through the work, as also shown in Figure 10.2b. For this, the full advance position of the tool at completion of machining (event 4) is either at the point where the side land of the tool is just leaving the lower work surface to produce a minimum radii, or up to 0.1 in. past this point, for larger radii. Normally, however, the full advance position of the tool will be determined by the full depth of the shape to be machined in the work, less the machining gap size.

After completion of machining, the tool should retract from the work sufficiently to provide space for removal and replacement of the work, without risk of accidental damage to the tool.

10.4 SURFACE PREPARATION

Grease, paint, oxide films, and scale on the surface of a component can interfere with an ECM operation to be performed on it. Such debris is a barrier to the passage of the electrolyzing current; it may result in unduly small gap sizes at the start of machining and so cause electrical shorting or direct mechanical damage to the tool. Prior to ECM, components should be cleaned by degreasing, acid pickling, grit blasting, or by other similar methods. It is sometimes impractical to remove completely an oxide film, for example, on titanium alloys. Grit blasting then becomes a preferred method, since the stressed and rough textured surface provides numerous nuclei, which help the breakdown of oxide films during the start of machining.

Burrs and other projecting edges may either short the tool at the start or, in subsequent machining, break away and become trapped in the machining gap. They should be removed prior to the ECM operation.

CHAPTER

XI

Tooling Faults and Their Correction

One of the predominant misconceptions of electrochemical machining is that tooling requires a time-consuming period of development before it is suitable for production use. Certainly the author's experience, at one time, did indicate this, but it also indicated that 80% of the faults were mechanical errors in fixturing design and manufacture. The machine is a very expensive "bench" upon which to discover these errors. Resist those who say, "Never mind if it's right; is it ready?" Apply the proper diligence from conceptual design to final inspection of the tooling to ensure that it is right. The purpose of this book is to help users of the process avoid ECM process faults by properly designing the fixtures and tools. A fault discovered at the machine is a design error and should be recognized as such. Faults occurring at the machine and the details of their subsequent correction should be fed back to the drafting room for incorporation into tooling design instructions. This ensures that the fault will be avoided in future designs, and that there will be an improving, rather than stagnant, process capability within that company.

If all is not perfect, however, and faults become evident, then some corrective action must be necessary. The reader will, no doubt, take care of all mechanical faults without need of further advice. Some of the more frequently encountered process faults and the methods of overcoming them are discussed in the following sections.

The more obvious process faults result in visual imperfections on the surface of the component. A machine, with a very sensitive spark detection and protective system will detect faults and shut the machine down without visible spark damage. It may then be necessary to slow down the machine switching time, to permit a large enough spark to mark the work at the point of the process fault.

With a little experience, it is possible to identify the cause of the fault by its position on the work or tool surface, and by its appearance.

11.1 CAVITATION

Cavitation is the occurrence of a bubble of vapor in a liquid. Liquids vaporize below a specific value of pressure, which depends on the liquid and its temperature. For example, water at 212°F forms vapor bubbles at sea-level atmospheric pressure. Normally, we alter the temperature to create this effect and call it boiling. Boiling, or vaporization, occurs at lower temperatures if the pressure is reduced below atmospheric pressure. It is the occurrence of these low pressures within the electrochemical machining gap that causes cavitation and its resulting problems. The energy stored in the electrolyte is either pressure energy or kinetic energy due to its velocity. As the channel, through which the electrolyte flows, widens or narrows, the velocity decreases or increases, respectively, and there are then changes in the proportion of kinetic and pressure-stored energy. (Bernaulli's theory mathematically relates these and other energies.) A converging channel causes an increase in velocity; hence kinetic energy increases and the pressure is lowered. The reverse occurs with a widening channel, providing it is a gradual change. In a sharply divergent channel, the electrolyte cannot immediately decelerate so that vapor forms on either side of the main stream. The same problem occurs if the electrolyte flow sharply changes direction.

Cavitation is a pocket of vapor. It does not conduct the electrolyzing current, so that the work does not machine. A raised area, sometimes displaying a jagged edge on the downstream side, will be apparent on the work. A spark may occur as the defect touches the work. At other times, the cavitation disappears as the gap narrows and then reoccurs intermitently throughout the machining operation.

Cavitation primarily accounts for the striated vertical walls produced by a generating tool. The sharp change in flow direction, at the periphery of such tools, causes a sharp reduction in pressure with accompanying vaporization and release of process gases. The striations can be reduced or eliminated by using a large (0.020-in.) radius on the tool at exit, where component design permits. As in this example, the possibility of cavitation should be recognized at the time of tooling design, and allowed for by proper selection of the electrolyte flow arrangement, use

of back pressure devices, tool shape, and other methods. When it does occur during tool testing, however, judicious changes in the machining parameters can overcome the problem.

The simplest adjustment is to reduce the electrolyte supply pressure. This reduces the flow velocities at all points on the tool and, therefore, reduces the chance of cavitation. There are limits as to how low a supply pressure may be used, since inadequate flushing of process gases from the gap will produce work inaccuracies or, possibly, passivity of the work surface and process failure. Reduction in tool feed rate will reduce the rate of process gas generation and thus permit much lower supply pressures.

Increasing the tool feed rate (with a corresponding increase in voltage to maintain the required gap size) will sometimes eliminate cavitation. This is because the higher machining rate produces more process gases. The small gas bubbles add resilience to the electrolyte so that it can conform more readily to sudden changes in the flow channel geometry.

The use of "back pressure" is a sure way to overcome cavitation; about 20 psi is usually sufficient. If all adjustments to the machining parameters fail to prevent cavitation, then it will be necessary to rework the tooling, either by smoothly blending the feature giving rise to the problem or by incorporating a back pressure dam. As back pressure is increased, the electrolyte supply pressure should be increased by the same amount to maintain the same flow velocities across the machining surface.

11.2 STRIATIONS AND BRIGHT SPOTS

Striations or ripples on the work surface, in the direction of electrolyte flow, are caused by variations in flow velocities, but are *not* always flow problems. In certain fairly critical areas of operation, with regard to material, electrolyte, current density, and flow velocity, oxide films on the work surface become sensitive to small variations in flow velocity. The corresponding changes in anode potential (voltage drop local to the work surface) produce different machining gaps; hence the machined surface records the variation in flow velocities. For a particular material and electrolyte, the critical function is the ratio of current density to flow rate. If the ratio is appreciably altered then the striations will disappear. Usually a decrease in current density or an increase in flow rate are the most effective changes. If the striations still persist after making these adjustments, then a change in electrolyte composition is indicated.

Bright raised areas on the work surface are formed in the same manner and may be dealt with in the same way as striations.

11.3 SURFACE FINISH

The type of finish obtained in an electrochemical machining operation is dependent on the material, electrolyte, and current density. If the surface finish obtained is not to the required standard, then some adjustment in machining parameters, electrolyte composition, or heat treatment of the material will usually achieve the necessary improvement.

An alloyed material has many varied compounds within its crystalline structure. Each compound or phase of the material may be variously sized and shaped crystals or cement between crystals. A particular alloy may vary in its crystalline grain size and types of phases present, depending upon heat treatments to which it has been subjected, and whether it is cast, wrought, cold worked, and so on. Also important, in the ECM context, is that the phases display different anode potentials for different electrolytes. Phases with low anode potentials electrolytically dissolve readily, while those with higher values are slower to dissolve and so project into the electrolyte. Thus depending on the range of anodic potentials and the crystal size of the various phases, the texture of the surface varies with machining conditions. The higher the potential gradient in the electrolyte the smoother will be the surface finish.

An increased machining feed rate, and therefore increased current density, steepens the potential gradient and so improves the surface finish. Also, a reduction in electrolyte conductivity, with a corresponding increase in voltage, will have a similar effect. This type of adjustment in the machining parameters is only appropriate if a small improvement in surface finish is needed.

Considerable improvement in surface finish is usually possible by correct heat treatment of the material, if this aspect has been previously overlooked. Generally, the solution treated condition is best, since the number of phases are sometimes reduced and grain size is smaller. The individual surface features are, therefore, more frequent and smaller. Sometimes, because of a favorable change in anode potential characteristics, other metallurgical states of the material may produce superior finishes.

Electrolyte composition and temperature, in addition to the material composition and its metallurgical state, are prime factors in the anode potential characteristics of the electrochemically machined surface. Reselection of the electrolyte is, therefore, a most effective way of obtaining surface finish improvement. In electropolishing, additives are used that raise all the anode potentials of the various material phases, so that their differences become less significant. While additives like glue and glycerine are effective in electropolishing, they rely on viscosity effects that are not of value in ECM. Oxidants, however, which raise the anode potentials by increasing oxidation of the surface, are worth trying; sodium nitrate being widely used. Alternatively, a more active chemical (like sodium bromide) may be used to break through spasmodic oxide films on the material, with a corresponding improvement in surface finish. Quick trials of oxidizing and activating types of electrolytes will usually establish the best route to follow, but the selection of the optimum electrolyte is then largely by trial and error.

11.4 INACCURACY

Inaccurate tooling will produce inaccurate work. If an electrochemically machined component, therefore, fails to display the required standard of accuracy, the tool alignment and contour should be checked first. A study of the errors may show some relationship to the initial component shape; if so, the calculations for minimum excess material (Section 7.3) may be used to check whether the surplus material on the component is adequate. Another possibility is that the part was not fully stress relieved before electrochemical machining, so that, on removal from the fixturing, it may have "sprung" to a new but incorrect shape. Effects of residual stress may be detected by placing indicating dials at various points on the component surface, while it is still in the ECM fixture, and observing component movement as retaining clamps are removed.

The above faults, leading to inaccuracies, are typical of those which occur in other methods of metal removal. There are also ECM process faults which must be considered.

It will be remembered that several assumptions were made in deriving the simplified formula for tool correction (Section 7.11). Also, in the application of this formula to the design of a tool, the operating gap size was predetermined. Therefore checks should be made to ensure that the correct gap size is used and that none of the original assumptions are being violated in the operation of the tooling.

The following assumptions were made:

- The entire work surface is at a uniform potential.
- Electrolyte has uniform properties.

- There are no appreciable field effects in the path of the electrolyzing current.

Only very thin components are likely to be troublesome because of resistive losses in the transmission of the electrolyzing current. The voltage variations on the component surface can be calculated from the current density during machining, the geometry of the finished component, and its electrical resistivity. A simplified calculation, using approximations, is all that is necessary to determine if power losses in the components are significant. Roughly, the positive component error, say E, is given by

$$E = \frac{\text{voltage loss in component}}{\text{machining voltage} - \text{anode potential}} \times \text{machining gap}$$

Anode potentials are approximately:

titanium alloys = 4–6 V
nickel alloys = 1–3 V
Ferrous alloys = 0–1 V

If power loss is the cause of component errors, then the correction is to increase the machining voltage, with an appropriate reduction in electrolyte conductivity to maintain the required gap size. The power loss in the component can be reduced by operating at lower current density, but while this will reduce the error, it will also lengthen the machining time for the component. Reduction in the machining gap will also reduce this particular type of error, but other errors then result, since the corrected tool shape is correct only for a specific operating gap size.

The assumption that the electrolyte has uniform properties over the whole operational surface of the tool is not precisely correct, but in practical terms it is possible to limit property variations so that close tolerances are met. Variance in electrical conductivity and anodic potentials are due to introduction of gases and metal hydroxides. Dimensional control decreases with flow path length and with current density, but increases with flow volume. Excessive flow path length should be avoided during tool design; if this is not done, a tool modification or rebuild are the only proper corrective actions if that is the cause of inaccuracy. The electrolyzing current causes depletion of the electrolyte by introducing process by-products; the electrolyte flow, if sufficient, sweeps these clear and should dilute them so that their influence is insignificant. Increased electrolyte flow or reduced current density will reduce inaccuracies

to acceptable levels. The first method is preferable, since it does not extend the machining time for the component.

Inaccuracies, due to field effects in the distribution of the electrolyzing current across the electrolyte, result from sharp features on the tool or component surfaces. The former will produce too little material removal from the corresponding work surface, while the latter will result in excess material removal. Empirical development of the tool shape can be used to correct for these field effects, but analysis of the necessary tool correction using field equations is often the more direct method. The mathematical analysis required is somewhat involved, but many existing computer programs are available which may be adapted to provide solutions to the equations that define this type of field. Usually two or three exercises in tool design, for various common geometrical features causing field effects, are adequate to set up "easy to use" design data sheets for use in similar applications.

Excessive machining of the work, at the boundaries of the machining area covered by tool, may be reduced by insulating all parts of the tool except its operational surfaces. Extra material around the periphery of the component, by acting as a sacrifical surface to collect the field concentrated current at the boundary, prevents loss of accuracy over that part of the machined surface defining the finished component.

Deflection of the tooling or the component, due to electrolyte pressure forces or clamping forces, can also cause component errors. These can be detected by observing indicating dials placed at various points on the component and tooling, while simulating operational forces.

All the types of inaccuracy discussed so far may be expected to repeat from one component to the next. Random errors, on the other hand, are likely to be caused by poor electrical contacts or inadequate control of the machining parameters.

Any loss of power in the electrical circuitry will reduce the voltage available between the tool and component and cause a reduction in the machining gap. If this is suspected, all joints throughout the circuit, particularly within the wet environment of the work enclosure, should be checked for cleanliness and tightness. The contact to the component itself is critical, since this is frequently remade. An appreciable electrical resistance in this contact due to inadequate area of contact, conformity to the component surface, or pressure of the contact will invariably result in poor dimensional repeatability. A poor contact can also create localized hot spots on the component, which, due to differential expansion, cause distortion of the component during machining. This effect can be recognized by careful examination of the contacting surfaces; locally oxidized areas indicate overheating.

A carefully kept record of the following machining parameters permits correlation between these and component dimensions:

- Electrolyte temperature and pressures.
- Tool feed rate.
- Voltage.
- Starting and stopping positions.

Errors related to lack of parameter control will then become evident; thus an appropriate improvement in the level of control can then be made.

11.5 TOOL DAMAGE

Sufficiently pronounced any form of process malfunction will produce damage to the operative area of the tool. A short circuit across the gap will result in a spark that can crater the tool surface; mechanical engagement, between tool and work, can distort the tool surface.

Sparks may be attributed to direct engagement of the work and tool surfaces caused by local failure of the machining action, vibration of the tooling, sudden movement of the work, or conductive particles in the electrolyte flow bridging the machining gap. Most electrochemical machines are equipped with spark sensing and fast switching equipment, which, if of the more sophisticated type, practically eliminates spark damage. The equipment, however, is purely a protection in the event of process or machine failure; it is still necessary to identify and correct all process faults. ECM is a precision high production process, and should not be abused as an irratic roughing method. The following paragraphs discuss the identification of the causes of tool damage and the appropriate corrective actions.

The previous four sections have dealt with various faults that can result in tool damage. Careful study of the location and appearance of the damaged work or tool area will indicate the nature of the fault and the corrective actions recommended previously may then be taken.

The remaining possible faults are caused by particles in the electrolyte flow or inclusions in the work surface. The latter is fairly rare but should be considered if all other possibilities have been checked. An inclusion in the work may machine at a reduced rate, compared with the surrounding metal, or may not machine at all. If the extent of spark damage does not camouflage its presence, the inclusion will appear distinctly as a raised area or projection from the machined surface, usually also differing in color. It can be confirmed as an inclusion by chemically

etching the surface, or by sectioning, followed by metallographic examination. (An inclusion could be detrimental to the component's function; ECM provides a safeguard by ensuring its detection.) Improved material quality is the best correction if inclusions are frequent. Inclusions do not readily electrochemically machine, but are sometimes characteristic of the metallurgical structure of a material. An electrolyte that more vigorously machines the inclusions can improve machinability; refinement of the material by heat treatment can also help. The size of such inclusions is usually fairly uniform, so that operation at a larger machining gap permits unmachined inclusions to be swept away by the electrolyte flow, as they became detached from the work surface. It must be emphasized that inclusions are rarely a problem, but beware of "imaginary inclusions" used to explain away unsolved process faults.

Particles present in the electrolyte flow, if large enough to bridge the machining gap, will produce process failure. If the particles are conductive, a spark occurs immediately. If several spark craters are produced, they will be in line along the direction of electrolyte flow, corresponding to the path taken by the particle. The damage is most likely to occur in the convergent entry flow area of the tool. Nonconductive particles bridging the machining gap cause adverse flow conditions and may also produce mechanical damage to the tool surface. The sudden change in flow conditions, usually cavitation just downstream of the particle, causes a small, but distinct, change in the machining current. Many machines are equipped with a "rate of current change" detector, which shuts the machine down when this type of fault occurs. Alternatively, the flow blockage should be detected as the unmachined area of the work surface shorts onto the tool, causing the spark detection system to operate; unfortunately this does not always occur. In either case, inadequate electrolyte flow conditions will be evident in addition to spark damage which may have occurred. A highly reflective surface, a rough layer, or oxides in a local area indicate poor flow.

The use of filters in the electrolyte supply to the machine is essential to the operation of the process. These should be checked periodically for deterioration of the filter elements caused by corrosion or overloading, proper operation of all seals, and prevention by the filter of the passage of particles that are larger than 33% of the operating gap for the tooling in use on the machine. Breakdown of tool insulation, seals, or joints, chemical corrosion, scaling, or hydroxide deposits in the electrolyte ducting can all produce particles that enter the electrolyte flow. If the filter proves adequate, all electrolyte ducts, from filter element to the operative area of the tool, should be checked internally for loose materials or damaged areas.

Table 11.1 Faults Check List

Fault	Location	Cause	Sequence of corrective action
Machine stops operating but no damage is apparent.		Small spark insufficient to damage tool.	Reduce sensitivity of protective circuit to increase damage to tool in order to locate fault.
Small irregular raised area, often with bright surface and downstream pattern on work. As above with spark damage. Uniform patterned raised area (like a fossilized shell).	Sharp change in tool geometry or in very divergent flow path.	Cavitation.	Reduce electrolyte supply pressure. Blend out sharp radii on tool. Increase tool feed. Apply back pressure. Redesign tool for convergent flow and back pressure.
Striation, ripples on work surface, or polished raised spots.	Usually nearer fluid entry to tool, or in divergent flow areas.	Anode potential sensitivity to flow velocity variations.	Appreciably increase electrolyte pressure. Reduce tool feed rate (also reduce voltage to maintain the same gap). Select alternative electrolyte.
Slightly inadequate surface finish.	Surfaces most closely angled to tool feed direction.	Differential machining of material phases.	Increase tool feed rate (also increase voltage to maintain gap size). Dilute electrolyte and increase voltage to compensate.
Poor surface finish.	All surfaces.	Differential machining of material phases.	Ensure component is in solution heat treated condition. Reselect electrolyte.
Consistent work inaccuracy.	All surfaces fo work.	Incorrect tool alignment or tool contour error.	Reinspect tooling for accuracy of contour and alignment.
	Positions relating to original material shape.	Inadequate material allowance on part prior to ECM.	Recalculate material allowance and correct.
	Inaccuracies on surfaces most closely angled to tool feed direction.	Incorrect operating gap or incorrect design of tool contour.	Check that designed operating gap is in use. Check calculations used in designing tool contour.
	Inaccuracies increase with electrolyte flow path length.	Electrolyte conductivity variation across work surface.	Increase supply pressure to improve electrolyte flow. Decrease tool feed rate. Apply back pressure.
	At work boundaries or sharp work features.	Electrical field concentration of machining current.	Insulate all inoperative areas of cathode (tool). Design field corrections into tool. Add surplus material to work blank at field concentration areas.
	Isolated thin sections of component.	Voltage loss in transmitting machining current through component.	Apply additional electrical contacts near area of inaccuracy where possible. Apply maximum available machining voltage and dilute electrolyte correspondingly to retain gap size. Reduce tool feed rate with corresponding electrolyte dilution to maintain gap size.

(*Continued*)

Table 11.1 (*Continued*)

Fault	Location	Cause	Sequence of corrective action
Random inaccuracy in work.	Random areas.	Overheating of electrical contacts to work causing distortion.	Check for contact burning—increase contact pressure and/or areas. Use contact grease.
	All work surface displaying similar error.	Any poor electrical contact—reduces gap size.	Increase contact pressures and/or areas. Use contact grease.
		Poor control of machining parameters.	Correlate errors with records of machining parameters. Apply greater control of parameters as indicated.
	Occurring in similar areas.	Distortion of part due to electrolyte pressure, or clamping forces, or residual stresses in part.	Check distortion with indicating clocks as work is unclamped after machining. Stress relieve work before machining. Rearrange clamping. Provide additional support of work against electrolyte forces.
Spark damage to tool or work.	Near point of fluid entry into machining gap.	Particles in electrolyte.	Check internally filters, electrolyte ducts, seals, and joints.
		Insulation failure within tool.	Check insulated surfaces of tool.
	At location of some other process fault.	Extreme condition of a previously considered fault.	Identify and eliminate basic process fault.

Many methods of tool repair have been tried but copper plating is the only method, when used on copper tools of course, that provides an effective and permanent repair. The repair requires polishing of the damaged area, masking all undamaged areas of the tool, plating the required depth of copper, stripping the mask, and blending the new copper to the original tool contour. Normally the completion of this sequence takes 12 hours.

11.6 FAULTS CHECK LISTS

The check list shown in Table 11.1 should prove useful to the reader in locating the cause of process faults and in taking prompt corrective action.