a ridge of material is left between these areas, Figure 7.4. These can be removed by mechanical polishing or milling, but it is sometimes permissible to leave them on the finished component.

7.3 MATERIAL SHAPE PRIOR TO ECM

There are two factors to consider in planning the forging, casting, or other materials from which a component is to be electrochemically machined. These are its shape and the depth of metal to be removed.

Frequently, the initial shape of the material is quite different from the final component. At the start of a machining operation, therefore, the tool is close to the work material only in small localized areas. To prevent the free escape of electrolyte and to direct it over the areas initially machined, considerable complexity has to be built into the tool-

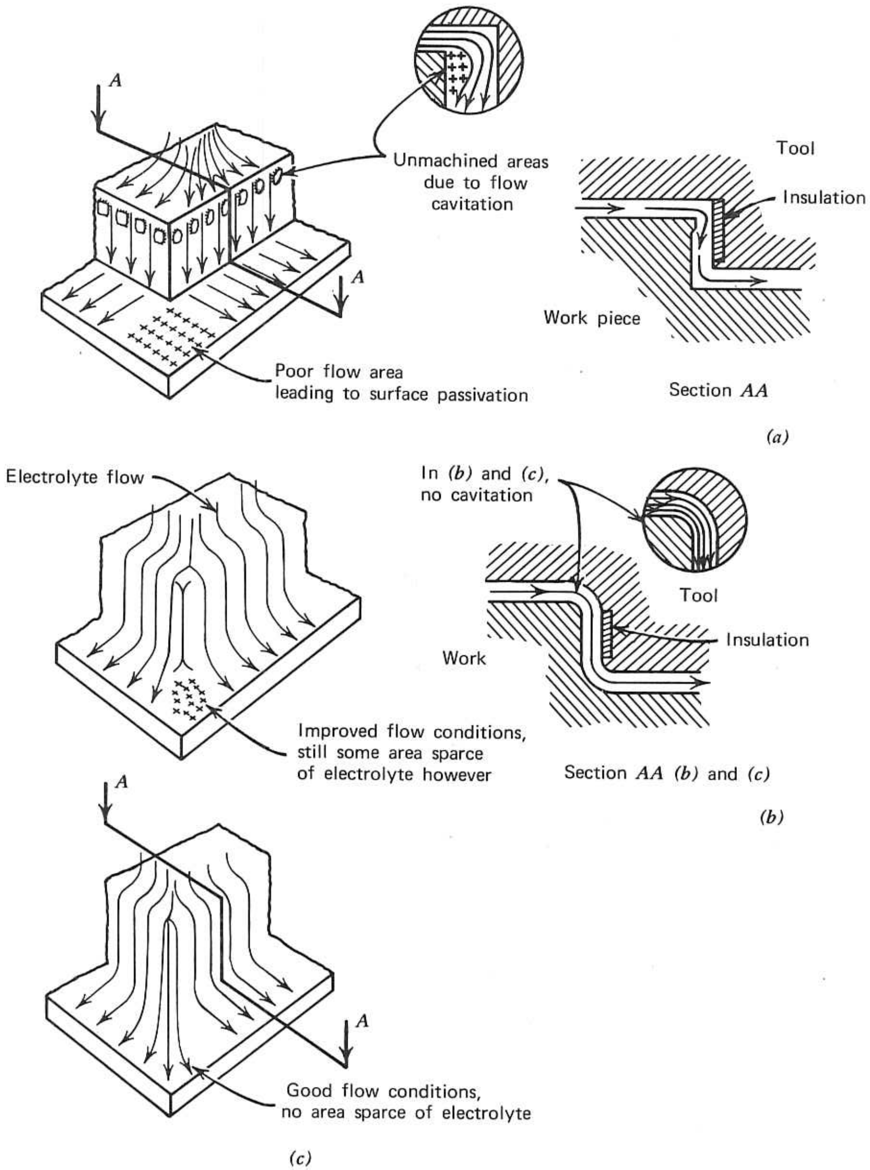


Figure 7.1 Sequence of changes in component geometry for improved electrolyte flow.

ing, that is, tool portings, slots, dams, and restrictors. Tools can be simplified, however, by careful selection of the starting material shape. The engine casing shown in Figure 7.5*a*, for example, has to be machined with a tool feeding radially into its periphery. The forging, if a uniform envelope of the final form, does not initially conform to the tool shape, so that dams are required. In Figure 7.5*b*, however, the forging has

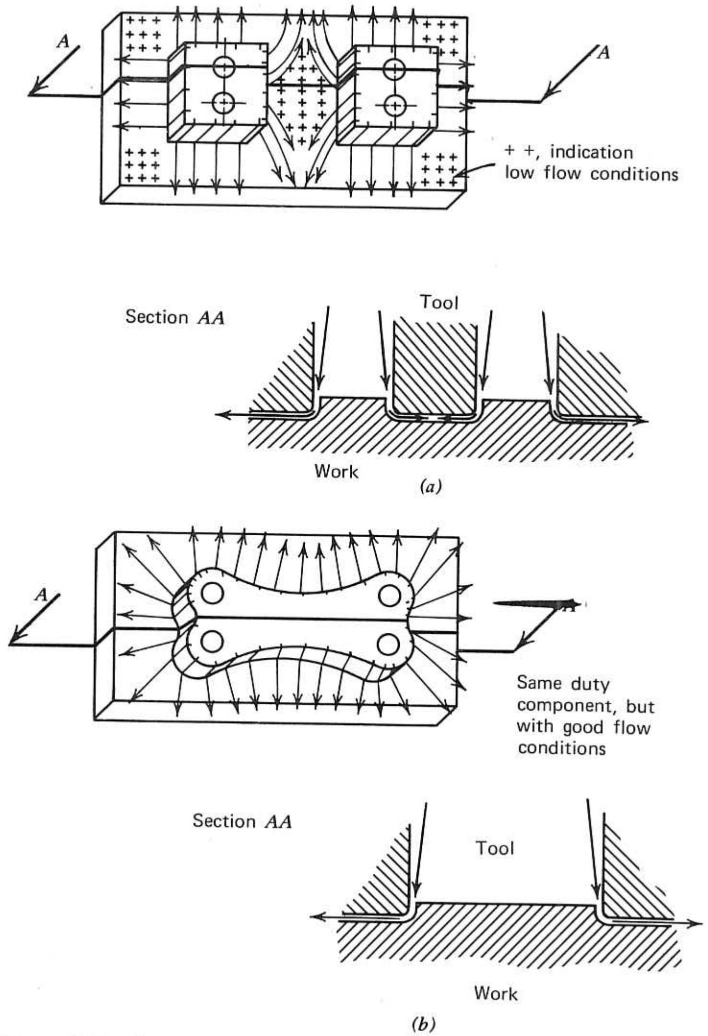


Figure 7.2 Component design change for improved electrolyte flow.

a uniform radial allowance and so it conforms to the tool shape. The tooling and machining operations are thus simplified.

The simple boss, shown in Figure 7.6*a*, if machined from a preformed piece of material as in Figure 7.6*b*, requires complex EC tooling to prevent free escape of electrolyte. On the other hand, machining into a plain rectangular piece of material (Figure 7.6*c*) is a simple operation. Preelectrochemical machining mechanical rough machining operations are a hinderance rather than an asset. The same principle is illustrated in Figures 7.7*a* and *b*, but, in addition, it can be seen that the distance *a* of tool movement required in Figure 7.7*b* is less than *b* in Figure 7.7a, so that machining time is saved.

Unlike conventional machining operations, ECM requires a depth of metal for removal, in order to produce the final form of the work ac-

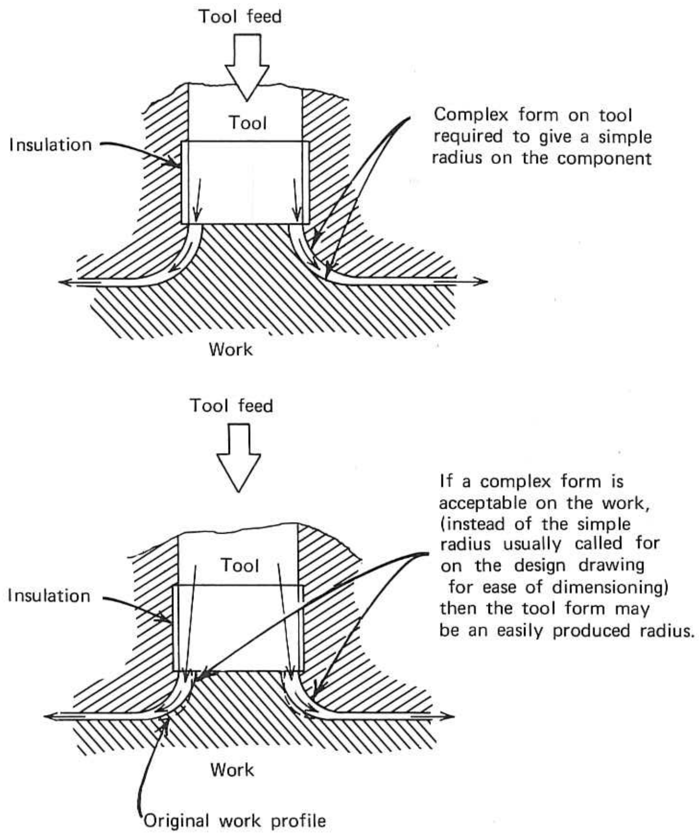


Figure 7.3 A small change to a component drawing can simplify the ECM tool.

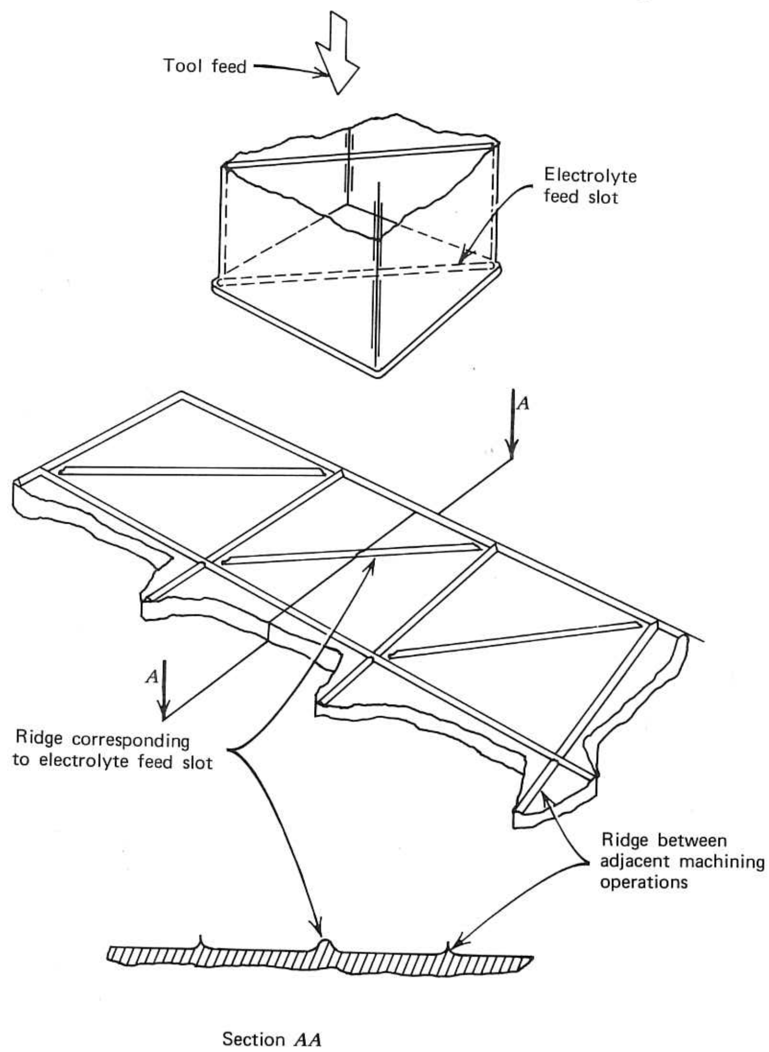


Figure 7.4 Typical ridges, corresponding to electrolyte flow boundaries, left on an ECM component.

curately. This is because all parts of the work, in contact with the electrolyte, are being dissolved away throughout the machining cycle. It is the differential rates of metal removal, dependent on tool proximity, that eventually produce accuracy in the final work contour. Thus for any combination of tool shape, material shape, and equilibrium gap, there is a minimum depth allowance of material to be removed by the

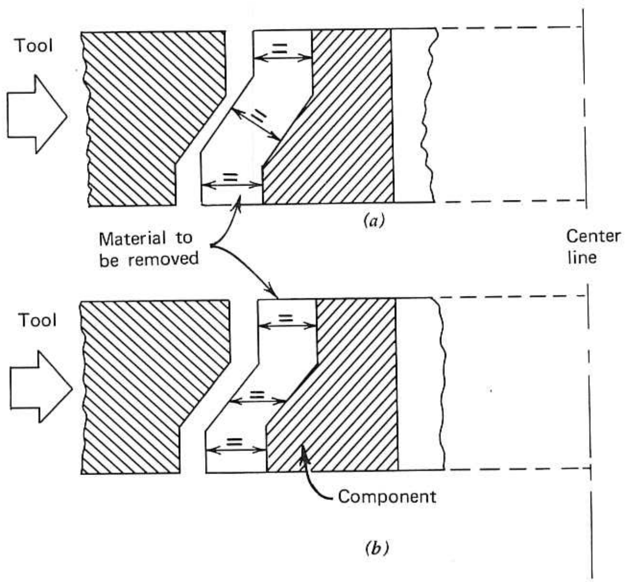


Figure 7.5 Material shape. (*a*) Forging is a uniform envelope of the work and therefore does not conform to tool shape. (*b*) Forging has a uniform radial allowance and thus does conform to the tool shape.

ECM operation, if the tolerance on the final component contour is to be met.

The following calculation determines this minimum allowance. It is theoretically only applicable if the machining action is started when the tool, at its closest point, is at the equilibrium gap h_e from the work; and also when the surface of the tool, at the point of maximum initial gap E, is square to the tool feed direction. In practice, the formula can be used successfully on most applications, if a safety factor of 1.5 to 2 is employed.

The tool, touching the work material, is shown in Figure 7.8*a*. The maximum difference in shape between them is E. Machining is started (Figure 7.8*b*) when the tool at Q, the point nearest the work, is at the equilibrium distance h_e from the work. This gap remains constant throughout the operation. The initial distance at P from tool to work is $Y = E + h_e$ and the minimum material allowance at this point on the work is A.

As the tool advances into the work (Figure 7.8*c*), the gap y between the tool and work at point P progressively closes. The work will just be of an acceptable shape when $y = h_e + t$, where t is the maximum

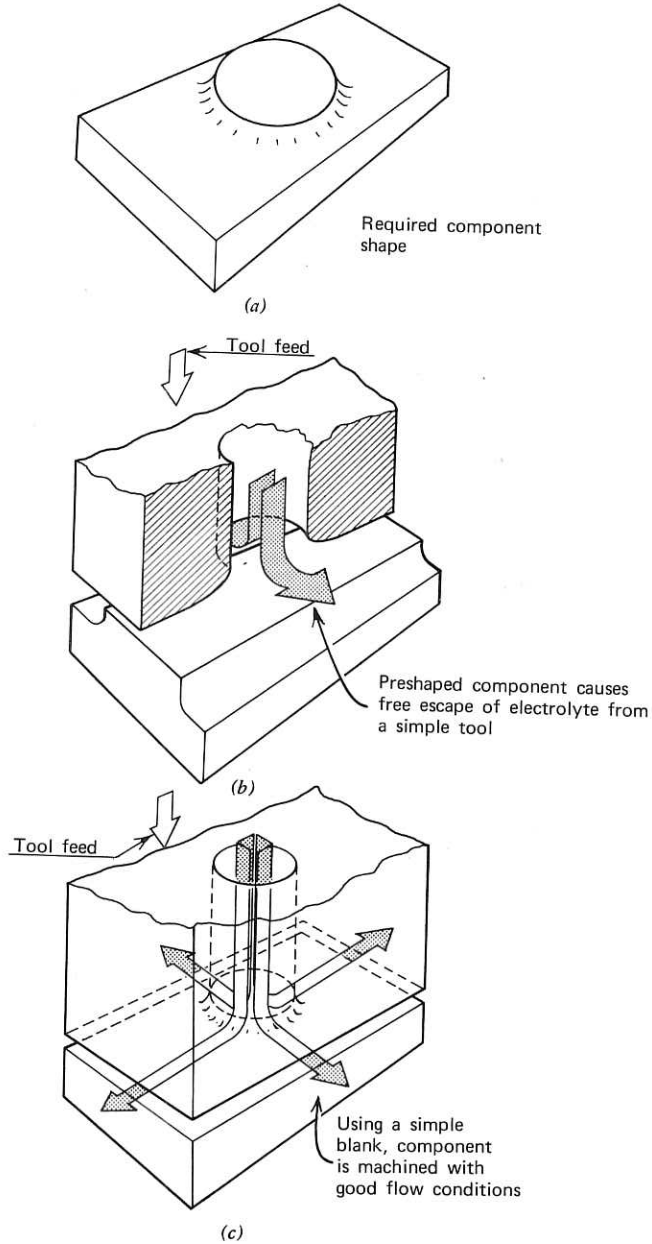


Figure 7.6 The importance of initial material shape for good electrolyte flow distribution.

permissible component error or tolerance. There is extra material removal at this point, since the tool is always catching up the work. In theory the tool moves an infinite distance before $y = h_e$ at this point:

$$\begin{aligned} \text{Initially:} \quad & y = E + h_e \\ \text{Finally:} \quad & y = h_e + t \end{aligned} \tag{1}$$

The rate of change of y, dy/dt, is the difference between the tool feed rate f and the rate at which the work is machining. The machining rate, at any point, is proportional to the current density and this, in turn, is inversely proportional to the resistive path through the electro-

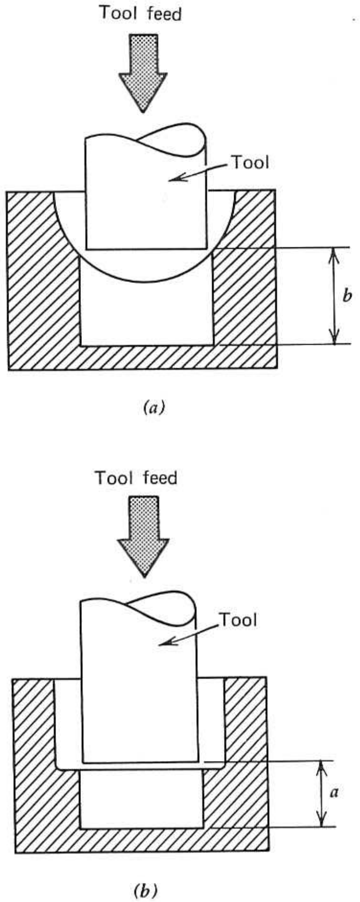


Figure 7.7 Electrolyte flow can be improved and the depth of machining reduced by choice of initial component shape.

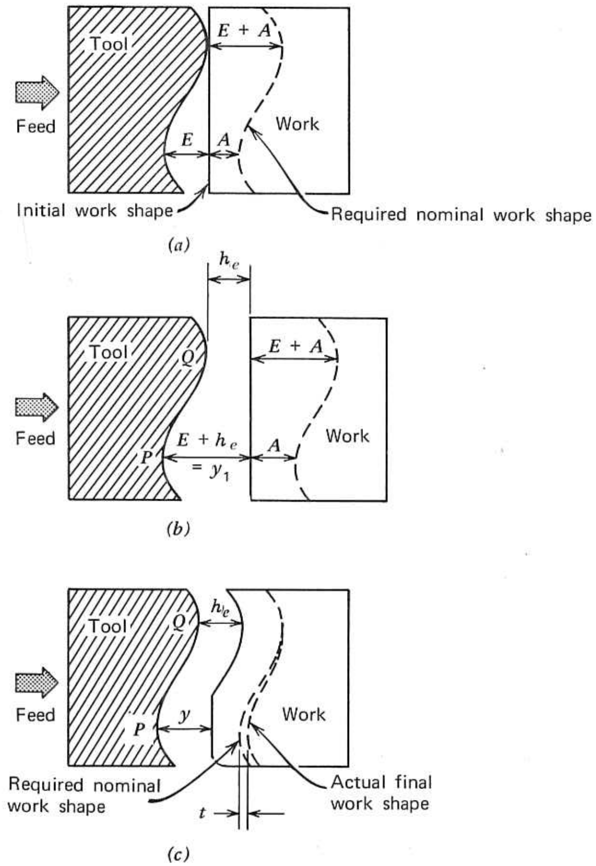


Figure 7.8 Values used in the calculation of material allowance. (*a*) The initial work error E is the maximum gap with the tool and work just touching. (*b*) Tool position at the start of machining with a minimum gap h_e. (*c*) Tool position with work partially machined.

lyte that relates directly to the gap. Thus the *machining rate is inversely proportional to gap*. The machining rate at Q is f at a gap of h_e, so that at P, machining rate $= f\,h_e/y$,

and

$$\frac{dy}{dt} = f - f\frac{h_e}{y}$$

$$dt = \frac{1}{f}\,\frac{1}{1 - \dfrac{h_e}{y}}\,dy$$

Using the limit conditions from eq. 1 the time of the operation T is given by

$$T = \frac{1}{f} \int_{h_e+t}^{E+h_e} \frac{dy}{1 - \frac{h_e}{y}} \tag{2}$$

At Q the tool moves a distance $(E + A)$ to remove $(E + A)$ of material, since h_e is constant. Therefore,

$$T = \frac{\text{distance}}{\text{feed rate}} = \frac{E + A}{f} \tag{3}$$

Equating eqs. 2 and 3, and canceling the $1/f$ common term gives

$$\int_{h_e+t}^{E+h_e} \frac{dy}{1 - h_e/y} = E + A$$

$$\int_{h_e+t}^{E+h_e} \frac{y}{y - h_e}\, dy = E + A$$

$$\int_{h_e+t}^{E+h_e} \left\{1 + \frac{h_e}{y - h_e}\right\} dy = E + A$$

$$\left[y + h_e \log_e (y - h_e)\right]_{h_e+t}^{E+h_e} = E + A$$

$$E - t + h_e (\log_e E - \log_e t) = E + A$$

Hence the minimum material allowance A is given by

$$\boxed{A = h_e \left\{\log_e \frac{E}{t}\right\} - t}$$

For example, a blade forging can be produced within an envelope error of 0.050 in. It is to be electrochemically machined using an equilibrium gap of 0.010 in. to within a final accuracy of 0.005 in. What minimum material allowance should be made?

$$E = 0.050 \qquad t = 0.005 \qquad h_e = 0.010$$

$$A = h_e \left(\log_e \frac{E}{t}\right) - t = 0.010 \left(\log_e \frac{0.050}{0.005}\right) - 0.005$$

$$= 0.018 \text{ in.}$$

This is the absolute minimum allowance. Using a factor of safety of 1.5:

$$A = 0.018 \times 1.5 = 0.027 \text{ in.}$$

The forging limits should therefore lie between an envelope of the blade form of 0.027 and 0.077 in.

7.4 POSITION OF ECM IN MANUFACTURE CYCLE

ECM may be one of a number of processes used in the manufacture of a component. Where then should an ECM operation take its place in the manufacturing cycle? There are two principle factors to be considered. These are the stress free nature of ECM and the possible corrosive effects of the electrolyte on finished machined areas adjacent to an ECM operation.

If heavy sections of material are removed by conventional metal cutting methods, stresses, which may subsequently lead to distortion, are created in the component. It is normal practice, therefore, to remove the bulk of metal in a roughing operation, and then stress relieve by heat treatment before final machining. This practice should *not* be followed in ECM. Where heavy conventional machining is involved and heat treatment required, this should be completed before any ECM operations are performed. The reasons for this are that the stress-free nature of ECM permits the removal of large volumes of metal after heat treatment, without causing component distortion; a roughing ECM operation would require an additional tool.

It is possible for corrosion, usually in the form of small pits caused by electrolytic action, to occur on finished machined areas adjacent to an ECM operation. Selection of the electrolyte and careful design of the tooling are methods used to avoid this problem. Considerable effort and cost can be saved, however, if material is left on these adjacent areas for removal by conventional machining after the ECM operation.

Both these principles are illustrated in the example shown in Figures 7.9*a*–*c*.

The initial material shape and final component shape are indicated in Figure 7.9*a*. The rectangular sections of material are to be removed by conventional machining, and the more complex boss form shaped by ECM. The traditional approach is shown in Figure 7.9*b*, in which five separate operations are required. Two ECM tools are used, one for roughing and a smaller tool for finishing. In the sequence of operations shown in Figure 7.9*c*, only rough conventional machining precedes

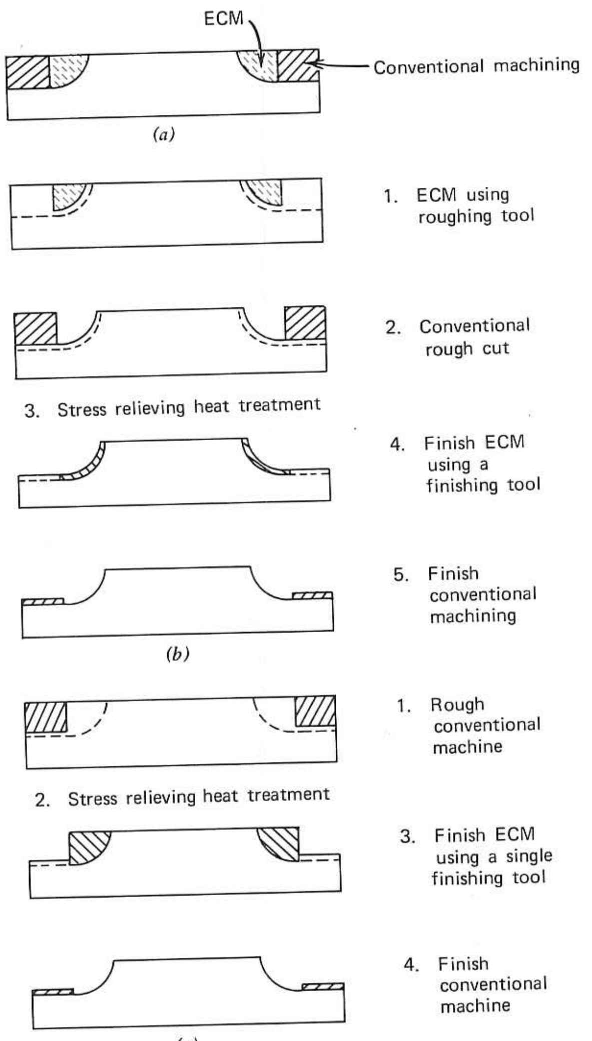


Figure 7.9 Position of ECM in the manufacturing cycle. (*a*) Material is to be removed partly by ECM and partly by conventional machining. (*b*) In this process sequence the stress relieving operation is incorrectly placed so that two ECM operations are required. (*c*) In this sequence only one ECM operation is required.

the heat treatment. One ECM operation, using a single tool, then finishes the boss form to final depth. Final sizing of the surrounding areas by conventional machining avoids problems of stray corrosion. This is the sequence of operations that should be used.

7.5 TOOLING ARRANGEMENT

At this stage, in the tool design procedure, consideration should be given to the various methods of applying ECM and their suitability to produce the component under study.

There are three basic methods by which any particular feature of a component may be machined. These are termed "generating," "die sinking," and "static machining." Generating is an operation in which a hole or shaft is produced using a two-dimensional template. In die sinking, a cavity or a raised form is produced by a three-dimensionally shaped tool. If only a small depth of metal is to be removed, a stationary tool can be used; this is then termed "static machining." In practice, tools often incorporate more than one of these methods.

The principle of generating is shown in Figure 7.10*a*. The tool is insulated on its outer surface so that, by limiting the overcutting action to the tool land, a parallel walled recess is produced. The insulation is normally stepped back from the tool land, since this protects the insulation from the stripping action of the electrolyte stream, and also provides clearance for unrestricted electrolyte exhaust. The last point is important, since a tool without clearance will suddenly overcut by an increased amount part way through an operation. This effect is shown in Figure 7.10*b*. The explanation is that, if there is no clearance, the resistance to flow in the annular electrolyte exhaust passage increases with increasing hole depth. The electrolyte normally emerges as a jet from the tool land, so that there is an air gap between the tool and work. Increased resistance to the exhausting flow causes the jet to be drowned, and full flow conditions are established. Where this happens the tool overcut increases. Generating can be better understood by referring to Figure 7.11*a*. The tool is insulated both externally and internally. The lines radiating from the tool indicate the density of the machining current. The current density under the tool is maintained at a high value, but the current densities on the vertical generated walls are small, hence do not produce good surface finish. The overcut of the tool on the exhaust side is small, since hydrogen, produced by the machining action, forms large bubbles in the electrolyte stream, which

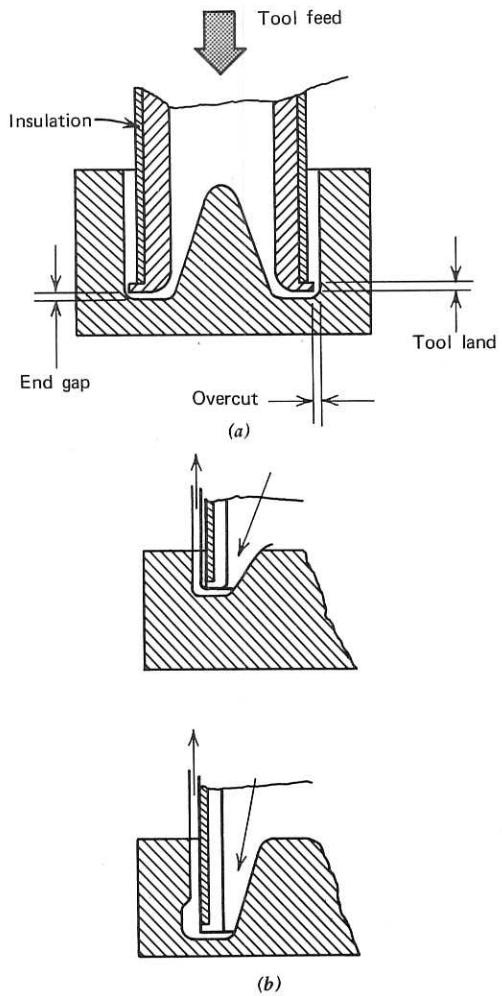


Figure 7.10 (*a*) Simple generating tool with clearance for electrolyte exhaust. (*b*) Effect of not providing clearance for electrolyte exhaust. Top—At the start of cutting electrolyte jets clear of tool land, so that side cutting is limited. Bottom—At depth, added restriction of exhaust flow forces electrolyte to remain in contact with tool land, so that increased side cutting occurs.

resist the passage of the electrolyzing current at that point. The release of hydrogen bubbles and their rapid expansion is due to the low pressure of the exhaust. The hydrogen tends to form streams and these give uneven overcutting around the tool land, striations then appear on the component wall. The vertical wall is subject to very low current density and this, together with the striation effect, results in a poor finish of

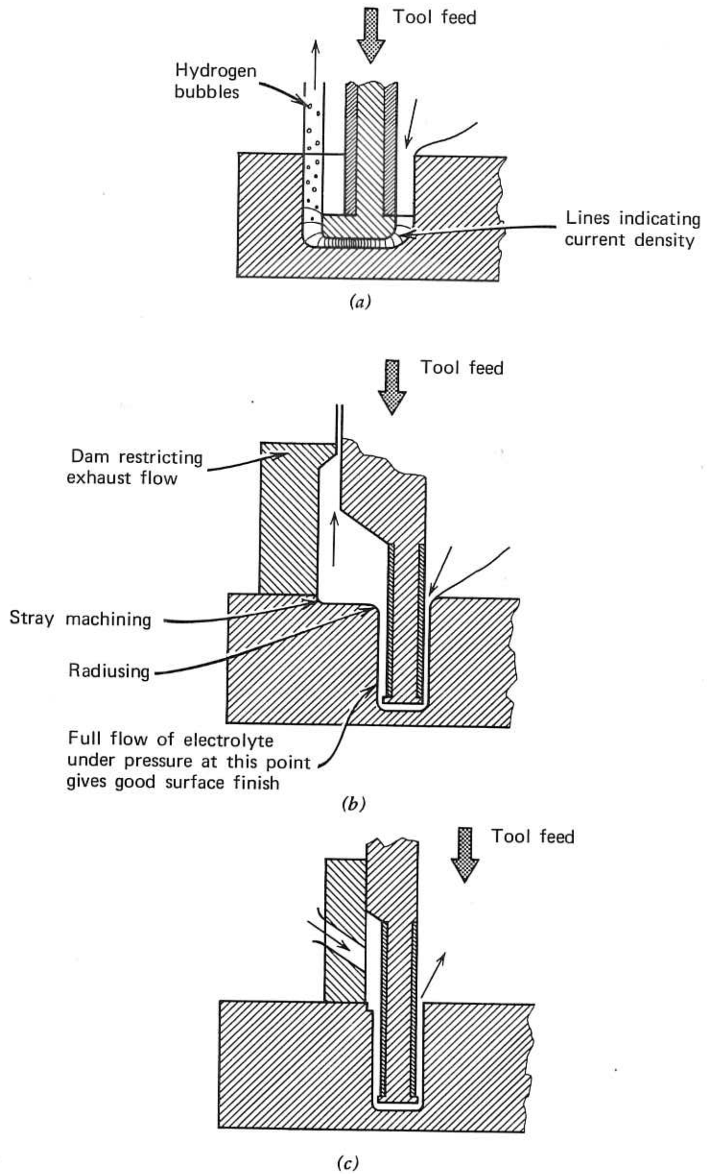


Figure 7.11 Variations in generating tool operation. (*a*) Forward flow, free exhaust. (*b*) Forward flow, restricted exhaust. (*c*) Reverse flow.

60 to 600 μin. The tool, as shown in Figure 7.11*a*, is, however, very simple to manufacture and operate; its principle of operation should be employed whenever component surface finish requirements permit. Again, referring to Figure 7.11*a*, the workpiece on the inlet side of the tool is subject to a higher current density, because of the gas-free nature of the electrolyte at that point, and the surface finish is better. The method is, therefore, very suitable for machining boss forms.

A superior surface finish can be obtained, on the exhaust side of the tool, by pressurizing the electrolyte. This is achieved with a dam that restricts the exhaust, as shown in Figure 7.11*b*. To prevent excessive tool overcut, the tool land should not exceed 0.020 in. The tool overcut will vary slightly with length of electrolyte flow path, but if the maximum variation of these is less than 3:1, and the maximum flow path does not exceed 1 in., then accuracies of 0.0015 in. are possible.

For better control of accuracy, especially if flow paths are long, reverse flow of the electrolyte, as shown in Figure 7.11*c*, can be employed. The disadvantages of both these methods are increased tooling cost and excessive stray machining of the work.

High-quality surfaces can usually be produced by careful selection of electrolyte, with regard to its composition, operation at high voltage and low strength electrolyte to achieve high potential gradients, or by operating at high current density. The latter is the simplest and more convenient method. In generating, the conditions of high current density occur on surfaces advancing before the tool, but not on walls parallel to the direction of tool feed; these are subject to a relatively low current density. When a component of high surface quality is to be produced, it is advisable to use two machining operations. The first, Figure 7.12*a* produces an undersize recess, or boss, by one of the previously described methods, and the second, Figure 7.12*b*, removes, at high current density, a uniform envelope of material to produce final size. The second tool is usually a 0.010-in. envelope of the work to be machined and is not insulated. Electrolyte portings are the same size and in the same position, as on the first operation tool. The tool is held static during the machining, in which 0.010 in. of additional material is removed uniformly from the component. The electrolyte flow is restricted at the exhaust to provide full flow conditions, and to suppress the formation of hydrogen bubbles.

A typical tooling arrangement for trepanning a hole, by the generating method, is illustrated in Figure 7.12*c*. The component is backed with an insulating piece of material in which a track is cut to receive the tool. This ensures continued flow of electrolyte around the tool land after breakthrough. The rubber pad is sprung against the trepanned

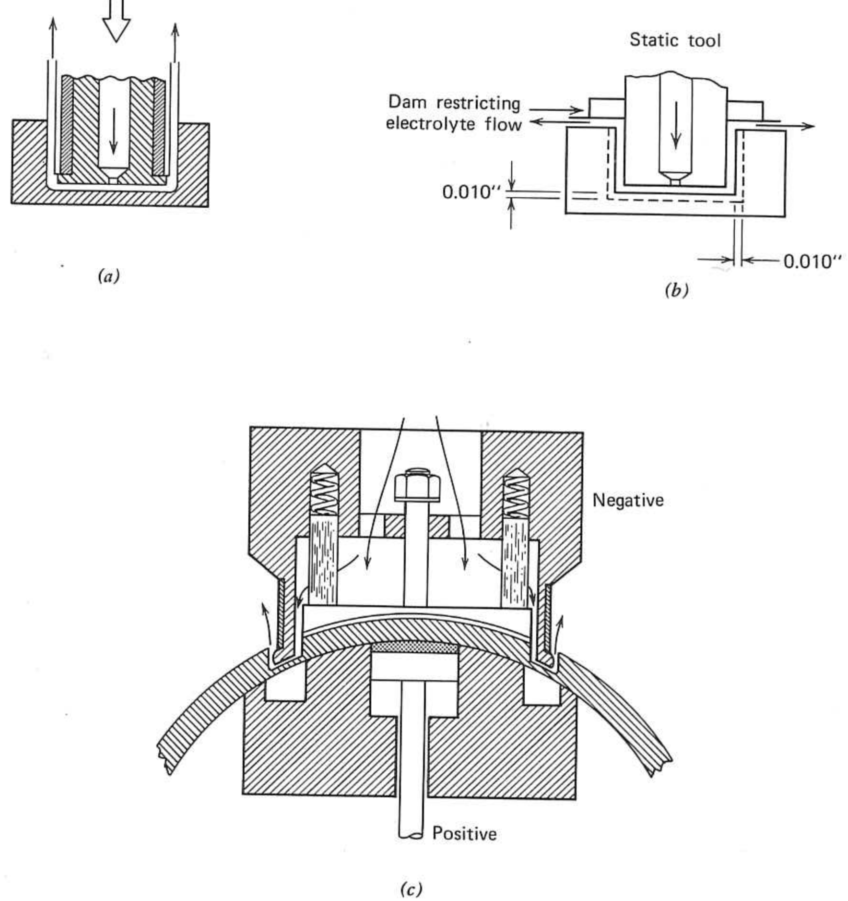


Figure 7.12 (*a*) A generating operation may be followed by a static tool operation to produce better accuracy and surface finish on side walls. (*b*) A generating tool for trepanning a hole.

section to prevent it moving as it becomes detached. A separate anodic electrical connection is made, so that the detached piece continues to machine after tool breakthrough.

Components produced by the generating technique together with examples of tools are shown in Figures 7.13 to 7.23.

Die sinking is the term used to describe the machining of a three-dimensional recess or boss. The tool is not a pure envelope shape of the work, but operates at an increasingly larger gap size as the work is more closely angled to the feed direction. This is shown in Figure

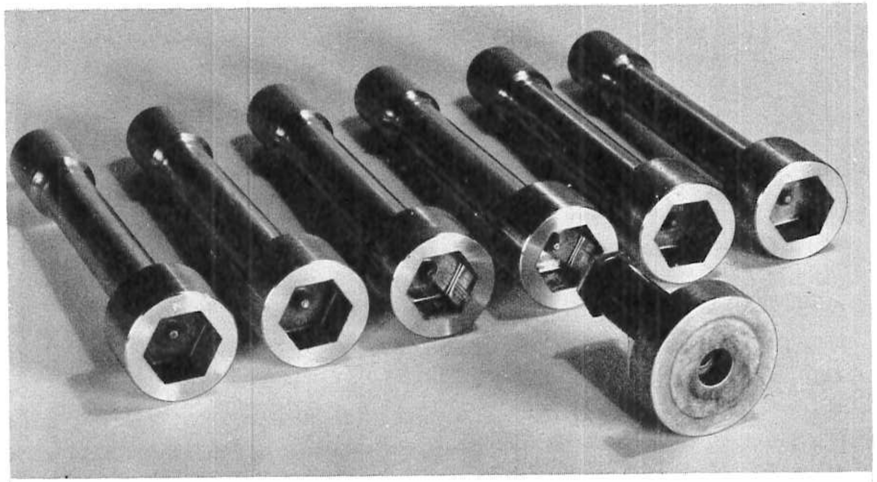


Figure 7.13 These hexagonal pockets are typical of work that can be produced with simple, forward flow generating tools. (Courtesy of the Anocut Engineering Company.)

7.24a. As the gap size increases, the current density is reduced, so that surface finish deteriorates and control of work accuracy becomes more difficult. The limiting conditions for such a tool to produce ± 0.005-in. accuracy, and better than 50-μin. finish, on a nickel alloy occurs where the work surface is at 20° to the direction of tool feed. The limiting angle is larger than this for materials that exhibit less favorable surface finish.

At angles less than 20° the tool must operate at a very high feed rate to achieve small gaps, high current density, good surface finish, and accuracy. This is possible, if all surfaces of the workpiece to be machined are steeply angled to the tool feed direction. For example, if the workpiece shown in Figure 7.24*a* is premachined, as in Figure 7.24*b*, the tool then machines only the steeper walls of the recess. Although operating at the same minimum gap of 0.010 in., the tool is much closer to the remaining surfaces of the workpiece. Very small angles, therefore, can be machined using this technique.

In producing a blind recess, a two-stage operation is required, as shown in Figures 7.25*a* and *b*. The first tool forms a simple recess, Figure 7.25*a*; in this example it is a generating operation. The second tool machines the angled walls at a high feed rate at a small gap. Machining the bottom of the recess occurs as the tool rapidly approaches; precise termination of tool movement and machining current is required during

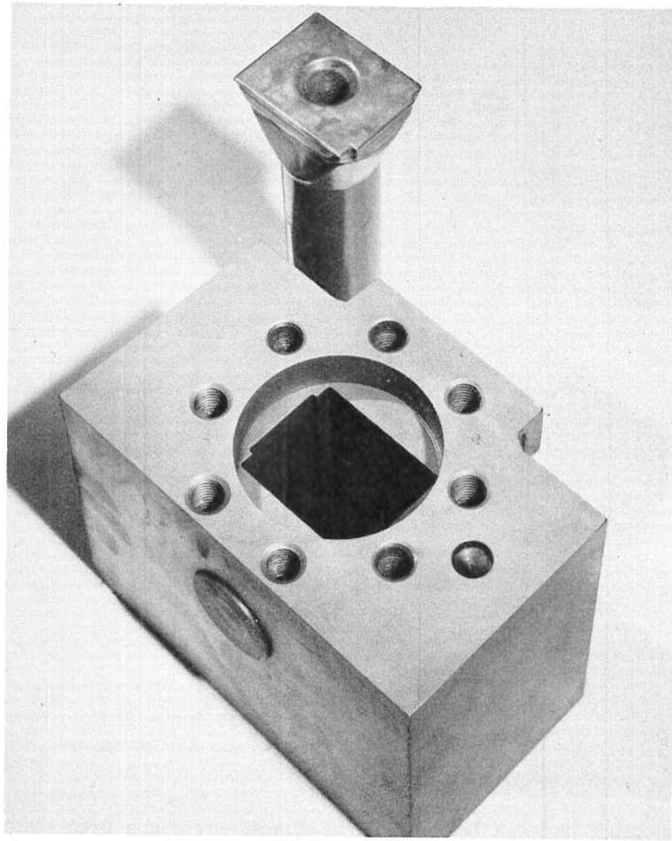


Figure 7.14 Precise rectangular hole produced with a generating tool. A tool, such as this, will penetrate into the work at 0.1 to 0.3 in./min on ferrous materials. (Courtesy of the Cincinnati Milacron Company.)

the rapid closure of the gap. These principles are equally applicable to machining raised shapes such as bosses.

In die sinking, all surfaces of the work that are to be produced are machined simultaneously at high current density. This assures better surface finish, easier control of accuracy, and sometimes, simpler tooling, than that characteristic of an equivalent generating operation. Where there is a choice, die sinking should be preferred to generating. An example of a simple shape that could be machined by either method is shown in Figures 7.26*a* and *b*. The tool for die sinking is simpler and requires no insulation. Examples of die sinking are shown in Figures 7.27 to 7.30.

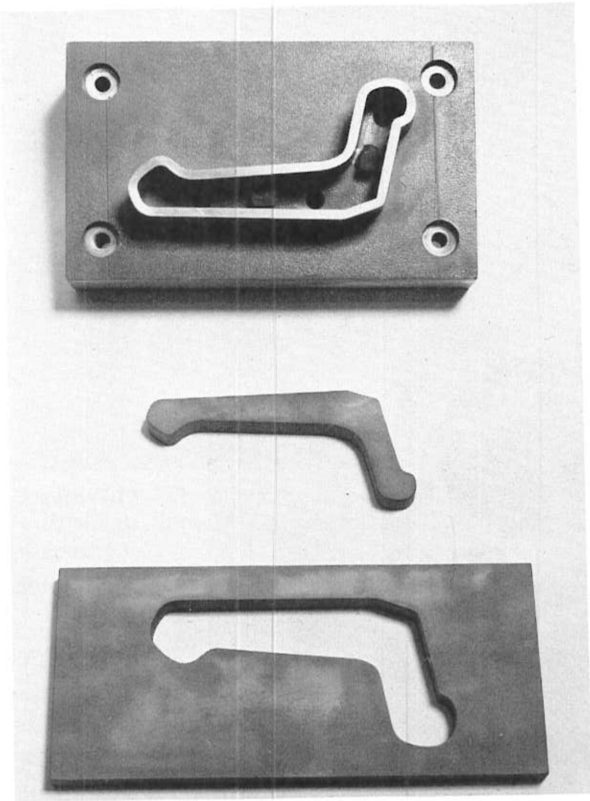


Figure 7.15 A generating tool can be used to cut almost any shape from plate material. The tool is a simple envelope of the shape to be machined. (Courtesy of the Cincinnati Milacron Company.)

Where only a small depth of metal is to be removed, a static electrode can be used. An application of this method is in the improvement of surface finish following a previous electrochemical generating operation. An illustration of this, Figure 7.12*a*,*b*, has already been described. The electrode configuration and electrolyte flow arrangement for dealing with a larger, more complicated work area, is shown in Figure 7.31. Recesses to a depth up to 0.1 in. can be produced accurately, either to a uniform depth, Figure 7.32*a*, or to a varying contour, Figures 7.32*b* and 7.33. Because the electrode is static it may be used to completely envelope a work piece, and so achieve 360° machining in a single operation. The

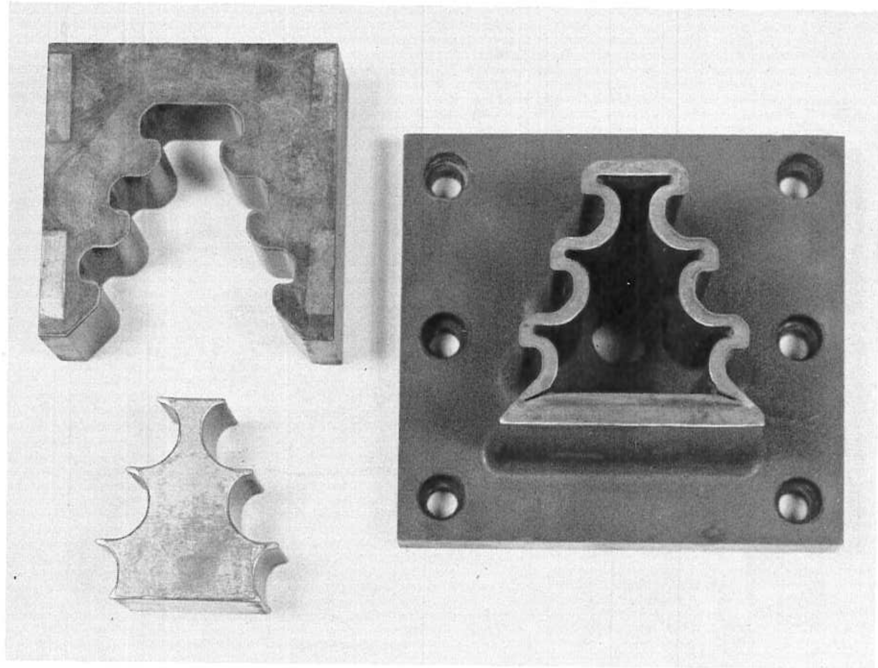


Figure 7.16 The dovetail shape, produced by an ECM generating tool, is typical of that used to secure airfoils to their rotors in both gas and steam turbines. A single tool, as shown, can machine to ± 0.0005 in. tolerance. If a secondary ECM operation is performed then tolerances of ± 0.0001 in. are possible. (Courtesy of the Cincinnati Milacron Company.)

way in which a single electrode can be used to machine leading and trailing edges, and root and shroud platforms of an airfoil, as shown in Figures 7.32*c* and 7.34*a*, is a good example of this technique. The electrode is a simple envelope of the work piece (usually 0.010 in.), and 0.010-in. depth of material is machined away. In the example shown, the electrolyte flows across the root platform along the length of the airfoil and exhausts over the shroud platform. If a greater depth of material is to be removed, a series of static electrodes may be used, each being an envelope size of the final work piece shape. Several operations are required, Figure 7.34*b*, so that the method is most suited to large quantity production. Electrodes only vary from a pure envelope shape, if a feature of diameter less than 0.1 in. is to be machined, such as the sharp leading and trailing edges of the airfoil, shown in Figure

Figure 7.17 Variety of components, test pieces, and the ECM tools that produced them. The helical splined gears are generated with a tool having combined axial and rotational motions. (Courtesy of LTV Vought Aeronautics Division, LTV Aerospace Corp.)

7.34*c*. This is because of field concentration of the machining current that is very pronounced on sharp features of a work piece.

Static machining should always be considered, when reviewing a component for ECM, since it has special merits; that is, several areas of a component can be machined simultaneously, which also can be very accurately related, and a machine tool is not required so that capital investment is much reduced. If a shaped recess is to be produced in a flat, radiused, or similarly predictable starting surface, then static machining can be a simple, inexpensive, but effective method. Recesses less than 0.1-in. deep are usually best performed with a single electrode, if the starting shape is predictable. Contoured reentrant gear bores 0.3-in. deep are manufactured by several companies using single static ECM tools, Figure 7.33.

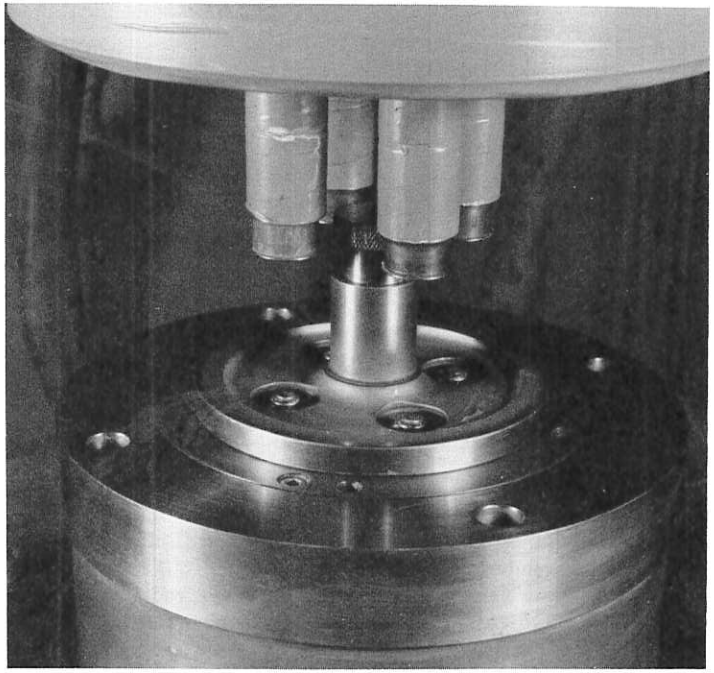


Figure 7.18 Generating tools after machining four lightening holes in a gear. At the center of each hole can be seen the small slug of material isolated by the machining. (Courtesy of the General Electric Company.)

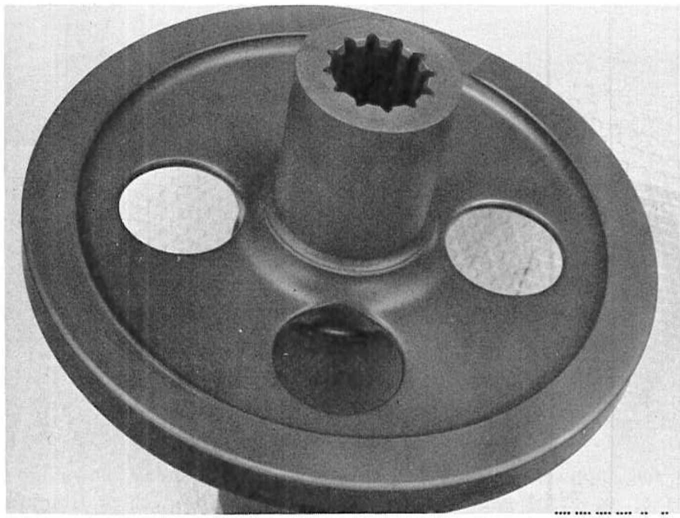


Figure 7.19 Gear blank showing lightening holes produced by the tooling in the previous illustration. ECM replaces both mechanical drilling and blending operation at a saving of $8 per piece. (Courtesy of the General Electric Company.)

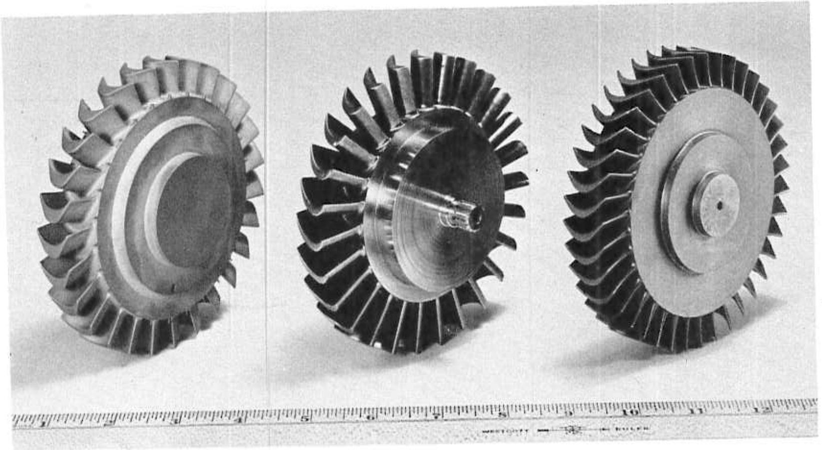


Figure 7.20 Integrally bladed turbine wheels electrochemically machined from waspalloy and titanium forgings. In operation a tool moves in radically to generate one airfoil; the wheel is then indexed. While wheels take under 3 hr to process, because of the many tool passes which have to be made, multielectrodes can be used to process several wheels simultaneously to achieve low manufacturing costs. Tooling is patented by Garrett-AiResearch. (Courtesy of the Garrett-AiResearch Manufacturing Company of Arizona.)

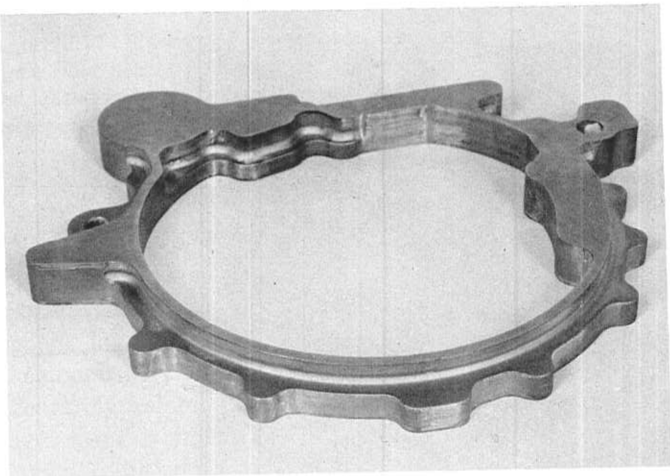


Figure 7.21 This ring, approximately 10 in. in diameter, was cut as shown by a single, 20-min pass of an ECM generating tool through a 0.75-in.-thick titanium plate. (Courtesy of the General Electric Company.)

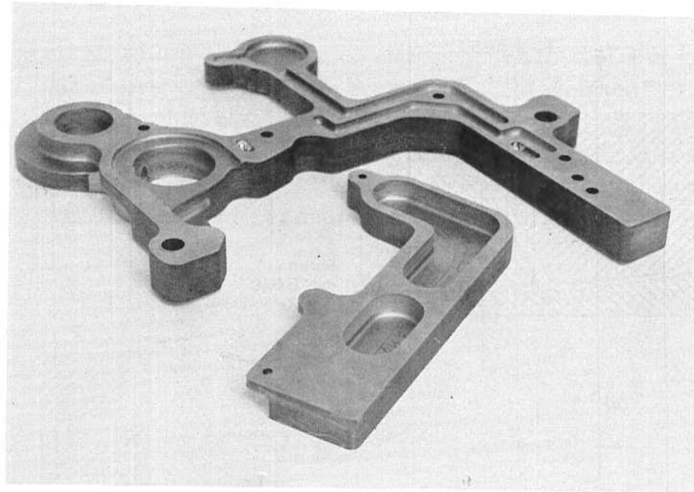


Figure 7.22 In order to fully utilize a 10,000-A machine both these components, the larger measuring 10 in. across, were machined simultaneously in 20 min by a single ECM generating tool. (Courtesy of the General Electric Company.)

Geometric aspects of the tooling require special attention, if several electrodes are to machine adjacent areas on a component. The problem is simple if all electrodes have a common direction of movement, as shown in Figure 7.35. In this example a large shaped cavity is to be machined. Four tools are used in succession, so that each section of the cavity is machined at a suitably high current density, but at an

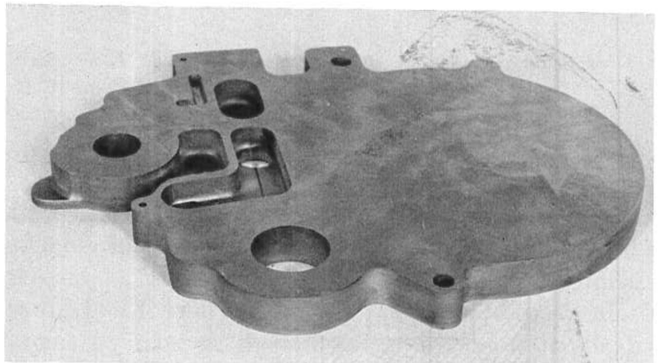


Figure 7.23 This component was cut from a titanium plate by a single pass, of a generating tool. The recesses were also produced during the 20-min operation. (Courtesy of the General Electric Company.)

Figure 7.24 (a):

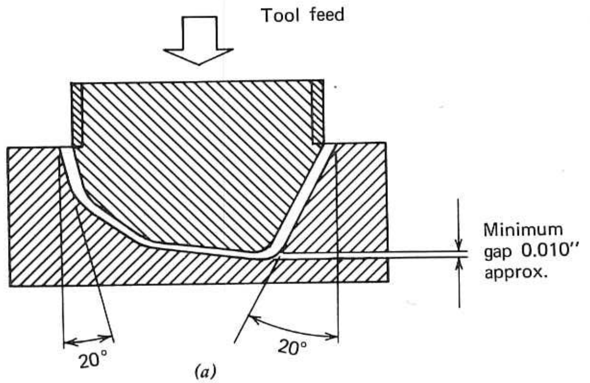


Figure 7.24 (b):

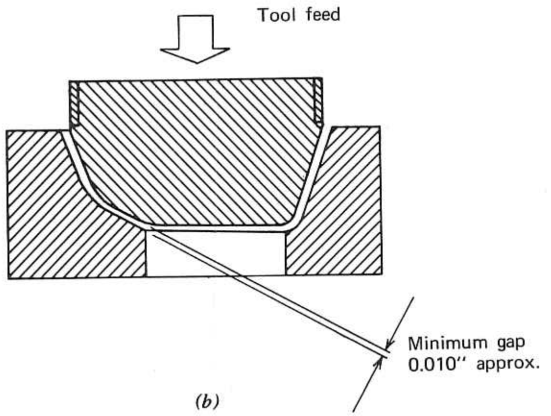


Figure 7.24a, b Die sinking tools. The machining gap increases as the work surface becomes more acutely angled to the tool feed direction.

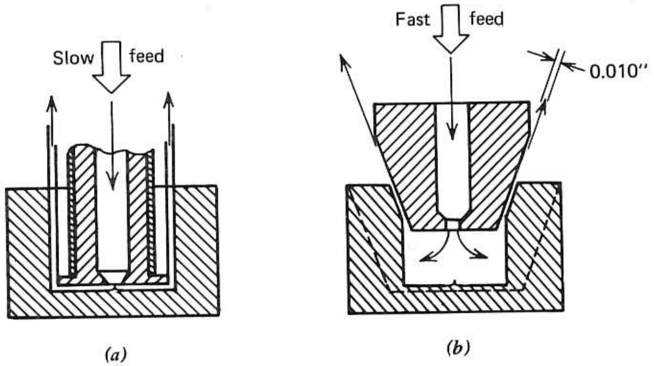


Figure 7.25a, b Two operations are used to produce a recess with steeply angled walls.

amperage within the machine's capacity. Each tool can be dimensioned so that it machines right up to the adjacent finished surface, produced by a neighboring electrode. A perfect blend between adjacent surfaces can be obtained but is difficult to control. It is safer, therefore, to leave a small projecting ridge of material, as shown, rather than risk a machining overlap, hence a local depression in the work surface.

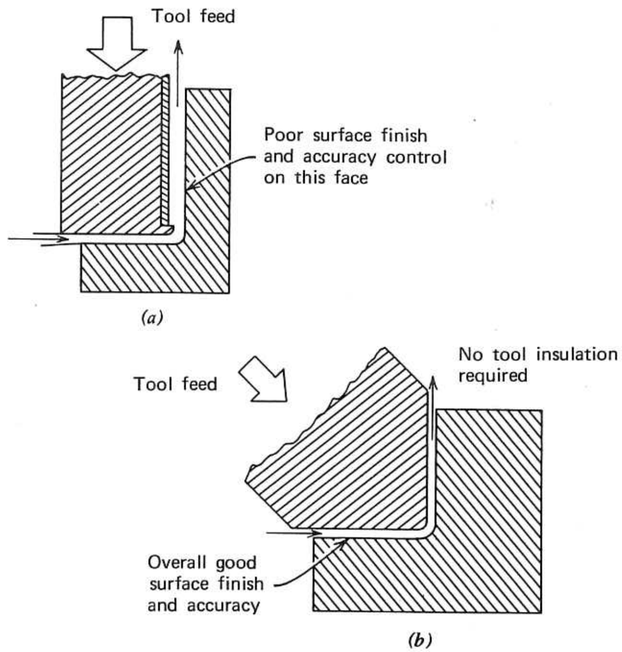


Figure 7.26 This component shape may be produced by (*a*) a generating tool or (*b*) a die sinking tool.

In operating tools with different feed directions, as would be necessary on a curved surface, there is a tendency to leave an unmachined wedge of material between operations. This can be avoided by radially sloping the sides of each tool, as shown in Figure **7.36**. The cut made parallel to the tool feed direction, corresponding to the insulated face, will display excess overcut as shown, unless compensation is built into the tools. This is because the apparent sideway expansion of the tool, due to the sloping side faces of the tool, is very slow compared with the forward motion of the tool. This effect can be corrected by machining the side land and insulated surface of the tool, as shown in Figure **7.37**.

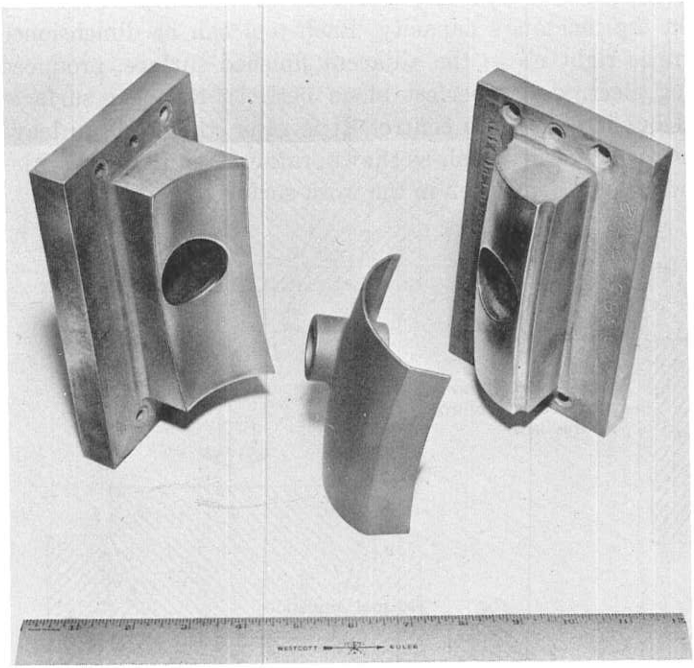


Figure 7.27 Complexly shaped component and ECM tools used to produce it. (Courtesy of Klik Industries.)

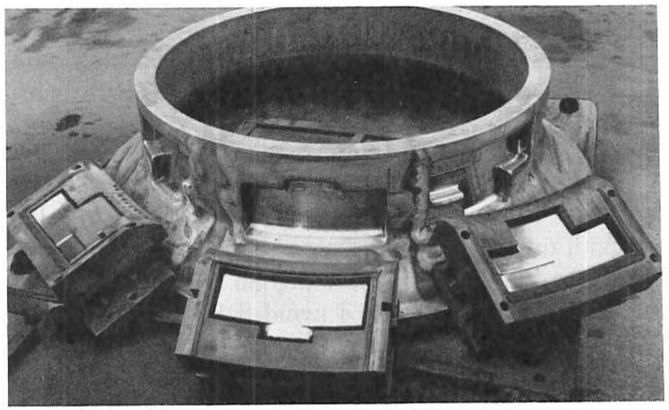


Figure 7.28 Large areas of material, 130 in. each, removed from a jet engine casing forging by ECM. While this illustrates the bulk metal removal capability of ECM, it is interesting to note that this tooling was soon displaced by tooling which electrochemically machines the complete inner and outer complex contours of the casing. (Courtesy of the Bristol Engine Division, Rolls-Royce Limited.)

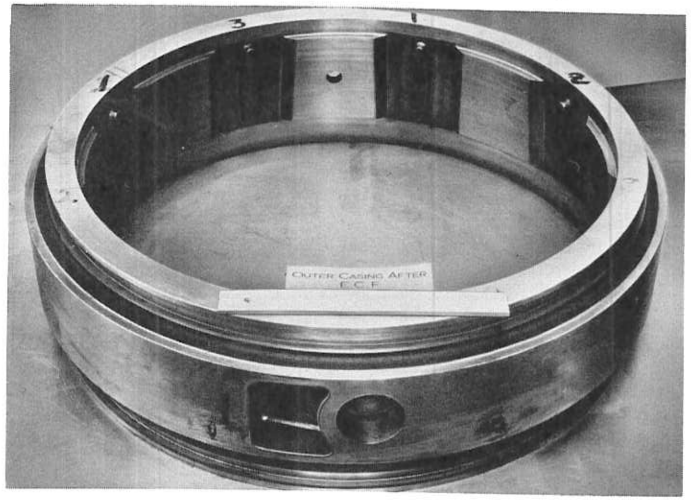


Figure 7.29 Jet engine casing, with integral "vane ends" and pockets produced by ECM. The process is used extensively to produce this type of component in the gas turbine industry. (Courtesy of the Aero Engine Division, Rolls-Royce Limited.)

7.6 SELECTING AREAS OF A COMPONENT TO BE MACHINED

The electrochemical machining of a component may comprise a single operation or, more frequently, a number of operations each producing a select area of the component. The selection of these areas is dependent on the amperage capacity of the machine on which the work is to be performed, and features of the component, which determine the best tooling arrangement.

To achieve a good surface finish on nickel, titanium, and steel alloys, a minimum current density of 100 A/in.^{2} is normally required. A tool, operating at 5000 A, will machine a flat area of 50 in.^{2} to a quality finish. If the surface of a component is contoured, however, the surfaces angled to the direction of tool feed will be subject to a lower current density. In Figure 7.38*a*, the 30° surface of the boss form is machined at a current density of $100 \times \cos 30° = 87$ A/in.^{2}, while the amperage in terms of "plan area," that is, the area viewed in the direction of tool feed, is 100 A/in.^{2}. In view of this, a minimum of 200 A/in.^{2} of plan area should be used as a "rule of thumb" figure in designing tools for contoured shapes. For example, suppose that the casing, shown in Figure 7.38*b*, has six bosses and is machined as twelve equal areas, and that the current available for each gives 150 A/in.^{2}. This value

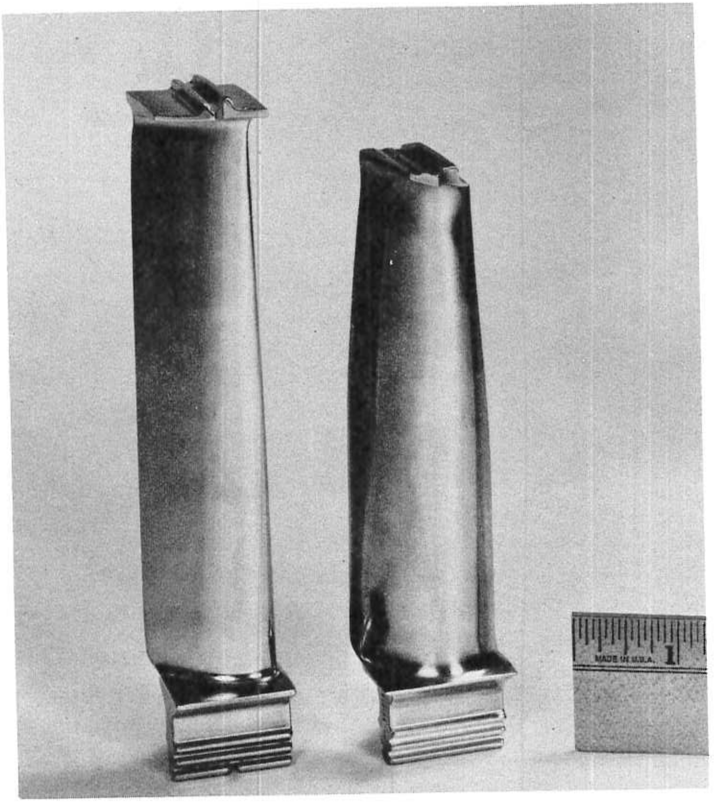


Figure 7.30 Both sides of the airfoil and the platform areas of these blades were electrochemically machined to final size. (Courtesy of the Utica Division of Kelsey-Hayes Company.)

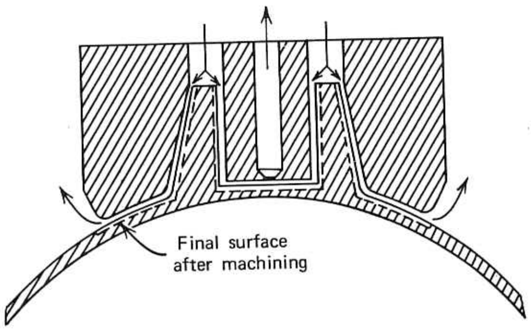


Figure 7.31 Static tool for removing a uniform envelope of material.

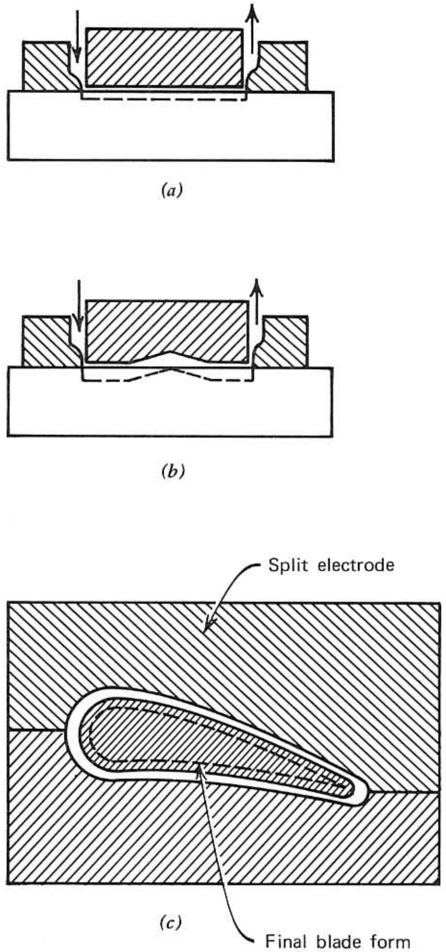


Figure 7.32 Static tools can machine simple recesses or remove an envelope of material from a component.

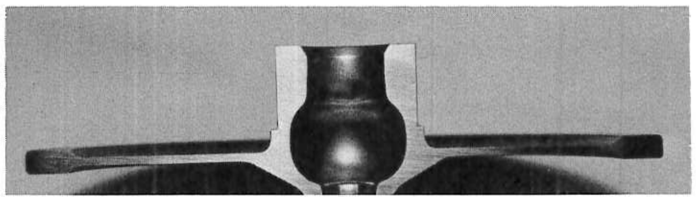


Figure 7.33 Sectioned gear blank showing the smooth finish, re-entrant 1.25-in. bore produced by a stationary ECM tool. (Courtesy of the General Electric Company.)

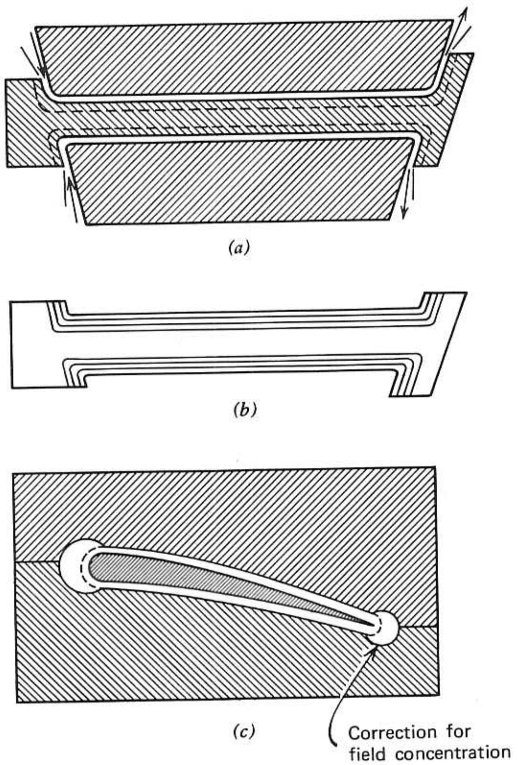


Figure 7.34a, b, c A series of enveloping static electrodes can be used to machine a turbine airfoil.

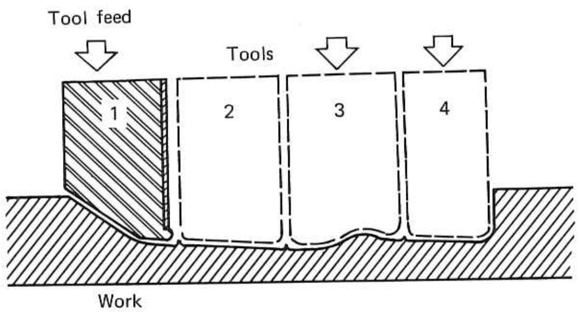


Figure 7.35 Several operations used in machining a large cavity.

is adequate for the plain areas between bosses, but the sloping walls of the bosses will machine at a much lower current density and display poor surface finish. The correct procedure is to divide the areas unequally, so that the bosses machine at 200 A/in.^{2} (of tool plan area), and the plain area between bosses at 100 A/in.^{2}. This arrangement satisfies the minimum, real rather than apparent, current density requirement

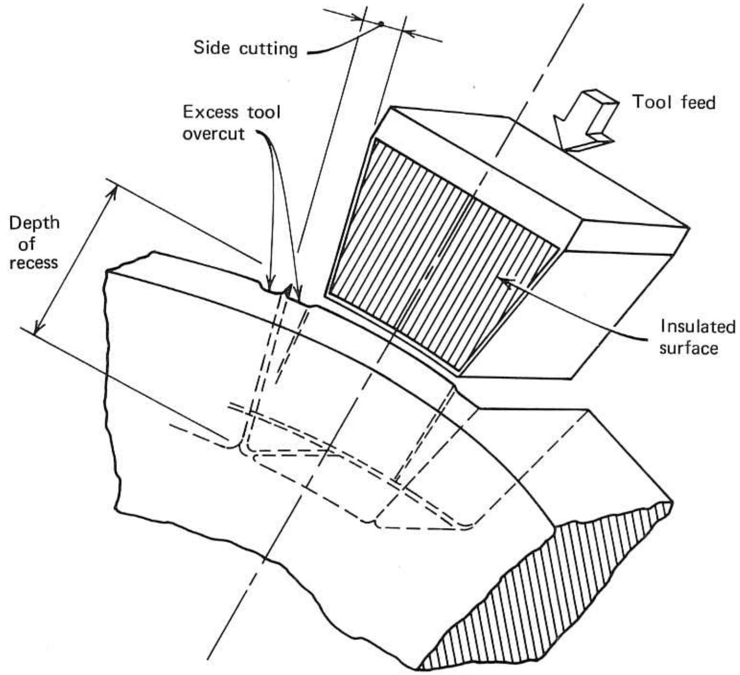


Figure 7.36 A tool for performing a series of radial cuts into a circular component.

for both areas. The same principle can be applied, when ample current is available, to achieve a more balanced standard of surface finish over the whole of the component surface. Provided that each tool will operate at the maximum amperage of the machine on which the work is to be performed, then the adjustment of tool areas makes no difference to the overall machining time for the component. The practical upper limit of current density, on equipment at present available, is 1000 A/in.^{2} for nickel and titanium alloys, and 2000 A/in.^{2} for ferrous materials. It is safer, however, to design tool areas for operation at 500 A/in.^{2}, and 1000 A/in.^{2}, respectively, to be sure of using all the amperage capacity of a machine.

The component, shown in Figure 7.38b, also illustrates how component features dictate the way in which the areas are divided for machining. In this case, the boss form provides a "natural" point at which electrolyte may be introduced to the work area, so that a tool, as shown in Figure 7.38*a*, can be used.

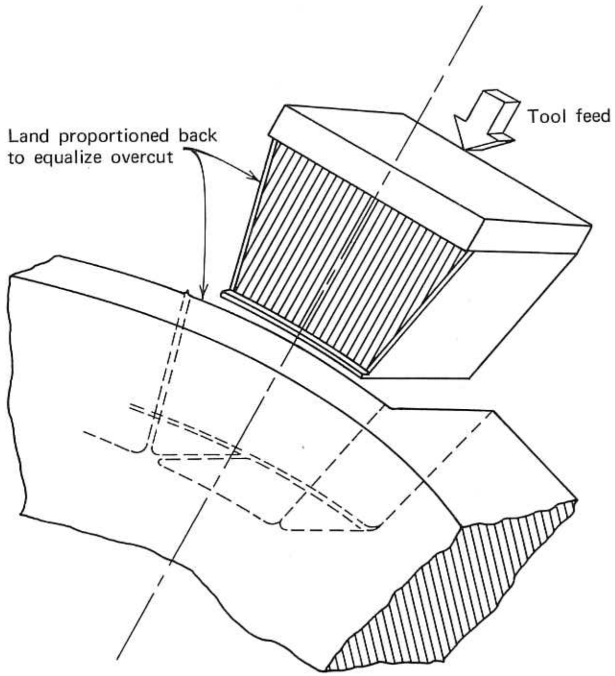


Figure 7.37 Correct tool design to obtain a blend between adjacent radial operations.

Electrolyte can be supplied from side to side of a tool, or flow from portings in the tool face. The first method requires dams and other flow directing devices; it is, therefore, expensive and cumbersome. The second method is simpler, but each porting results in a raised area on the work surface that, unless it forms a required feature of the component, has to be removed by an additional operation. Even a narrow slot produces a small ridge, as shown in Figure 7.39*a*. Thus maximum use should be made of natural component features to simplify tools and to avoid operations additional to ECM. Typical natural features

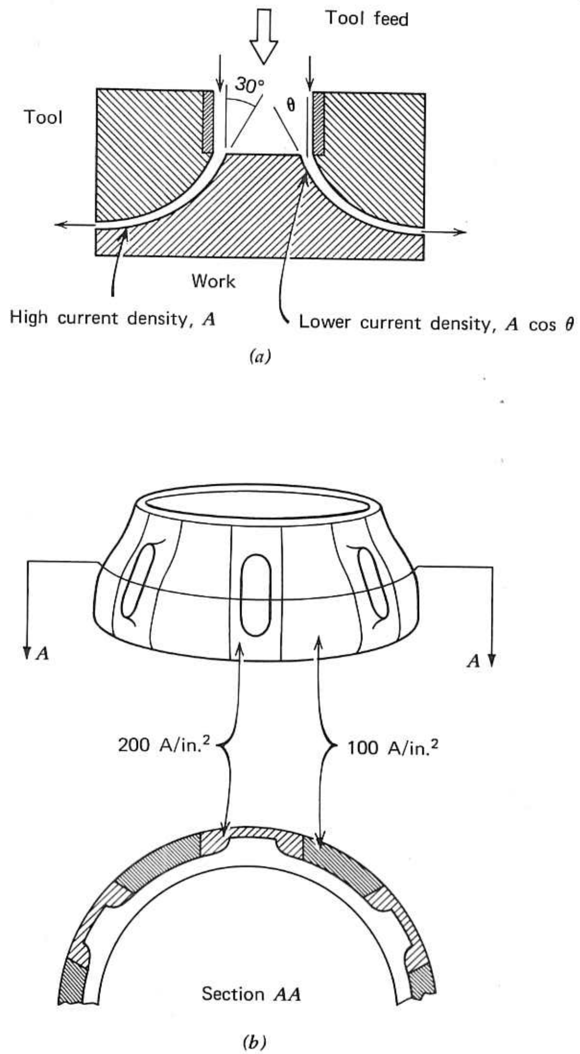


Figure 7.38 Selecting areas to be machined by individual tools.

are bosses, as in Figure 7.38*a*, steps or ridges, as in Figure 7.39*b*, or a hole in the work, as in Figure 7.39*c*.

7.7 SEQUENCE OF OPERATIONS

Where there are a number of electrochemical machining operations on a single component, several factors need to be considered in deciding

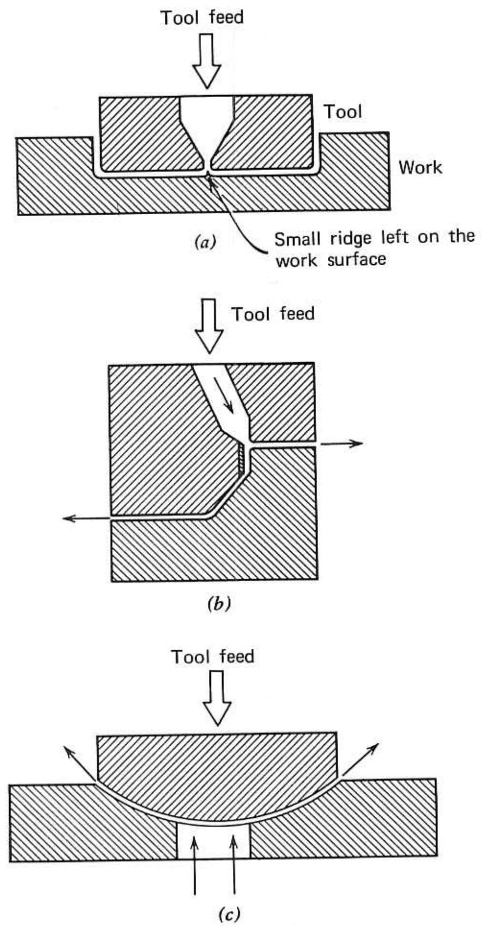


Figure 7.39 (*a*) Electrolyte supplied through a slot in the tool. (*b*) Tool slot positioned at a natural feature of the work piece. (*c*) Hole or similar feature of the work piece used as electrolyte supply.

on a sequence of operations. Apart from normal considerations of tooling costs and ease of operation, other factors such as stray corrosion, component distortion, component strength, and power distribution through the component are also important.

Stray corrosion of finished machined surfaces that are adjacent to an area being machined occurs only if electrolyte, exhausting from the tool, impinges on these surfaces, or if they and the tool are immersed in the electrolyte. A surface film of electrolyte does not cause damage.

If surplus electrolyte does not naturally drain from the component, then it should be blown clear; exhausting electrolyte should be directed away from the component. Correct sequencing of operations can be helpful in meeting these conditions. On the component shown in Figure 7.40*a*,

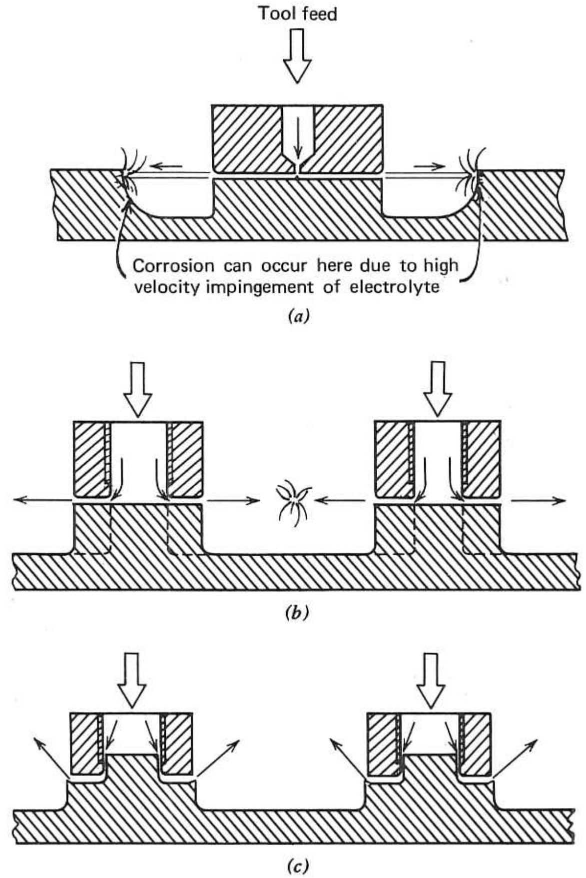


Figure 7.40 Control of corrosion produced by exhausting jets of electrolyte.

the boss shapes and areas between bosses are machined separately. If the bosses are machined first, they are then subject to the corrosive action of the jet of electrolyte exhausting from the second operation tool. By reversing this sequence of operations, Figure 7.40*b*, the exhausting electrolyte does not impinge on the finished areas between bosses, even at the start of this operation. During machining, Figure 7.40*c*, a small ridge forms that deflects the electrolyte clear of the component.

Strictly speaking, no distortion of a component should occur during an ECM operation, since the process does not induce stresses. In practice, it is not always possible to remove all the stresses from a component prior to ECM. The relaxation of these stresses, during metal removal, can cause the component to distort. Also, as a localized area is machined, it will be heated by the electrolyzing current, and the local flow of hot electrolyte; the resulting differential expansions then cause small distortions. Careful processing of the component prior to ECM, and close control of tooling, machine, and ECM variables usually limits the distortions to within component tolerances. For very accurate work, however, it is usual to leave 0.020 in. of material on all surfaces of the component during the bulk metal removal and then, using the same tooling, machine to final depth. This is also a useful technique where absolute integrity of surface finish is required, since it minimizes the time of possible stray current damage to finished surfaces.

The heavy electrolyzing currents used in ECM have to pass through the component to the area being machined. Tough alloys are poor electrical conductors, so that thick sections of the component are required to pass these heavy currents, if distortion is to be avoided.

The sequence of operations can aid power distribution. Machining a thin section airfoil, shown in Figures 7.41*a*, *b*, and *c*, illustrates this point, several operations are required to produce the airfoil and the root and shroud platforms. If most of the airfoil is machined first, Figure 7.41*a*, then power distribution for this operation and the subsequent operations, Figure 7.41*b*, is adequate. On the other hand, if these operations are reversed, Figure 7.41*c*, all the power passes through the thin airfoil section. This results in power loss, overheating, distortion, and machining error.

Quite large forces are exerted on a component, because of the pressure and kinetic forces of the electrolyte. Thin sections are prone to flex and sometimes vibrate; conditions that lead to inaccuracy and process failure. The example, chosen to show correct power distribution in a blade, Figures 7.41*a* and *b*, also shows how the component is strengthened to withstand machining forces.

7.8 ELECTROLYTE FLOW ARRANGEMENT

Correct electrolyte flow across a tool is fundamental to its success and is the most important feature of tool design. Each component should be considered for full use of its natural features to achieve suitable flow; also decide if electrolyte should flow from side to side of the tool

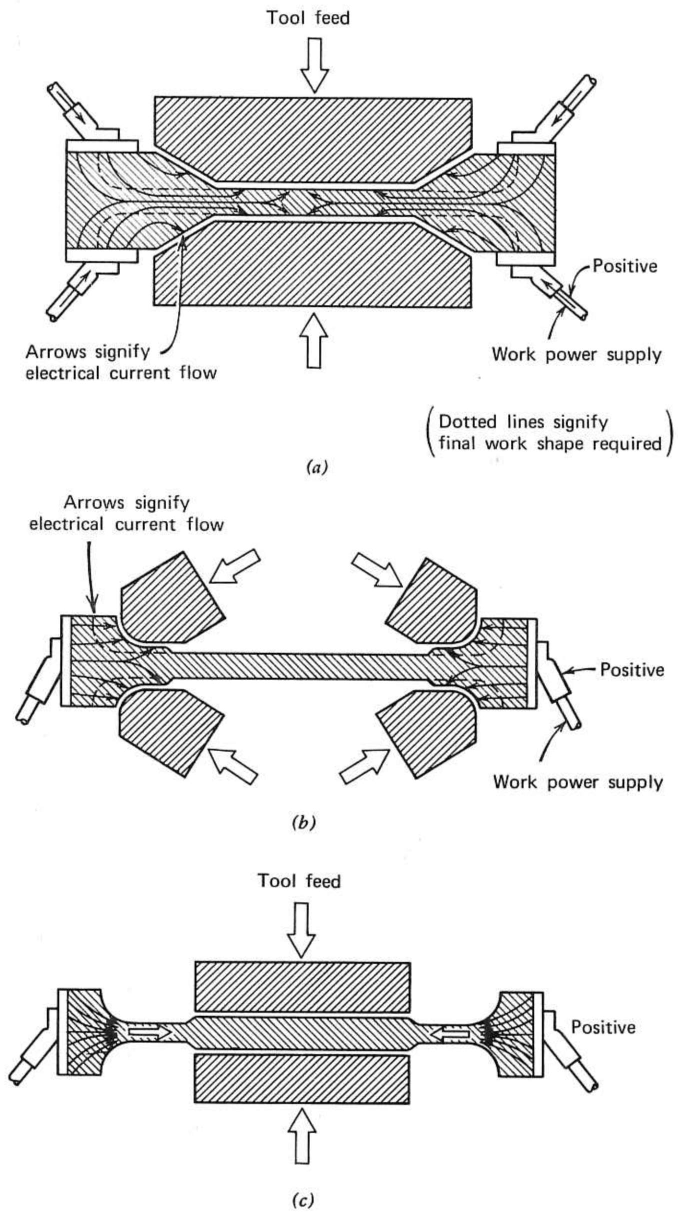


Figure 7.41 The effect of machining sequence on the distribution of current in the component.

or flow outwards from portings in the tool. Thought should be given to the tool shape in those areas where cavitation of the electrolyte is likely to occur.

The initial shape of a component is rarely compatible with the shape of the tool, so that only small areas of its surface will be in close proximity to the tool at the start of machining; the problem of supplying electrolyte over these areas is usually solved by flow restriction techniques. Since many variations of these are possible, it is important that the principles of their operation be clearly understood.

A tool that makes use of a natural feature of the component as an aid to electrolyte flow distribution is usually inexpensive to manufacture and simple in operation, and leaves no unwanted ridges on the work. The simplest natural feature is a boss. Whatever its shape, a correspondingly shaped, but larger port, is cut into the tool. Electrolyte supplied to the port flows outwards over the area to be machined, as in Figure 7.42*a*. Such bosses may have sloping or vertical walls.

A ridge on the workpiece can also provide a suitable position for electrolyte entry, as in Figure 7.42*b*. In this case, however, dams are required on two sides of the tool to prevent side waste of the flow. A hole or slot in the work can also be used, as in Figure 7.42*c*. A similar effect can be achieved by grouping two or more components together and machining them simultaneously with one electrode. This is illustrated for two airfoils, Figure 7.42*d*.

Tools, with electrolyte supply slots cut in them, are simple to manufacture and operate but leave small ridges on the work. Small ridges result even if narrow slots are used.

A slot twice the estimated operating gap size will supply adequate flow. The flow from a slot tends to be orthogonal to the slot, and end flow is very poor. For these reasons, slots are best terminated in corners of the work, as in Figure 7.43*a*. If the corner has a radius greater than 0.1 in. then the slot is blended into a larger diameter, as shown in Figure 7.43b. In machining a simple rectangular area, Figure 7.43*c*, the slot forms a diagonal. Straight slots ease problems of tool manufacture, but a curved slot may be required on some operations, for example, to terminate the slot in corners, as in Figure 7.43*d*. They are shaped to direct flow into reentrant areas, as shown in Figure 7.43*e*. Avoidance of sharp changes in direction and blending of the slot exit ensure smooth flow conditions. The effect of a sharp change in slot direction is shown in Figure 7.43*f*.

The configuration of the component, or its accuracy and surface finish requirements, sometimes indicate the need for a *reverse flow* tool. This is the term used when electrolyte is supplied from the periphery of the

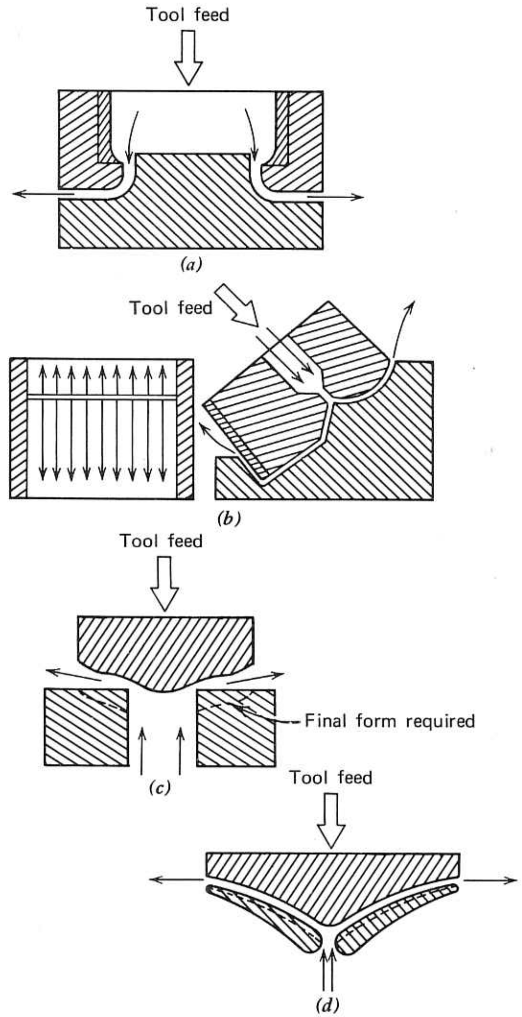


Figure 7.42 Natural features of the work surface are used as electrolyte supply points.

tool to exhaust through portings cut in it. The advantages of this method are that the tool cuts the work more accurately and produces a superior surface finish around the edge of the tool. This is because fresh electrolyte is supplied in these areas. These benefits are not always required, however, and since the tool is more complicated and expensive because of added flow controlling dams and so on, the reverse flow method should not be used exclusively. Some work configurations might require the

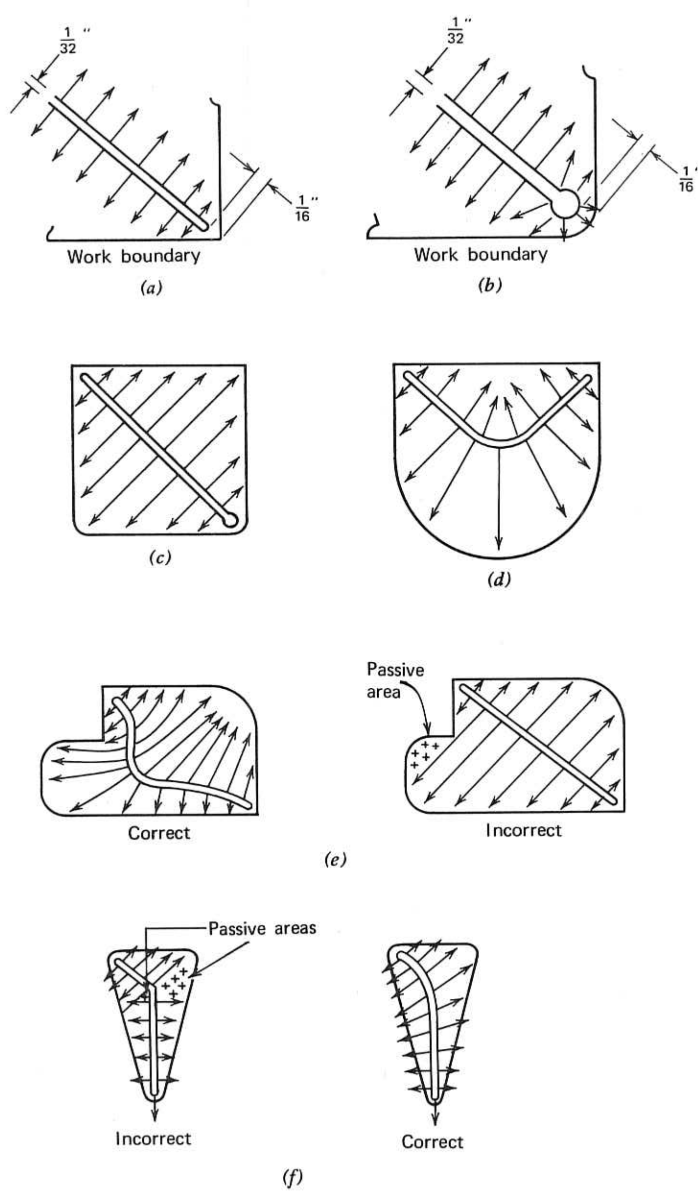


Figure 7.43 Design of electrolyte supply slots.

use of reverse flow tools to achieve suitable electrolyte flow distribution. Further study of flow, towards and away from intersecting boundaries, is needed to fully understand these flow requirements.

Flow from intersecting boundaries is shown in Figure 7.44*a*. The two fronts of flow, leaving the separate boundaries orthogonally, are forced

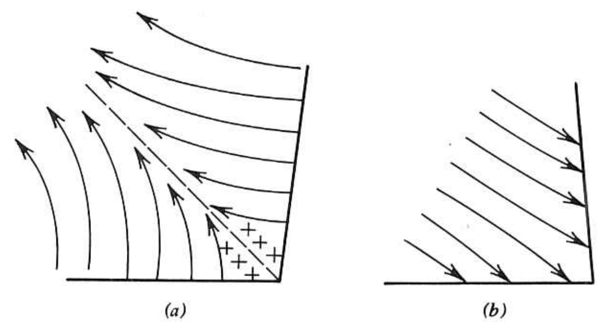


Figure 7.44 Effects of flowing towards and away from intersecting boundaries.

by their interaction to flow in the direction of the dotted line. The resulting variation of flow velocities causes a local rise in pressure that opposes flow in the small area adjacent to the corner formed by the boundaries. Inadequate flow and failure to machine can, therefore, occur in this area. Flow moving *towards* the intersection of the boundaries, as shown in Figure 7.44*b*, has only a small tendency to spill sideways away from the corner. This is because viscose losses, favoring the shorter flow path, are very small compared with the kinetic energy of the flow. Provided that the corner angle is greater than 60°, flow towards such an irregular boundary will be adequate, in all areas, to support machining.

The general rule is *Supply Flow from Smooth Boundaries and Exhaust Flow from Intersecting or Irregular Boundaries, Terminate Supply Slots at Exhaust Boundary Intersections and Terminate Exhaust Slots Close to Supply Boundaries.*

In terms of slotted tools, this means that only single smoothly blended slots, terminating in corners of the tool, may be used as supplies; exhaust slots may be crossed or irregular but should terminate close to a supply boundary.

In machining a simple rectangular recess, for example, either forward or reverse flow may be used. In the former case, a single slot across the diagonal, as shown in Figure 7.45a, suitably distributes the flow. In the reverse flow condition, two intersecting diagonal exhaust slots are required to avoid flowing away from an intersecting boundary, as shown in Figure 7.45*b*. Again, the reverse flow tool, shown in Figure 7.45*c*, requires three intersecting slots; while, in the forward flow condition, a single curved slot terminating in two corners of the triangle, as shown in Figure 7.45*d*, is required.

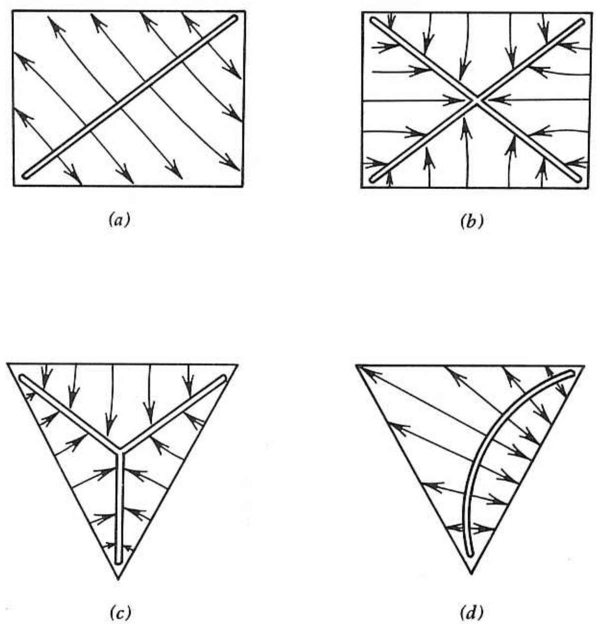


Figure 7.45 Variation in slot design for forward and reverse flow tools.

Interesting examples of slotted tools and the work that they produce are shown in Figures 7.46 and 7.47. Each tool machines into 80 in.^{2} of the outer surface of an anular forging. A series of such tools produce the entire complex outer contour of this gas turbine engine casing in a nickel alloy material. The original shape of the forging can be seen from the thick "rib" of material, left between adjacent machining operations. Because of the radial movement of the tool, relative to the conical component, this "rib" is very thin at the finish depth. In fact, it can be seen that the rib has been completely machined through. It would be difficult to categorize either of these tools as "forward" or "reverse" flow, since both flow conditions are present. The tools comprise a main cutting surface, which machines the outside diameter of the casing and a recessed insert, which machines the raised platforms on the casing.

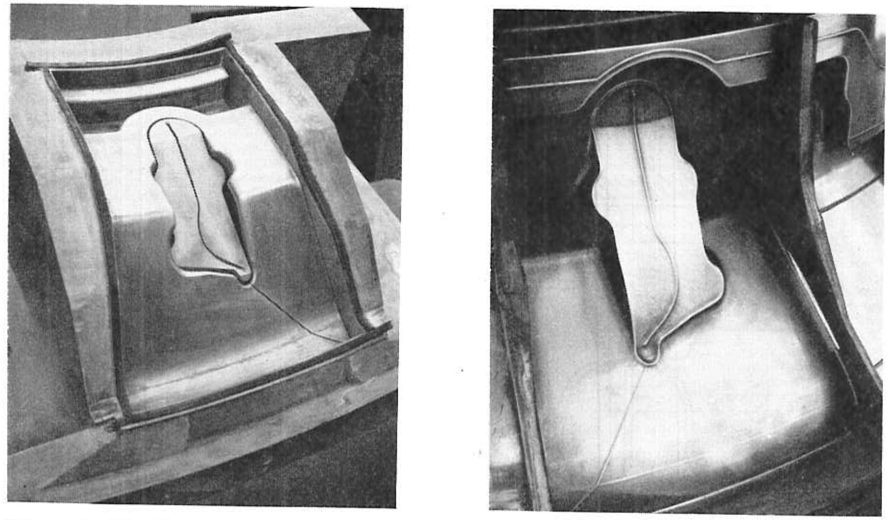


Figure 7.46 Complex contour (6 x 8 in.) cut in a tough wrought nickel alloy jet engine casing by a single pass of the ECM tool shown. Machining time 30 min. (Courtesy of the Bristol Engine Division, Rolls-Royce Limited.)

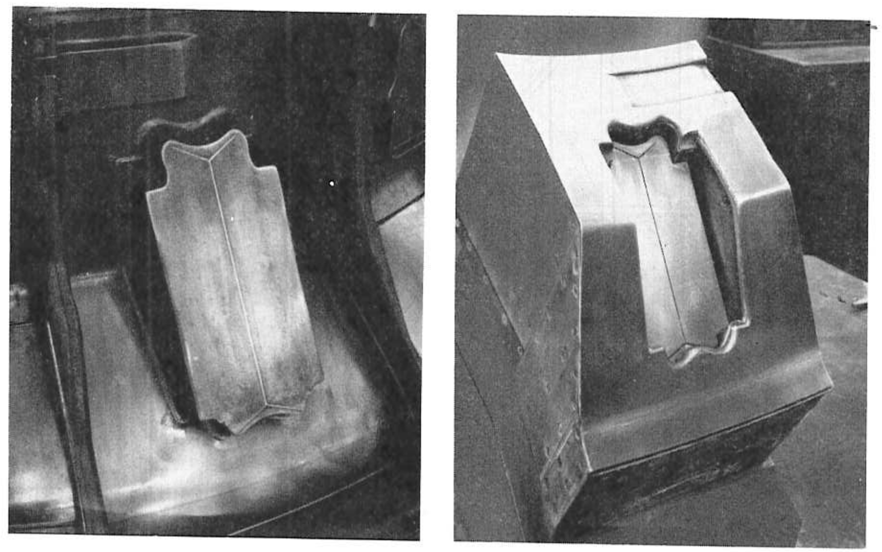


Figure 7.47 This tool, which machines the contour shown, and the tool shown in the previous figure are examples of a number of tools used to produce the entire outer contour of a 4 ft diameter jet engine casing. (Courtesy of the Bristol Engine Division, Rolls-Royce Limited.)

Electrolyte is supplied from the slot between the insert and main tool surface. The flow pattern for the first tool, Figure 7.46 is shown in Figure 7.48.

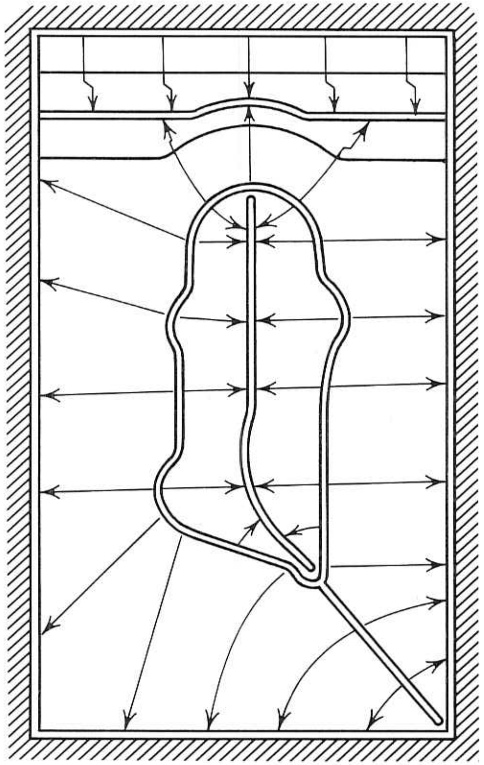


Figure 7.48 Electrolyte flow pattern for the tool shown in Figure 7.46.

The main area of the tool operates with forward flow. The slot shape is not ideal, however, since the sharp radius of the lower lobe would produce too divergent a flow condition. For this reason, a single additional supply slot, extending to the lower right-hand corner, has been added. A single exhaust slot terminating close to the supply slot permits adequate flow across the insert tool. An additional exhaust slot, together with a supply from the top edge of the tool, have been provided to ensure adequate flow in the deep channel running across the upper part of the tool.

The second tool, Figure 7.47, displays similar features, but there are

additional points of interest. The flow pattern is shown in Figure 7.49. It will be noticed that the main supply slot has four sharp corners; this does not meet the normal requirements for a supply slot. There are two factors, which in this case, permit the tool to machine satisfactorily in these areas. First, the tool has a generously blended supply

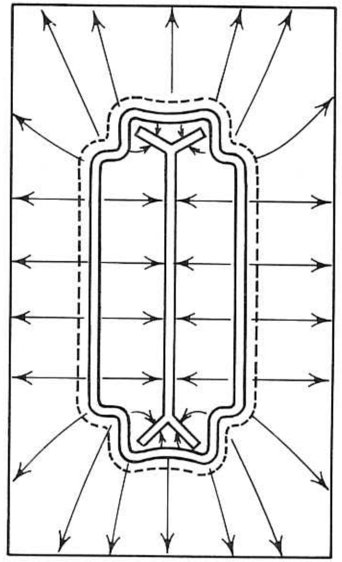


Figure 7.49 Electrolyte flow pattern for the tool shown in Figure 7.47.

slot, so that a correspondingly large fillet radius is produced on the work. The radius moves the supply boundary outwards and so increases the smoothness of the supply slot in these areas. Second, the tool is surrounded by a restrictor dam. The main purpose of this is to permit entry of the tool into the incompatibly shaped forging surface (the principle of this will be explained fully later), but the restrictor dam also creates a back pressure to the electrolyte flow. The back pressure suppresses any tendency to cavitate, and the restrictor dam meters the flow more uniformly towards the periphery of the tool. Slots for distributing electrolyte flow over a machining area are illustrated in Figures 7.50 to 7.57. The cross section geometry of a slot is shown in Figure 7.58*a*.

Cross flow of electrolyte from side to side of the tool requires the use of dams of insulating material. These seal onto the work and tool

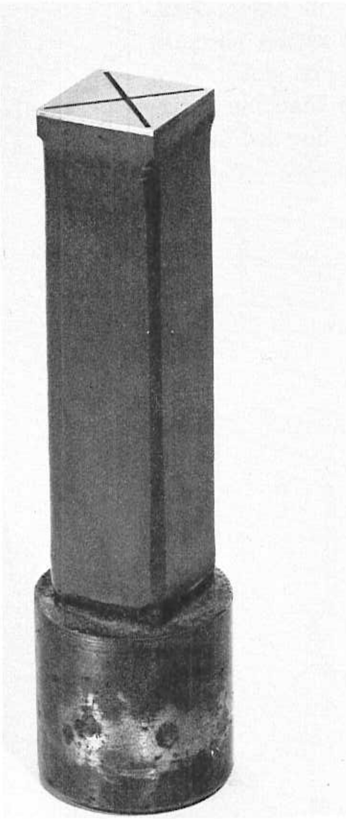


Figure 7.50 Simple generating tool. Electrolyte is supplied from the periphery of the tool and flows into the cross slots. The sides of the tool are insulated to prevent side-cutting. (Courtesy of the Anocut Engineering Company.)

surfaces as shown in Figure 7.58*b*. The left-hand dam restricts the exhaust so that a back pressure is applied. This suppresses cavitation and prevents individual streams from forming in the electrolyte flow. The use of such a dam to give back pressure is usually necessary only where features of the component cause sharp changes in flow direction or extreme flow divergence. Such features, and the effect of applying back pressure, are shown in Figures 7.58*c* and 7.59*a* and *b*. The dams may be spring loaded onto the work surface, and slide and locate on the tool, as shown in Figure 7.59*c* or preferably locate and clamp onto the work, as in Figure 7.60*a*.

The use of dams provides extra control of electrolyte flow, and ridges are not produced on the work, but the method is expensive and should be used only where necessary.

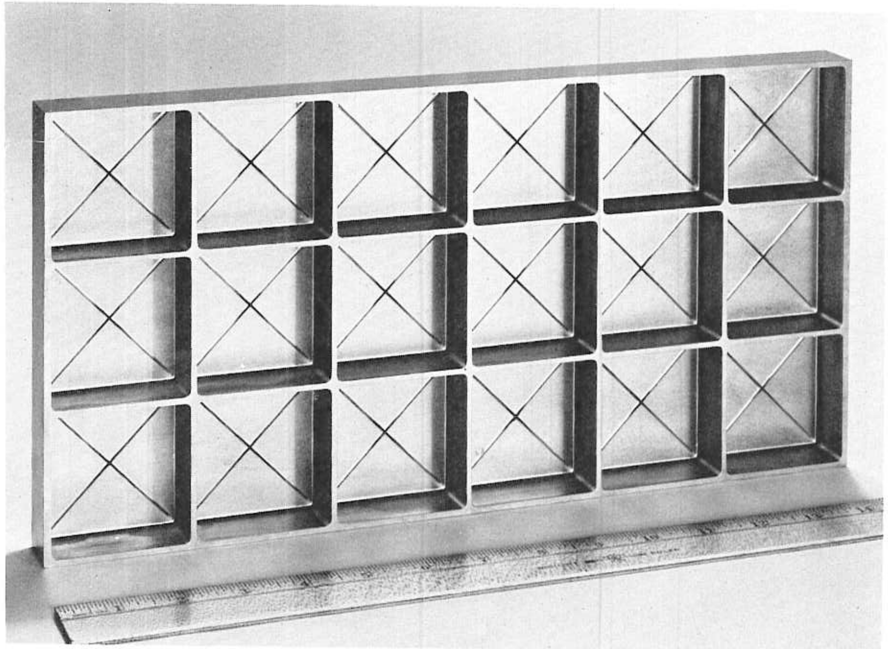


Figure 7.51 Titanium plate with rectangular pockets produced by a repetetive ECM operation. The dimensional repeatability and surface quality is apparent. (Courtesy of the Anocut Engineering Company.)

Flow cavitation, with resultant process failure, can be a problem where sharp changes in flow direction or channel width occur. The most critical condition is at entry to the machining area; the electrolyte, then in a clean state, is a pure liquid. Further into the machining area, process gas builds up so the extra resilience that this gives the electrolyte permits it to flow over more complicated sections without cavitating. The normal tool entry condition is shown in Figure 7.60b.

At the sharp entry the electrolyte pulls away from the tool face, while the blended entry gives smooth convergent flow. A minimum radius of 0.1 in. should be used, although smaller radii are effective if back pressure is applied. A frequently encountered cavitation condition occurs where a vertical wall of the work is to be generated, as shown in Figure 7.61. The insulation is recessed back by at least 0.1 in. and smoothly blended to meet the tool profile to prevent the cavitation and the poor geometry of the workpiece surface that would otherwise result.

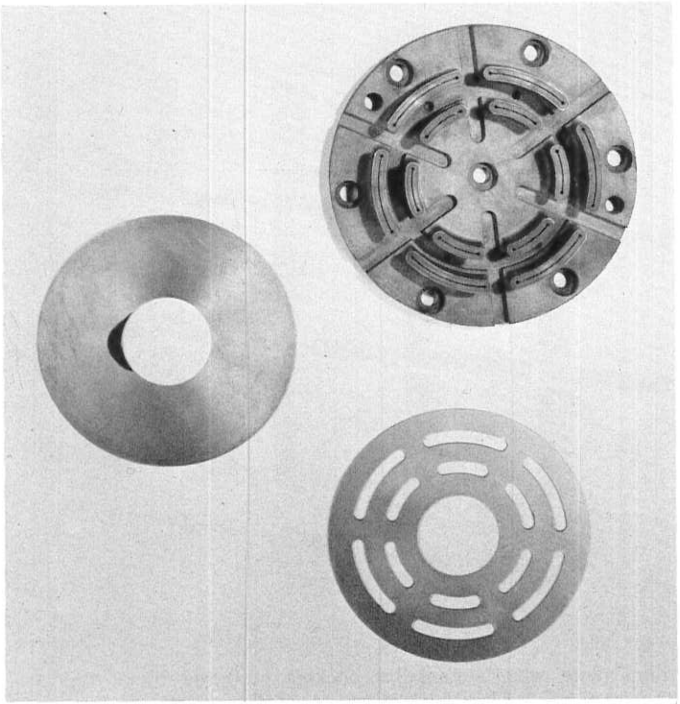


Figure 7.52 ECM slotted disk. Each individual electrode on the tool has insulated vertical walls and its narrow electrolyte supply slot is produced by electro-discharge machining (EDM). (Courtesy of the Cincinnati Milacron Company.)

The limit of electrolyte flow path length is difficult to estimate, since there are many factors involved. Within the limits of present-day equipment, and in the light of experience gained in machining titanium, nickel, and steel alloys, to tolerances of ± 0.002 in., the following approximate factors emerge. The maximum path for parallel flow is 6 in., as shown in Figure 7.62. Where the flow is divergent, the maximum flow path is twice the radius of the boundary, at which the electrolyte is introduced to the machining area. This radius is taken from where the inlet radius of the tool blends into the main work form, as shown in Figure 7.63.

An area selected to be machined in a single operation may contain several features suitable for use as electrolyte supply ports. For example, a number of bosses within a small area. Two or more adjacent sources of flow cannot be used, however, since the opposing flows result in static areas of fluid, as illustrated in Figure 7.64*a*. The area must therefore be subdivided by exhaust boundaries, usually slots, as in Figure 7.64*b*.

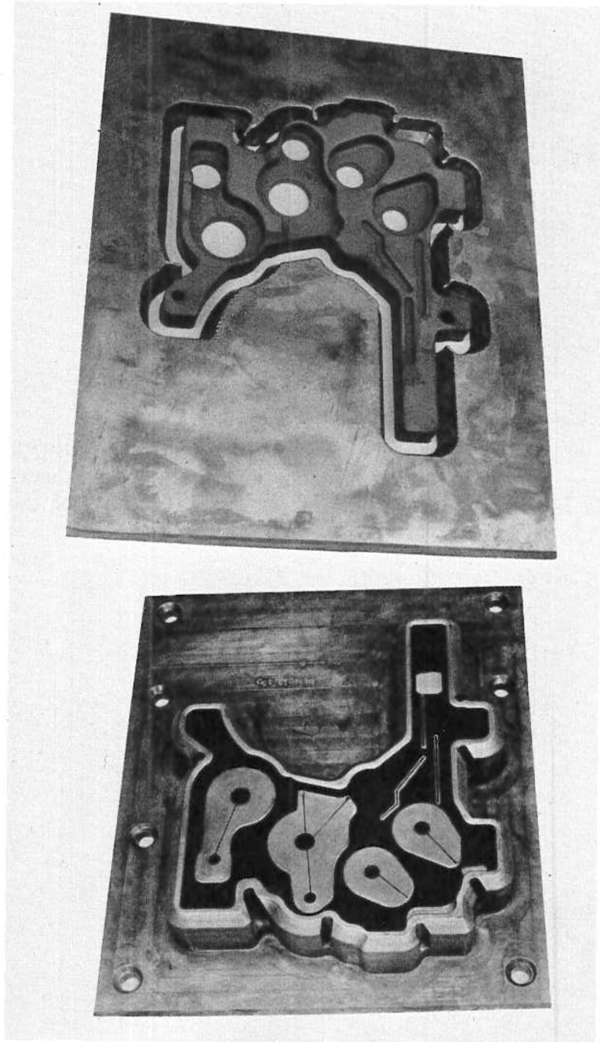


Figure 7.53 This ECM trepanning tool cut the component shown, from a solid 0.75-in.-thick titanium plate, in 20 min. The base of the tool measures 12 x 18 in. (Courtesy of the General Electric Company.)

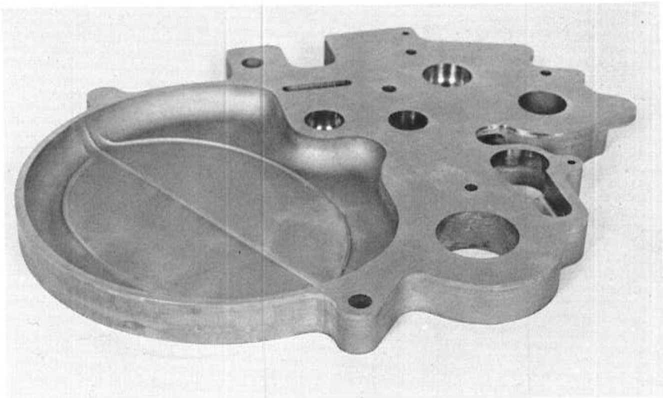


Figure 7.54 The large recess in this 1-in.-thick titanium plate was machined with a forward flow tool. The periphery of the recess, and straight rib, form exhaust boundaries while the curved ribs correspond to flow supply slots. (Courtesy of the General Electric Company.)

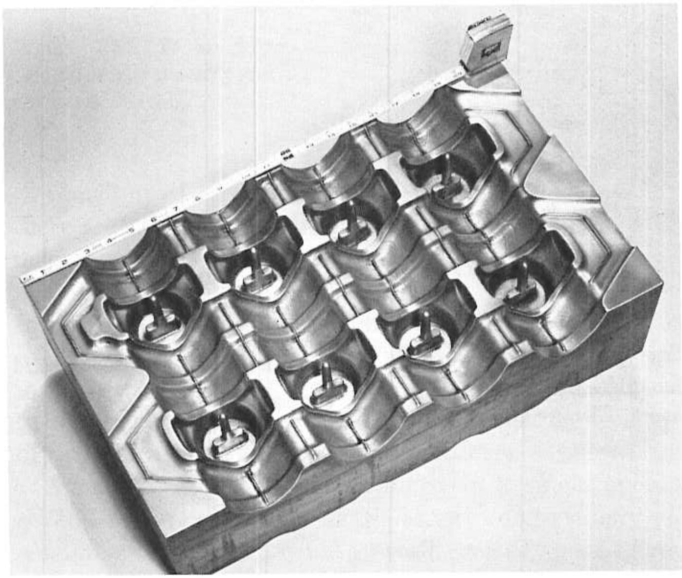


Figure 7.55 Steel forging die produced by two ECM operations. A 20,000-A machine will produce a part of this size and complexity in 4 hr. (Courtesy of the Anocut Engineering Company.)

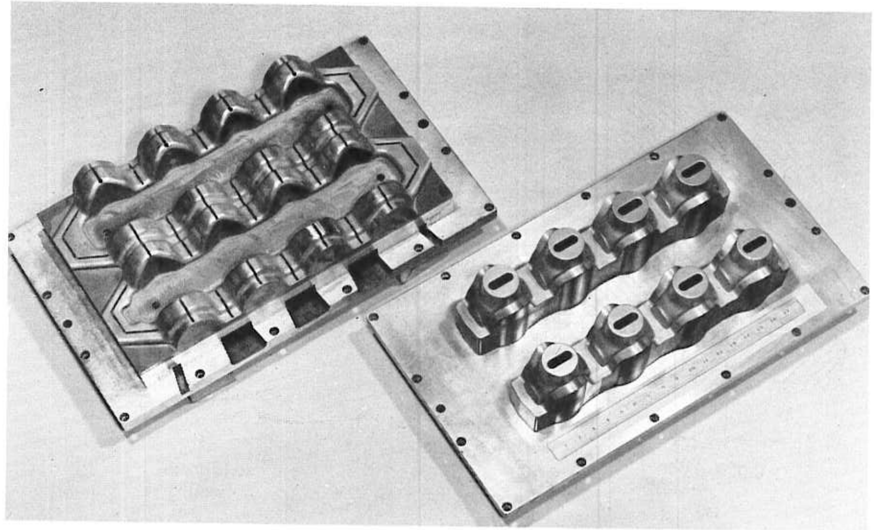


Figure 7.56 ECM tools that produced the steel forging die shown in Figure 7.55

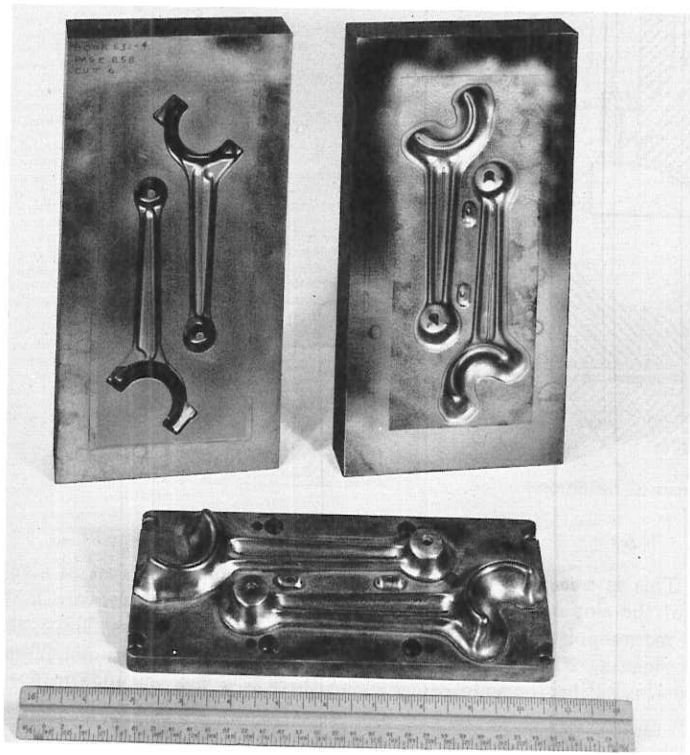


Figure 7.57 Automobile engine connecting rod forging dies and one of the ECM tools used to machine one of them from a solid blank in 20 min. (Courtesy of the Anocut Engineering Company.)

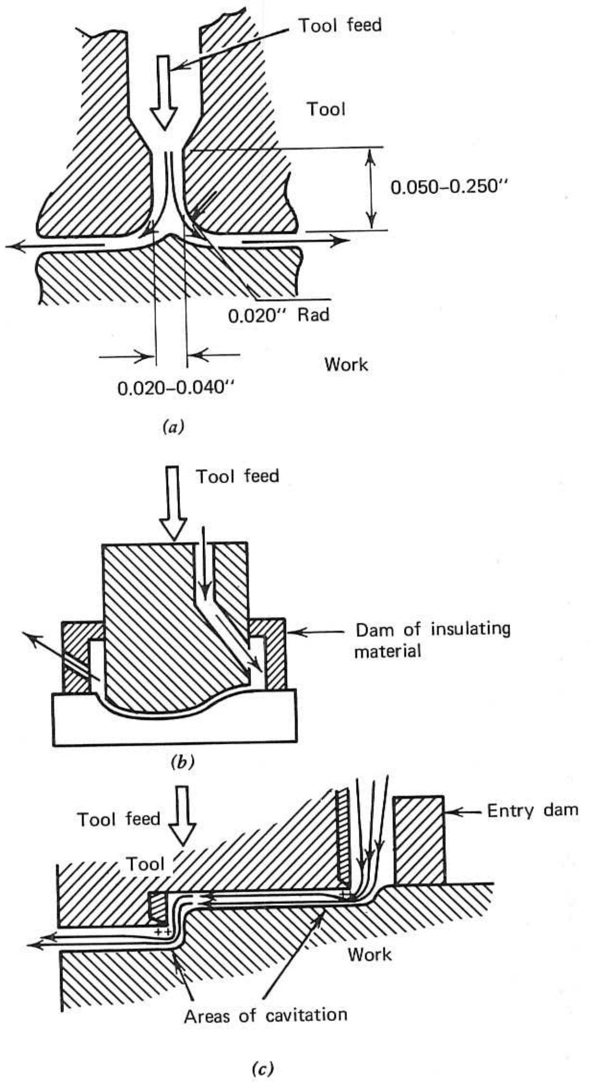


Figure 7.58 (*a*) This is a section of a typical slot for supply or exhaust of electrolyte. Blending of the slot into the tool operative face is critical for forward flow tools; it will also reduce pressure loss at the entry to the slot in reverse flow tools but otherwise the blending is unnecessary. (*b*) Dams are used to provide cross flow of electrolytes. (*c*) Cavitation tends to occur where there is a sharp change in flow direction.

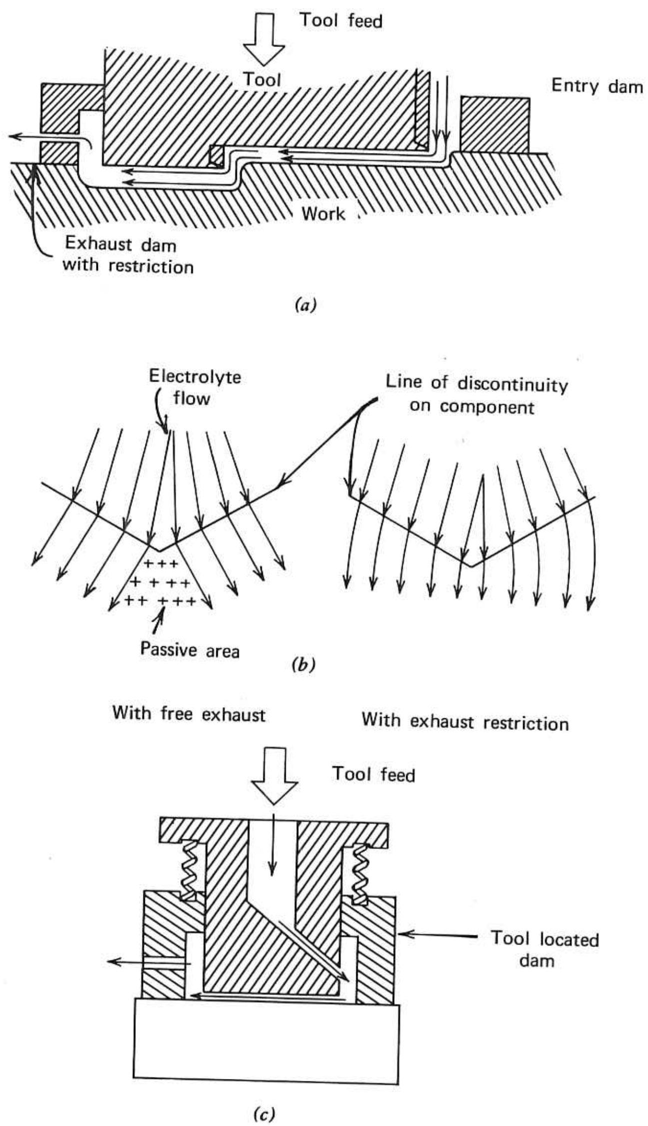
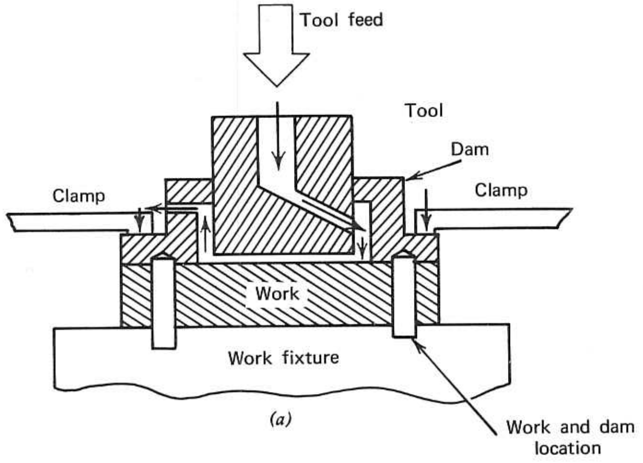
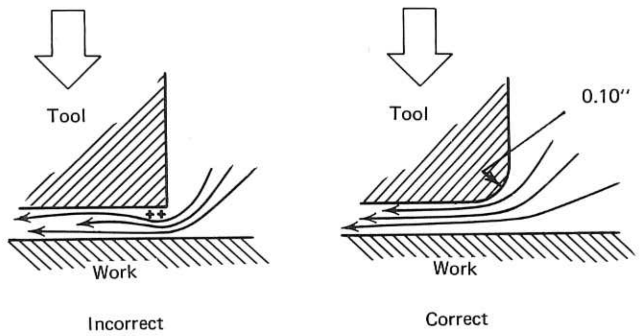


Figure 7.59 (*a*) A dam can be used to produce a back pressure to suppress cavitation. (*b*) Back pressure can prevent cavitation in a divergent flow condition. (*c*) A dam can locate and slide on the tool while being spring loaded onto the work piece.





(b)

Figure 7.60 (*a*) Location of dam to the work piece. (*b*) Overcoming cavitation at electrolyte entry to the operative tool surface.

This area is supplied from two bosses and a slot, the latter reducing the flow path length from the smaller boss. Each supply port is isolated from its neighbors by an exhaust slot. In this way the full area is, in a manner of speaking, produced by a number of individual tools operating simultaneously.

7.9 ELECTROLYTE FLOW RESTRICTOR PRINCIPLES

In the preceding section, the figures show tools that conform quite well to the initial work shape. The electrolyte flow distribution over

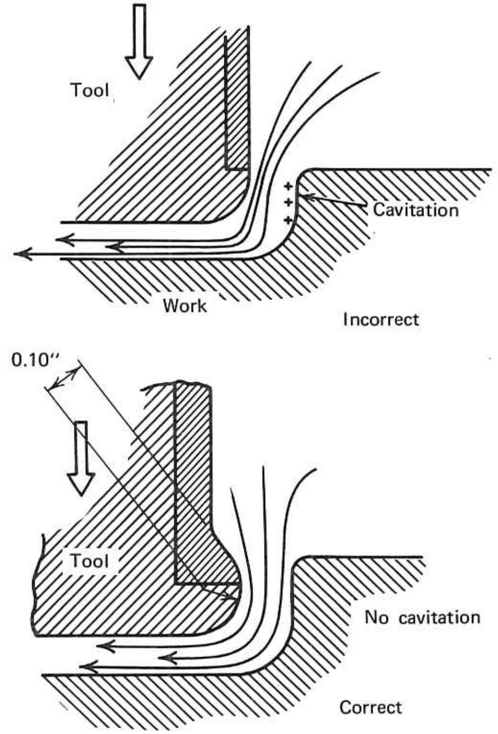


Figure 7.61 A change in tool design that will prevent cavitation at electrolyte entry to the operative area of the tool.

the operative surfaces of these tools is, therefore, reasonably easy to obtain. Many components, however, will present a completely incompatible shape to the tool at the start of machining. An example of this is shown in Figure 7.65*a*. The recess, with a central boss, is to be produced in the sloping face of the work piece. As the tool approaches the work piece, the electrolyte flows freely from the tool. Although some

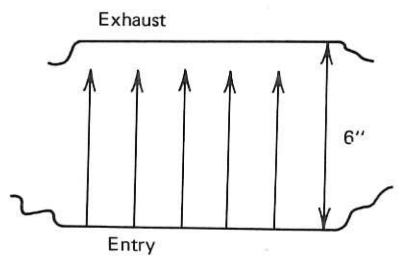


Figure 7.62 The maximum path length for parallel flow is 6 in.

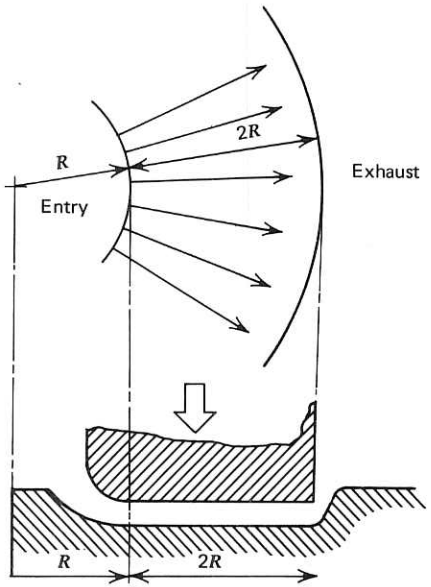


Figure 7.63 The maximum path length for divergent flow is $2R$ or 6 in. whichever is smallest.

of the electrolyte will pass under the point A, where machining is to commence, it will lack the velocity to support machining, particularly at fast tool feed rates. A high electrolyte pressure differential across the area to be machined, A, will ensure a high velocity of flow, hence permit fast machining. A dam positioned, with clearance, around the tool, as in Figure 7.65*b*, restricts the escape of electrolyte to raise the pressure under the tool. There is then an increase in pressure differential across A that may just support machining. Area A, however, is still remote from the final exhaust point at B. Fluid, bypassing A, will raise the pressure in the annular channel around the tool, and so reduce the pressure differential across the area to be machined. If the tool is provided with annular clearance for the escaping electrolyte, then the low pressure exhaust point is brought close to the area A; full pressure differential across the area is then obtained, as in Figure 7.65*c*. Pressure differential ensures adequate flow, but the direction of flow is relatively unimportant. The tool in Figure 7.65*c* would, therefore, work equally well if the flow direction were reversed. A considerable volume of fluid is lost around the periphery of the tool, during the initial machining. Provided that the machine pump can supply this loss and still maintain the required pressure under the tool, then these losses in no way influence

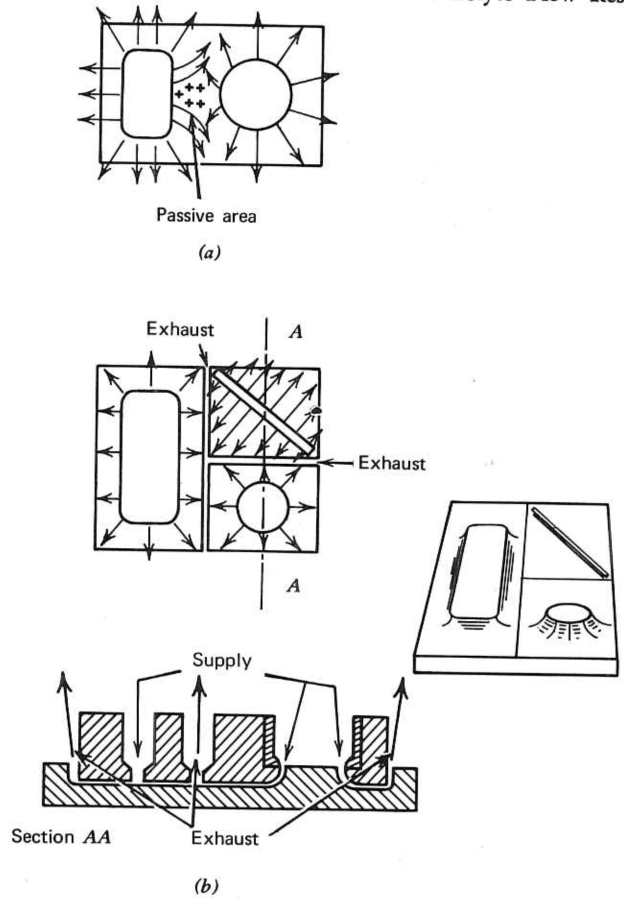


Figure 7.64 (*a*) Opposing flows from adjacent electrolyte supplies produce a stagnation area. (*b*) To machine the component shown on the right exhaust slots must be provided between the supplies to prevent stagnation of the flow.

the flow conditions across the area A. Suitable tooling dimensions, for this particular flow restrictor arrangement, are shown in Figure 7.66*a*. It will only work if the locally protruding area to be machined is close to the periphery of the tool. If a raised area on the work is not positioned close to the flow restrictor, as shown in Figure 7.66*b*, the main flow of electrolyte bypasses the area and tends to equalize the pressure on either side. The low pressure differential across the raised area produces poor flow, so that passivity of the work surface will occur.

The correct tooling approach to this condition is shown in Figure 7.67*a*. Since the raised area is not close to the tool periphery, a new

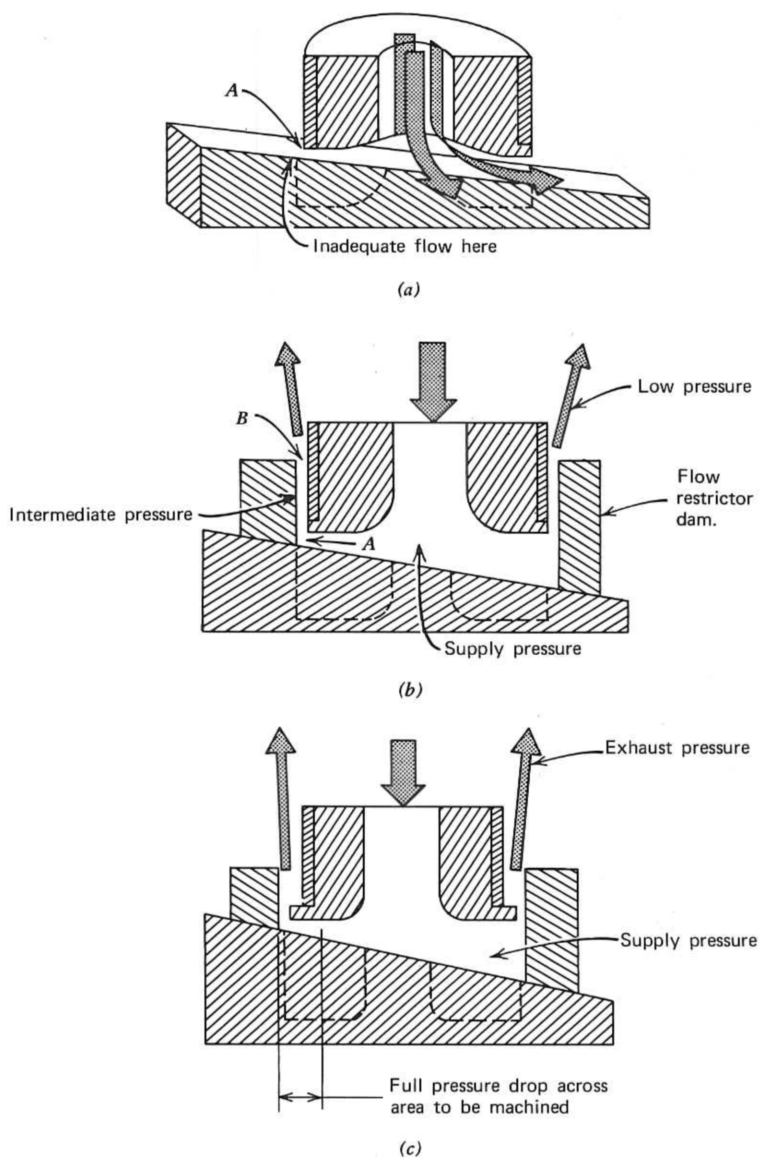


Figure 7.65 Principle of a flow restrictor at the periphery of a tool.

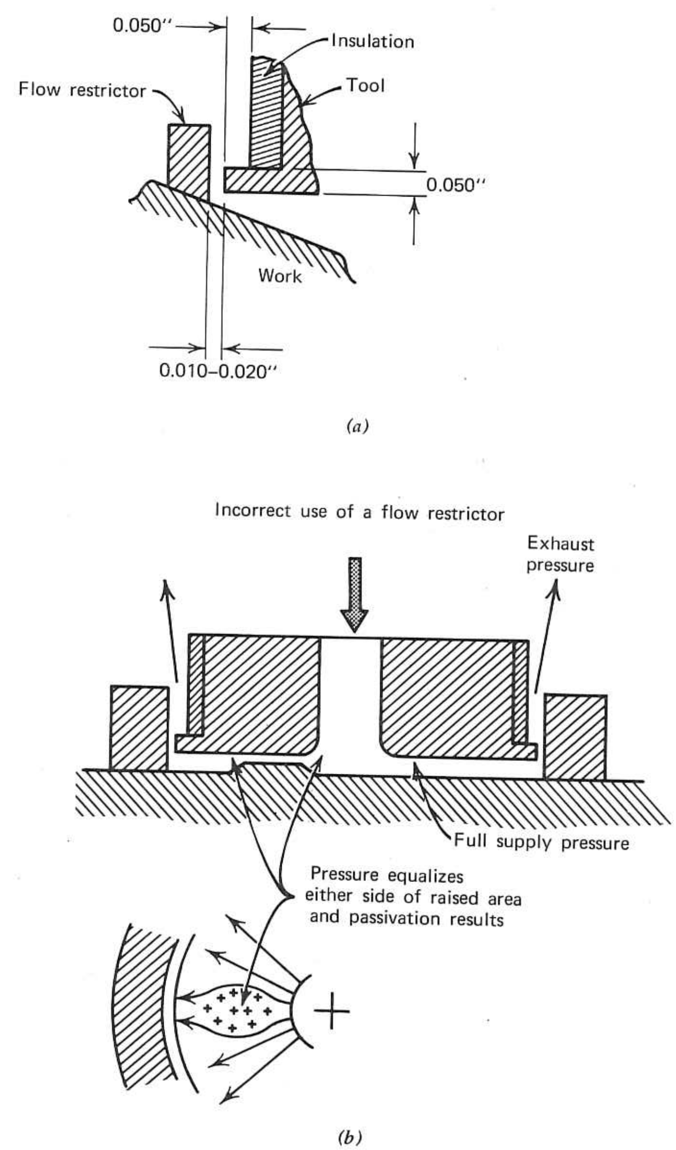


Figure 7.66 (*a*) Design dimensions for a flow restrictor. (*b*) Ineffective use of a flow restrictor.

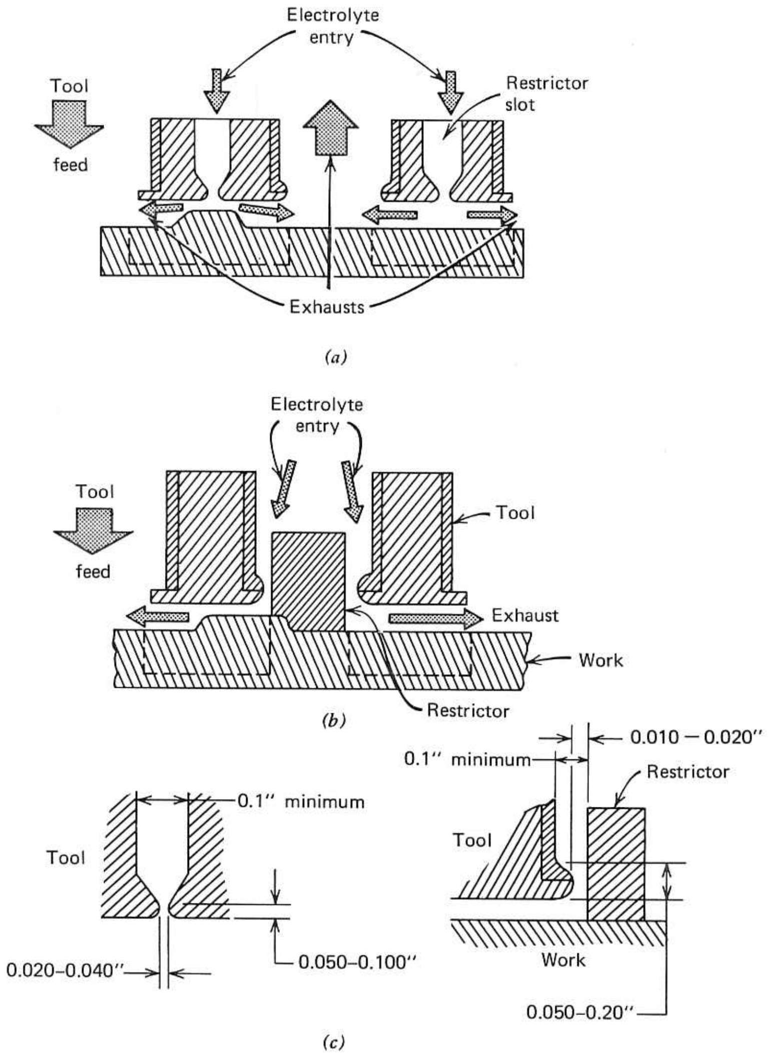


Figure 7.67 (*a*) A supply or exhaust slot in the tool face is required in this example to restrict electrolyte flow. (*b*) A plastic plug provides the required flow restriction in an electrolyte supply port. (*c*) Design dimensions for the flow restrictors.

annular electrolyte supply slot is cut in the tool. The narrow slot exit forms the flow restrictor. This keeps the annular chamber, prior to the slot, primed with electrolyte at full supply pressure. The electrolyte from the slot must flow across the raised work area to reach the surrounding regions, which are at low pressure. Both the boss part of the tool and its periphery form exits for the flow.

If the raised area of the work is close to the boss forming part of the tool, then a central plug restrictor may be used as shown in Figure 7.67*b*. Typical dimensions for these restrictors are shown in Figure 7.67*c*.

Each component presents special flow problems; the exact method of restricting the flow will vary accordingly. While the preceding discussion illustrates ways in which flow restrictors can be used, it is the underlying principles of fluid flow that are important. The following rules, however, do emerge:

1. The flow restrictor must be adjacent to the area of initial close proximity between tool and work and must be very short in flow path length.
2. The flow restrictor must be at electrolyte supply or exit positions.

7.10 TOOL INSULATION

Areas on a tool, where electrochemical machining action is not desirable, are insulated. Used principally on generating tools to confine the action of the tool to its tip, insulation is also used on die sinking tools to minimize stray machining of the work piece.

The action of a generating tool, without insulation, is shown in Figure 7.68*a*. The lines between the tool and work represent the current density. The side machining action of the tool produces a parabolic shaped wall in the work and reduces the center column of the work to a cone. However, on the insulated tool, Figure 7.68*b*, the machining action is limited so that vertical walls are produced.

The lack of insulation on the die sinking tool, Figure 7.68*c*, causes considerable stray machining of the work and loss in accuracy. These effects are much reduced by the use of insulation, as shown in Figure 7.68*d*.

It is essential to the success of the machining that the insulation remains secure and intact on the tool for a major part of the tool's life. Failure of the insulation can cause component scrap, serious tool damage, and delay. The insulations that meet this requirement, despite the rigorous environment within the working area, must be tough and securely bonded to the tool.

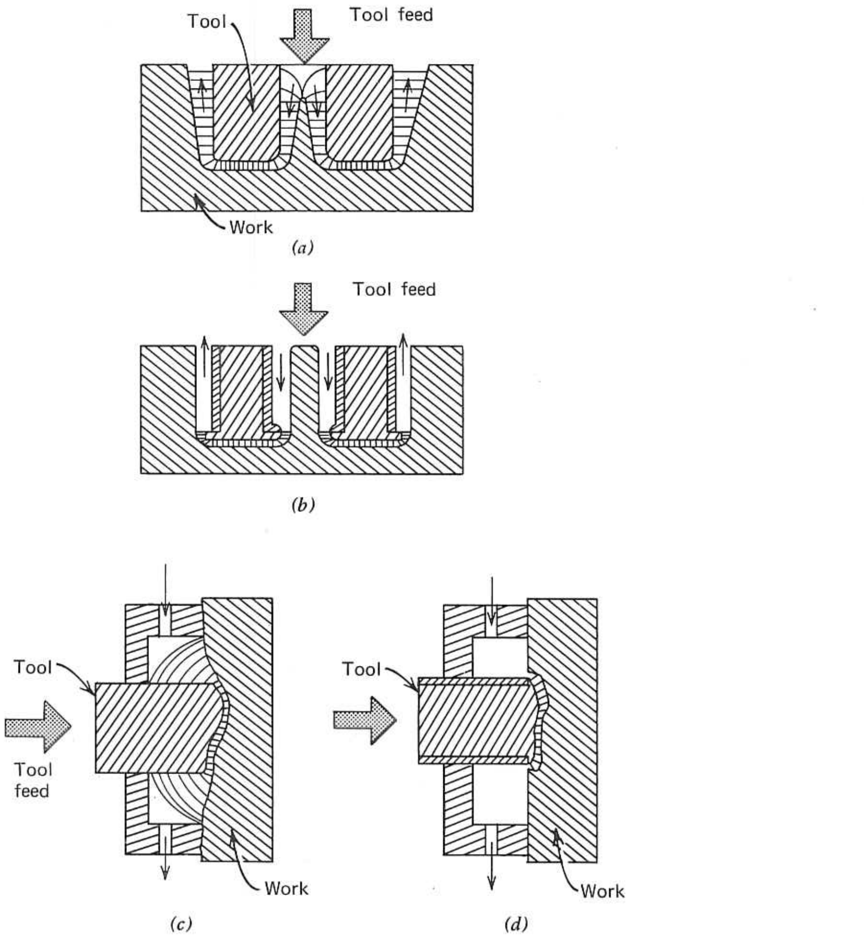


Figure 7.68 (*a*) Considerable side cutting occurs with an uninsulated generating tool. (*b*) Side cutting is substantially reduced if the sides of a generating tool are insulated. (*c*) An uninsulated die sinking tool heavily machines surfaces around the intended machining area. (*d*) An insulated die sinking tool limits stray machining of adjacent surfaces.

If the use of a thin insulation is unavoidable, a synthetic rubber coating, applied in liquid form on top of a primer coating, gives reliable results. Good adhesion is obtained by raising a "nap" of oxide crystals on the copper tool using a hot chemical oxidizing solution, prior to applying the insulation. This is shown in Figure 7.69*a*. The most reliable insulation, however, is achieved by securing reinforced solid plastic mate-

rial to the tool with an epoxy resin cement and plastic screws, as in Figure 7.69*b*. Suitable reinforced plastics are constructed of glass, cotton, paper, or asbestos flock in a resin matrix. These insulating materials may be preshaped or finally machined after securing to the tool.

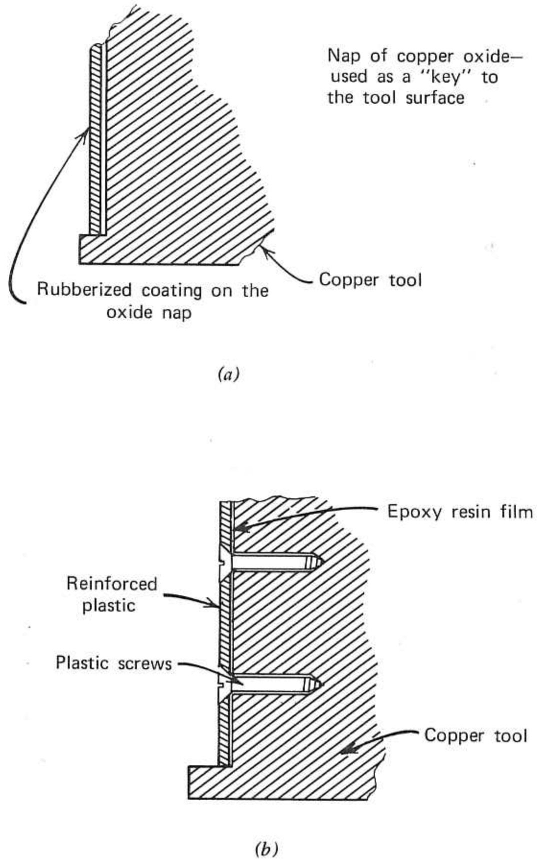


Figure 7.69 (*a*) Method of applying an insulating coating. (*b*) Method of securing insulating sheet material.

The strength and reliability of insulating coatings can be considerably enhanced, if the boundaries of the insulation layer are not exposed to high velocity electrolyte flow. A cross-sectional view of an incorrectly designed, insulated tool is shown in Figure 7.70*a*. The areas indicated are where insulation failure may occur. At such points, it is better to

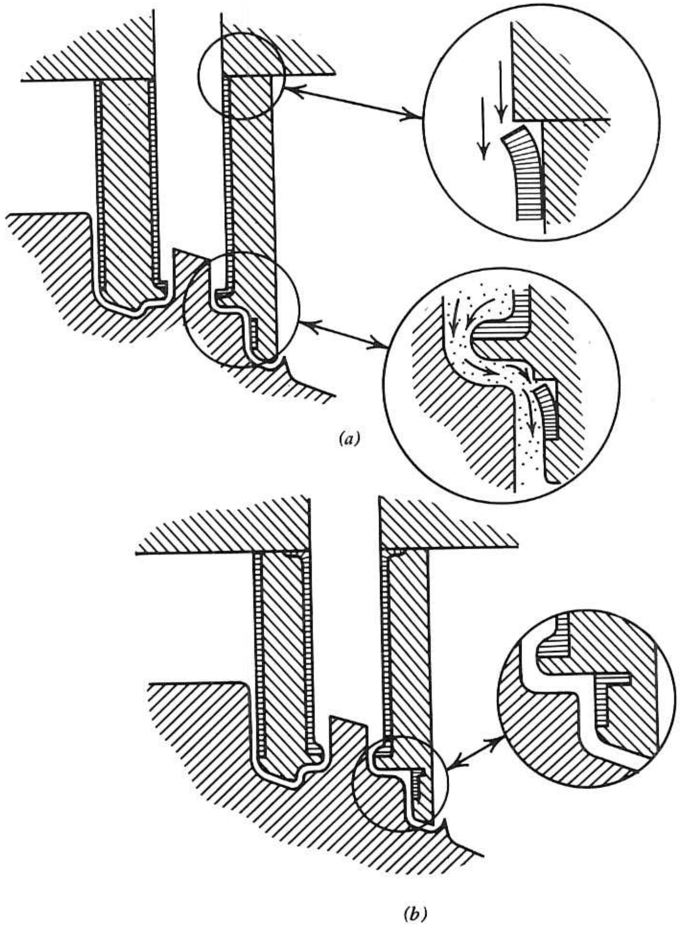


Figure 7.70 (*a*) High velocity flow of electrolyte will strip insulation coatings in this tool design. (*b*) Correct tool design to prevent electrolyte flow stripping insulation.

securely key the insulation to the tool, as shown in Figure 7.70*b*. Details of insulating coatings are given in the appendix.

7.11 CORRECTION OF TOOL SHAPE

An ECM tool does not produce the reverse image of its own shape in the work piece. In practice, the geometry of the tool, feed direction, flow path length, and general variables of the process all influence the

finally produced component shape. The complexity of the problem indicates an empirical method for determinating tool corrections. Such techniques have been used and some information is available. Application of empirical work to other than simple tool shapes, however, involves an unacceptable amount of experimental work. The problem can be simplified by reducing the effects of process phenomena, such as hydrogen evolution, so that they are insignificant. This can be achieved by careful selection of process conditions. Analytical methods can then be used to derive simple formula and tabulated data for predicting tool corrections.

Generating Tool Overcut

The simplest correction is for a generating tool, as shown in Figure 7.71*a*. For the land sizes shown, the overcut is about 1.5 times the end gap at the point where the electrolyte exhausts to atmosphere. The operating gap is usually 0.010 in. but is smaller for small intricate tools, and larger for tools operating with long electrolyte flow paths. The exact dimensioning of the tool is not critical, providing that it is a uniform envelope of the required work shape. Final adjustment of the end gap, when the tool is on the machine, permits accurate sizing.

A similar tool operated with electrolyte back pressure, or with the electrolyte flow direction reversed, will display a larger overcut. This is about twice the normal overcut; that is, three times the machine gap or 3 h_e. Again, fine adjustment of the overcut can be made during the final determination of the machining parameters.

A standardized generating tool land size is suitable, if the tool is to pass completely through the work piece. A tool land will require a special radius to produce a specific radius at the base of a recess, boss, or similar feature. The tool land radius is smaller than the radius to be produced, and the overcut increases as the radius increases. This type of tool is shown in Figure 7.71b.

Die Sinking Tool Correction

Providing that the effects of hydrogen evolution and metal precipitates, temperature changes in the gap, and electric field concentrations are minimized, then the following analytical method of tool correction may be used for die sinking tools. In practice, products of the process can be reduced to acceptable levels by using high electrolyte flow rates, by avoiding divergent flow conditions near the flow exit from the tool, and by using electrolyte back pressure, which suppresses the volume

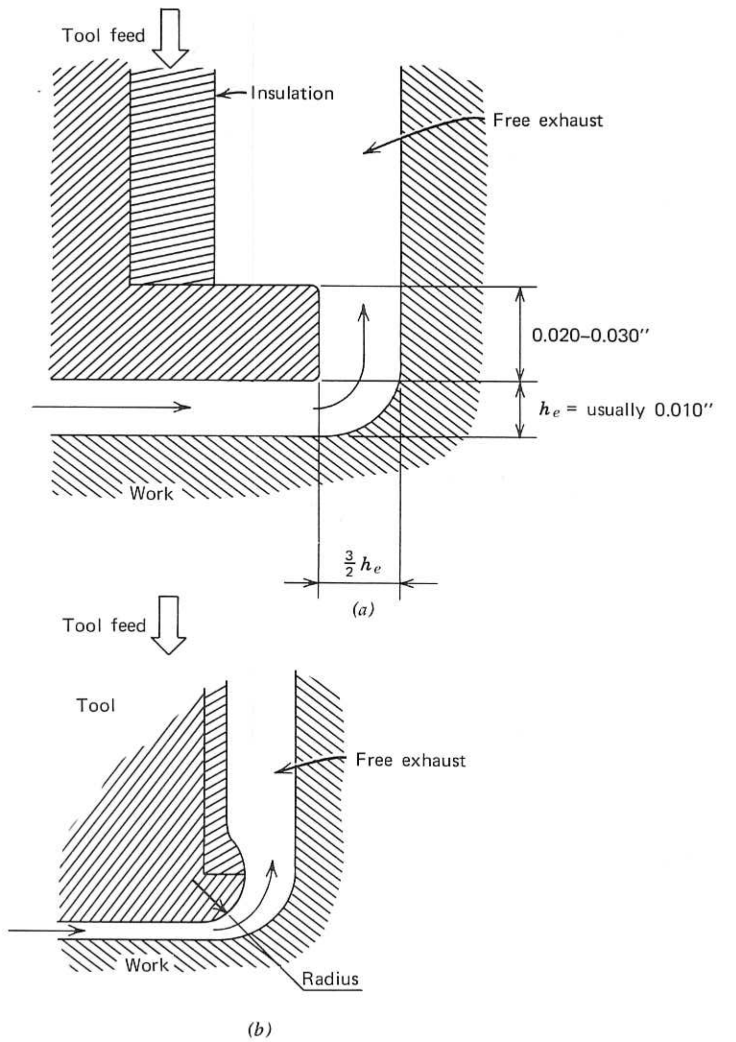


Figure 7.71 (*a*) Size of overcut for a generating tool. (*b*) Design of a generating tool to produce a corner radius.

of liberated gases. Concentrations of the machining current at the boundaries of the area to be machined, or at sharp features of the work, of radii smaller than 0.050 in., will produce excess machining. The analysis is not applicable in these areas.

The general relationship between tool and work for a die sinking operation is shown in Figure 7.72*a*. The work profile and corrected tool

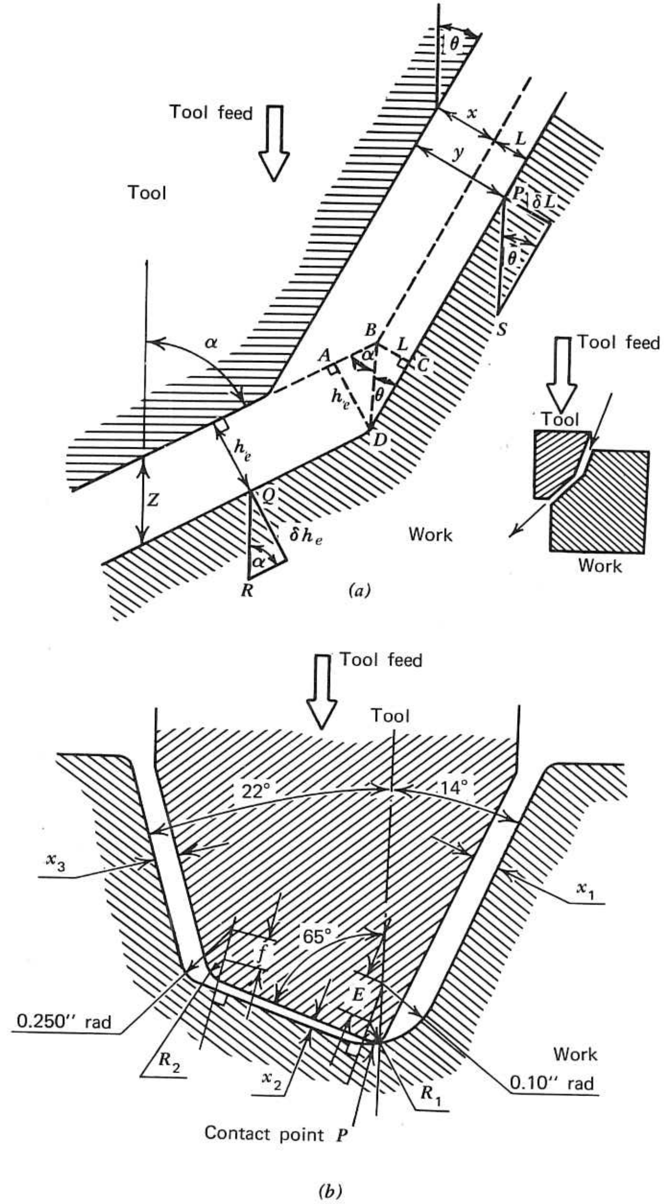


Figure 7.72 (*a*) The geometry of the machining gap during a die sinking operation. (*b*) Actual variation of tool and work piece profiles for a die sinking operation.

profile are shown in dark lines. The dotted line indicates the shape of the tool if it were an exact replica of the work but retracted a distance Z in the tool feed direction. The difference between work and tool shape, at any angle θ on the surface of the work, is x.

The minimum tool end gap during operation is h_e, which occurs at the maximum angle α of the work surface to the tool feed direction.

From Figure 7.72*a*, tool correction

$$x = y - L \tag{1}$$

From triangles ABD and BCD

$$\frac{h_e}{\sin \alpha} = \frac{L}{\sin \theta}$$

$$L = h_e \sin \theta \operatorname{cosec} \alpha \tag{2}$$

Within the conditions previously given as applicable for this analysis, the potential gradient across the gap at any point is uniform. Metal removal rate is, therefore, inversely proportional to gap size.

Thus incremental metal removal at P and Q are related as follows:

$$\frac{\delta L}{\delta h_e} = \frac{h_e}{y} \tag{3}$$

At equilibrium machining conditions, metal removal rate in the direction of tool feed at any point on the work surface is equal. Therefore, $PS = QR$, and so

$$\frac{\delta L}{\sin \theta} = \frac{\delta h_e}{\sin \alpha}$$

$$\frac{\delta L}{\delta h_e} = \frac{\sin \theta}{\sin \alpha}$$

Substituting from eq. 3,

$$\frac{h_e}{y} = \frac{\sin \theta}{\sin \alpha}$$

$$y = h_e \sin \alpha \operatorname{cosec} \theta \tag{4}$$

Substituting eqs. 4 and 2, in eq. 1,

$$\boxed{x = h_e(\sin \alpha \operatorname{cosec} \theta - \sin \theta \operatorname{cosec} \alpha)}$$

In most die sinking applications the tool feeds orthogonally towards some area of the work surface. Hence $\alpha = 90°$, so that the following simplified formula can be used:

$$\boxed{x = h_e(\operatorname{cosec} \theta - \sin \theta)}$$

Values of x for various values of h_e and θ are tabulated in Figure 7.73.

Example

Figure 7.72*b* shows a final component shape and the corrected tool shape. The tool shape will be the same as the component shape less amounts x_1, x_2, x_3 on its various sloping faces. Small radii may be blended in, while for large radii values of x can be found at several angular positions to define the tool shape.

The minimum gap h_e will occur at P during actual tool operation. Suppose this is 0.008 in. for this particular tool. Also at P, $\theta = 90°$, so that since α is the largest value of θ_1, in this example $\alpha = 90°$ and the simplified formula can be used.

$$x = h_e(\operatorname{cosec} \theta - \sin \theta)$$

$$x_1 = 0.008\ (\operatorname{cosec} 14 - \sin 14) = 0.031 \text{ in.}$$

$$x_2 = 0.008\ (\operatorname{cosec} 65 - \sin 65) = 0.002 \text{ in.}$$

$$x_3 = 0.008\ (\operatorname{cosec} 22 - \sin 22) = 0.018 \text{ in.}$$

The tool radius R_1 to give 0.1 radius on the work becomes

$$0.1 - 0.031 = R_1 = 0.069 \text{ in.}$$

The new center of curvature will be as shown on the diagram where

$$e = 0.1 - 0.067 - 0.002$$

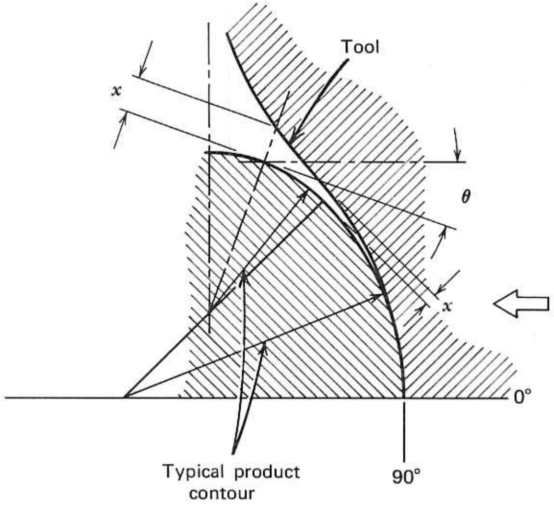
$$e = 0.029 \text{ in.}$$

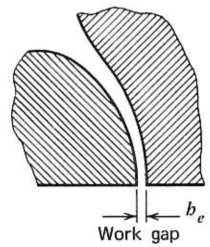
The tool radius R_2 to give an 0.250-in. radius on the work becomes $0.250 - 0.018 = R_2 = 0.232$ in.

The new center of curvature will be as shown on the diagram where

$$f = 0.250 - 0.232 - 0.002$$

$$f = 0.016 \text{ in.}$$





Formula: $x = h_e(\operatorname{cosec}\theta - \sin\theta)$
Values of x for $\alpha = 90$

θ	$h_e\|.010$	$h_e\|.012$	$h_e\|.014$	$h_e\|.015$	$h_e\|.020$
	x	x	x	x	x
1	.5728	.6874	.8020	.8593	1.1457
2	.2861	.3434	.4006	.4293	.5723
3	.1905	.2286	.2667	.2858	.3810
4	.1426	.1711	.1997	.2139	.2853
5	.1138	.1366	.1594	.1708	.2277
6	.0946	.1135	.1324	.1419	.1892
7	.0808	.0970	.1131	.1212	.1616
8	.0704	.0845	.0986	.1057	.1409
9	.0623	.0748	.0873	.0935	.1247
10	.0558	.0670	.0782	.0838	.1117
11	.0505	.0606	.0707	.0758	.1010
12	.0460	.0552	.0644	.0690	.0920
13	.0422	.0506	.0591	.0633	.0844
14	.0389	.0467	.0545	.0584	.0778
15	.0360	.0432	.0504	.0540	.0721
16	.0335	.0402	.0469	.0503	.0670
17	.0312	.0375	.0438	.0469	.0626
18	.0292	.0351	.0409	.0439	.0585
19	.0274	.0329	.0384	.0411	.0549

Figure 7.73 Table of tool correction values.

Formula: $x = h_e(\operatorname{cosec}\theta - \sin\theta)$
Values of x for $\alpha = 90°$

θ	$h_e\|.010$	$h_e\|.012$	$h_e\|.014$	$h_e\|.015$	$h_e\|.020$
	x	x	x	x	x
20	.0258	.0309	.0361	.0387	.0516
21	.0243	.0291	.0340	.0365	.0486
22	.0229	.0275	.0321	.0344	.0458
23	.0217	.0260	.0304	.0325	.0434
24	.0252	.0246	.0287	.0308	.0410
25	.0194	.0233	.0272	.0291	.0388
26	.0184	.0221	.0258	.0276	.0368
27	.0175	.0209	.0244	.0262	.0349
28	.0166	.0199	.0232	.0249	.0332
29	.0158	.0189	.0221	.0237	.0315
30	.0150	.0180	.0210	.0225	.0300
31	.0143	.0171	.0199	.0214	.0285
32	.0136	.0163	.0190	.0204	.0271
33	.0129	.0155	.0180	.0193	.0258
34	.0123	.0147	.0172	.0184	.0246
35	.0117	.0140	.0164	.0175	.0234
36	.0111	.0133	.0156	.0167	.0223
37	.0106	.0127	.0148	.0158	.0212
38	.0100	.0121	.0141	.0151	.0202
39	.0096	.0115	.0134	.0144	.0192
40	.0091	.0109	.0128	.0137	.0183
41	.0087	.0104	.0122	.0130	.0174
42	.0082	.0099	.0115	.0124	.0165
43	.0078	.0094	.0110	.0117	.0157
44	.0074	.0089	.0104	.0111	.0149
45	.0071	.0085	.0099	.0106	.0141
46	.0067	.0080	.0093	.0100	.0134
47	.0064	.0076	.0089	.0095	.0127
48	.0060	.0072	.0084	.0090	.0121
49	.0057	.0068	.0080	.0085	.0114
50	.0054	.0065	.0076	.0081	.0108
51	.0051	.0061	.0071	.0076	.0102
52	.0048	.0058	.0067	.0072	.0096
53	.0045	.0054	.0063	.0068	.0091
54	.0043	.0051	.0059	.0064	.0085
55	.0040	.0048	.0056	.0060	.0080
56	.0038	.0045	.0053	.0057	.0075
57	.0035	.0042	.0050	.0053	.0071
58	.0033	.0039	.0046	.0049	.0066
59	.0031	.0037	.0043	.0046	.0062

Figure 7.73 (*Continued*).

Formula: $x = h_e(\text{cosec}\ \theta - \sin\ \theta)$
Values of x for $\alpha = 90$

θ	$h_e\|.010$	$h_e\|.012$	$h_e\|.014$	$h_e\|.015$	$h_e\|.020$
	x	x	x	x	x
60	.0029	.0034	.0040	.0043	.0058
61	.0027	.0032	.0037	.0040	.0054
62	.0025	.0030	.0035	.0037	.0050
63	.0023	.0028	.0032	.0035	.0046
64	.0021	.0026	.0030	.0032	.0043
65	.0019	.0024	.0028	.0029	.0039
66	.0018	.0022	.0025	.0027	.0036
67	.0017	.0020	.0023	.0025	.0033
68	.0015	.0018	.0021	.0023	.0030
69	.0014	.0017	.0019	.0021	.0027
70	.0013	.0015	.0018	.0019	.0025
71	.0011	.0013	.0016	.0017	.0022
72	.0010	.0012	.0014	.0015	.0020
73	.0009	.0011	.0013	.0013	.0018
74	.0008	.0009	.0011	.0012	.0016
75	.0007	.0008	.0010	.0010	.0014
80	.0003	.0004	.0004	.0004	.0006
90	.0000	.0000	.0000	.0000	.0000

Figure 7.73 *(Continued).*

Selecting a value for h_e, that is, the machining gap for which the tool will be designed to operate, is largely a matter of judgement and experience. At small gaps, faster tool feed rates are possible and closer work-piece tolerances can be held. An added benefit is that less material allowance is needed to meet a specific tolerance. This can be an important factor if the work material is expensive, for example, in electrochemically machining a gas turbine airfoil. On the other hand, high electrolyte pressures are needed; tooling must be rugged and precision built and is more complex to avoid flow problems such as cavitation. Also, finer filtration and closer process controls are necessary, if the benefits of using small gaps are to be realized. Tooling and process control are less critical for operation at large gaps; which also favor long flow paths, since these require a greater volume of flow to sweep away process products. Although the best tool feed rates cannot be achieved at large gaps, this is seldom a problem, since the feed rate for large tools is usually limited by the available machining amperage. Each operation must be separately considered, therefore, before selecting a value for the machining gap, the following table can be used as an approximate guide to values of h_e.

Machining gap h_e (in.)	Maximum flow path (in.)	Tolerance (in.)
0.005	2	±0.0005
0.010	6	±0.0015
0.015	10	±0.0025
0.020	15	±0.005

7.12 CHECK LIST FOR TOOL DESIGN

The sequence of steps set out in the preceding description of the tool design procedure appeared to be the most logical. In practice, however, it is necessary to work through the sequence several times, starting with roughed out ideas, schematic layouts, and so on, until the full concepts of the tooling are developed, drafted out, and detailed. The process of developing the design is one of continued cross checking and rethinking to achieve a final complement of all the design factors. In all this activity, it is possible to overlook some factor essential to the eventual operation of the tooling. For this reason, the following check lists may be used to help minimize these oversights. The first covers the general functioning of the tooling, from strength and corrosion resistance to directing electrolyte and power to the working area. The second sets out the main points for consideration, in the procedure leading to the finalized tooling design.

Check List for General Design Considerations

Materials

METALS

- Use copper, stainless steel, brass, monel, bronze, or gunmetal.
- Ensure quality before using cast metals for electrodes or electrolyte ducts
- Use a minimum number of metals to limit galvanic corrosion.
- Make all metal parts cathodic where possible.
- Sheath all metal parts in plastic where possible.

PLASTICS

- Use epoxy resins reinforced with glass, paper, asbestos cotton, or clear plastics and poly vinyl chloride.

- Select material for strength, stability, low water absorption, and machinability.
- Ensure material is stress relieved to avoid subsequent cracking.
- Do not use plastics to support high loads.
- Minimize use as location, but if used, design for simple replacement due to wear or damage.
- Use neoprene rubber for pipes, gaskets, seals, and so on.

Alignment

FIXED TABLE MACHINE

- Locate tools and fixture to platen and table with fixed keys.
- Use stepped keys to permit correction of initial alignment errors.
- The alignment is in the machine; do not duplicate this in the tooling.

MOVING TABLE

- Locate tools and fixture for squareness to platen and table with fixed keys.
- Position tools to fixture with removable setting pieces and slip gauges.
- Or use removable alignment pieces so that tools and fixture can be placed in the machine as one unit.
- Do not use alignment devices that force tooling into position.

GENERAL

- Provide for checking accuracy and functioning of tooling prior to its entering the machine.
- Minimize the time required to set the tooling into the machine.

Strength and Stability

- Check that electrolyte forces will not deflect tooling more than 0.001 in.
- Ensure that pressure will not distort tooling parts to cause interference or misalignment.
- Check effect of load, temperature, and water absorption, on structural and location parts of tooling.
- Check forces against capability of intended machine.

Electrical Power

- Calculate maximum machining current.
- Check power capacity of intended machine.
- Copper circuits to work or tool must be 1-in.^{2} section per 1000 A; half that section if water or electrolyte cooled.

- Other materials in circuit require larger sectional areas. Check their conductivity against copper.
- Seal all anodic parts against electrolyte to prevent corrosion.
- Simplify anodic parts, which cannot be sealed for easy replacement.
- Provide a large flexible area of anodic contact to work.
- Minimize number of electrical joints.
- Use the smallest possible number of anodic parts.
- Make all electrical joints easily accessible for servicing.

Electrolyte Requirements

- Estimate tool operating pressure and maximum electrolyte velocity.
- Calculate minimum cross-sectional area of flow across the operational surfaces of the tool.
- Determine flow requirement of tool including losses due to leakage.
- Check pressure and flow requirement against capability of intended machine.

Electrolyte Supply Ducts

- Make cross-sectional area of supply ducts 10 times minimum area of flow across the operational surfaces of the tool if possible.
- If less than the ratio above, smoothly blend and shape ducts.
- Conduct careful analysis of flow if ratio of areas is less than 5 : 1.
- Build in adequate strength to withstand electrolyte pressure.
- Port joints and other interspaces to atmosphere.
- Provide inspection access to all ducts.
- Prevent possible entry of seal or gasket material into electrolyte system.

Check List for Design Procedure

Component Appraisal

- Determine volume of production, material, tolerances, and surface finish requirements of component.
- Estimate ECM time.
- Estimate component cost using ECM, taking into account: ECM floor to floor machining time; volume of production; supporting manufacturing operations (remember ECM is stress and burr free); tooling costs and maintenance; machine depreciation; post ECM surface treatments.
- Make cost comparisons with alternative methods of manufacture, taking similar factors into account.

- Consider other advantages, such as, design flexibility, stress-free machining, reduced work in progress, and reduced floor space.

Design Changes

- Ensure that the component designer has made full use of versatility of ECM in arriving at design.
- Request design modifications that simplify tooling.

Material Shape

- Determine the component shape before the proposed ECM operation.
- Request changes in material shape, which will simplify ECM tooling.
- Calculate depth of metal removal necessary to achieve component tolerances.
- Stipulate minimum depth of surplus material on component prior to ECM operation.

Position of ECM in Manufacturing Cycle

- Complete all bulk metal removal by conventional methods before ECM.
- Stress relieve component just prior to ECM.
- Finish conventional machining of location surfaces after ECM except where such surfaces are required to locate the component for ECM.

Tooling Arrangement

- Consider generating, die sinking, and static tooling methods and how each could be used to machine the component.
- Select, for each individual area of the component, the most suitable tooling arrangement to meet tolerance and surface finish requirements.
- Consider the merits of using totally enclosed tooling, using dams and possibly reverse flow.
- Use static tools for metal removal less than 0.1 in. or for reentrant shapes requiring a uniform volume of metal removal.

- A secondary operation using static tools (to remove 0.010 in.) should be used where single operations cannot achieve the required standard of surface finish.

Sequence of Operations—Several ECM Operations on One Component

- Assess costs and ease of operation for various tooling operating sequences.
- Check each tool for its possible corrosion effects on surrounding machined area.
- Determine the effects of localized metal removal on component: in-process strength, distortion due to removal of stressed material, and the distribution of the electrolyzing current through the component.
- Select the most suitable sequence of operations based on the above factors.
- Consider performing all operations simultaneously.

Electrolyte Flow Arrangement

- Look for natural features of the component for convenient ducting of flow.
- Alternatively select cross flow method using dams or supply flow slots in the tooling.
- Consider grouping components to obtain simpler flow arrangements. If slots are used limit their width to 0.030 in. Terminate slots in corners of work area. Enlarge end of slot if sharp corners are not available in work area. Check that each slot will distribute flow to cover all areas of the work.
- Study contours of work surface and decide if back pressure is necessary.
- Use dams where back pressure is necessary.
- Check flow path for possible points of flow cavitation. Modify tool design accordingly.
- Flow path lengths must be less than 6 in. for parallel flow or less than twice the inlet radius for divergent flow.
- Make sure flow supply and exhaust points are alternated to prevent static electrolyte areas forming.
- Do not rely on luck. Check your flow pattern carefully and *know* that it will work.

Electrolyte Flow Restrictions

- A flow restrictor will need to be used, if the tool engages a limited area of the work surface during some part of its operation.
- Place the restriction, entry or exit dam, or flow slot close to or over the limited area of engagement.
- Extend restriction to follow progressive engagement (or disengagement) of tool with work.
- Limit flow path length through restrictor to 0.1 in.
- Consider each flow problem on its merits; decide where the restrictor is needed and then design it. Do not rely on repeating previously successful tooling.

Tool Insulation

- Insulate tool surfaces where machining action is not required.
- Insulate or shield all cathodic surfaces where stray corrosion of the component is not permissible.
- Insulate anodic parts of fixture to protect them against corrosion.
- Use solid plastic insulation bonded and secured with plastic screws where practical.
- If it is only practical to use an insulation coating, specify approved insulation method and an experienced, qualified source for carrying out the work.
- Shield the edges of coated insulation from high velocity electrolyte flows.

Tool Correction

- Decide if tool correction is necessary, based on component configuration and tolerances.
- Estimate tool operating gap and use this value in determining tool correction from data sheet.
- Prepare glass layouts of corrected tool shape.
- Sometimes an envelope shape of the required work contour will fit the true corrected shape closely. This can then be used to simplify tool manufacture.
- Excessive material dissolution will occur at sharp features having radii smaller than 0.050 in. or at boundaries. Use field theory to calculate additional tool correction at these points.
- Or refer to empirically developed data.

CHAPTER VIII

Generating Surfaces of Rotation by Electrochemical Turning and the Use of Tapered Electrodes

8.1 ELECTROCHEMICAL TURNING

Electrochemical turning adds a new dimension to electrochemical machining application but requires little extension of the ideas already discussed on tooling.

Concentricity and balanced material distribution are often requirements for circular components. It is the ability to produce these properties that gives turning its advantage over the single motion ECM tools. Ordinary ECM tools could be used, in many instances, to produce the same component but less accurately. Large surfaces of rotation can be machined with small segmental tools. These operate at high current density so that requirements for surface integrity of the component can be met while fully utilizing the machine's amperage capacity.

The rotational movement of the tool, relative to the component, does pose some new problems in the use of flow restrictors, back pressure devices, and so on. On the other hand, the rotation effectively camouflages many flow defects and local tool inaccuracies, so that excellent results can be obtained with simple tooling. In addition, circular parts are easily fixtured. Generally, the principles already outlined for ECM