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Electrochemistry in the Service of Engineering [and Discussion]

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Electrochemistry in the service of engineering

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Reports from a number of government investigations into our declining industrial efficiency have clearly shown that enormous savings are possible in the costs of manufacture and maintenance by the better use of readily available materials and methods. If electrochemistry is to be of service to engineering and manufacturing industry, it must therefore assist in the national effort to increase productivity.

Electrochemistry can be applied uniquely in the field of tribology, corrosion control and manufacture to provide genuine alternative techniques to the more traditional methods.

Further prospects for electrochemistry in the service of engineers would be good were it not for what appears to be a strong inclination by industry to place barriers against the use of 'wet methods', due perhaps to the present generation of design engineers who are taught little chemistry, and chemists who receive little education at universities and polytechnics in electrochemistry applied to engineering.

The engineering industry is a major creator of wealth; any service rendered to it must lead to increasing its productivity. At present our exports contribute about 30% to the gross national product, and half of this is from the engineering industries.

Since the end of World War II an almost continuous debate has taken place about our lack of productivity, which continues to the present day. Whilst it has been fashionable to blame organized labour and management, the size of certain manufacturing units (small is beautiful), low investment/output ratio, or the lending strategy of our banks, this has obscured the findings of several major enquiries made by the Government of the day into various deficiencies of industry. These enquiries, held by some of our top industrialists, are embodied in a number of reports to Ministers of State, in which many important factors affecting our economy are clearly identified and recommendations have been made that provide clear measures to be adopted to reduce costs and therefore attract greater sales without losing quality.

Government reports that are especially relevant where electrochemistry could make a large contribution are: (1) engineering design (the Feilden Report, 1963); (2) tribology (the Jost Report, 1966); (3) corrosion (the Hoar Report, 1970); (4) Maintenance (the Maddocks Report, 1970).

The Feilden Report (Feilden 1963) sounded an early warning of the relatively poor quality of many of our manufactured goods, which lacked not only reliability but also sales appeal. This committee attributed this to the inadequate use of new knowledge by the present generation of engineers whose training had not included an awareness of the properties of engineering materials and who had failed in many cases to consider the problems of maintenance in manufactured goods. One of the remedies proposed was in the education of our future design engineers to take into account these necessary skills. In many ways the Finniston Report seems to be a belated response, 17 years later, to the Feilden Committee's recommendations.

The Jost Committee (Jost 1966) at first began to look into the reliability of machinery and in particular the disturbing number of failures in bearings. Where there is machinery there is usually the need for bearings; this turned out to be a much greater problem than they at first thought. Although their mandate was to study lubrication, preliminary investigations showed that although considerable cost–benefit improvements could be made in the design and operation of bearings, even greater savings were possible if more attention was paid to all aspects of friction and wear. The term 'tribology' was coined to cover all aspects of the use in engineering of the surface contact of materials. Table 1 gives the main savings that they calculated could be achieved by the correct choice of materials and with greater attention to lubrication and other friction-reducing devices.

TABLE 1. POTENTIAL SAVINGS IN INDUSTRY FROM THE APPLICATION OF TRIBOLOGY (JOST 1966)

	saving/M£ (1966 prices)
less friction	28
less manpower	10
less lubrication	10
less maintenance	230
less breakdown	115
greater utilization	22
greater durability	100
total	**515**

TABLE 2. POTENTIAL SAVINGS IN INDUSTRY FROM THE APPLICATION OF CORROSION CONTROL (HOAR 1971)

	saving/M£ (1970 prices)
power	25
general engineering	35
transport	100
government	20
marine	55
construction	50
water	4
metals	2
food	4
oil and chemical	15
total	**310**

Potential savings are enormous since one-third of all electrical energy used by machinery is used to overcome friction. By applying present knowledge it was suggested some £515 M (1966 prices) could be saved in this country and £10000 M worldwide. The existing knowledge was not reaching our engineering designers either as information or as part of their education.

In a similar manner the Hoar Report (Hoar 1971) showed that the cost of corrosion was also very high, estimated at £1300 M (1970 prices), and they suggested that by applying existing knowledge some £300 M could be saved (see table 2). Again the most important conclusion was that this knowledge was not being applied by our engineers and that information and education in this field was inadequate at universities and colleges.

This committee also concluded that most of the savings could be made at the drawing board

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stage by engineering designers if they had been adequately informed and educated in the subject of corrosion control.

The Maddocks Report (Maddocks 1970) on the high costs of maintenance takes into account all types of maintenance that arise as a result of the faults outlined in the three previous reports. Wider issues, such as the human element, the cost of maintenance staff, loss of production and replacement equipment costs, were studied, as was the ratio of planned maintenance to costly emergency and breakdown incidence.

More recent studies (Department of Industry 1978) have shown that between 20 and 50% of maintenance is emergency or unplanned and therefore expensive.

The results of these reports were so disturbing that the Government mounted a campaign to show how these potential losses might be saved. Thus the Council for Industrial Technologies (C.F.I.T.) was set up by the Department of Industry in 1975. This Council has shown that the potential savings, by halving the cost of maintenance, could be as high as 4–5% of the gross national product, which may be compared with the 15% generated from the engineering industries towards our exports. This level of savings could make a large contribution to increasing profitability.

Thus several committees were set up by the C.F.I.T. to generate information for distribution to industry, including the subjects of tribology and corrosion. The overall view, combining design, maintenance and economics, was brought together under the new subject title of terotechnology.

All these committees had a common theme, i.e. to educate and inform the engineering profession by providing suitable handbooks and by carrying out smaller but intensive cost comparisons within industry. Teachers of engineering in universities, polytechnics and colleges were encouraged to include this information in their courses.

Electrochemistry, by means of electrodeposition, can provide materials with a variety of mechanical and electrical properties that can directly contribute to the alleviation of the problems outlined above. The failure of many engineering materials occurs at the surface. Wear-resistant, low friction and corrosion-resistant materials can be produced as coatings on cheap and tough steel surfaces. Thus, thin coatings of relatively expensive materials can be used to enhance these metal surface properties, and electrochemical deposition is one of the most important ways of achieving this.

Costs in industry are often associated with speed of manufacture and so the reverse of electrodeposition, i.e. controlled corrosion, is being used as an alternative metal cutting and forming process for materials that are difficult to machine. This is called electrochemical machining (e.c.m.).

There are several other ways of coating metals and of manufacturing without mechanical chipping, e.g. metal spraying, hot-dipping, electrodischarge machining, laser cutting. However, electrochemical methods are chosen if they are more economical than the other alternatives and so find their rightful place in manufacturing. They will also suffer the ups and downs of economics, and incentives to improve have consistently led to developments in quality and cost-effectiveness to meet the competition from other coating or manufacturing methods. In general, more than one machining method has to be used for each component and so electrochemical techniques may be part of a manufacturing system, or more often metal finishing.

There are many case histories where electrochemistry applied to engineering has led to the improvements so desperately sought after, by the committees whose reports were so critical of

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British industry, but in general there is a marked reluctance to use wet methods, not shared by our competitors (Vivian 1980).

The following examples illustrate the range of services provided by electrochemical methods that have been most successful and have directly led to improved performance and productivity over non-electrochemical processes.

1. Engineering with chromium electrodeposits

The automobile industry consumes a vast amount of materials, mainly steel, but reliability and durability have to be carefully planned. The decision facing all engineers is whether low capital cost and frequent maintenance is preferable to high capital cost and infrequent maintenance. Replacing tyres, batteries, exhaust systems is relatively easy to do and not time-consuming, and therefore not expensive. Internal engine maintenance is undesirable and should be undertaken only after several years of service. Because of the concentration on design, the efficiency of sealing by piston rings has led to major changes in engine performance over the last 20 years. Thus a typical family car can now exceed 150000 km before the engine internals need replacing, and for large diesel engines this can be 300000 km. A large contribution to this improvement is the use of a chromium electrodeposit on the piston rings and on cylinder liners which, because of the low coefficient of friction of chromium, will have long durability.

Electrodeposition seems at first deceptively simple, and by making the workpiece, e.g. the piston ring, into the cathode of a suitable electrochemical cell containing an anode and a suitable chromium salt, the required deposit can be achieved. The chromium salt turns out to be chromic acid, conveniently dissolved in sulphuric acid. The mechanism of plating from a bath containing the hexachromium ions Cr^{6+} is not yet fully understood by electrochemists, although the process has been used for over 100 years. Electrolytes containing hexavalent chromium ions are used and in actual plating, since six electrons have to be used to produce one Cr metal atom, this is relatively inefficient. The negative electrode potential also allows hydrogen ions to be discharged, and about 15% of the current is used to deposit metal. From this unlikely process comes a hard, metallic chromium deposit which, because of its inherent brittleness, is usually cracked. One of the great advantages of electroplating is the very strong adhesion that is possible between a metal substrate and electrodeposited coating, provided that care has been taken to clean the surface, which must be free from grease, loose deposits and oxide films. The chromium electroplate, in spite of its brittleness, can be ground to fine dimensions to give a variety of surface finishes. Much development work has been carried out on chromium electrodeposits for piston rings and cylinder liners for diesel engines (Smith 1978). The most dependable system for cylinder liners requires a fissured plateau surface profile, and this has been achieved with a chromium electrodeposit of undulating surface profile of 15 centre line average, and the naturally occurring cracks are enlarged by anodic polarization to give the randomly distributed fissures. To minimize the time for the initial 'bedding in' period, a 'flash' coating of electrodeposited iron has often been applied on top of the chromium layer.

The use of chromium electrodeposit for hydraulic pistons is widespread in industry because of its low coefficient of friction. In the last 20 years the use of hydraulic pit props for roof-supporting systems has led to great advances in the mechanization of mines and as a bonus there has been a marked decrease in the number of accidents where they have been introduced, and the extraction rate of coal or ore can be greatly increased. This particular development is entirely British and has been widely adopted, adding considerably to the U.K. export business, a good example of electrochemistry serving engineering.

Engineers have been concerned that chromium plating reduces fatigue life. This arises from the firm adhesion of the chromium to mild steel, the tensile stress inherent in the Cr deposit and the ready-made cracks in the surface. This can be overcome by underplating with another deposit such as nickel, or by shot peening the substrate metal to induce compressive stresses before electroplating with chromium.

2. Electronic applications

Electrodeposition has a long history, and besides the simple method required of a dissolving anode and the workpiece made the cathode, hidden bonuses were found in the strong adhesion that is possible between metal and substrate, the fine grain size, which gave tough deposits, and the freedom from porosity if careful surface treatment is carried out.

An early discovery was throwing power, i.e. the ability to follow a shaped surface profile. Some electrolytes allow deposits to become thicker on surfaces nearest to the anode, whereas other electrolytes deposit even in the deepest recesses. Both extremes of behaviour have their advantages: high throwing power gives good coverage on all surfaces and is used to plate intricate shapes, whereas low throwing power evens out or 'levels' the surface and is independent of an undulating surface.

This latter process allows rough surfaces to be smoother, saving costly mechanical smoothing and polishing and providing a good base for smooth coatings of, say, another metal layer. A good example is the electrodeposition of 'levelling' copper on steel before chromium plating. The brightness of the chromium arises from the flatness of the copper electrodeposit. This process can replace the very expensive mechanical grinding and polishing processes.

The high throwing power has been put to a very unusual but cost-saving process in 'through-hole' plating for printed circuit boards. To connect the two sides of the copper printed circuits the most economical method is making use of high throwing power to deposit down the sides of the hole to give electrical contact. The need arose for multilayer boards to increase the density of circuits, and holes of 1 mm diameter, plated through by this technique, connect each of the circuit boards, a much cheaper method than is possible by any other way.

Complex and expensive electrolytes were necessary for this effect and the theory of throwing power was not really understood.

It was predicted that those solutions of high acidity (lower efficiency, because of the discharge of hydrogen) and low metal concentration should worsen the situation, but if current densities are lowered, high throwing power can in fact be obtained, i.e. the conductivity is an overriding factor. Thus acid copper sulphate can be used at considerably lower cost and as electronic circuits become more miniaturized the rate of deposition is not important but there is a need for even smaller diameter through-hole plating. More recently, pulse plating has been developed when rates of pulsing are so rapid that a thick diffusion layer does not build up, and thereby increases throwing power.

The increasing reliance on computers and on electronic control requires components that will have long durability and, in particular, connectors and contacts should not tarnish with time and so suffer an increase in electrical resistance.

Gold has a very important role in maintaining low contact resistance for long periods, and justification can be made for its use because the thickness of deposit required to achieve low contact resistance is very small, e.g. *ca.* 1 μm. Gold electrodepositers have to maintain strict housekeeping to prevent waste of this very expensive material.

Electrodeposition of gold is chosen because of the close control on thickness, the ease of accountability of solution wastes and the easy placement of deposits in strategic areas, preventing wasteful use. Because of the nobility of gold it can easily form bimetallic corrosion couples, especially with copper. An underlay of nickel, also electrodeposited, is often used because of the passivity of this metal, which prevents it from corroding as a result of contact with the gold yet maintaining good electrical continuity with both the gold top layer and the copper beneath.

3. Electroforming – the shape to come

Three-dimensional shapes are possible by electrodeposition methods when mandrels of the required shape are plated to an appropriate thickness. The method is generally used for internal configurations of high precision, requiring close tolerances for components that require exceptional skill or that would in some cases be impossible to manufacture by other processes.

Table 3. Some engineering uses of electroformed products (Watson 1977)

components	comments on use
moulds and dies for molten materials such as plastics, glass, typemetal, chocolate, etc.	Elecroforms have good thermal conductivity and cool quickly. Precise parting lines minimize flashing. Undulating parting lines are easy to produce.
dies for pressing sheet metals such as brass or steel	Compared with cast iron punches, etc., electroformed dies have less tendency to metal pick-up and galling.
electroformed tools	Electroformed spray painting masks exactly fit contoured surfaces, and paint or vacuum films are sharply defined. Electroformed tools can be used to give textured finishes to soft metals, unpolymerized plastics or unvulcanized rubber. Electroformed abrasive sheets used for surface finishing or roughening of plastics, soft metal, wood, textiles, etc. Printing plates electrodes, etc., also produced in electroformed nickel.
roughness standards	Roughness standards (0.05–15 × 10^{-6} in) used for visual comparison of surfaces.
printing rolls	Electroformed screen printing rolls give fast printing with good colour register.
optical components	Electron microscope grid carriers, diffraction gratings, electron tube grids, etc.
batteries	Electroformed mesh and foil used in alkaline batteries to strengthen sintered plates and provide a means of electrical contact.

An example of this is the reproduction of phonograph record stampers from a master, the fine detail being carefully reproduced by the modern methods of nickel plating, that have made this possible. For electroforming, specially formulated nickel plating baths can deposit at high rates, e.g. 1 mm in 1 h. A range of proven engineering products is given in table 3.

This method of manufacture has found widespread use in the radar and communications industry and in particular for the intricate shapes required for waveguides, for which this technique has been particularly well developed (see figure 1). In some fields it has revolutionized production. For example, the development of plating fine mesh screens of large length and diameter has led to a series of products used for printing textiles and carpets. In the U.K., about half the carpets produced are now printed on electroformed screen printing cylinders.

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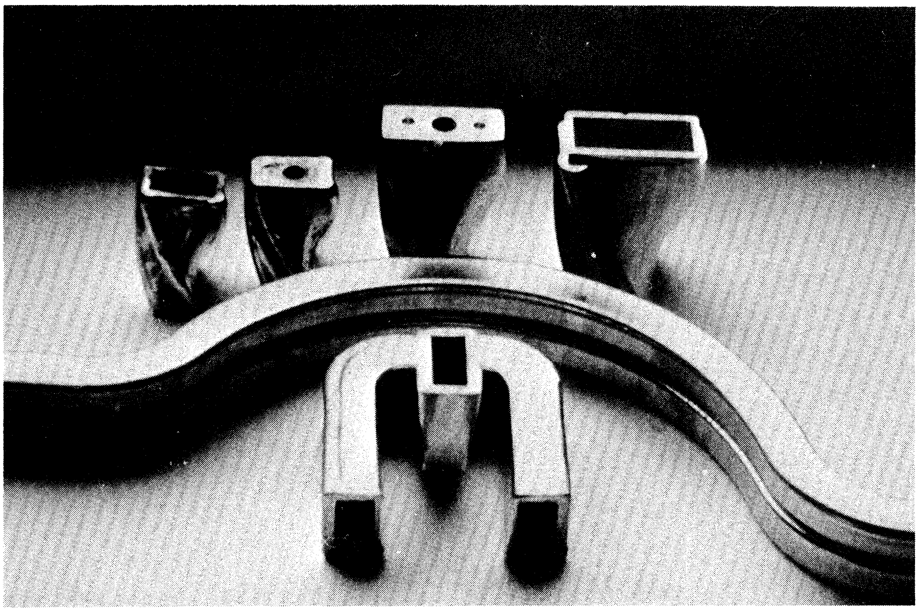

FIGURE 1. Electroforming by electrodeposition: examples of waveguides.

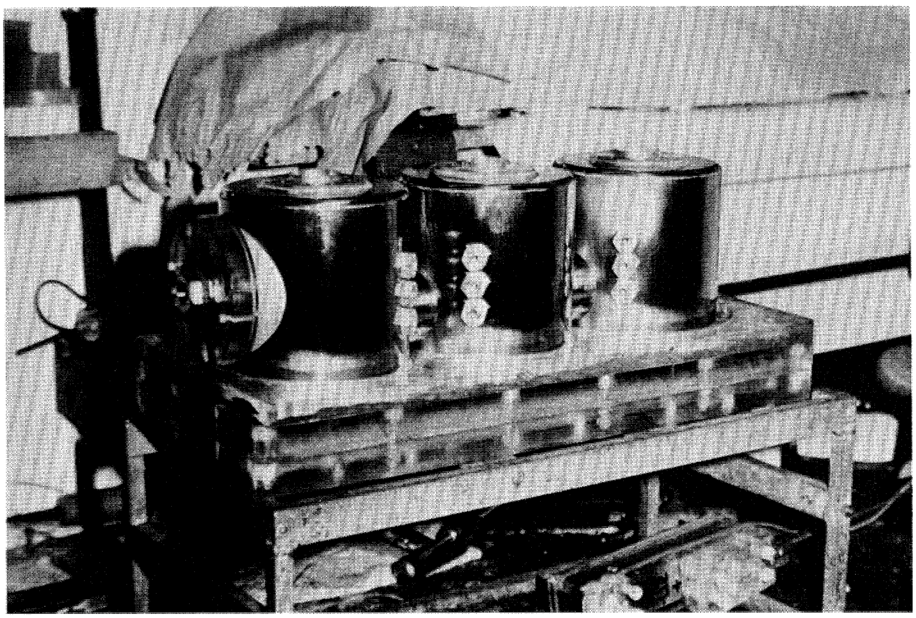

FIGURE 2. Mandrel used to produce the electroform shown in figure 3.

By means of electrodeposition techniques it is possible to produce foils that are much thinner and wider than any mechanical method can give. Thus ultrathin metal foils are produced, 0.01–0.1 mm thick, such as copper foil, which finds widespread use in electronics and printed circuit manufacture. An interesting development is the production of ultrathin iron foils, of much lower cost than non-ferrous metals. It has been used as a heat and dampness barrier in packaging when used as a sandwich between cardboard or polymer material. The foil also adds strength to the composite material as well as flame resistance and wet strength.

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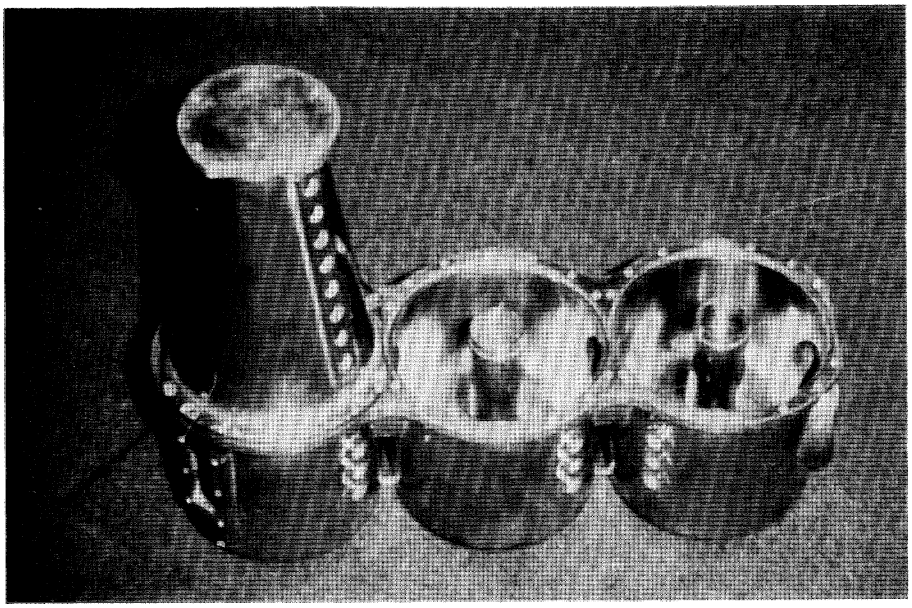

FIGURE 3. Electroforms produced from the mandrel.

TABLE 4. SOME ENGINEERING USES OF ELECTRODEPOSITED COMPOSITE COATINGS (BIDMEAD & DAVIES 1978)

components	comments on use
bores in aircraft components	Bores coated to size with cobalt plus chromium carbide to reduce wear and fretting at high temperatures. Has eliminated costly welding and grinding operations.
piston rings	Cast-iron piston rings coated with cobalt plus chromium carbide in external diameter to give good wear resistance and anti-scuffing properties.
aircraft nose wheel steering body	Coated with cobalt plus chromium carbide in the bore to provide wear resistance in sliding contact with piston made from aluminium alloy.
automobile shackle-pin	EN 58 hardened pin coated with nickel plus aluminium on outside diameter to provide resistance to wear, abrasion and corrosion. The pin is in bearing contact with phosphor bronze bush and nitride-hardened shackles.
glass moulds	Nickel plus alumina deposited onto the face of cast-iron mould to provide good oxidation and wear resistance.
aerospace air-conditioning systems	Components coated with cobalt plus chromium carbide to resist dry rubbing wear and fretting at 500 °C.
pump components	Coated with nickel plus chromium carbide to protect against combined wear and corrosion.
rotary engines	Nickel plus silicon carbide particles used on rotary engines to reduce wear on the rotating apex seal of a Wankel engine.

In contrast to other methods of manufacture, electroforming can be very economical when only small numbers of components are required. Thus special thin-walled boxes have been produced from an appropriate mandrel, rather than a deep drawing die set and the use of a large pressing tool machine (figures 2 and 3).

There is an increasing use of electroforming in making moulds and dies for plastics, zinc die casting, foundry patterns, glass and press tools. Major developments have been made in the use of nickel electrodeposits, or, for high temperatures, nickel–cobalt electrodeposited alloys. They are used as a thin shell with an appropriate backing of a cheaper material, which may be sprayed metal or epoxy resins or, for press tools, sometimes concrete. There is a growing interest in composite electrodeposited coatings, where insoluble particles are co-deposited. Future prospects for these systems are good, as the technical problems are being overcome (see table 4).

4. Management of corrosion control

The many studies of the costs of corrosion show that unplanned maintenance is often associated with failure due to corrosion. Statistics from the Hoar report (table 5) show that corrosion accounts for about 38 % of the broad national maintenance costs in the U.K. In some industries,

Table 5. Relation between maintenance costs and corrosion (Hoar 1971)

gross national product	£38 × 10^9 per annum
Treasury recorded figures for capital replacement (which are regarded as maintenance at about 10 %)	£3.6 × 10^9 per annum
corrosion costs identified (both figures to be fairly consistent)	38 % of broad national maintenance figure or 10 % of gross national turnover

such as electrical power generation, some 50 % of maintenance work is as a result of corrosion. Engineers in power generation are probably more aware than most of the understanding and need for corrosion control, but even in that enlightened industry, substantial cost savings are still being made by further application of electrochemical methods. A typical example is the protection of the huge network of pipes and pumps associated with sea-water cooling at large coastal power stations. These pipes, when large enough, may be coated internally, but this is more difficult in the pumps and valves in which water velocities are high, and coating life can be very short. In fact, in these particular situations coatings perform unsatisfactorily. Because of the large sizes, only casting can be considered for pumps and valve bodies and in many cases only cast iron can be considered on grounds of cost. In some estuary waters a severe form of corrosion, known as graphitic corrosion, occurs on cast iron. The graphite network of the cast iron remains surrounded by iron oxide and thus the corroded cast iron is eroded quickly from the affected regions by the flow rate. In a large circulating sea-water system, replacements had cost about £2.5 M over a few years. It was decided to blast surfaces clean and apply cathodic protection at a cost of £0.6 M. Since then very little corrosion has occurred, and pay-back will be within about 2 years. Impressed current was chosen so that the protection current could be varied to maintain a protective potential as water flow conditions changed. A computer simulation enabled the number and siting of electrodes and electrode potential monitors to be optimized. Automatic control is possible with such a system, which applies a few volts at a current density on the iron work (cathode) of about 100 mA/cm². The materials for the small anodes are relatively cheap lead alloys with platinum, or platinized titanium, which may have a current density of several hundred amps per square centimetre. Reference electrodes are usually copper – copper sulphate or silver – silver chloride. In figure 4 the engineering aspects of such an electrode for this arduous service are given. Cathodic protection has also been successfully applied to ships, tanks and pipelines in sea and river water. An important use of this electrochemical technique had been in buried pipelines, and in 1970 some 17000 km of

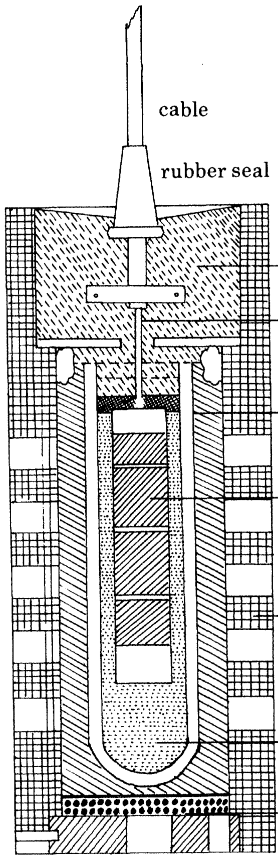

FIGURE 4. Silver – silver chloride reference electrode system for use in fast flowing sea-water.

pipeline were under cathodic protection in Germany, 20000 km, in France and over 640000 km in the U.S.A. (Backmann & Schwenk 1975). This is combined with a coating, and cathodic protection effectively protects the gaps in the coating, whether this is sub-microscopic porosity or large gaps caused by deterioration of the coating or by damage during construction. There is now a large-scale application to buried metal pipelines throughout the world, but its use is by no means extensive. There are many situations in industry where this form of corrosion control would be applicable and it could reduce present maintenance costs, so that the prospects for this application of electrochemistry should be good. The misunderstanding of the electrochemical process by engineers has meant that in many instances it is added as an afterthought; this produces many difficulties, which raise the cost of its application, whereas if it had been considered at the design stage it would have been more successful and easier to apply.

5. Machining by controlled corrosion

Electropolishing has been known for a long time as a useful but minor method of removing metal to achieve a final dimension and more important to give an acceptable smooth, if not bright polished, surface to metals and alloys. It is only in the last 20 years that the electrochemically assisted process has been adopted on a large scale, principally by the aeroengine manufacturers, to machine hard metals quickly, with good accuracy and with an excellent surface finish.

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Although e.c.m. can provide the analogues of conventional machining such as drilling, milling, turning and grinding, the tool does not touch the workpiece and so does not wear out (Meleka & Glew 1977). The method has been adopted when it is considerably cheaper than conventional methods, and this is largely in very long runs of components, e.g. turbine blades,

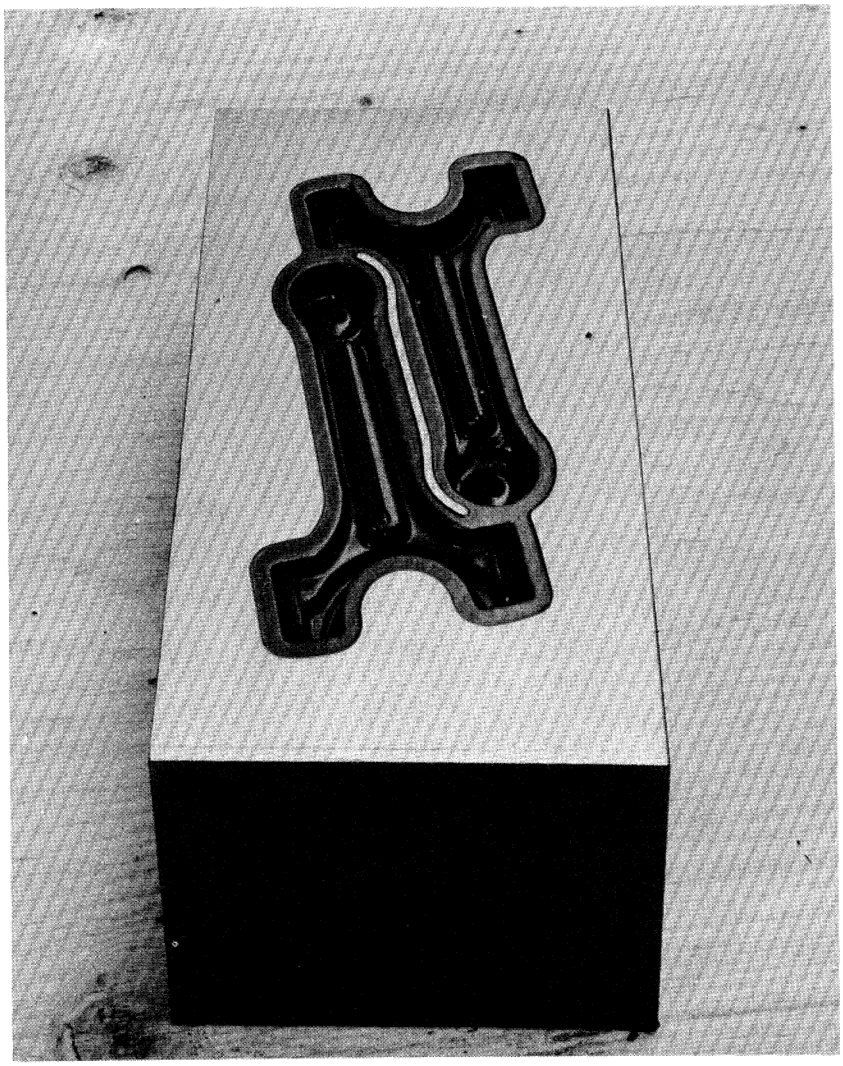

FIGURE 5. Die sinking press work, manufactured by e.c.m. (Courtesy Matchless Machines Ltd).

and when the hardness of the alloys slows down considerably the machining rate when cutting, chipping or grinding techniques are used. There have been remarkable developments in the 'sculpturing' of metals (Wilson 1971), e.g. manufacture of dies for die sintering or other moulds (see figure 5).

In some instances it has been found that the process was unique in the sense that no equivalent mechanical process could be found for certain operations. This is particularly true for long, small diameter holes.

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Small hole drilling

The development of power in gas turbine engines is limited by the availability of heat-resistant materials; this has been overcome in a novel way. Since the gas turbine engine relies essentially on expanding gases, the skin temperature of the enclosure is not so important. In fact, development work has shown that the temperature of the blades may be as much as 300 °C below the gas temperature without significantly impairing the efficiency (Glenny & Hopkins 1976). To maintain the mechanical properties at these high gas temperatures, which in some areas are above the melting point of the alloys used, the blades are manufactured with a complex series of cooling holes. These vary in diameter and length from 0.1 to 2 mm diameter and from 1 to 30 mm in length. For the large holes it is now possible to produce them in the

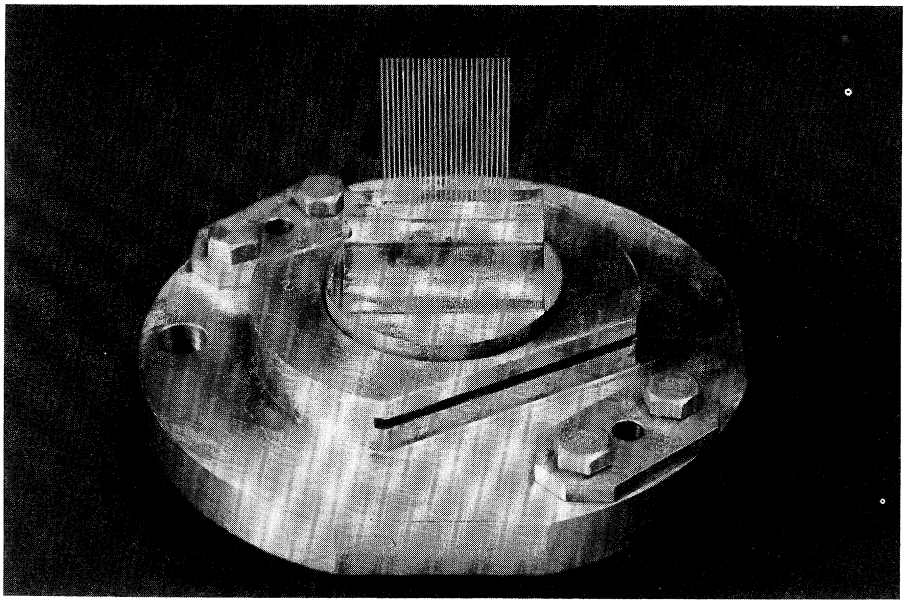

FIGURE 6. Multiple glass capillary fixture for drilling small holes. (Courtesy Rolls-Royce Ltd.)

casting process (such are the developments in precision moulding), and the method of electro-discharge machining is often preferred for the small diameter holes. However, for the long, fine holes, where discharge machining suffers overheating, then electrochemical machining is at present the most economical method. As the demand for very small diameter holes increased, it was difficult to produce the fine metal electrodes down which the electrolyte flows. This has been overcome by the use of a fine glass capillary that can be manufactured by specially developed machines. The glass capillary, containing a conducting metal wire, is used to drill the holes electrochemically. Acid electrolyte flows through the glass capillary and the extended electrolyte path requires 60–100 V for dissolution to take place, and as dissolution proceeds the capillary is fed into the workpiece. Good accuracy and reproducibility are possible with this technique, surface finish is excellent, and the method lends itself to multiple hole drilling (figure 6).

A further development has been the removal of the metal or glass capillary altogether, and current is passed down the stream of electrolyte (Rolls-Royce Ltd, private communication; Jollis 1978).

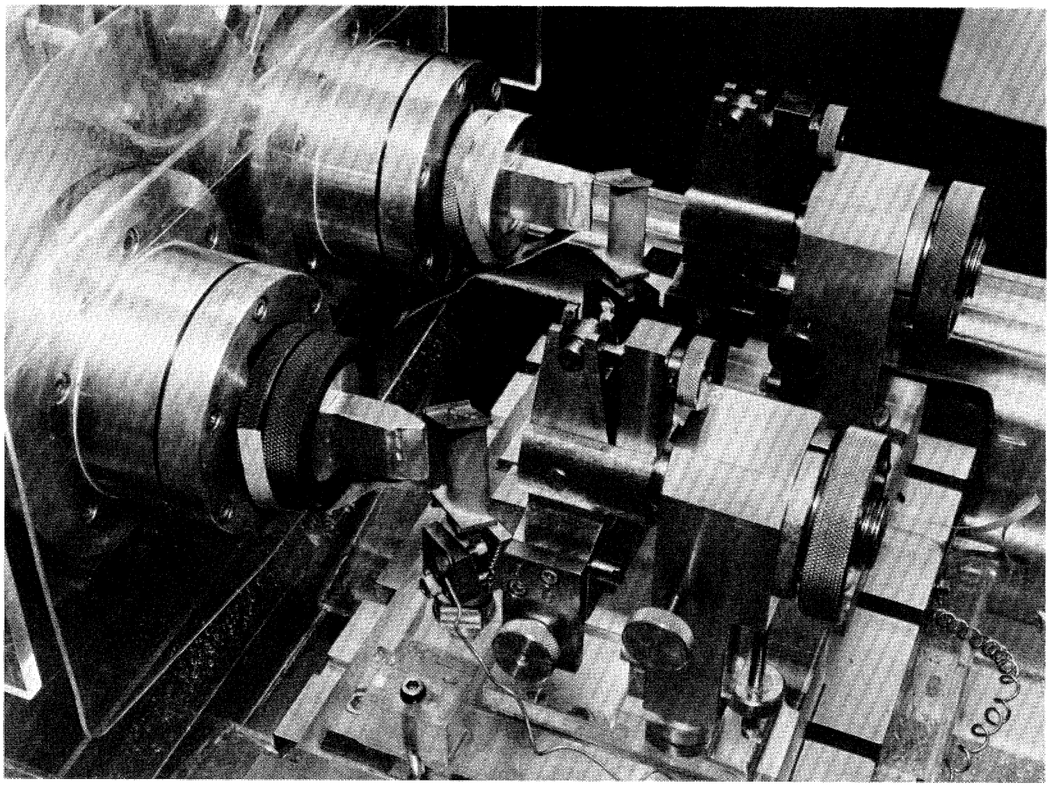

Figure 7. Spinneret or nozzles for electrojet machining. (Courtesy Rolls-Royce Ltd.)

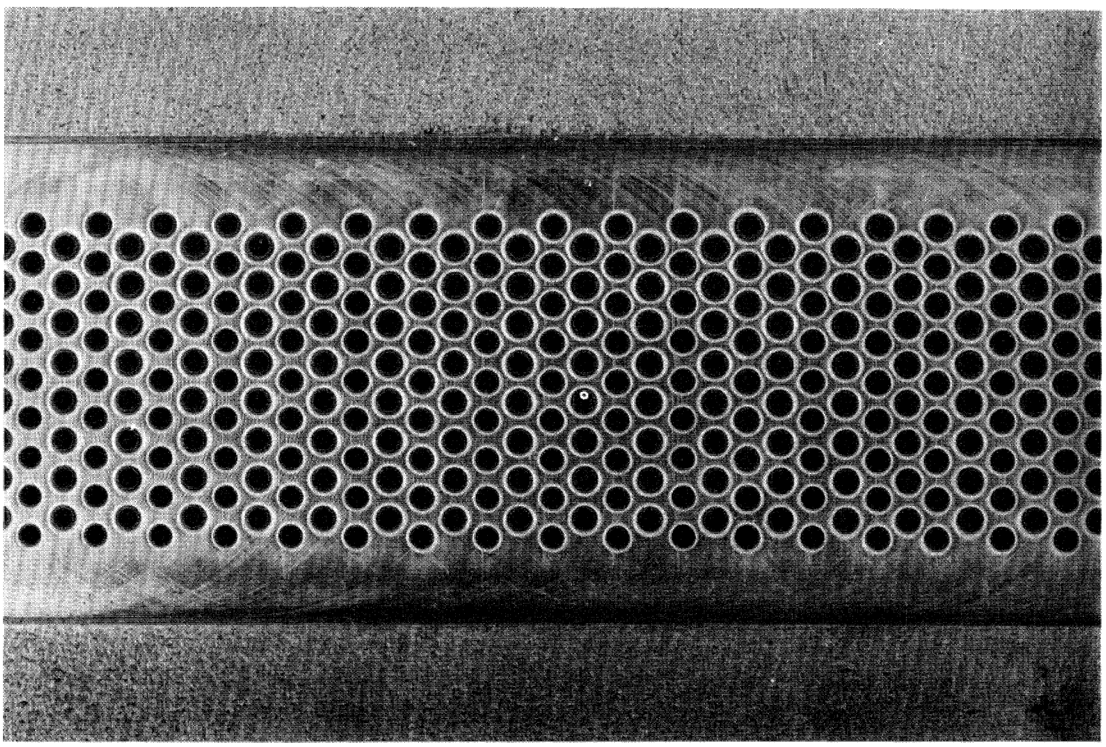

Figure 8. Density of holes possible with electrojet machining. (Magn. × 6.) (Courtesy Rolls-Royce Ltd.)

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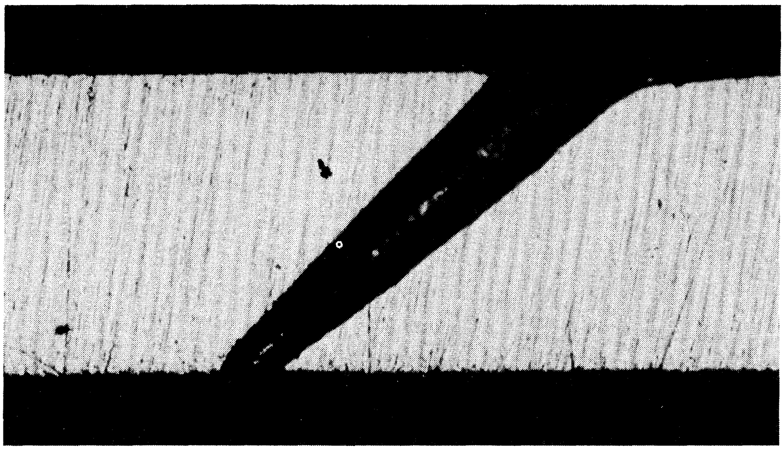

FIGURE 9. Cross section of hole drilled by electrojet at 45° angle.

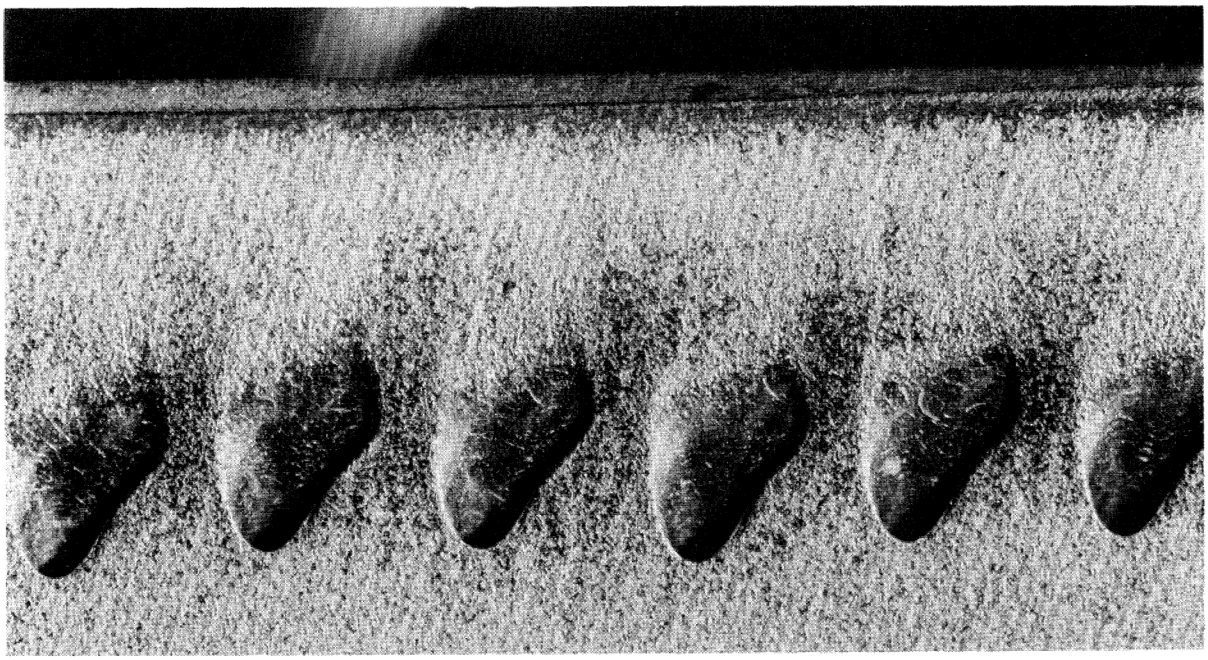

FIGURE 10. Contouring of hole at the surface for improved flow, by electrojet machining. (Magn. × 13.5.) (Courtesy Rolls-Royce Ltd.)

In the electrojet process, developed by Rolls-Royce Ltd, the 'tool' is a stable jet of dilute acid electrolyte that impinges on the workpiece. The jet is conveniently formed by passing the electrolyte under pressure through a suitable nozzle or orifice. By applying a potential of about 600 V between the nozzle and workpiece a current is caused to flow down the liquid jet. In the region of the jet impingement, metal is removed by an electrochemical process. During the drilling process at these voltages there is a stable glow discharge, and metal is removed in both the liquid and vapour phase. For through-holes, breakthrough is indicated visually when the discharge moves inside the hole away from the entrance. After breakthrough the discharge becomes more diffuse and gentler in action. The glow discharge removes local asperities and polishes the bore, thus providing a stress-free surface. It also increases the diameter of both the

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entrance and the exit. In this drilling mode a hole is produced some four times the diameter of the jet, has a taper of 5–10° including angle, and is radiused at the entry and exit. The process has been used to drill holes on a production basis of 0.1–3 mm diameter with a length : diameter

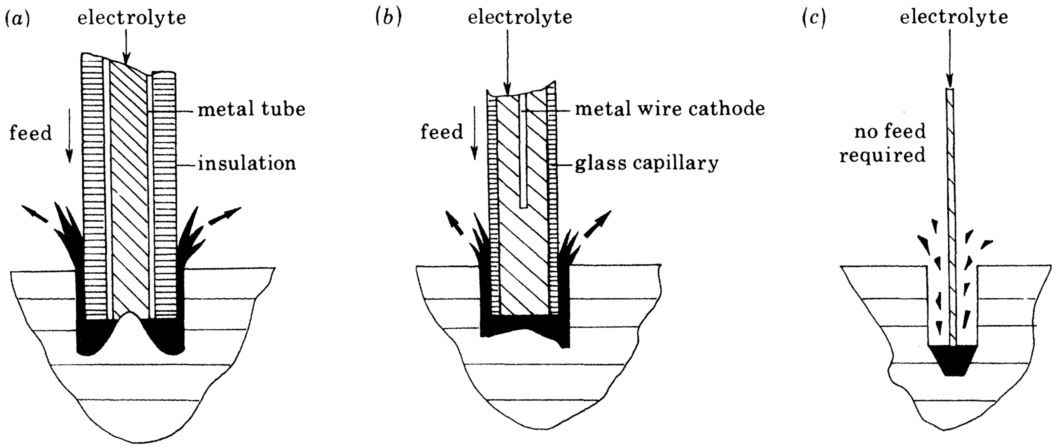

Figure 11. Development of small hole sinking tools for electrochemical machining. (*a*) Metal tube drill, which used a salt–acid electrolyte at 12–20 V; (*b*) glass capillary drill, which uses an acid electrolyte at 100 V; (*c*) electrojet, which uses an acid electrolyte at 500 V. (Courtesy Rolls-Royce Ltd.)

ratio not exceeding 10. Several holes can be drilled simultaneously by using a multi-jet arrangement (spinneret) (figures 7 and 8), and in addition to holes perpendicular to the workpiece it is possible to drill holes at angles (see figure 9), which is virtually impossible with mechanical methods, and by varying the movement of the jet, holes of varying shaped sections can be produced (figure 10). A comparison of the three hole-drilling methods is shown in figure 11.

Although e.c.m. is well established in the aero-engine manufacturing industry, it is rarely considered by other industries in the U.K. There is now sufficient knowledge about its possibilities to make accurate estimates of its costs, and yet its prospects in the U.K. seem grim although it is being increasingly applied in other countries in a wide range of industries. The subject matter of e.c.m. once again suffers from the numerous disciplines that must be understood for its application, such as electrical chemical fluid dynamics, mechanical, metallurgical and manufacturing. Nevertheless, one industry has shown that it has been worthwhile to develop these techniques in spite of the interdisciplinary approach required.

With the advance in computer control methods on traditional machine tools, prospects for e.c.m. would be good if a single-point tool could be developed to make use of these very sophisticated control techniques. It has been argued that for e.c.m. this would enhance its adoption (Meleka & Glew 1977) since it already allows almost full automation with little attention from the operators, and by *X-Y-Z* control of, say, the electrojet 'tool' this ideal could be achieved.

Conclusions

Both the Jost and Hoar committees concluded that the failure by engineers to apply known methods of preventing friction, wear and corrosion was the result of the interdisciplinary nature of these subjects, requiring as they do a knowledge of chemistry and in particular electrochemistry as well as physics and mathematics. It has been suggested that there is, as a consequence, a direct correlation with the high cost of maintenance found in industry even today

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(Department of Industry 1978). We take pride in this country that we can educate our engineers by means of a 3 year course in universities and polytechnics, but in almost all our competitors' countries they may take 4–5 years to educate their engineers. Some engineering students have 'A'-level qualifications in chemistry, but these courses also do not have the appropriate chemistry. The Finniston Committee proposed that a proportion of those studying engineering should take a 4 year course. It is to be hoped that the whole 4 years will be restructured to accommodate this interdisciplinary subject matter, so vital to the manufacturing and engineering industry. The Royal Institute of Chemistry (1978) made submissions to the Finniston Committee, pointing out the common ground that exists between the two disciplines (cultures?), but even so the Royal Society of Chemistry does not appear to have convinced the traditionalists in the pure chemistry departments of the importance of the science of electrochemistry as applied to engineering. In addition, 3 years may not be long enough to educate our chemists to their full potential. At the moment the relevant electrochemistry is taught in our Metallurgy and Materials Science schools, but the output of metallurgists is pitifully small (Cottrell 1976); this is partly due to industry's lack of appreciation of their worth reflected in the many industries who would normally be expected to employ them but do not do so.

A service function to industry is required to increase productivity, reliability and provide cost-saving improvements. The examples given in this paper are only a few of the many contributions that electrochemistry can make to progress in industry. The greater barrier to further progress is not in further innovation but in filling the information gap, which has clearly been shown to exist. If serious efforts are made to close this gap, particularly by our educationalists, then the prospects for industrial electrochemistry would be good and would fulfil a vital service to industry.

The author wishes to acknowledge the assistance of Electroform Products Ltd, Rolls-Royce Ltd, W. Canning Materials Ltd, C.E.G.B., S.W. Scientific Services, and Matchless Machines Ltd.

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Discussion

J. A. McGeough (*Department of Engineering, University of Aberdeen, U.K.*). I congratulate Dr Boden on an interesting paper, with his comments on the various reports by Feilden, Jost, Hoar, Maddocks and Finniston. The lack of knowledge of chemistry and electrochemistry by engineers which he has suggested, may stem from the fact that many universities that offer engineering degrees do not require chemistry as an entrance qualification. It may be relevant to Dr Boden's remarks for me to say that although my own university still stipulates an 'O'-level and preferably a Scottish 'Higher' in chemistry for entrance to the B.Sc. degree course in Engineering Science, of the 90 first-year entrants to this course, only about 20–25 opt for chemistry at that level. Although engineering students have to read physics, mathematics and engineering at first-year level, chemistry is only one of three other options: geology and computing science are the others. Prospective mechanical engineers tend to take first-year chemistry; civil and electrical engineers seem to prefer, respectively, geology and computing science. It is only in later years in materials science lecture courses that all our engineering students have an opportunity to learn electrochemistry, which is needed for an understanding of corrosion.

I was interested too in Dr Boden's presentation of electrochemical machining, and would like to ask his opinion of the industrial prospects that he sees for this process now in the U.K. and Europe, particularly outside the aircraft industry. In what areas does he see the process being applied, for example drilling, or surface-smoothing or die-sinking?

The technique of drilling small holes of 0.2 mm diameter, several cm long by use of a flowing acid electrolyte is of interest. Can he supply any references to this work, or provide further details?

P. J. Boden. Education in chemistry for pre-university engineers is similar throughout British universities and polytechnics, and suffers from a lack of those topics that would allow electrochemistry and surface science be developed to a higher level. At present, those chemical aspects of materials science that are thought to be important have to be taught at a much more elementary level than they ought to be. Because of the lack of time or perhaps inclination, suitable courses in chemistry to cover this gap in knowledge are rarely attempted. This is the subject matter taught by metallurgists and material scientists who are given first-year courses in which to put over the main aspects of the properties of materials, very often without laboratory courses to support it; little wonder, then, that these vital subjects are barely touched on or followed through to the final-year level.

With regard to the further application of e.c.m. outside the aero-engine industry, this will only be possible if it is economical to do so. In my experience, very few manufacturers will even consider it and there appear to be very few serious studies outside the aero-engine manufacturers to assess its economic worth. Fortunately the Production Engineering Research Association have made several studies in this field, and I would recommend that they be consulted.

To my knowledge there is only one manufacturer of machines in this country that also provides 'jobbing' shop facilities.

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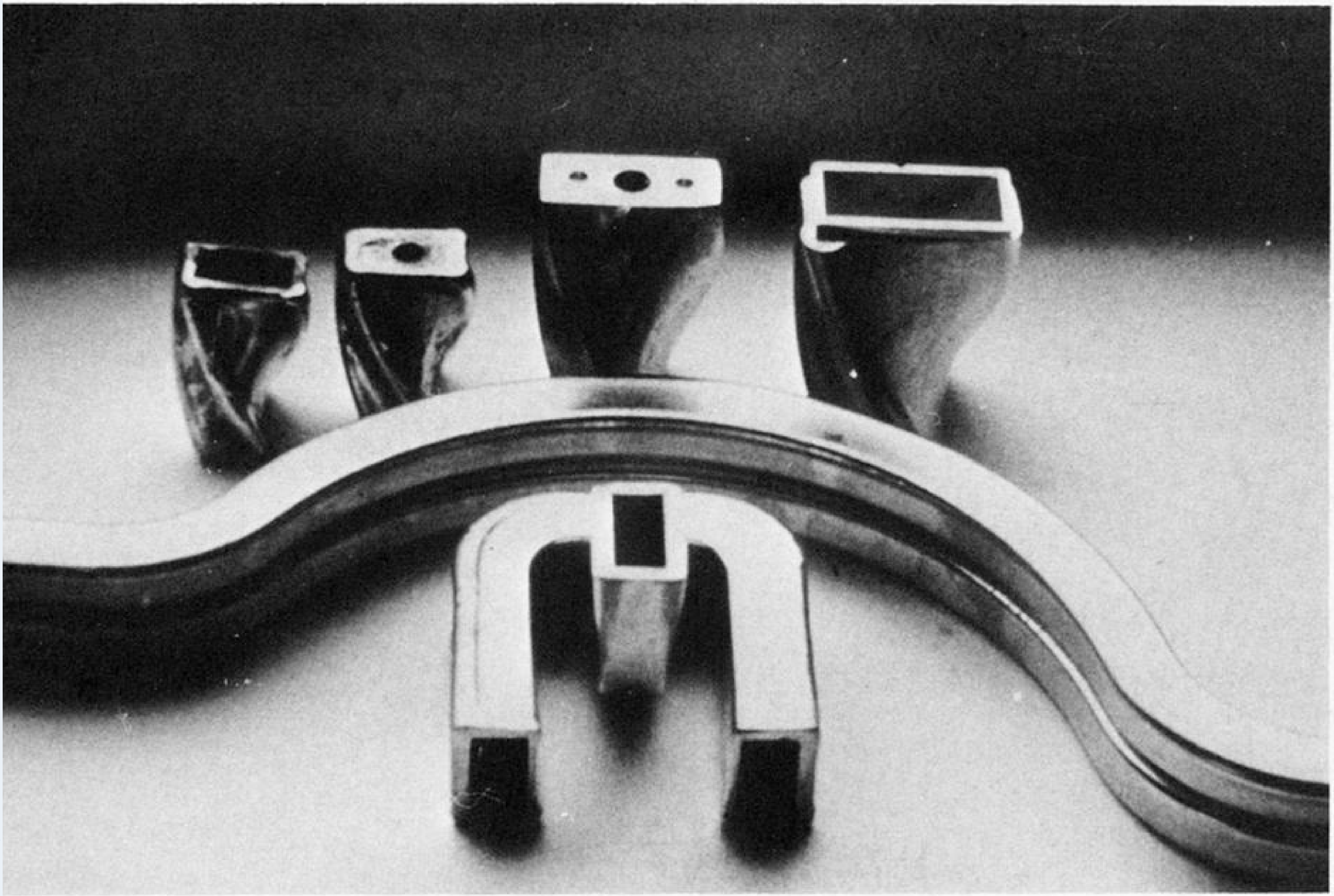

FIGURE 1. Electroforming by electrodeposition: examples of waveguides.

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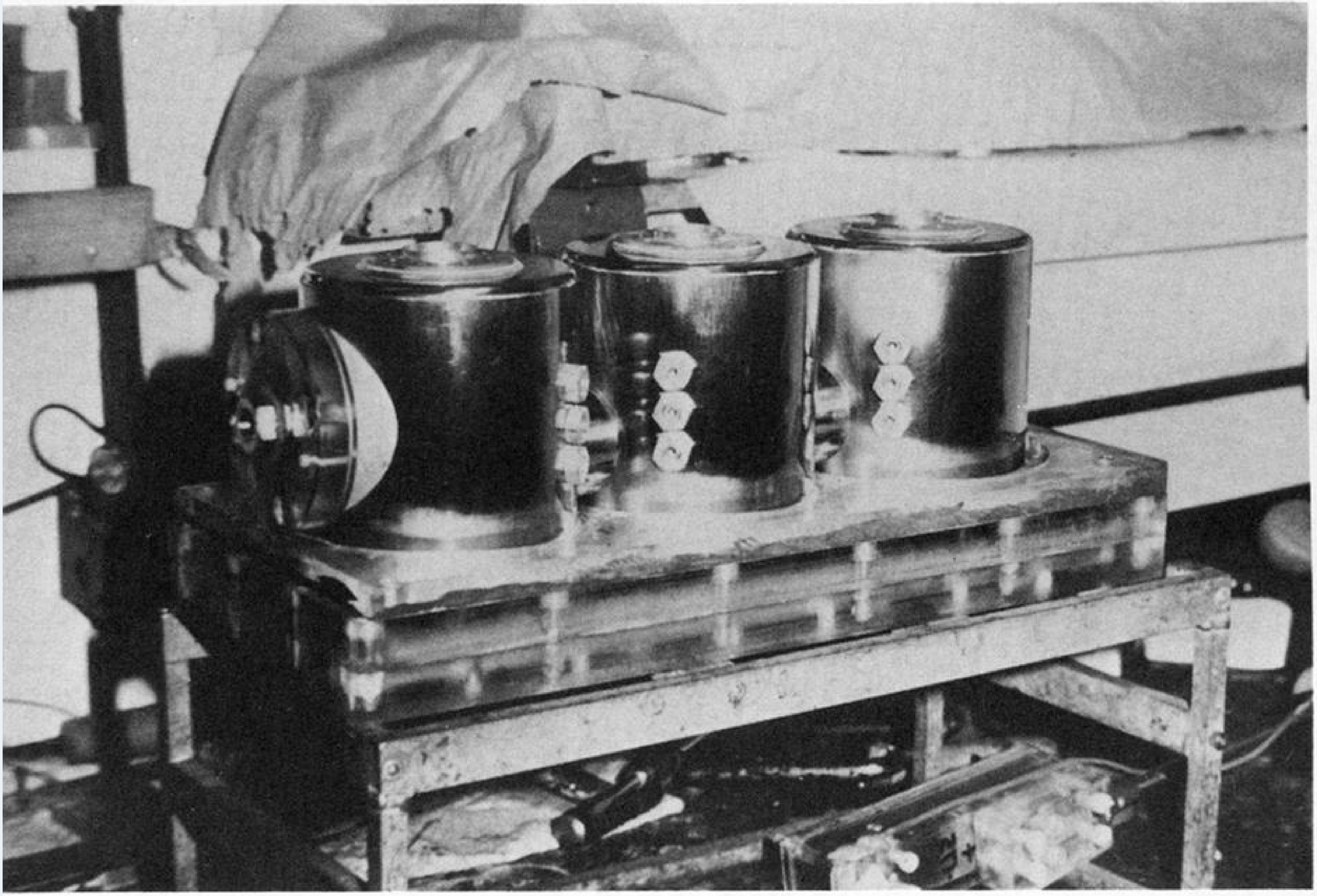

FIGURE 2. Mandrel used to produce the electroform shown in figure 3.

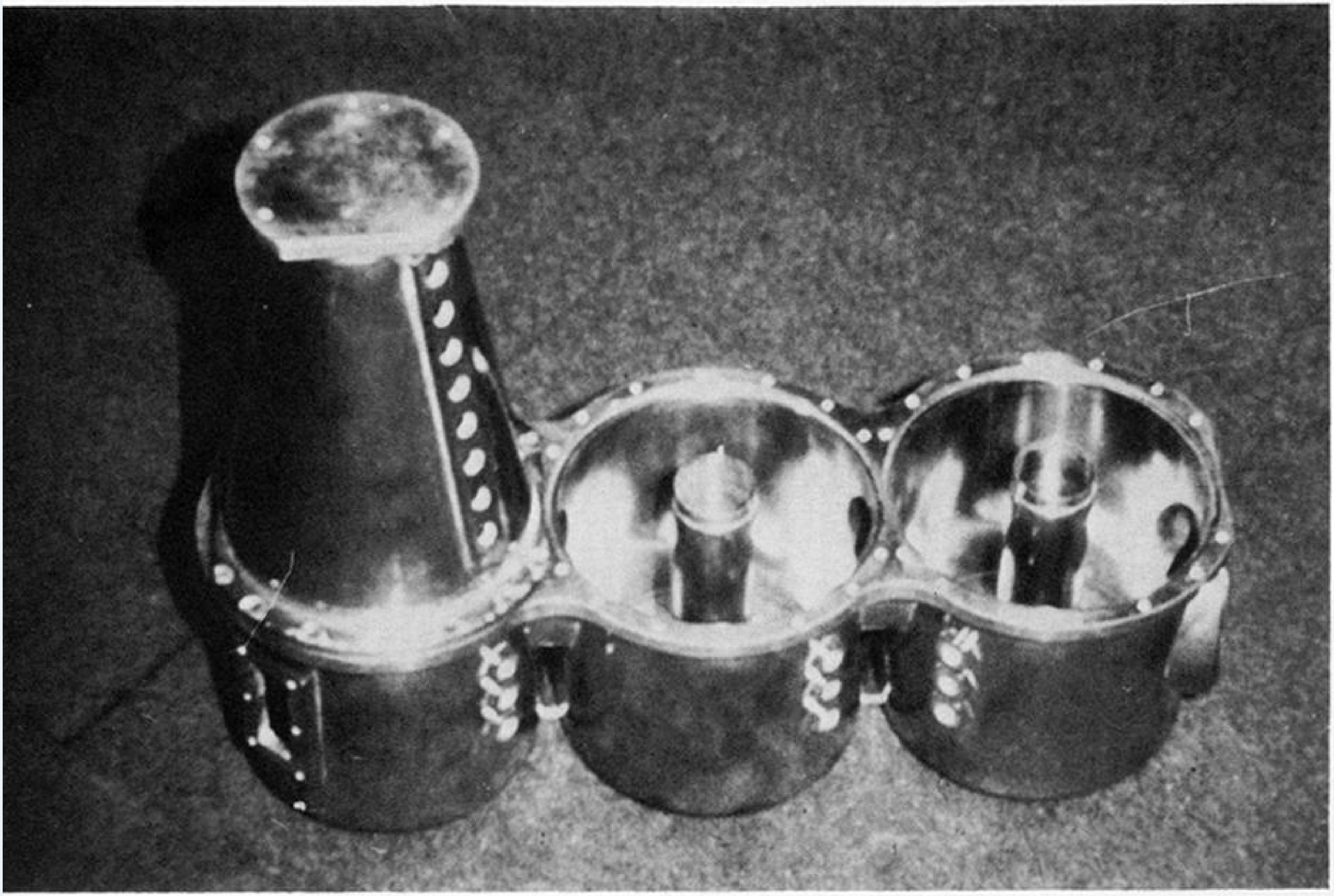

FIGURE 3. Electroforms produced from the mandrel.

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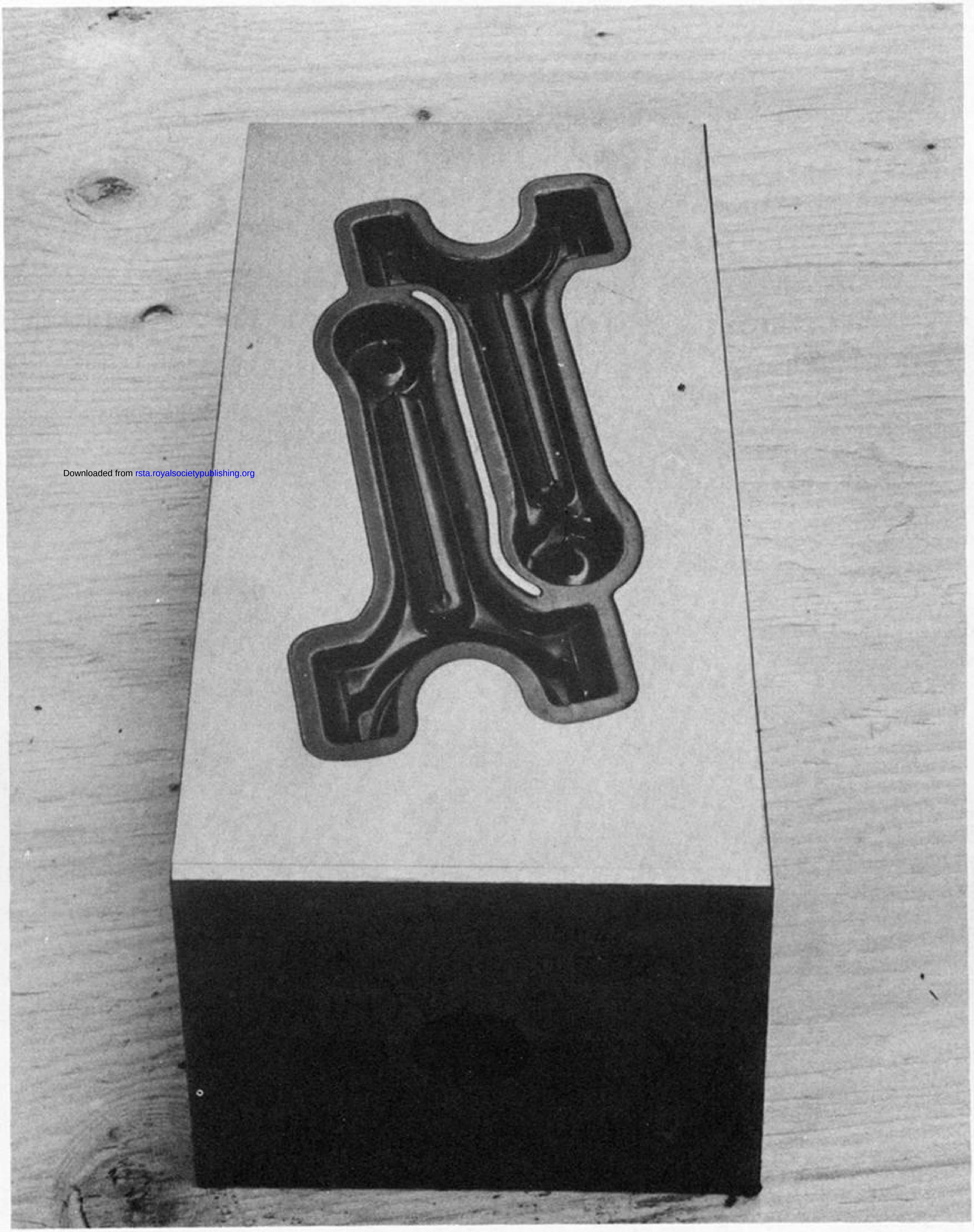

FIGURE 5. Die sinking press work, manufactured by e.c.m. (Courtesy Matchless Machines Ltd).

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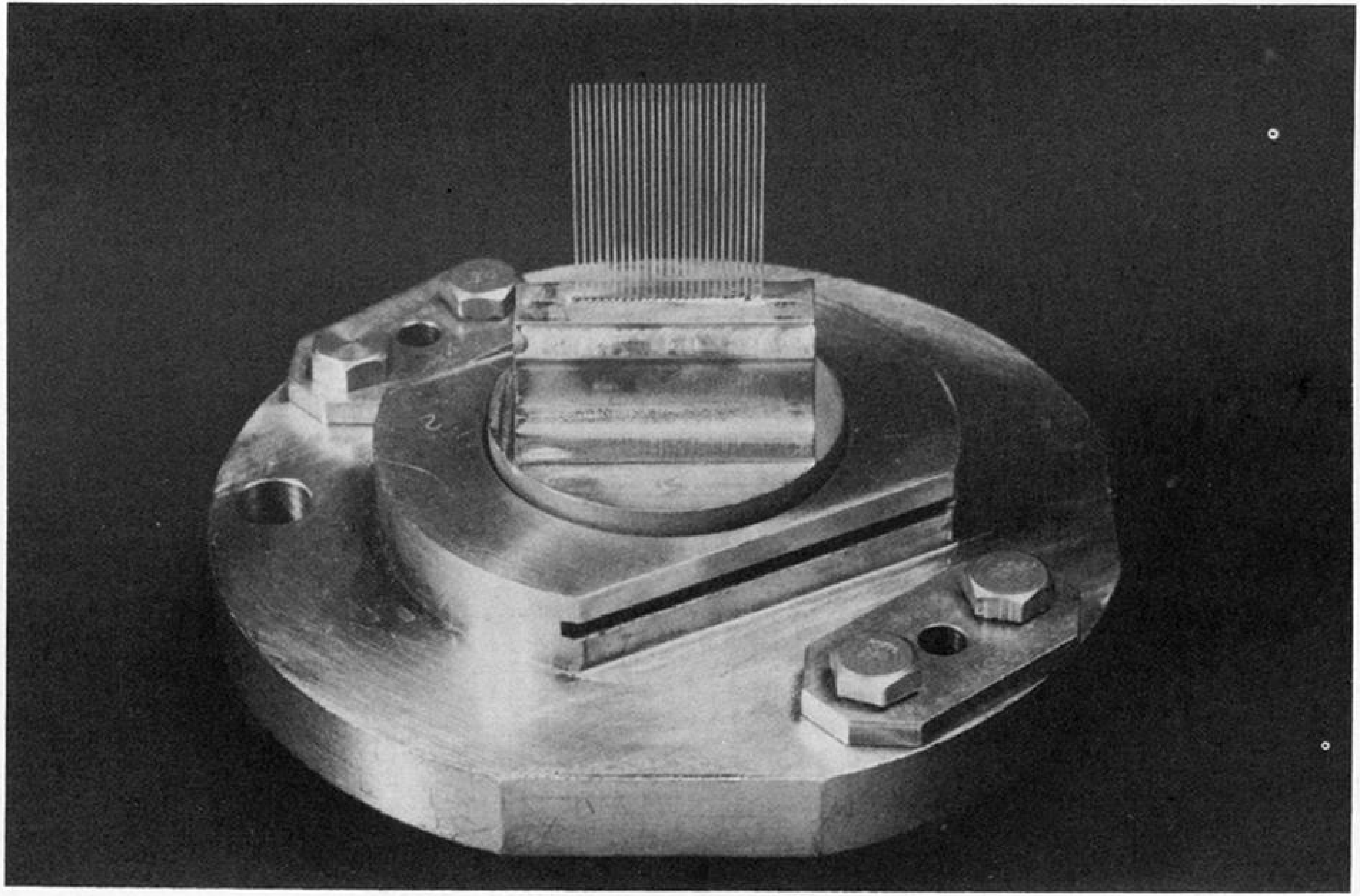

FIGURE 6. Multiple glass capillary fixture for drilling small holes. (Courtesy Rolls-Royce Ltd.)

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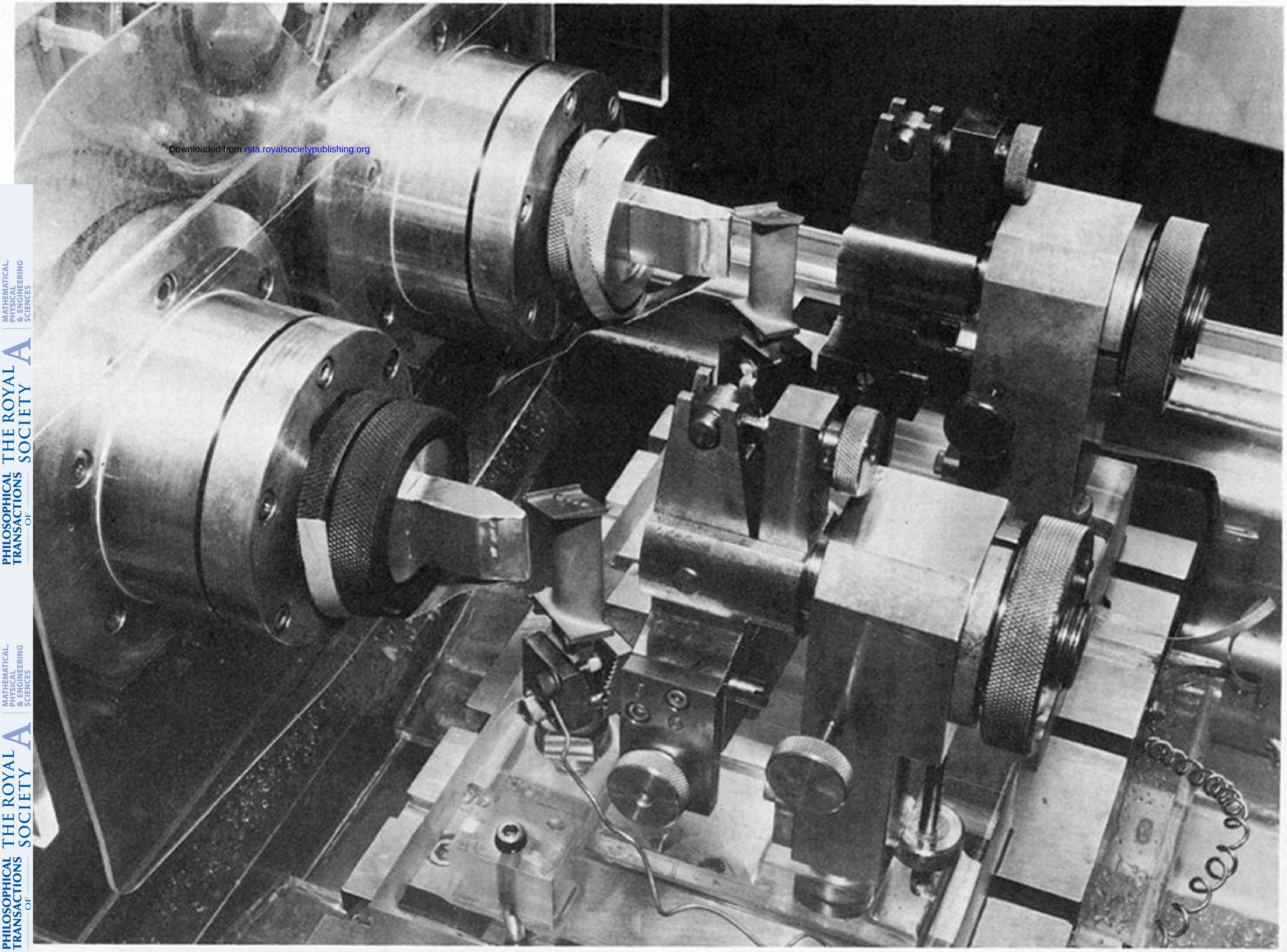

FIGURE 7. Spinneret or nozzles for electrojet machining. (Courtesy Rolls-Royce Ltd.)

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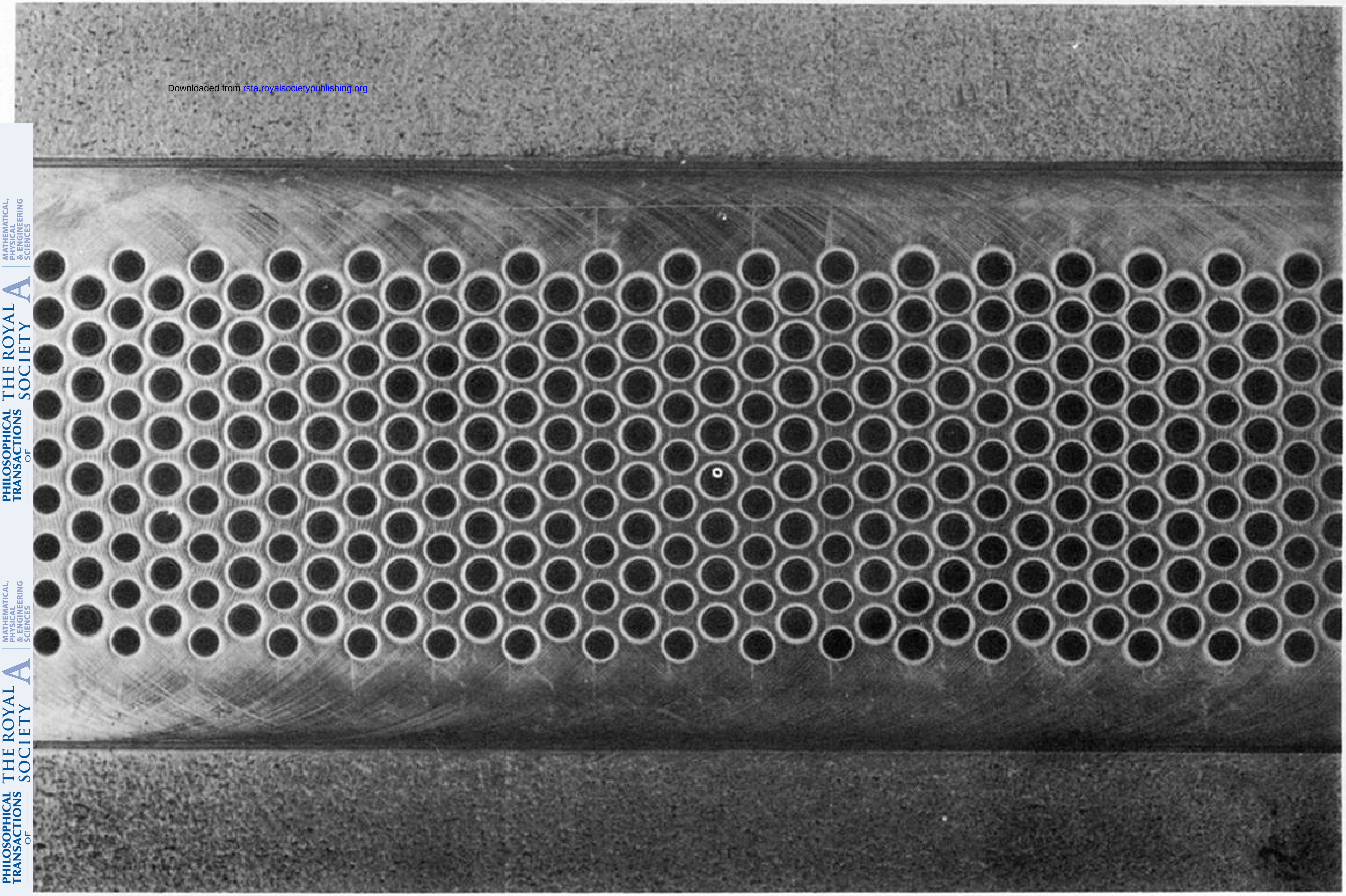

FIGURE 8. Density of holes possible with electrojet machining. (Magn. × 6.) (Courtesy Rolls-Royce Ltd.)

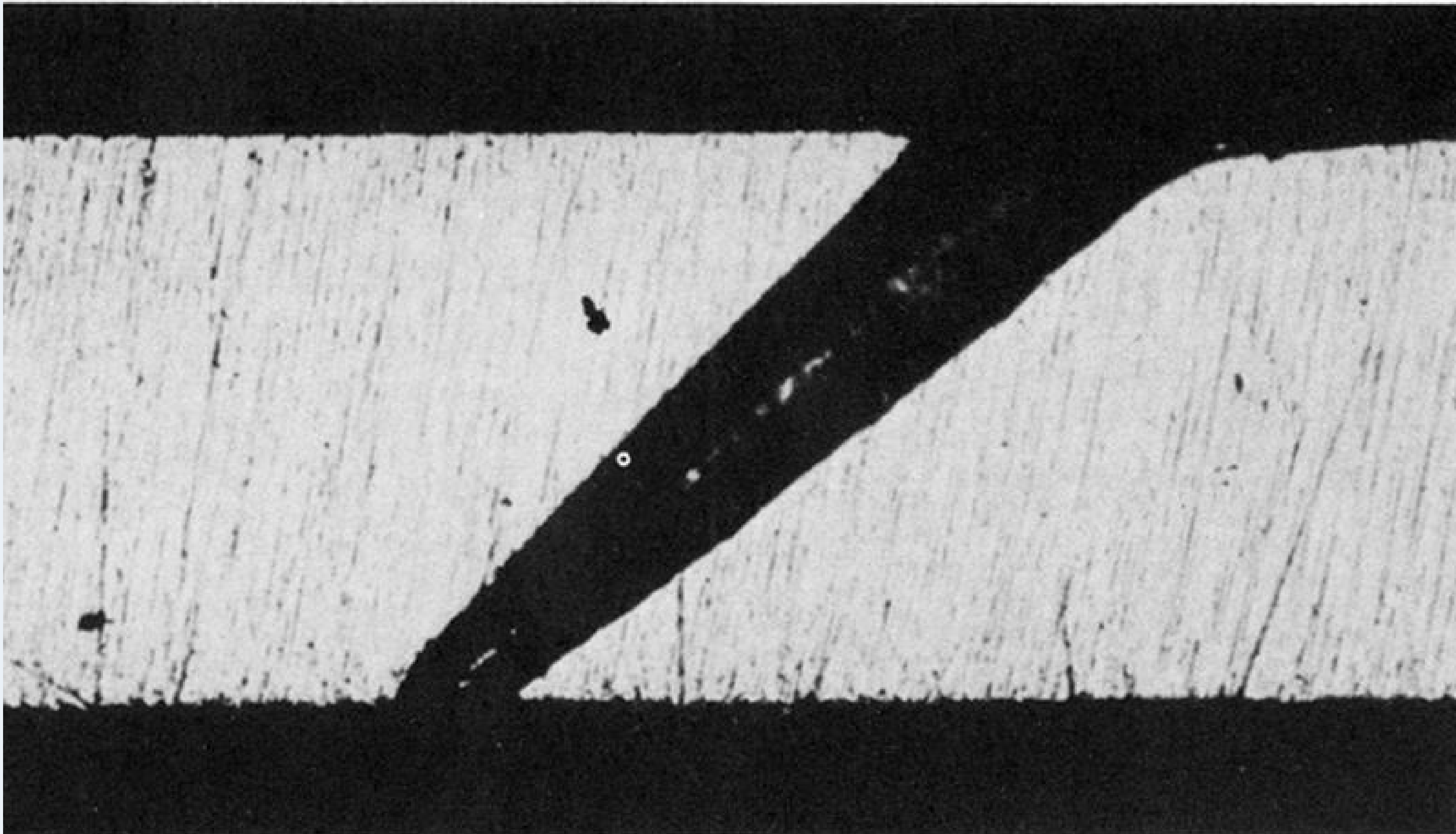

FIGURE 9. Cross section of hole drilled by electrojet at 45° angle.

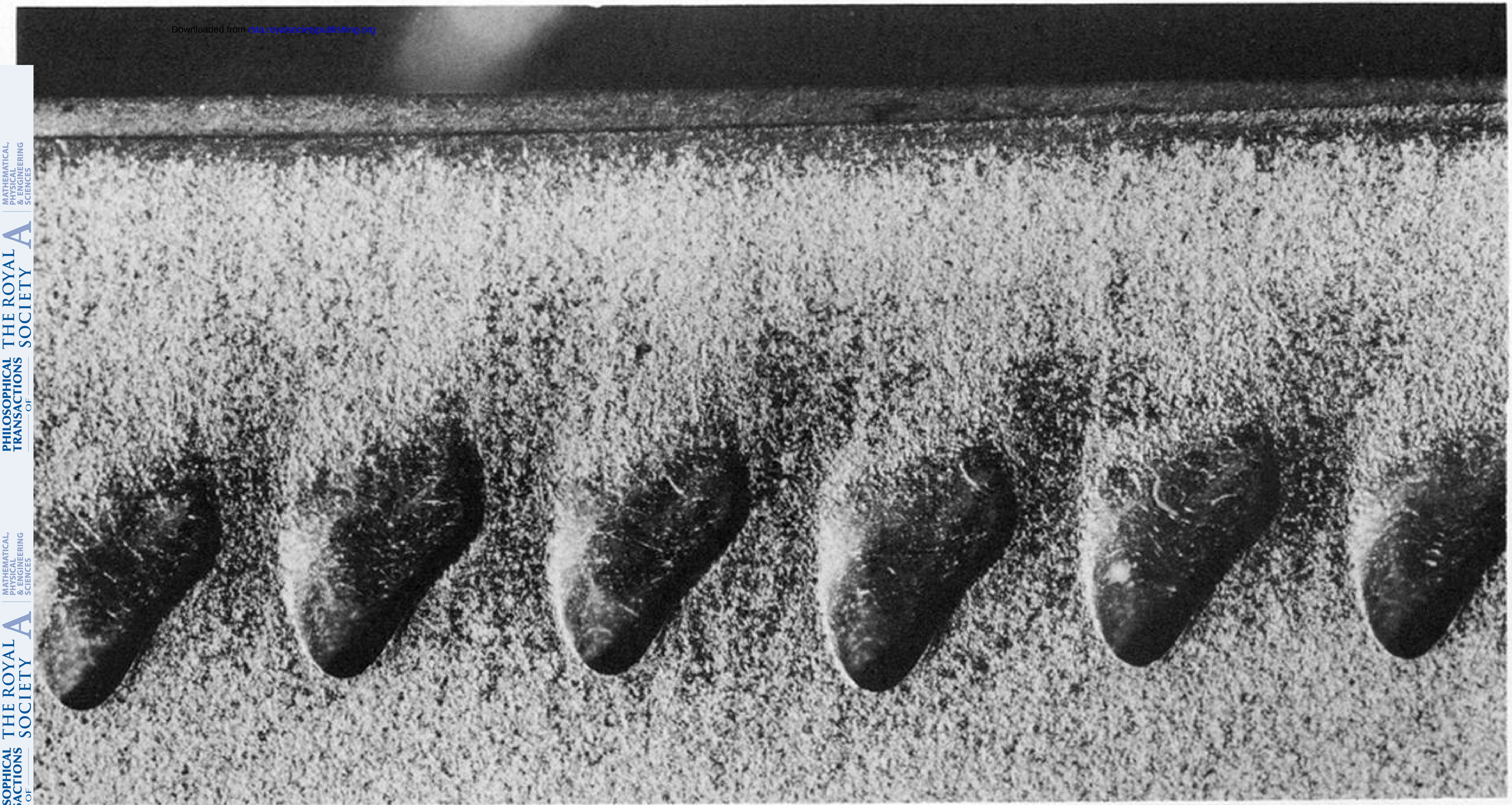

FIGURE 10. Contouring of hole at the surface for improved flow, by electrojet machining. (Magn. × 13.5.) (Courtesy Rolls-Royce Ltd.)

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