cal noise. The machining power must be cut in less than 10 μsec to prevent severe electrical spark damage to work or tools. Power supplies using SCRs can be shut down in 10 μsec. This method of switching is adequate on most ECM applications although some damage to tooling does occur.

On very precise tooling, damage is not acceptable; it may be eliminated by using an SCR bank placed across the DC input to the machine. In the event of a process malfunction the SCR bank is electronically signalled and immediately short circuits the machining current. Tool damage is usually undetectable. This type of protection is expensive but very worthwhile for proving development tooling, operating sophisticated tooling, or providing protection in machining components of high surface integrity.

CHAPTER IV

Economics

It is wise, of course, to carefully review the economic merit of electrochemically machining a component, before committing to this method of manufacture. There are many facets of cost which must be fully considered, and many, when given a generalized understanding of them, may be dismissed as trivial. The economic considerations fall into three categories. These are actual operating costs, cost compared with alternative processes, and equipment investment.

4.1 OPERATING COSTS

Accounting practice varies from company to company, so on "face value" an identical ECM operation in one company may show different operating cost from that in another. This is because, for convenience in controlling the overall finance of a company, factors such as tool maintenance and repair and capital depreciations are covered by a blanket "overhead" charge. The overhead is a percentage of the direct labor used in performing the operation. In ECM, however, there are aspects of the cost, some beneficial and some not, that, if included as part of a general overhead rate, would be misleading as to the true operation cost. Hence it is more accurate to identify separately costs that relate directly to the ECM process. These are itemized in the following paragraphs.

Direct Labor

- Loading and unloading of the component.
- Indexing of the component or tool changes, where a number of separate areas of the component are machined.

- Machining cycle time—this is actual cutting time plus automatic positioning of the tools before machining and retraction of the tools away from the component after machining.
- Inspection of the first component machined to check the tooling alignment and machine setting and measurement of components subsequently produced.
- Component washing to remove electrolyte and hydroxide deposits if cleanliness is important.
- General cleaning and maintenance of the ECM facility and tooling comprises about 15% of the available machine time. This allows for washing salt deposits from the machine, cleaning surrounding work surfaces, and cleaning hand tools and measuring instruments and applying corrosion preventatives to them. Also electrical contacts in the tooling must be checked frequently and tooling cleaned prior to a period of inactivity.
- Setting up tooling in the machine and adjusting operating parameters, also removal of tooling after a production run of parts have been completed. Only a portion of this time will show against the operation time, depending on the number of components in a batch.

The labor cost will depend on whether an operator controls one or more machines. If the actual cutting time is long, then the operator may have time to load and initiate the machining cycle on additional machines.

Tool Maintenance

The "no tool wear" concept of ECM is true providing the process is always operated within control limits. Loss of process control, however, leads to tool damage and the need for repair. In an efficiently operated ECM production area, with machines equipped with protective devices, tooling damage is slight and infrequent and will not be significant in tool maintenance costs. The controlled operation of tooling, however, does require periodic tool checking for sound electrical joints, absence of wear on location surfaces, proper electrical insulation, and lack of any adverse condition. The labor involved in tool maintenance is 5 to 30% of the direct tool operating labor, depending on the experience and efficiency of the production personnel and the engineering quality of the tooling.

Electrolyte Costs

In the single small tank system, the electrolyte is discarded each time a different mix is needed. The cost of renewing the electrolyte is the cost of the electrolyte salts plus the labor used in mixing the solution.

For example, a 500-gal tank of 20% by weight of sodium chloride requires 380 lb of the salt, at an approximate cost of $17.00. A man will take 2 hours to perform the work, at a cost of about $20.00 including overhead rate. The total cost of $37.00 is shared over the number of components to be processed before a new type of electrolyte is needed. About 30 min of labor is also needed per shift to check the strength of the electrolyte, by chemical titration or by specific gravity measurement, and to make additions of salts or water as appropriate. The changes in the electrolyte are caused by "drag out," that is, electrolyte wetting each component as it is removed from the machine, some break down of the salt because of the slight inefficiency of the process, and water evaporation.

Storage tanks require only occasional checking for electrolyte strength, since a large stored volume is subject to gradual changes only. A weekly check and correction of the electrolytes to maintain close control requires about 2 hours of labor. Complete replenishment of the electrolyte may be necessary once a year, but the cost of this per component is negligible.

Electrical Power

At first, the electrical power used in an ECM operation seems immense. There is a high *rate* of power consumption, but the short duration of the machining action makes the total power consumed quite moderate, and commensurate with that used in mechanical machining methods. This has been demonstrated by comparing the power consumption of an EC machine with that of a contour milling machine, to produce the same component.* The EC machine might typically produce a component in 1 hour using a 400-A, 440-V, 3-phase supply, while the contour milling machine may take 100 hours to perform the same work at an average of a 5-A, 440-V, 3-phase supply. The total power consumed per component, by either method, is very similar and is a minor factor in the overall operation cost.

The work in shearing metal mechanically is much less than the work of pulling away material, atom by atom, as in ECM. The mechanical methods, however, are very inefficient since high frictional forces, between the tool and work and mechanisms of the machine, consume the major part of the electrical power supplied to the machine. In the ECM process a large portion of the supplied power is used in dissociating atoms from the work.

The cost of removing metal by ECM can be expressed as *the cost*

* See A. E. Debarr and D. A. Oliver, *Electrochemical Machining,* McDonald, London, 1968, p. 210.

of the electricity to operate the machine, for a specific amount of material removal. A convenient way of stating this is in cents per cubic inch of metal removed. Naturally, any determination such as this will be dependent upon the local costs of electricity, but the following costs have been calculated for a variety of typical industrial rates.

These costs are for a 10,000-A installation operating at full amperage, 12 V, and including the cost of running an electrolyte pump having a 50-hp motor.*

Power Cost (typical 1966 industrial-electricity rates in cents per kilowatt-hour):

1.2	1.4	1.6	1.8	2.0

ECM power cost (in cents per cubic inch of removal):

4.4	5.2	5.9	6.7	7.4

Thus the cost for removing 1 in.^{3} of metal is slightly more than 3½ times the cost of a kilowatt-hour of electricity. At the highest rate on the chart (2¢/kilowatt-hour), the cost is $7.44 per hour at 100% utilization of 10,000 A; yielding a removal rate of 60 in.^{3} of metal per hour. If the equipment is run at lower than 12 V, the cost will be lower. Any voltage higher than that required for good results adds to cost and creates unnecessary heat.

4.2 COMPARATIVE COSTS

The preceding section dealt with the direct costs of an ECM operation, but other factors must be considered to make a true cost comparison between ECM and an alternative process. Many varied operations make up the manufacture of a component. The replacement of one operation by ECM may also remove the necessity for others. On the other hand, additional operations may be needed to prepare a component for ECM or to finish it after ECM.

Full use should be made of the capability of ECM to duplicate, in a single operation, several different mechanical operations. Consider, for example, a flat circular component having through holes and contoured recesses in one surface. Normally, turning, drilling, and milling operations would be used to produce the component, but the same work could be performed by a single ECM operation. At first, ECM may have been considered as a replacement of the milling operation, since it is very competitive in that area, but not for the turning and drilling work.

* Courtesy of the Anocut Engineering Company, Chicago, Ill.

These two operations, if added to the capability of the ECM tool, in effect become "free." The lack of mechanism in ECM tooling also makes it relatively simple to use multitools to machine several components simultaneously; the machine's work enclosure size, available amperage, and electrolyte flow capacity are the limiting factors.

The stresses induced in a material, during mechanical metal removal, cause distortion, hence dimensional errors in a component. It is good practice to use both roughing cuts and finishing cuts to minimize these stress effects. In producing a very thin, close tolerance component, a series of cuts, on alternate sides of the component, may be used in addition to stress relieving heat treatments. The stress free nature of ECM, however, permits the same material to be removed in a single operation. It is important, however, that the component is free of stress before it is electrochemically machined, since the removal of stressed layers of material can also result in a finally distorted part. Forged, cast, or premechanically machined parts should be stress annealed prior to ECM to prevent problems of distortion.

Many mechanical machining operations leave characteristic tool marks in the component surface. Additional operations such as grinding, polishing, and so on may be required to improve the finish. Also polishing operations may be required to remove sharp burrs left by mechanical machining methods. The finished and burr-free electrochemically machined surfaces require no further work. ECM also blends corners so that special blending operations are not required.

On the deficit side, operations may be required in support of ECM. The need for these is discussed fully in later chapters and this is treated briefly now.

Mention has been made of stress annealing prior to ECM and its beneficial effect on subsequent dimensional stability. The surface finish produced also relates to the heat treatment condition of the material. It is best when the material is in the "solution treated" condition. An additional heat treatment operation may be necessary to meet a surface finish requirement.

Surface films, oxide, scale, paint, grease, and so on may inhibit the start of ECM. A degreasing or grit blasting operation to prepare the component surface may be needed, if such adverse conditions are expected.

Although sharp burrs are not produced by ECM, there are small ridges of material left by some types of tools, as illustrated in Figure 4.1. These, which are usually less than 0.060 in. high, correspond to the position of electrolyte flow slots in the tool or lack of matching between adjacent ECM operations. If these are not acceptable on the finished

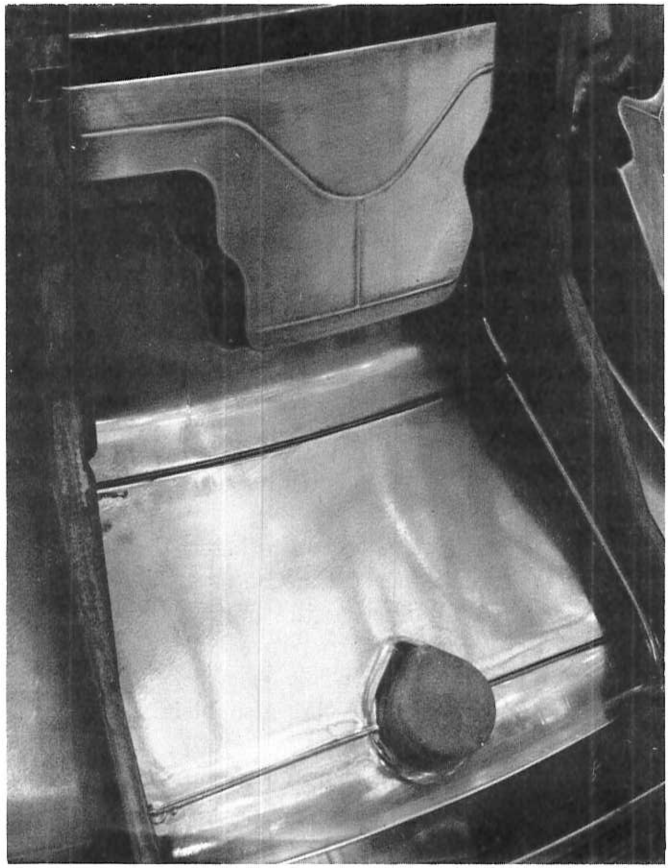

Figure 4.1 Electrochemically contoured component displaying characteristic ridges corresponding to the tool's electrolyte flow boundaries. (Courtesy of the Bristol Engine Division, Rolls-Royce Limited.)

component, additional polishing or milling operations will be required for their removal.

An electrochemically machined surface is free from stress or distortion of its crystalline structure, unlike the worked surface typical of mechanical machining methods. Mechanical working is very beneficial to fatigue strength, however, and thus if this property is required, a post ECM surface conditioning operation will be necessary. Suitable methods include glass ball peening, barreling, Vibro polishing, and grit blasting.

In summary, the following are typical operations to be considered in assessing the comparative costs between ECM and alternative

processes. Consider discarding those operations which do the following:

- Perform work suitable for inclusion in a single ECM operation
- Minimize machining stresses
- Obtain improved surface finish
- Remove burrs or blend corners

Consider adding operations to

- Stress anneal heat treat prior to ECM
- Solution heat treat prior to ECM
- Degrease or grit blast prior to ECM
- Polish or mill off ridges after ECM
- Condition ECM surface for fatigue strength

4.3 INVESTMENT COSTS

The investment required to establish an operating ECM factory is very high. Certainly, the machines that are available today are much less expensive, in proportion to their engineering content, than machines available 5 years ago. There is a limit, however, to how low prices may drop, since an ECM facility comprises not only the machine tool itself but also many costly auxiliary pieces of equipment. An indication of why machine costs are so high can be found in Table 4.1. An effective,

Table 4.1 Breakdown of Costs for Vertical 10,000—A, EC Machine

Basic machine	$ 25,000
Extras	
Digital readout of ram position	
Work enclosure washing and lighting	
Automatic door operation	$ 7,000
Electrolyte System (Basic)	$ 30,000
Extras	
Inline filtration	$ 3,000
Flow meter	$ 1,000
Centrifuge	$ 15,000
Evaporative condenser	$ 15,000
Power supply unit (Basic)	$ 29,000
Extras	
Fault detection	$ 10,000
Ampere hour meter	$ 1,000
Basic minimum cost	$ 84,000
Normal Cost	$136,000

but moderately priced at $50,000, EC machine has a frame of reinforced concrete construction and output of 3000 A. Machines built to perform special and very limited work can be obtained at slightly lower costs than that. Apart from these, the approximate costs of fairly standard machines are shown in Table 4.2. The prices include the extras normal for the most effective use of the machines; the machine structures and electrolyte systems are those best suited for the power rating indicated.

Table 4.2 Approximate Costs of Standard Machines

Vertical 10,000 A	$135,000
Vertical 20,000 A	$200,000
Vertical 40,000 A	$350,000
Horizontal 10,000 A	$150,000
Horizontal 20,000 A	$250,000
Beam machine 10,000 A	$280,000
Beam machine 20,000 A	$340,000
Vertical lathe 10,000 A	$245,000
Vertical reinforced concrete 3,000 A	$ 50,000
Vertical reinforced concrete 5,000 A	$ 60,000
Vertical reinforced concrete 10,000 A	$ 80,000

Installation of EC machines is also costly, and is about 10 to 12% of the purchase price. All the units comprising the machining facility are placed in position and leveled only, since it is unnecessary to lay foundations or to bolt the units down. It is normal, however, to surround the facility with a drainage channel to handle accidental electrolyte spillage and to facilitate washing the machine area. Electrical interconnection of the units, plumbing the electrolyte system, and providing services to the machine form the major part of installation costs. The following services are required:

- *Cold water* is used for making up electrolyte solutions and washing the work enclosure and general machining area, and as make-up for an evaporative condenser cooling system. The supply provides water at about 50 gal/min to minimize delays in making up electrolytes, washing out the electrolyte system, and so on.
- *Hot water* is better than cold for washing the work enclosure, fixturing, and components, since it removes more readily deposits of metal hydroxides.
- *A large power line* is needed to connect the machine to an electrical substation. As a guide, a 10,000-A machine requires a 550 A, 444-V, 3-phase supply.
- *Steam,* if readily available, is a cheap source of heat for electrolyte heating.
- *Exhaust ducting* is installed to exhaust process fumes from the work enclosure to the building exterior.
- *Component wash tanks,* placed adjacent to the machine, may be made from stainless steel or plastic.
- *Benches* are used for servicing tooling, and cabinets used for storage of hand tools and measuring instruments.
- *Storage facilities* are for ECM tooling and electrolyte salts.

Additional installation charges, above the 10 to 12% are incurred if services are not within the vicinity of the machine (i.e., within approximately 50 ft). Current costs for these services, including materials, labour, and 100% overhead rate, are as follows:

Water lines	$ 5.00 per foot
Power lines 550 A	$25.00 per foot
Drainage	$75.00 per foot

Should there be a need for an electrical substation, it will cost about $45,000, but will supply six to ten EC machines.