CHAPTER

IX

Establishing Correct Electrolyte

The main problem in selecting electrolytes is that superficially most of them work well, and the tendency is to standardize on one type for several different alloys and varied applications. This simplifies the installation of machining facilities and reduces operating costs. There is much merit in this approach, since simplification is so often the key to success. Initial ECM investment is high and so economic pressures tend to force the simplified system, if its penalties are not recognized and taken into consideration. This can result in reduced productivity and quality, since electrolyte selection is a prime factor in determining machining rate, accuracy, surface texture, and surface integrity. The freedom to use a selected electrolyte permits finishing a component, as opposed to roughing, which will have much less or perhaps no economic merit.

The following sections deal with the factors to be evaluated and the work that must be done, to permit a suitable selection of electrolyte for machining a particular component.

9.1 MACHINABILITY

The first, but certainly not the only consideration, in selecting an electrolyte to suit the material to be machined is that it will permit continuous electrolytic action at a reasonably high tool feed rate. A single salt, or combination of neutral salts, in a water-based solution usually meets this requirement. For example, ferrous- and nickel-based

alloys machine satisfactorily with sodium chloride, sodium nitrate, or a combination of these. A small addition of sodium fluoride to a sodium chloride solution will often overcome a work surface passivity problem. Titanium alloys machine well with sodium chloride solutions, with additions of sodium bromide or sodium fluoride if passivity problems arise. Normally it will not be necessary to look further than these salts to determine a suitable electrolyte for machinability or to provide a good standard of surface integrity. These salts make highly conductive solutions, which permit fast metal removal, and since they are neutral, dissolved work material precipitates from the solution. The electrolyte can be cleaned by gravitational settling or centrifuging to remove the precipitated metal hydroxides, so that its working life is almost indefinite. It is also easy to handle, and is inoffensive with regard to safety and hygiene.

The presence of metal hydroxides, to a limited extent in an electrolyte, is reported by some sources to have a beneficial effect on the machining process with respect to flow distribution and surface finish. There does not appear to be any detrimental effect when an electrolyte solution, laden with hydroxides of one material, is used to machine a material of different composition.

9.2 SURFACE INTEGRITY

The ability to electrochemically machine a material smoothly and rapidly is, of necessity, the first requirement; but the requirement to produce good surface integrity is often the more critical factor in selecting a suitable electrolyte. Essentially, surface integrity is divided into surface texture, which is directly measurable, and the subsurface condition of the material, which can only be determined by sectioning the machined surface and, after polishing, metalographically examining the sectioned surface under magnifications of 400 to 800 times.

The surface texture produced is related to the electrolyte composition, material structure, and potential gradient in the electrolyte. This is because the various phases of the material structure have passive films having different compositions. These exhibit different etching characteristics, and so protrude from the machined surface to the extent that the different etching rates are compensated by the reduction in distance to the cathode tool. Thus a material having structural phases with very different passive film characteristics will tend to machine to give a rough surface. A single-phase material usually machines to a very smooth surface. Increased potential gradient in the electrolyte will almost proportionately improve surface texture (this will be discussed more fully in a later section). The electrolyte composition affects the etching characteristics displayed by passive films of the phases in a particular material, hence the surface finish obtained.

It is for the same reasons that preferential intergranular machining and pitting can occur in electrochemical machining. Components, subject to high stress or cyclic stresses, can fail in service if these defects go unnoticed. Such defects can be detected by sectioning the machined component surface and examining it metalographically. If fissures at the grain boundaries or pits are evident, then a change of electrolyte is indicated. Providing the compounds forming the electrolyte mix are present, their proportion or strength are not usually critical factors in ensuring that machined surfaces are free from defects.

The formation of oxide films on the surface of a material during machining can be a detrimental factor to surface finish in some instances. For example, the machining of titanium appears as a spasmodic process in which local areas of the surface are machined preferentially until saucer-shaped pockets have been produced. When the machining rate falls off in these areas, as their distance from the cathode increases, other preferred areas take their place. At very low current densities large pockets form up to 0.050 in. deep. While at higher current densities the pockets become smaller and more numerous until a good surface finish is evident. Other effects, which can sometimes occur due to oxides, are random bright raised spots on the surface or an "orange peel" textured surface. When an electrochemically machined component shows these surface defects, it is best to use a very active electrolyte, such as sodium chloride with sodium bromide, sodium fluoride, or acid additives. This applies especially to titanium and its alloys.

Tenacious oxide films, which form during machining, can have very beneficial effects on surface finish. Nickel-base alloys, for example, usually display bright smooth surfaces when machined with sodium chloride electrolyte, since the electrically resistive oxide film tends to equalize the etching characteristics for each phase of the material. This electrolyte, however, does not promote oxidation to the same degree at the grain boundaries of nickel-base alloys; so that more rapid machining in these areas produces crevices, which are very detrimental to the fatigue endurance properties of the surface. The use of an oxidizing electrolyte such as sodium nitrate, promotes oxidation at the grain boundaries and prevents inter-granular corrosion in nickel alloys. Steels and iron-base alloys machine well with sodium chloride but the resulting surfaces tend to be rough and covered with loose oxide films. Oxidizing electrolytes, particularly sodium chlorate, produce very thin tenacious

oxide films on the machined surface. Higher machining voltages are then required, but the finishes produced are bright and smooth. There is the added advantage that areas adjacent to the immediate machining area tend to be protected by the oxide film against stay current machining or pitting.

It is not only the composition of the material to be machined which will determine the electrolyte selection; the geometry and function of the component and position of ECM in the complete manufacturing cycle may often be predominant factors. An electrolyte, which produces a bright surface finish on a component, for example, may not be suitable to ensure against intergranular corrosion that would be detrimental to the performance of, for instance, a highly stressed jet engine airfoil. Again while producing good surface finishes at high current density, surfaces exposed to low current density may be badly pitted. Each individual electrochemical machining application may, therefore, present a new problem in the selection of a suitable electrolyte. If it does not, then other factors such as toxicity, ease of storage, equipment corrosion, cost, and general convenience, may form the basis for a decision. In any event, it is hoped that Table 9.1, showing electrolytes generally in use today, and the comments as to their properties will be helpful to the reader.

9.3 ELECTROLYTE CONCENTRATION

The rate at which a material is electrochemically machined is dependent on the density of the electrolyzing current. The smaller the resistance of the path between the tool and work, then the larger the current density will be for a specific operating voltage. Operation at small gaps minimizes the resistance, but there are practical limitations of gap size; these are filtering size, tool and machine rigidity, flow distribution, and so on. A very conductive electrolyte permits operation at high tool feed rates (high current density), using practical operating gap sizes and moderate machining voltages. The advantages of avoiding use of high voltages are that they increase the degree of damage in the event of a spark and the electrical power consumed; also voltages over 30 V become a hazard to the machine operator. The more concentrated the electrolyte the more conductive it will be, but this effect diminishes with concentration. A disadvantage is that salts crystallize out of the solution at high concentrations; areas in the machine work enclosure then become clogged with salt crystals.

Relatively dilute electrolytes can be used to advantage on some types

Table 9.1 Electrolytes and Their Properties

Material	Electrolyte	Advantages	Disadvantages
Steels and iron base alloys	NaCl Up to 2.5 lb/gal (or KCl which is more conductive but also more expensive)	Inexpensive. Nontoxic. No fire hazard. Will machine a variety of materials. Produces smooth blending of machined area into surrounding surfaces. At high concentration conductivity is easy to control and current efficiency is high.	Removes material from surrounding finished surfaces. May pit and damage surrounding surfaces. Tends to selectively machine grain boundaries of stainless steels. Conductivity is temperature sensitive.
	$NaNO_3$ Up to 5 lb/gal	Produces better surface finish than NaCl. Limits stray machining and pitting of adjacent surfaces.	Twice the cost of NaCl. It is a fire hazard. High concentration is required for good conductively. Electrical resistively can vary with flow velocity to produce, so called, flow lines. Higher voltages are required. Conductivity is temperature sensitive.
	$NaClO_3$ 2 to 4.5 lb/gal	Produces very smooth bright surface finishes. ECM surface is very resistant to subsequent corrosion. Conductivity relatively insensitive to temperature. Usually displays no stray machining or pitting of adjacent surfaces. Easier to control for very precise machining.	High Cost. Toxic. High fire risk if allowed to dry on combustible materials. Requires special handling and storage. Poor current efficiency at lower concentration. High voltages (about 20 V) are required for best results. Machining stops below 9 V.
	NaCl 1 lb/gal + 0.1 lb/gal citric acid	Citric acid is a complexing agent which prevents formation of metal hydroxide precipitates. Suitable for operation at very small gap sizes for definition of intricate work shapes. Lower electrolyte pressures may be used, for example, in the operation of delicate electrodes as used in deep hole drilling.	Very expensive if used for other than small intricate parts. Electrolyte must be discarded frequently.
	NaCl up to 2.5 lb/gal + HCl or H_2SO_4 acids to pH3 to pH2	Prevents formation of metal hydroxide precipitates. Suitable for operation at very small gap sizes. Lower electrolyte pressures may be used.	Electrolyte must be discarded frequently or reclaimed by neutralizing with NaOH and centrifuging to remove hydroxides. Cathode tool becomes platted with a black smut and so must be cleaned frequently to retain accuracy. The acid must be continuously replenished. Very corrosive.
Gray cast iron	NaCl up to 2.5 lb/gal or $NaNO_3$ up to 5 lb/gal		Large machining gap sizes must be used (0.020 to 0.030 in.) to allow graphite particles to be swept clear.
White cast iron	$NaNO_3$ up to 3 lb/gal		A rough surface finish is produced.

(Continued)

Table 9.1 (*Continued*)

Material	Electrolyte	Advantages	Disadvantages
Nickel- and cobalt-base alloys	$NaCl$ – 1 lb/gal + $NaNO_3$ – 1 lb/gal	Inexpensive simple mixture. Prevents intergranular attack. Produces good surface finish. It is successful on most nickel- and cobalt-base alloys.	Characteristics of oxide film can sometimes vary with flow velocity to give, so called, flow lines on work surface. Electrochemically machined surface carries lightly adherent grey smut.
	$NaNO_3$ up to 5 lb/gal	Prevents intergranular attack. Produces good surface finish.	Disadvantages same as previous electrolyte. More expensive than previous electrolyte. Needs higher operating voltage. It is a fire hazard.
	$NaCl$ up to 2.5 lb/gal	Produces bright smooth surfaces. Surfaces do not need cleaning after ECM.	Intergranular corrosion is almost always evident. This drastically lowers the fatigue endurance of components machined with this electrolyte. Surfaces adjacent to the machined area are usually badly pitted.
	$NaCl$ up to 2.5 lb/gal + 0.02 lb/gal NaF	Some materials, which display irregular black oxide films when machined with one of the above electrolytes, for example, IN718, will machine to a good finish with this electrolyte.	Will exaggerate the disadvantages listed for $NaCl$ for most nickel and cobalt alloys.
Titanium alloys	$NaCl$ 1.5 lb/gal + $NaBr$ 0.5 lb/gal + NaF 0.02 lb/gal	Readily machines most titanium alloys. Produces good surface finish. Characteristics of surface oxide films insensitive to flow velocity. Easy to control close contour dimensions.	Higher voltages reduce chance of passivity. A loose grey oxide film remains on surfaces after ECM. Pitting occurs on surfaces adjacent to machining area.
	$NaCl$ less than 1 lb/gal	Can produce surface finishes better than previous electrolyte. Electrochemically machined surface does not have a loose oxide film remaining.	High voltages are required. The tenacious oxide films are sensitive to flow velocity so that so-called flow lines may be formed on the work. Bright raised areas may occur on the work surface. Surface is more prone to passivity during machining. Close contour dimensions are difficult to maintain. Pitting occurs on surfaces adjacent to machining area.
Tungsten and molybdenum	$NaOH$		$NaOH$ is consumed during machining and so must be replenished.
Tungsten carbide	$NaCl$ 1 lb/gal + $NaOH$ 0.5 lb/gal + Triethanolamine 2 lb/gal	Capable of producing 10-μin. surface finish.	
	$NaCl$ 1 lb/gal + $NaOH$ 0.6 lb/gal + sodium tartrate 1.7 lb/gal	Capable of producing 10-μin. surface finish.	
Aluminum and aluminum alloys, copper and copper alloys, beryllium	$NaNO_3$ up to 5 lb/gal or $NaCl$ up to 2.5 lb/gal	$NaNO_3$ usually gives the best surface finish.	
Cobalt chromium, tungsten alloys (stellite type)	$NaCl$ up to 2.5 lb/gal		
Uranium zirconium nonmetallics B_4C, ZrB_2, ZrC, TiB_2	$NaCl$		

of work. If, for example, surface finish is of prime importance, then it is better to use a high machining voltage together with a small gap and dilute electrolyte, rather than a low voltage and concentrated electrolyte. This is because the higher voltage gradient, in the former case, will produce a smoother surface finish. This affects both very high and very low current density areas of machining.

A problem, which can be solved in the same way, is that while normally it can be assumed that the entire surface of the work is at the same voltage, this is not so with very thin components. The electrical resistance of thin sections causes power loss in the component as the electrolyzing current flows through it. Some areas of the work then operate at lower voltages and so machine with smaller gaps. Thus these machined surfaces will be in error. The effect is reduced as higher machining voltages are used together with more dilute electrolytes. This is because, for a fixed gap size, the error is proportional to

$$\frac{\text{voltage loss in the work}}{\text{machining voltage}}$$

9.4 FATIGUE TESTING

Many engineering components, particularly those used in jet engines, are subject to high cyclic loading. The surfaces of such components experience the highest stresses so that cracks slowly start to form between grains at these surfaces, which ultimately propagate far enough into the component so that it fractures. This is termed a *fatigue failure*. The ultimate *fatigue strength* of a material, for a specific surface preparation, is usually considered as the value of surface stress (measured parallel to the surface in psi), at which it will endure alternate compressive and tensile loading in excess of 10^7 cycles without fracture.

Mechanical methods of machining produce characteristics in the surface of the worked material that differ from the parent body of the material. These characteristics usually benefit the strength of the component, especially with regard to its fatigue endurance; sometimes their effects are detrimental. For example, residual compressive surface stresses moderate the tensile stresses produced by cyclic loading of a component, this raises its fatigue strength; but residual tensile surface stresses have the opposite effect. In addition, the mechanical work on the surface laminates and overlaps the grain structure to increase resistance to the tensile forces that tend to open up cracks at the grain boundaries. Problems sometimes arising with mechanical metal removal are surface tearing, cracks in heat affected zones, and excessive surface stress. The last problem can promote grain growth at elevated temperature operation of the component. Components produced by carefully controlled mechanical machining methods, however, usually exhibit fatigue strengths that are superior to the natural fatigue properties of the virgin material.

Electrochemically produced surfaces, on the other hand, do not have the benefits of mechanically machined surfaces (but do not have the other problems either), and so display natural and somewhat lower fatigue properties for the material. The difference in fatigue strengths is related to the mechanical properties of the material. As a rough guide, the fatigue strength (at 10^7 cycles) of an electrochemically machined surface, expressed as a percentage of the value for standard mechanically prepared surfaces, for various material types are as follows:

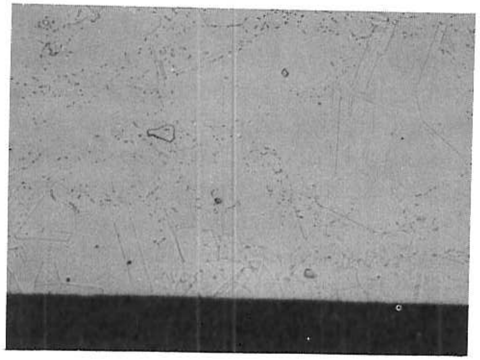
Ferrous alloys	100 to 90%
Titanium alloys	90 to 80%
Nickel alloys	80 to 60%

Micrographs of a ground, an electrochemically machined, and a sand blasted electrochemically machined surface are shown in Figure 9.1.

9.5 POST ECM TREATMENTS

If the functional operation of a component is such that its fatigue strength is important, then post ECM surface conditioning will be necessary. The fatigue strength of a properly electrochemically machined surface can be raised to values equal or greater than those displayed by mechanical metal removal processes, by using simple finishing treatments. While, within the author's experience and that of others in the field, this invariably appears to be true, it is advisable to conduct fatigue tests to select the most suitable post ECM treatment and to put a firm value on the fatigue strength. The following processes have all proved effective in suitably conditioning the surfaces of electrochemically machined materials.

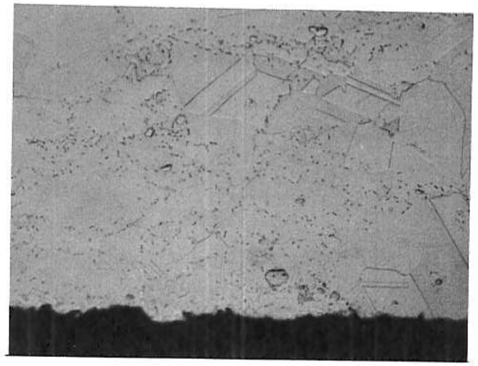
- Glass ball peening
- Barreling
- Grit air blasting
- Vibropolishing
- Vapor honing
- Mechanical polishing



IN718

Electrochemically machined. Etched to show grain structure.

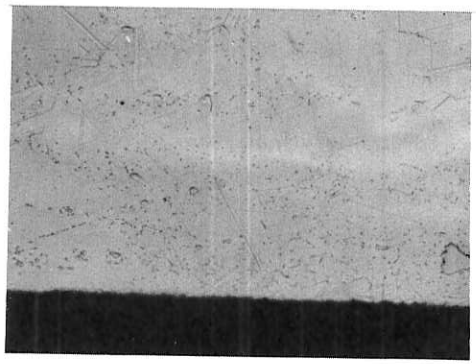
X400



IN718

Electrochemically machined and sand blasted. Etched to show grain structure.

X400



IN718

Ground only. Etched to shown grain structure.

X400

Figure 9.1 Comparison of surface structures produced by mechanical and ECM processes on a nickel alloy material. (Courtesy of the General Electric Company.)

All these processes provide some mechanical working of the surface and induce compressive stresses. Some also remove a small layer of surface material. They are processes that are easily controlled to give reliable, repetitive results and are, of course, already widely used in industry.

9.6 TESTING EQUIPMENT

Correct electrolyte selection can only be verified by success in machining a component so that all its quality requirements are met. A choice can be made before the ECM tooling is available, however, with a good chance of success. Specialized equipment, designed solely for testing electrolytes, can be used to evaluate electrolytes with a minimum of effort and expense. An electrolyte should ideally have the following properties:

- Support smooth, rapid machining.
- Produce acceptable surface quality in both high and low current density areas.

Apparatus using a simple static tooling arrangement would, at first, appear to satisfy both the above requirements. This is not so, unfortunately, since some materials will machine, with a particular electrolyte, for a short duration before the oxidizing action at the anode stops the process completely. This phenomenon is not easily detectable with static tooling. Another disadvantage is that machining rates and other parameters cannot be assessed.

The test apparatus should, therefore, be equipped with a drive system capable of moving a simple tool (e.g., 0.25-in.-dia. tube electrode) a short distance, about 0.5 in., at feed rates up to 0.2 in./min. The normal requirement for smooth feed and rigidity apply, of course, but the short stroke and use of small test pieces permit very simple construction of the apparatus. Small test holes can be machined in sample pieces of material to assess machinability. The tool can be operated statically to produce surfaces machined at low current density. Such test pieces can be measured for surface finish and sectioned for metallographic examination. The auxiliaries of the apparatus should include

- 0-25V, 100-A DC power unit.
- 50-μ stainless steel mesh filter.
- 100-psi 5-gal/min pump.
- 2-gal tank.

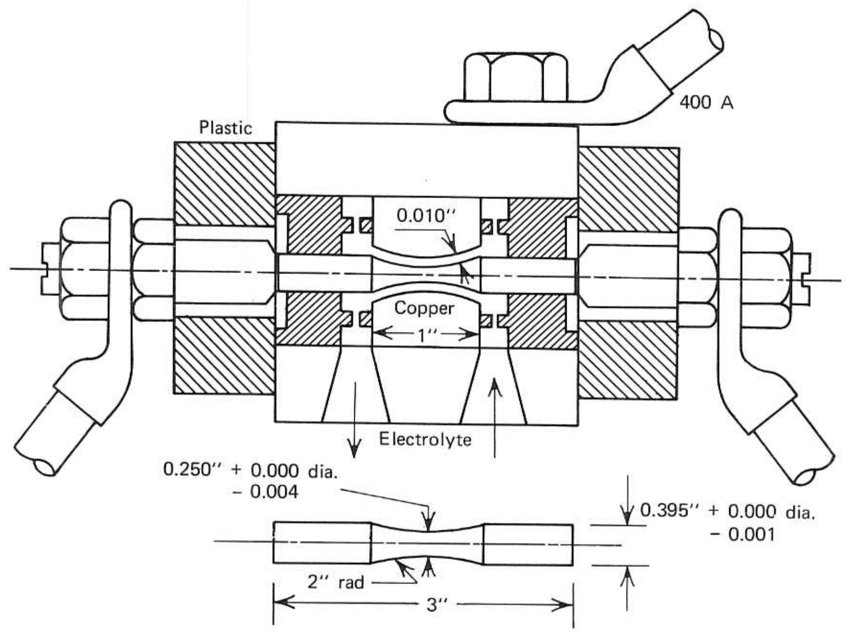


Figure 9.2 ECM static tooling for fatigue test bars.

The tank is of particular importance. Its small volume permits quick changes of electrolyte types so that a series of tests, necessary to determine the correct electrolyte, can be conducted with a minimum of time, effort, and expense.

Once a suitable electrolyte has been determined, then if the component application warrants it, the fatigue strength of the electrochemically machined surface and the effect of post ECM surface conditioning treatments need to be determined. The tooling, shown in Figures 9.2 and 9.3, is used to machine electrochemically *Krouse* fatigue specimens. This popular type of fatigue specimen is tested by placing one end in a high speed rotating chuck, while applying a radial load at the other. Therefore, the reduced section is subject to cyclic tensile and compressive surface stresses. A minimum of 12 tests is normal to determine the fatigue strength. This is usually defined as the maximum surface stress, due to the offset load, at which the specimen will rotate 10^7 times without breaking.

This ECM tooling is static in operation. The split copper electrode envelopes the specimen by 0.010 in. over the reduced test section. The specimens are premachined conventionally to fit within the electrode and to leave an envelope of 0.010 in. for final removal by ECM. The

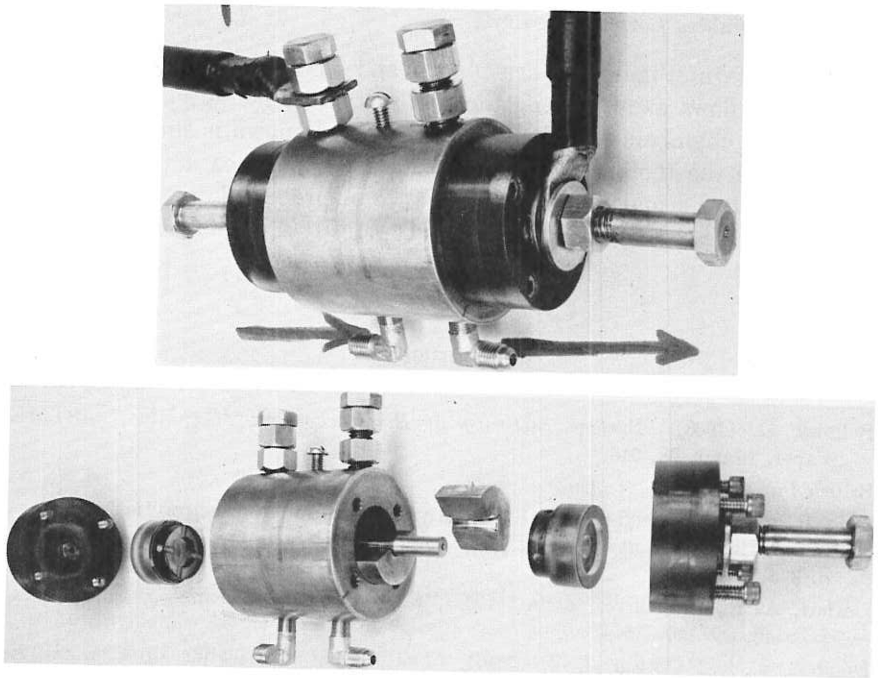


Figure 9.3 ECM fixture for Krouse fatigue test specimens. The specimen is placed between split electrodes for assembly purposes. During machining a 0.010-in. envelope of material is removed from the test section of the specimen by ECM. (Courtesy of the General Electric Company.)

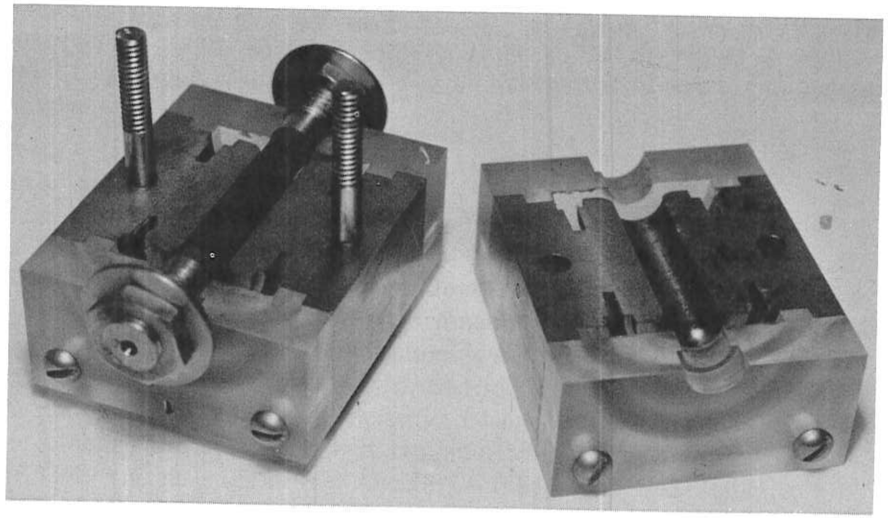


Figure 9.4 Static electrode used to produce electrochemical machined tensile test specimens. The specimens demonstrated that ECM has no effect on tensile strength. (Courtesy of the General Electric Company.)

shaded parts in Figure 9.2 are plastic and the remaining parts metal. Electrolyte flows axially along the test section of the specimen between the annular chambers at either end. The design shown is simple in order to minimize the tooling cost but provides positive location for the test specimen. The normal quantity of pieces to be processed does not warrant more elaborate tooling. An alternative type of tooling, however, is shown in Figure 9.4.

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CHAPTER

X

Selecting Operating Parameters

Consider electrolyte composition (already discussed at length), electrolyte temperature and pressure, voltage, tool feed rate, and tool positional depth settings; these are controllable parameters. They must be established during the first tool trials and then defined, with their permissible variation, for control of future production. Previous experience of the material to be machined, consultation with analytically or empirically derived data sheets, and of course, values used as a basis for the tooling design, can be used to set up the parameters for the first tool trial. Changes will then be required, however, to obtain optimum tool performance with regard to speed, accuracy, and surface finish, or to correct faulty operation. Therefore a basic understanding of these parameters is essential.

10.1 MACHINING GAP

The minimum gap between the tool and work is an independent variable, but with only minor reservations, it is the variable that relates directly to the geometry of the machined component. It will be remembered that the design of tool contour was based on corrections for an estimated operating gap. The gap used in the tool design must be used in the operation of the tool. Some variation from this gap can be made to establish the precise overcut required, when using a generating type of tool; but no such liberty should be taken with a die sinking type tool. If there are contour errors evident in the machined surface, they are probably due to component distortion or inadequate electrolyte flow;