Nov. 22, 1966 L. A. WILLIAMS **3,287,245**

METHOD AND APPARATUS FOR USE IN ELECTROLYTIC MACHINING

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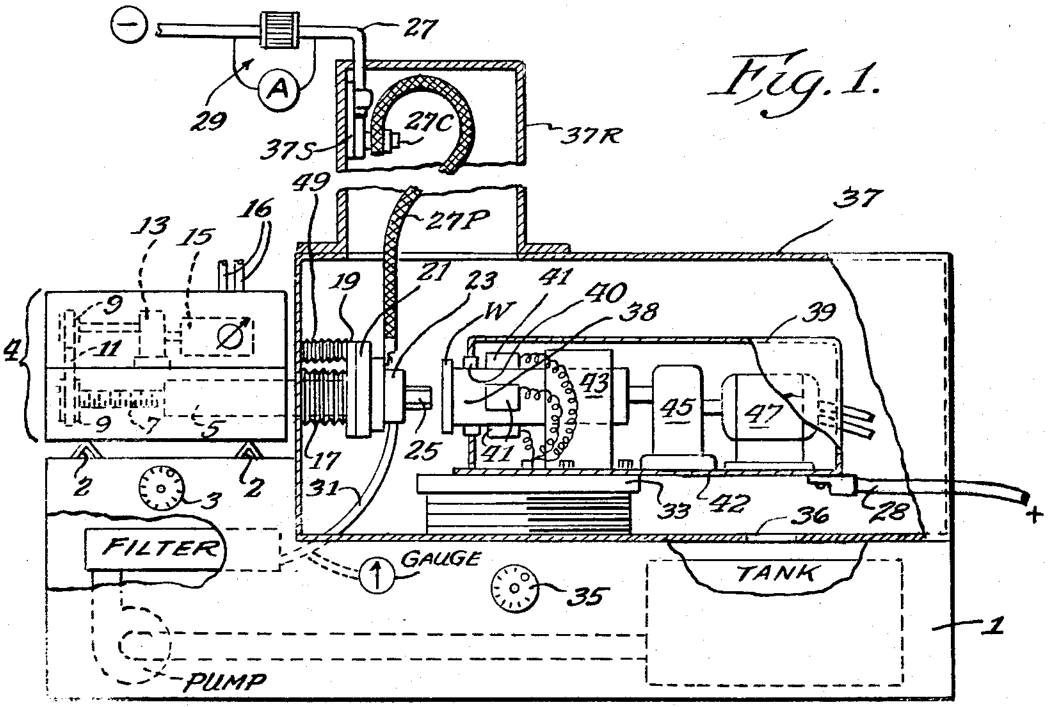

Fig. 1.

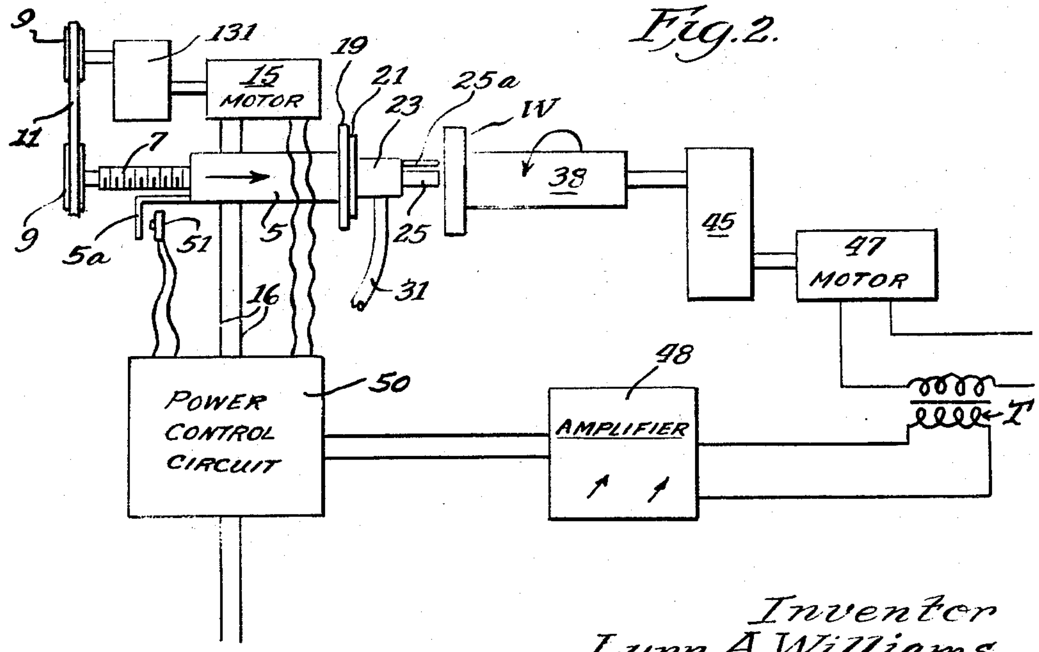

Fig. 2.

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Atty.

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Fig. 3.

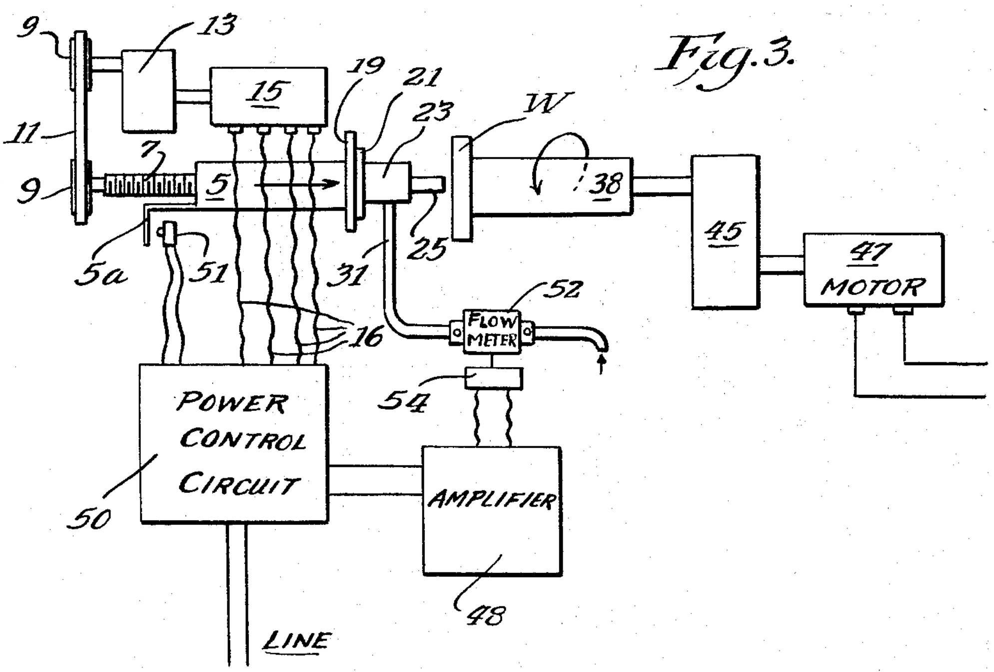

Fig. 4.

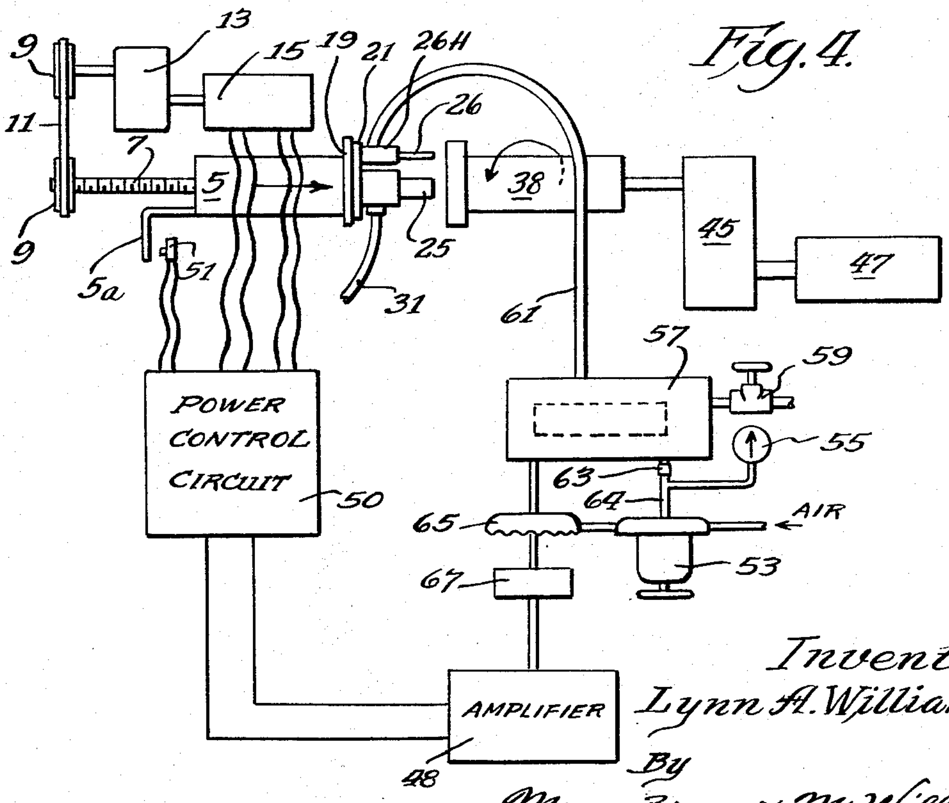

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Fig. 5.

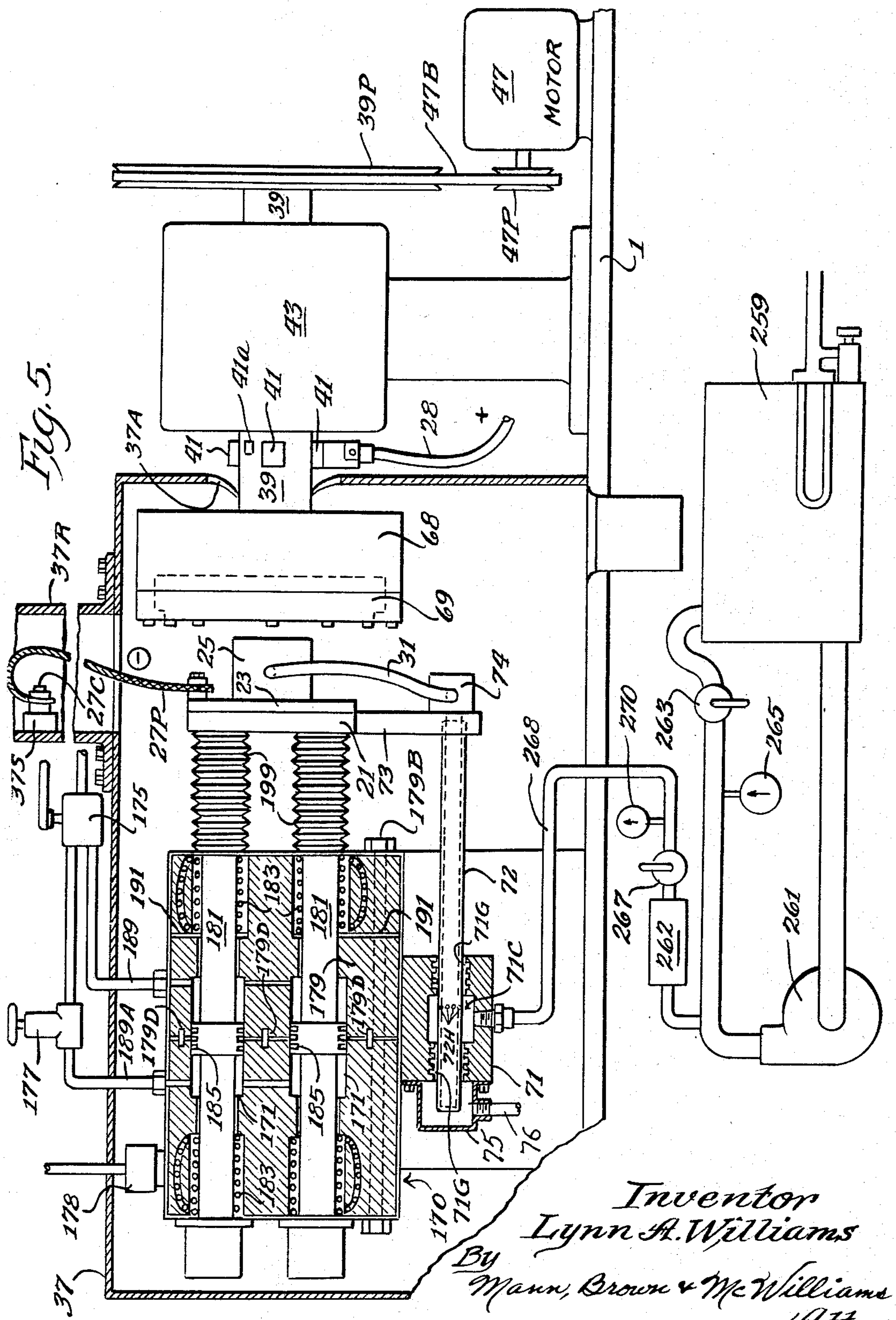

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Fig. 6.

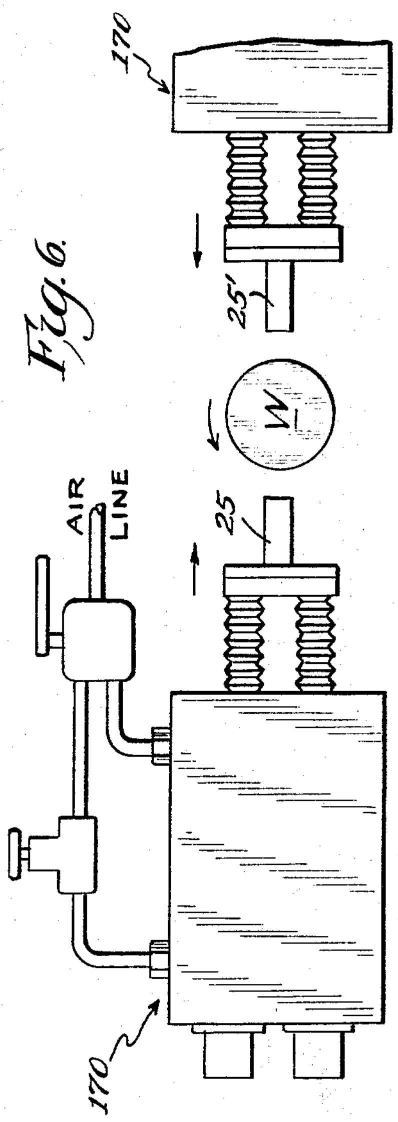


Fig. 8.

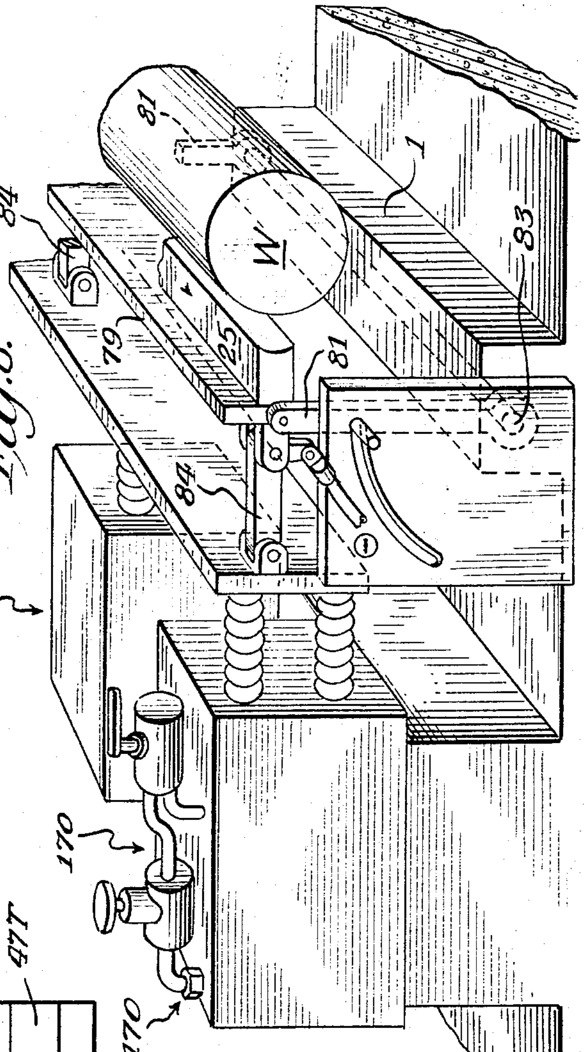
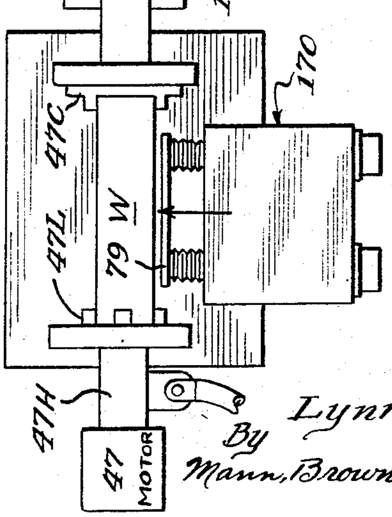


Fig. 7.



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METHOD AND APPARATUS FOR USE IN ELECTROLYTIC MACHINING

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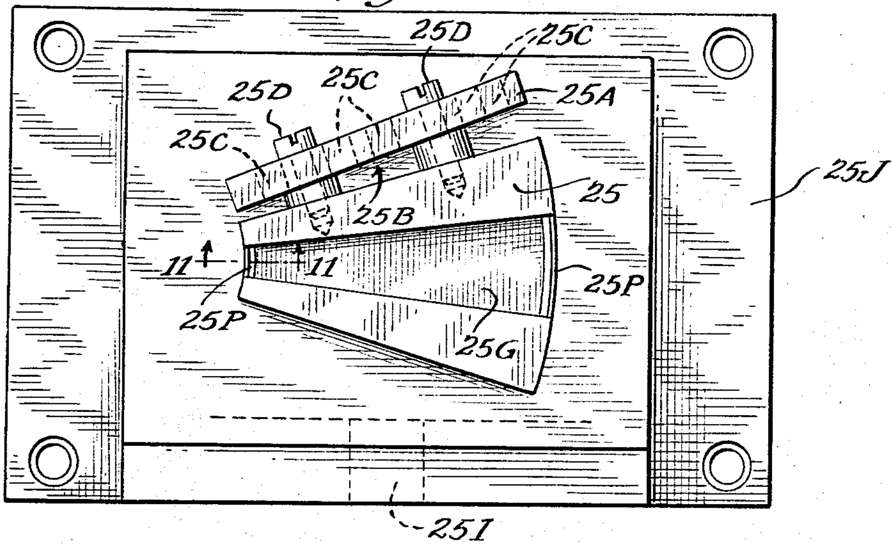
Fig. 9.



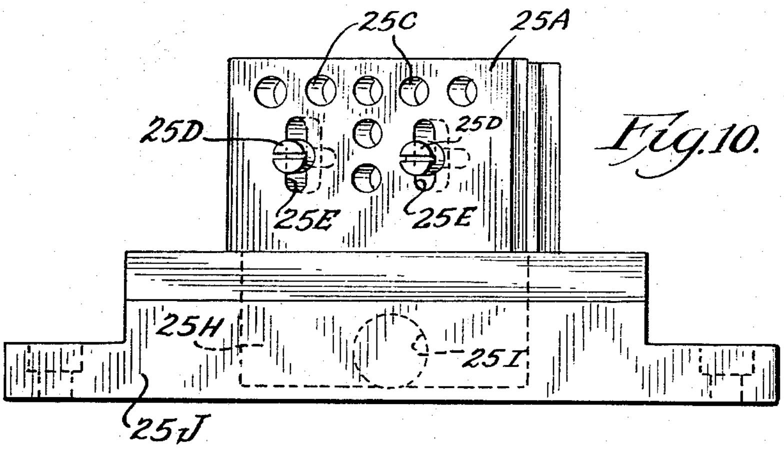


Fig. 10.

Fig. 12

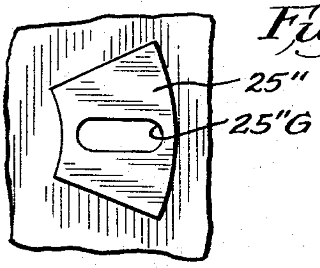


Fig. 11.

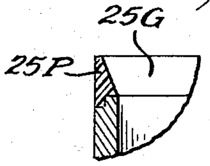


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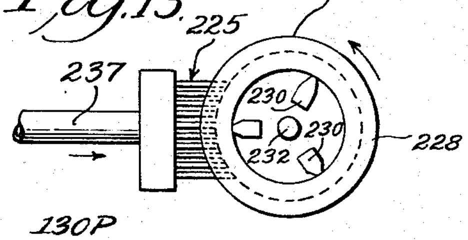
Fig. 13.



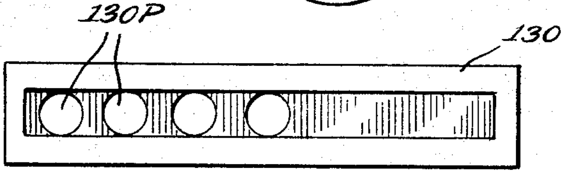


Fig. 16.

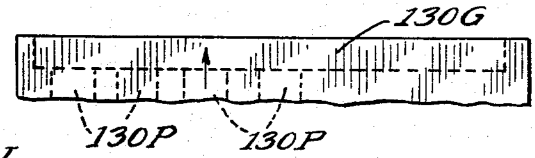


Fig. 16A.

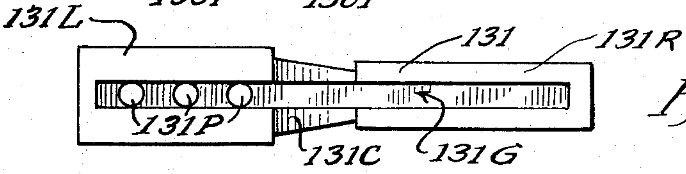


Fig. 17.

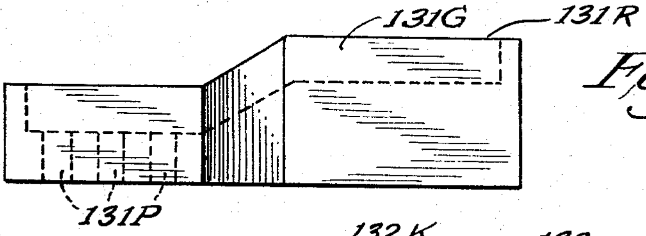


Fig. 17A.

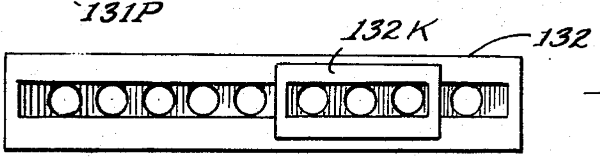


Fig. 18.

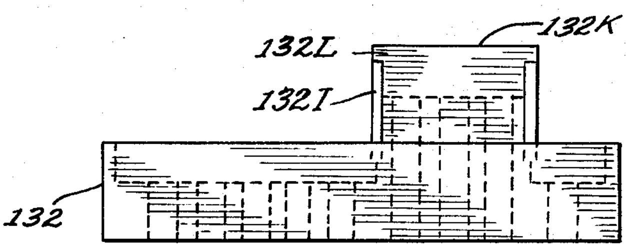


Fig. 18a.

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Fig. 14.

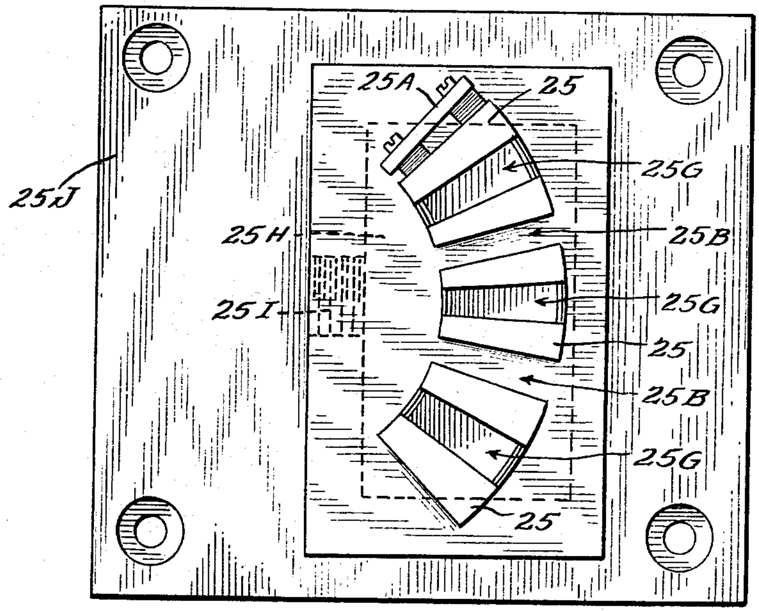

Fig. 15.

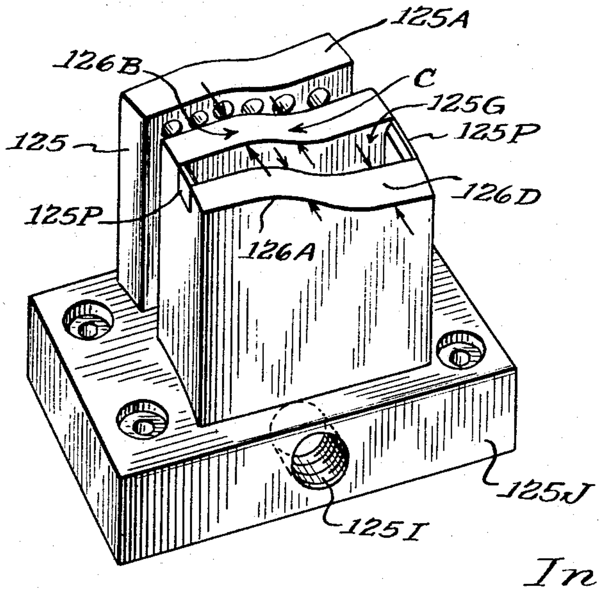

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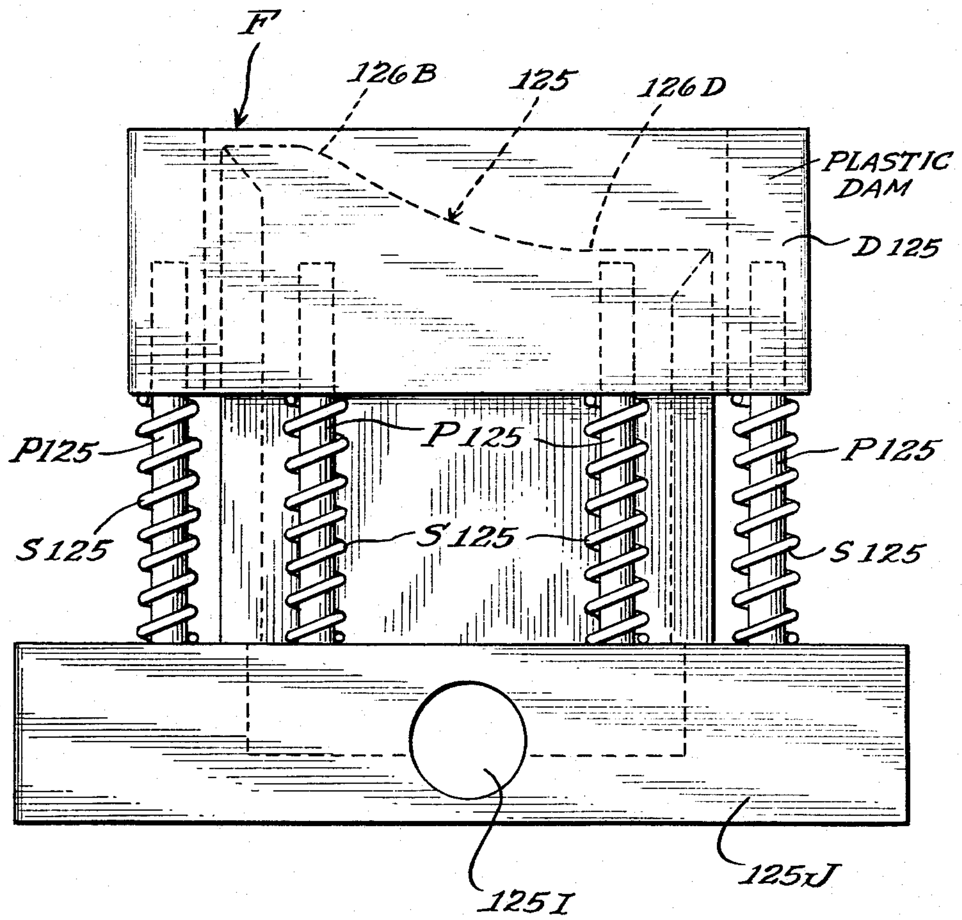
Fig. 19.



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METHOD AND APPARATUS FOR USE IN ELECTROLYTIC MACHINING

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Filed June 19, 1961, Ser. No. 117,965
7 Claims. (Cl. 204—224)

This invention relates to electrolytic machining of electrically conductive and electro-chemically erodible materials, and particularly to situations in which the work is revolved or rotated with respect to the electrode. This application is a continuation-in-part of my co-pending application, Serial No. 772,960, filed November 10, 1958, now United States Patent No. 3,058,895, issued October 16, 1962.

In the present instance, the term "metalloid" is used somewhat specially in referring to those electrically conductive materials which act like metals when connected as an anode in an electrolytic cell. The term as used here and in the claims includes metals and such similarly acting materials as tungsten carbide for instance, and distinguishes from such conductive nonmetalloids as carbon.

With advances in the art of removing metal by electrolysis as described in my above-identified application, it has become possible to remove metal by electrolysis at very high rates, and there seems to be no limit to the volumetric removal rate except the capacity of the direct-current power supply and the availability of sufficient work area to carry high current. As a rough rule, it is possible to remove one cubic inch of metal per minute (in steel, nickel alloys, etc.) with a power supply of 10,000 amperes. With a power supply of ten times this capacity, the removal rate is increased tenfold. At the same time, it has been found possible in laboratory experiments to apply currents as high as 8,000 amperes per square inch and a current density of the order of 1,000 to 2,000 amperes per square inch now is commonly used commercially with apparatus and process carried out in accordance with the teaching of my above-identified application.

Accordingly, it becomes attractive to carry out this type of machining in a configuration like that of turning or lathe work because of the fact that, unlike a single-point cutting tool, the electrodes or cathodes of this invention can be so designed as to embrace a very large work area, so that a large part of the surface to be machined is being attacked substantially concurrently by electrolytic action. Thus, although at any one point a conventional cutting tool might remove material more rapidly than would an electrode or cathode of equal size, the single-point cutting tool can remove material only where it touches the work, and of necessity this must be a limited area. If the surfaces to be formed in ordinary cutting are to be contoured or stepped, this is accomplished by moving the position of the single-point cutting tool in one way or another so as to accomplish this result. While this can be done with cathodes or electrodes, the better method is to design elongated electrodes having the appropriate contours so that the total surface of the work is machined simultaneously to form the desired shape.

Among the objects of this invention, are the following:

One object is to provide apparatus for electrolytic turning.

Another object is to provide a novel method of electrolytic turning.

Another object is to provide apparatus for electrolytic turning which includes automatic controls for moving the cathode electrode toward a revolving workpiece that is connected as an anode.

Another object is to provide automatic controls for electrolytic turning in which the infeed or advance of the cathode electrode is controlled in response to mechanical drag of the mechanism which revolves the workpiece.

Another object is to provide a control system in which the advance of the electrode is controlled automatically by reference to the flow rate of electrolyte through the electrode.

Another object is to provide automatic control means for electrolytic turning in which a pneumatic sensing device is used to control the advance of the cathode electrode into the work.

Another object is to provide a fluid driven mechanism for feeding cathode electrodes toward the workpieces.

Another object is to provide cathode electrodes for electrolytic machining in which a portion of the electrode structure is made of insulating material adapted to prevent accidental short-circuiting between the electrode and the work.

Another object is to provide cathode electrodes which will remove metal evenly over work surfaces having different diameters.

Another object is to provide electrodes which can accurately reproduce contoured shapes of different diameters and of different slopes in the contours.

Other objects will appear in the course of the detailed description of the invention which follows:

In the drawings:

FIG. 1 is a somewhat schematic elevation of one form of apparatus of the invention in which the cathode electrode is advanced toward the end face of a revolving workpiece, with part of the electrolyte supply system being shown in phantom;

FIG. 2 is a schematic diagram showing one form of automatic electrode feed control for the apparatus of FIG. 1;

FIG. 3 is a schematic diagram showing another form of automatic control system for the apparatus of FIG. 1 utilizing a flow meter in the electrolyte supply line;

FIG. 4 is a schematic diagram showing another form of automatic control system for the apparatus of FIG. 1 utilizing a pneumatic sensing device to control the rate of infeed of the cathode electrode toward the end face of the revolving workpiece;

FIG. 5 is a partially schematic elevation showing another form of apparatus for the practice of this invention in which the cathode electrode is advanced toward the end face of the work by fluid power;

FIG. 6 is a schematic end view showing the application of the fluid driven apparatus of FIG. 5 to the work configuration in which the cathode electrode is advanced in a generally radial direction toward the periphery of a revolving workpiece;

FIG. 7 is a top view, again schematic, of the apparatus shown in FIG. 6;

FIG. 8 is an isometric view, schematic, showing the apparatus of FIG. 6 applied to a long workpiece with a consequently long cathode electrode and with a multiplicity of pneumatic drive units to advance the electrode toward the work;

FIG. 9 is a frontal view of the working face of a sector-type electrode of a kind used with the apparatus of FIG. 1 or FIG. 5;

FIG. 10 is a side view of the electrode of FIG. 9;

FIG. 11 is a fragmentary sectional view taken in the direction of the arrows substantially along the line **11—11** of FIG. 9;

FIG. 12 is a frontal view of another electrode generally like that of FIG. 9;

FIG. 13 shows an adaptation to operation upon a rotating workpiece of a composite multiple tube electrode; this figure is taken from my above-identified copending application;

FIG. 14 is a frontal view of the working face of an electrode generally like that of FIG. 9 but modified to provide multiple working segments and increase the electrode working area and, consequently, the ability to remove material at high rates;

FIG. 15 is an isometric view of an electrode of the general type shown in FIG. 9 in which, however, the working surface is contoured to produce a contour in the workpiece;

FIGS. 16 and 16A are, respectively, frontal views and side views of a straight electrode intended for peripheral turning;

FIGS. 17 and 17A are, respectively, a frontal view and a side view of an electrode for peripheral turning in which a sloped contour is to be imparted to the work;

FIGS. 18 and 18A are, respectively, a frontal view of the working surface and a side view of an electrode in which a step is to be formed in the peripheral surface of a workpiece; and

FIG. 19 is an elevation partly in section showing a retaining dam in position on the electrode of FIG. 15.

Referring to FIG. 1, the apparatus may take the general form of that shown in copending application entitled, "Electrolytic Cavity-Sinking Apparatus and Method," Serial No. 73,154, filed September 2, 1960 or copending application entitled, "Electrolytic Cavity-Sinking Apparatus," Serial No. 73,155, filed September 2, 1960, now United States Patent 3,130,140.

A general frame or base **1** is provided, which may be made of a weldment with suitable openings and doors to permit mounting a tank, pump, filter, valves, gauges, etc., which constitute the electrolyte supply system. The tank, pressure pump and filter are shown in phantom. The pump is adapted to supply electrolyte under a pressure of the order of 50 to 250 p.s.i. as indicated by a gauge visible to the operator. It should be understood that the electrolyte supply system should be under the control of valves, following the general arrangement shown in FIG. 5. For convenience, this detail is not shown in FIG. 1.

Mounted to the frame **1** on suitable cross slides **2** and under the control of an adjustment wheel or crank **3** is a drivehead generally designated as **4**.

The drivehead includes a ram element **5** arranged to be driven by a lead screw **7** by means of a sprocket and chain connection comprising sprockets **9** and chain **11**, which in turn is driven through a reducing gear **13** by an electric motor **15** of the variable-speed type and fed with electric current from a suitable control system through conductors collectively designated **16**.

It should be understood that ram **5** is suitably guided in tight-fitting bearings; for example, of the linear ball-bearing type. The extended end of ram **5** is protected by collapsible boot **17** and terminates at its end in a mounting plate **19**, to which is fastened an insulating block **21**, which in turn carries the electrode holder **23** which carries the electrode itself **25**. It will be understood that the electrode holder **23** comprises a manifold through which fluid electrolyte is forced against the workpiece in a predetermined configuration and at a predetermined pressure.

Electric power for the electrode **25** is supplied from a cable **27** in the circuit of which may be a shunt and ammeter collectively shown as **29**. The enclosure **37** has a raised section **37R** equipped with an insulated support **37S** for mounting an electrical connector **27C**. The portion **27P** of the cable **27** that is connected between the connector **27C** and the electrode holder **23** is of flexible braid and is arranged in a hook-shaped configuration to undergo free swinging movement in following the travel of the electrode. This introduces a minimum drag. Electrolyte is fed to the electrode **25** through a suitable pressure hose **31** connected to the electrode holder **23**.

The electrode **25** may be of the form shown in FIGS. 9, 10 and 11 or it may be like that of FIG. 13, or it may be like that of FIG. 14 or, again, like that of FIG. 15.

Much of the foregoing apparatus has been described in the earlier copending applications referred to above (except not the electrode itself), and, accordingly, no more detailed description is given. This much of the apparatus, including the frame, drivehead and electrolyte supply system, is now commercially sold as Model HCS-59 Horizontal Cavity Sinker. It should be understood that suitable electrical controls are provided to control the motion of the ram **5** to feed the electrode toward the work, to retract it rapidly, to adjust the speed of advance, etc. It should be understood also, that the electrical supply system consists of a direct-current supply unit of the general type shown in copending application entitled, "Control and Operating System for Electrolytic Hole Sinking," Serial No. 863,246, filed December 31, 1959, now abandoned in favor of continuation application, Serial No. 436,383, filed December 23, 1964, of which I am co-inventor. It is intended that the automatic shut-off system of that copending application be included here.

The basic machine includes a worktable **33** arranged for vertical adjustment under the control of hand wheel **35**. The elevating mechanism extends up through the floor of a pan mounted on top of frame **1** and having an opening at **36** to provide a drain back into the electrolyte supply tank. The machine includes an enclosure generally designated as **37**, which surrounds the work area and is provided with an openable closure along the operator's side to facilitate access to the work area.

Mounted on worktable **33** is a drive mechanism adapted to receive and rotate a workpiece W on the end of a work spindle **38**. The mechanism for revolving the work spindle is entirely shielded by an inner enclosure **39** and is provided with a seal of any suitable type at **40** to prevent accidental entry of splattered electrolyte into enclosure **39**, where it might cause damage to the running elements. The work spindle **38** is fitted with current brushes **41** connected to the frame and to a mounting plate **42** that is mounted on the worktable **33** to support the rotating drive mechanism. A supply cable **28** is connected between the mounting plate **42** and the positive side of the direct-current power unit. The work spindle **38** is journalled in a suitable bearing **43** that may be made so that the work runs accurately and so that thrust from pressure of the electrolyte is absorbed. The work spindle **38** is driven through a reducing gear **45** by an electric motor **47**, which may be of the variable-speed type although it is not essential that this be adjustable.

In practice, good work has been accomplished with a rotary speed of approximately 21 revolutions per minute, but it is desirable to operate at speeds above this, and I regard a rotary speed in the general range from 100 to 3000 r.p.m. as preferable.

The work W is positioned relative to the electrode **25** so that the electrode attacks the work in the position where it is desired to remove material. Where the electrode is of a sector shape, as in FIGS. 9, 10, 11 and 12, the location is arranged so that the electrode **25** is in proper position with respect to the center of the workpiece to make its sides align properly with radial lines extending through the center of rotation of the work.

In operation, the workpiece W is mounted by any suitable means (for example, a chucking clamp, which is not shown) and the electrode **25** is then advanced under manual control until it is in close proximity to the workpiece, a spacing distance of the order of .012" being suitable. Then, the electrolyte supply system is energized, and electrolyte is pumped through the entrance opening in the electrode toward the workpiece. The electric current supply is then turned on, using a potential ranging between about three to four volts at a minimum and 16 to 20 volts as a maximum, and, concurrently, the feed of the ram **5** toward the work is energized so that as the workpiece rotates the electrode is advanced slowly toward and into its end face. The rate of advance will depend upon the total effective working area of the electrode **25** relative to the total annular surface area on the end face of the revolving workpiece that is swept past the electrode and which may therefore be said to be embraced by the electrode. Thus, in the particular material which is being machine, if the workpiece W were not rotating, the electrode could be advanced at an infeed of, say, .200" per minute. Then, if the effective area of the electrode amounts to only, let us say, one-tenth of the annular area that the electrode embraces by virtue of the rotation of the workpiece, the infeed rate must be reduced to one-tenth of this speed; that is, to .020" per minute, but the rate of material removal remains the same.

When the electrode has advanced to the desired depth, the infeed is stopped. This may be done manually by reference to a dial indicator which is driven by a booted push rod **49**. The indicator itself is not shown, being of a conventional type. Or the infeed may be arrested by an automatic depth limit switch.

Depending somewhat upon the material and, also, upon the activity of the electrolyte and, also, upon the applied voltage, the surface of the work will be spaced from the working face of the electrode by a distance of the order of .002" up to as much as .010" or even .015". I prefer to maintain the infeed rate at a speed high enough with respect to the potential metal removal rate so as to hold the interspace between the electrode **25** and the revolving workpiece W to about .005" or less. While the system will operate with greater spacing, the accuracy is impaired. It has also been found that a larger spacing distance results in a considerable waste of current, so that the current efficiency may drop to below 50 percent, whereas with a closer spacing distance the efficiency may be of the order of 80 to 90 percent.

With this apparatus, it has been possible to produce very smooth surfaces having a finish better than ten microinches R.M.S. and within an accuracy of reproducibility within less than .001". The electrolyte used consisted of a solution made by first making a mixture of equal weights of sodium chloride and potassium chloride and, then adding this mixture to water, using two pounds of the mixture to each gallon of water.

Turning to FIGS. 2, 3 and 4, three methods of automatic control of the apparatus of FIG. 1 are shown in schematic diagrams.

In FIG. 2, it is contemplated that the electrode assembly include an element **25A** made of insulating material having a face projecting toward the work with the same contour as that of the electrode segment **25**. This insulating element **25A** may be made of a durable plastic such as Teflon and is mounted a slight distance away from the electrode **25**, so that there is free exit space for electrolyte. The insulating member **25A** extends toward the work a predetermined distance beyond the working face of the electrode **25**. This may be of the order of .002" to .005". The details of the arrangement of the electrode **25** and its projecting insulating element **25A** are shown in FIGS. 9 and 10 and are described more completely hereinafter.

It should be understood that as work proceeds the ram **5** is moved toward the right, as shown in the diagram in FIG. 2, and initially that this movement occurs at a rate faster than the maximum removal rate of the electrode will accommodate. Under this condition, the projecting insulating member **25A** of the electrode assembly will make contact with the workpiece W and, thus, introduce a slight frictional drag resulting in an increase in the load on motor **47**. This increase in load is sensed by an amplifier **48** which is fed through a transformer T.

The detail of the amplifier circuit is not important to the invention, but it is provided with two adjustments, one of which sets a threshold level below which the amplifier has no response. This adjustment is set when motor **47** is running without any frictional drag against the workpiece. The other adjustment is the usual adjustment for gain or sensitivity.

Thus, the amplifier **48** delivers no output signal until the current drawn by motor **47** rises above its no-load condition. When this occurs, however, the rate of response of the amplifier is very high and it feeds a signal to a power-control circuit **50** to reduce the speed of motor **15** which is powering the advance of the electrode **25** toward the work.

The power-control circuit **50** is also conventional and may consist of a rectifier circuit to provide direct current for the field of motor **15** and a thyratron circuit, also intended to provide direct current, which, however, is supplied to the armature of motor **15**. The thyratron supply is modulated by signals from the amplifier **48** and, in response to an increase in signal, the voltage supplied to the armature of motor **15** is reduced and the speed of the motor is consequently decreased, and, indeed, the circuit constants should be arranged so that if a strong signal from the amplifier is received motor **15** will not turn at all.

In the normal operating condition, however, inasmuch as the electrode **25** and the passage of electroylzing current is constantly removing material from the workpiece, a reduction in the speed of motor **15** will allow the amount of electrolytic removal of material from the work to increase sufficiently so as to relieve the drag on the workpiece by the insulating electrode member **25A**, and this, in turn, will cause a slight increase in the speed of motor **15** until an equilibrium is achieved. A limit switch **51** is provided and is arranged to be engaged by an abutment **5A** attached to a ram **5** so that when the electrode **25** is advanced to the desired depth this will automatically de-energize the power control. Simultaneously, a relay (not shown) in the power-control circuit **50** is actuated to de-energize the direct-current power supply unit for electrolyzing current, so that the instant the limit switch **51** is actuated there will be not only a discontinuation of further advance of the electrode but, also, a discontinuation of electrolyzing current so that there will be no further removal of material from the work.

While the system of FIG. 2 is simple, it has the disadvantage that there will be some necessary wear on the insulating element **25A**. A somewhat similar general arrangement, which however overcomes this deficiency, is shown in FIG. 3. Here, however, a flow meter **52** is introduced into the supply line **31** from the electrolyte pressure pump and is arranged to actuate a transducer **54** which, in turn, feeds a signal to the amplifier.

The general principle of operation is the same. When the electrode **25** approaches the work closely, it causes a reduction in the volume of flow of electrolyte through the electrode **25**, and this reduction in flow is sensed by the flow meter **52** which, in turn, actuates the transducer **54**. Many flow meters are available for this purpose.

In one simple form, an orifice is provided and pressure-responsive transducers are connected upstream and downstream of the orifice. So long as the pressures are far apart, representing maximum flow, a signal is fed to the amplifier, which however is balanced out. However, as the flow rate is reduced because of close proximity of the electrode to the work, the pressure drop across the orifice is reduced, and the two transducers come closer, one to the other, in their signal. This reduction of differential causes the signal which actuates the amplifier **48**, which, in turn, feeds the signal to the power control circuit **50**, to reduce the speed of infeed motor **15**. By adjusting the response of the flow meter **52** and of the amplifier **48**, the gap distance between the electrode and work may be held at a predetermined and desired distance.

The work should be rotated rapidly enough so as not to cause significant variations in flow rate and, thus, in control signals as a result of differences in the height of the workpiece with respect to the electrode at the beginning of the work. Thus, the workpiece may revolve at, say, 1000 to 3000 revolutions per minute, and integrating networks of condensers and resistors may be employed in the amplifier **48** so that the response rate is lower than 1000 to 3000 cycles per minute. If desired, the amplifier circuit may be arranged without the integrating circuit but in such a way as to respond to the highest signal level which it receives as represented by the lowest pressure differential across the orifice of the flow meter. This will occur when the closest part of the work is in front of the electrode. This circuit may be referred to as a peak signal-responsive amplifier, and, inasmuch as such circuits are known in the art and since no invention lies in the electrical circuitry involved, per se, no detailed description of the circuit is given here.

Referring to FIG. 4, the same general scheme is followed, but, here, a pneumatic control system is used in which a sensing tube **26** is employed. This is mounted so that it is in the path being "cut" by the electrode **25**. This sensing element **26** consists of a rigid tube of insulating material which is fed air from a pneumatic system. The pneumatic system consists of an air pressure regulator **53** that may be fed from the air line of a factory, a gauge **55** so that the air pressure may be known, a header or manifold **57**, a bleed valve **59**, and an air supply line **61** connected to a chambered holder **26H** for the sensing tube **26**.

Air is fed through the pressure regulator **53** into manifold **57** through an orifice element **63** in the supply tube **64** between the regulator **53** and the manifold **57**. By opening valve **59** slightly, a pressure is established within manifold **57** which remains constant until sensing tube **26** comes in close proximity to the work. The sensing tube **26** is made slightly, but only slightly, longer than the electrode **25**, and as it approaches the work the flow of air through it is reduced and, thus, the presure in the manifold **57** rises. This increase in pressure is transmitted to a diaphragm **65**, which acts upon a transducer **67** to feed a signal to an amplifier **48** to slow down the motor **15** through operation of the power control circuit **50**. The same refinements as those described in FIG. 3 may be added to the circuitry if desired.

Referring to FIG. 5, another type of apparatus is shown. Here, a work spindle **39** is suitably journaled in bearings **43**, appropriately mounted to a frame **1**. Power brushes **41** are shown schematically for connection to the positive terminal of the direct-current power supply. A control brush **41A** is also provided to permit sensing the voltage actually present in the work spindle **39** after giving account to voltage drops on account of resistance in the cable **28** leading to the brushes **41** and, of course, the losses between the brushes **41** and the work spindle itself. A motor **47** is arranged to drive the work spindle through speed-reducing means, here shown as an arrangement of a belt **47B** and pulleys **47P** and **39P**.

The work spindle **39**, bearings **43** and motor drive, along with the power-supply brushes **41**, are arranged externally of an enclosure **37** provided with a suitable shaft seal **37A**. A chuck **68** to hold a disc-like work material is provided and has a clamp plate **69** which holds the work firmly within the chuck. The electrode **25** is mounted on an insulated block **21** and is supplied by conduit **31** with electrolyte and by a flexible cable **27P** with negative current from the power supply. The cable **27P** is of hook-shaped configuration and is mounted in suspended relation from a connector **27C** carried on an insulated support **37S** secured within a raised section **37R** of the enclosure.

The electrolyte system consists of a tank **259**, a pressure pump **261** capable of delivering up to 250 or 300 pounds per square inch, a filter **262**, a by-pass valve **263**, a guage **265** in the by-pass line and another valve **267** and gauge **270** to feed electrolyte to the electrode **25**.

Facilities are also provided for connecting the electrolyte supply system to the movable electrode in a manner that eliminates all drag effects. These facilities include a casing **71** stationarily mounted within the enclosure **37** and provided with a flow chamber **71C** bordered at its opposite ends by aligned guideways **71G**. A length of pipe or tubing **72** is carried in a support **73** that is secured to the insulating block **21**. The tubing **72** projects through the guideways **71G** and flow chamber **71C** provided in the casing **71** and preferably is rigidly suspended from its support **73** to maintain accurate alignment with the guideways and there is clearance with respect to the casing **71** to avoid actual sliding contact. The guideways are provided with labyrinth sealing grooves to provide the required sealing action without actual contact. The front end of the tubing opens into a connector block **74** mounted on the support **73** and fitted with the pressure hose **31** that communicates with an electrolyte flow passage in the electrode **25**. The portion of the tubing within the chamber is provided with a series of holes **72H** and electrolyte is supplied from the pump **261** through the filter **262**, valve **267** and supply conduit **268** to flow into the chamber **71C**, then into the tubing through the holes **72H**, and then through the tubing to the connector block **74**. The free end of the tubing is closed and projects from the casing **71**. A protective housing **75** is provided on the casing to shield the free end of the tubing and a vent line **76** is shown extending from the housing.

The electrode **25** is advanced by a fluid drive system following the general teaching of my copending application entitled "Electrolytic Shaping," Serial No. 772,960, filed November 10, 1958, now Patent No. 3,058,895, and particularly FIGS. 15 and 15A thereof. These drawings in my copending application, together with the full description of the apparatus explain in detail what is explained here in more elementary fashion.

This feeding apparatus for the electrode **25** uses air or hydraulic oil pressure to move the electrode toward the work and may be arranged to achieve an equilibrium spacing distance because of the counterforce of hydrostatic pressure between the electrolyte in the interface between the electrode and the work. For good results, it is important that the mechanism be made to have minimum frictional losses.

The fluid drive feeding apparatus is designated generally at **170** in FIG. 5. Two movable ram elements **181** extend through a bored block **179** and are supported at each end by recirculating type linear ball ways **183** which are mounted in the block. This permits the ram elements **181** to slide with great smoothness toward and away from the work holding chuck **68**. The block **179** is made in two halves which are doweled together as at **179D** and held by stay bolts **179B** of which only one is shown. The two halves of the block are doweled together and bolted and then bored, and then are separated to permit assembly.

Midway of the composite block **179** there are enlarged cylinder cavity portions **171** which constitute cylinders, and the ram elements **181** are fitted with enlarged elements **185** which constitute pistons. It should be understood that the ram elements **181** do not touch block **179** at any point and that they are supported solely by the linear ball ways **183** so as to be free of all frictional engagement. The same is true of piston elements **185** which run in close proximity to the bores of cavities **171** but do not touch the walls. The piston elements **185** may be grooved with labyrinth rings to prevent excessive blow-by of air.

Duct connections **189** and **189A** are arranged to feed the opposite ends of cylinders **171** so that fluid pressure may be admitted under control of a two-way valve **175**, either to advance the electrode toward the work or to retract it. A pressure regulator **177** is included in the fluid line **189A** which feeds the piston in a sense to move the electrode **25** toward the work. The pressure may thus be adjusted with respect to the pressure supplied to the electrode, so that the electrode will be advanced toward the work but will not touch it. This condition of dynamic equilibrium is achieved since the fluid pressure urging the electrode forward is held below the level sufficient to overcome the hydrostatic force of the electrolyte under pressure between the electrode and the work. Vents 191 are provided in such a way as to avoid having blow-by of fluid fill up the protective bellows **17**. The vents are connected by tubes, not shown, which lead outside the enclosure **37** so that electrolyte does not at any time enter the electrode feeding mechanism. An electric vibrator **178** may be added to help overcome any sticking friction which would prevent a smooth feed.

This same type of feed device may be used to feed an electrode toward a cylindrical workpiece in a generally radial direction so as to accomplish material removal on the periphery of the workpiece. This is shown in FIG. 6 wherein the pneumatic feeding apparatus is designated generally at **170**. FIG. 6 also shows a second electrode **25'** on the right-hand side of the piece which is advanced from right to left by the same type of feed mechanism, also designated generally at **170**. If desired, other electrodes may be mounted top and bottom so as to increase the effective area of electrode confronting the workpiece. Because of the curvature of the workpiece, it is not desirable, particularly with workpieces of small diameter, to employ electrodes that span a large arc because, while the electrode may be contoured to the finished diameters of the workpiece, it will not then have a curvature corresponding with the starting diameters and, if the electrodes embrace any substantial amount of arc, this will cause difficulty.

FIG. 7 is a fragmentary top view of the apparatus of FIG. 6, and shows a more-or-less conventional lathe-like arrangement having tail and head stock assemblies, **47T** and **47H**, respectively, with a motor **47** arranged to rotate the work W, which is held at one end by a chuck **47C** carried by the tail stock and supported at its opposite end by a chuck **47L** carried on the live center of the head stock assembly.

FIG. 8 is an isometric view of the same kind of feed mechanism 170 shown schematically in which the workpiece W is quite long so that the electrode **25** is extended in length. In this case, the electrode is mounted on an elongated support bar **79**, which is hinged at the top of upstanding support elements **81**, pivoted on the projecting ends of a horizontal pin **83** in a base **1**. A plurality of drive mechanisms **170** may be located in spaced apart relation along the bar **79** and may be connected by hinging links **84** to urge the bar **79** toward the workpiece. By providing a proper curvature on the working surface of electrode **25** with respect to the length of the support arms **81**, the effective area of the electrode **25** with respect to the work W may be held nearly constant as the electrode moves towards the center of the workpiece. The curvature on the face of the electrode may correspond to the curvature of the finished diameters desired in the work, but with this arrangement, the electrode curvature will not correspond with the original curvature of the workpiece.

To offset this change in curvature of the workpiece, the electrode is rocked about the pin **83**. At the start of the cut, the curvature on the front of the electrode does not correspond exactly with the curvature of the workpiece, but the angular position of the electrode **25** is optimum to maximize the effective area. As the electrode advances and reduces the size of the workpiece, the curvature on the electrode comes to correspond more and more closely with the curvature of the work. This would tend to increase the effective working area, but this is offset by the fact that the electrode is being rocked about pin **83**, and this angular displacement of the electrode tends to reduce its effective area at the same time that the closer conformity in curvature is tending to increase it. Thus, the effective area of the electrode remains nearly constant.

This arrangement is not a necessary one, as the entire electrode bar **79** may, if desired, be supported solely by the plurality of pneumatic drive elements without any rocking motion at all, as is shown in FIG. 7 with a single pneumatic actuator.

In any of these arrangements where a fluid drive is used, the work must be rotated at a high enough rotational speed so that the electrode drive does not follow the initial deviations of the part. This required rotational speed is a function of the mass-and-time response of the entire electrode drive and assembly and of the electrode area and disposition. For facing work, the electrode segments may be distributed evenly so that in starting the work the higher hydrostatic force in the zone of nearest proximity of the work to the electrode is offset by the lower forces elsewhere. In general, a rotational speed of 1000 to 3000 r.p.m. produces force pulses too high in frequency to be followed by the drive mechanism. Where the work is too large to be rotated at such speeds and where the problem of the electrode following the ups and downs of the work is severe, then the positive-drive system, such as, for example, a gear driven system, is preferred.

While the fluid drive mechanism has been described as being of the pressure-regulated type, it is also possible to use a hydraulic positive drive with careful regulation of the flow rate. In this case, the pistons **185** will be somewhat larger and will employ seals to prevent any leakage. Similarly, the end seals will be of the positive cup-leather or stuffing-box type instead of the labyrinth type. In this arrangement, the available hydraulic pressure is far above the minimum necessary to overcome the back force of the electrolyte on the electrode and the friction of the seals, so that the rate of advance is affected solely by the regulated volume of oil admitted to the pressure cylinders.

Turning to FIGS. 9 10, and 11, there is shown an electrode adapted for removing metal about the axis of rotation of the workpiece. Thus, the electrode **25** used in FIG. 1 and FIG. 5, may be made of copper and, as will be noted, is of the shape of a sector. A feed slot **25G** is provided through the center of the electrode sector **25** to divide the same into two sector shaped regions and the feed slot **25G** communicates with a chamber **25H** provided in a base plate **25J** which is fed with a hose connection **25I**. Electrolyte emerging from the feed slot divides and half flows across each region of the electrode. The base plate **25J** is adapted to be bolted to the insulating face plate **23** connected to ram **5**. It will be noted that the feed slot **25G** is also preferably in the shape of a sector.

Feed slots in electrodes of this kind are filled at the ends, as shown particularly clearly in FIG. 11, with a piece **25P** of plastic insulating material, so that there is no excessive metal removal over and beyond that brought about by the carefully calculated working surfaces on both sides of the feed slot. The plastic filler elements **25P** at the ends of the feed slots are tapered to a feather edge as they approach the work so that electrolyte will be fed uniformly across the working surfaces.

The electrode arrangement of FIGS. 9 and 10 is illustrated as including the insulating element **25A** of the same contour as the electrode and mounted to project slightly therebeyond to act as a spacer. The insulating element is mounted to provide a sector shaped space **25B** alongside the electrode **25** to act as an exit slot for electrolyte. To assure a free exit without building up pressure against the insulating element **25A**, holes **25C** may be provided in the element **25A**.

Screws **25D** pass through adjustment slots **25E** in the insulating element **25A** and anchor in the body of the electrode to accommodate adjustment of the projection of the element **25A** beyond the electrode face. This facilitates compensation for wear caused by rubbing of the element **25A** against the workpiece.

The electrode arrangement of FIGS. 9, 10 and 11 is mounted so that the area of the working surface of each region of the copper electrode segment **25** becomes linearly greater as the surface is farther away from the center of rotation of the work. This increase in area corresponds with the linear increase in surface speed of the work with increasing diameter. The greater area of electrode allows the passage of more current and, consequently, a faster rate of removal over the larger surface areas that are encountered at regions farther from the center of rotation, and, thus, brings about a uniform rate of removal. If the area of the electrode does not increase with greater diameter but if instead it remains constant, then a greater removal would occur near the slower moving and hence smaller surface areas encountered adjacent the center of the workpiece, and considerable inaccuracy would result.

While it is preferred that the feed slot also be in the shape of a segment an electrode configuration such as is diagrammed in FIG. 12 has been successfully employed in the practice of this invention. In FIG. 12 the electrode itself **25″** is substantially in the shape of a segment while the feed slot **25″G** is substantially rectangular.

However, if the shape of the electrode **25** and the feed slot were rectilinear, the depth of removal on a rotating workpiece would be greater near the center, and, even through the electrode itself might be flat, the bottom of the machined surface would not be flat.

It is not possible, however, to carry this principle too far, for merely widening the working surface of the electrode in the direction of flow of electrolyte does not assure a constantly increasing amount of removal. If the path which the electrolyte must take between the workpiece and the electrode becomes too long, then there are effects, on the one hand, of contamination of the electrolyte with metal salts and of depletion of ions through intensive electrolysis that tend to decrease the rate of removal, and there are effects, on the other hand, of heating of the electrolyte within the work gap that tend to increase the rate of removal. These accelerating effects from heating turn quite suddenly in the other direction as soon as the heating causes vaporization at the boiling point. I prefer, therefore, that at the widest point the width of the electrode segment should not exceed about ½″, and, if it becomes necessary to work between widely different diameters on a very large-diameter part, then a muliplicity of individual elements should be used in the electrode in order to preserve the principle that the effective area of the electrode be increased linearly for increased distances between the point of application and the center of rotation without at any time having any portion of the electrode so wide as to require the electrolyte to proceed more than about ½″ from the point where it enters through the feed slot to the point of exit.

Of course it is possible to use longer electrolyte paths than ½″ and in some cases simplicity of design may call for doing this. This may require, however, that the contour on the electrode face be slightly different from the contour desired in the workpiece in order to allow for the non-uniform removal effect when the path of the electrolyte becomes too long. In experimental work, I have found it possible to extend the path of the electrolyte to at least 3″ without undue change in the removal rate at the area near the point of introduction of electrolyte and the point of exit, but this requires maintenance of a larger gap between the electrode and the workpiece of at least .005″ and usually more, and the result of the larger work gap is a loss of efficiency and perhaps of accuracy.

FIG. 13 shows a composite electrode **225** used for forming grooves **228** in the surface of a rotating workpiece. The electrode is comprised of a plurality of tubes precut to different lengths appropriate to define a desired surface contour. In FIG. 13, the work, a ring W, is held by chuck jaws **230** and rotated upon a spindle **232**. The electrode is supported by the electrolyte supply pipe **237** in a tool rest and advanced into the work as the work rotates. Electrolyte at a pressure of 25 to 300 pounds per square inch is pumped through the electrode. It thus cuts a smooth slot in the workpiece periphery.

Turning to FIG. 14, it may be desired to increase the effective working area of an electrode, and this may be done to good advantage by introducing a plurality of segments **25**, to embrace a larger part of the arc than could be embraced by a single element. Once again each segment has a central sector shaped feed slot **25G** dividing the same into two substantially equal sector shaped regions and adjacent segments are separated by a sector shaped exit slot **25B** which receives half its flow from the segment on its left and half from the segment on the right. A single insulated spacer **25A** may be provided for the multiple segment electrode of FIG. 14 and it is preferably at one end to minimize the obstruction of return flow. While I have shown a plurality of electrode elements embracing about 90 degrees of arc, there is no reason why this cannot be extended so that there are enough elements to embrace a larger part of the arc or, indeed, all of it. In any case, it is preferable to distribute the segments evenly around the full circle of the arc.

In FIG. 15, a sectorial type of electrode **125** is shown in which the face is contoured to impart a contour to the work. A central feed slot **125G** and an insulating spacer element **125A** and plastic filler wedge **125P** are again provided corresponding to the general arrangement of the electrode of FIGS. 9, 10 and 11. The electrode **125** is provided with a mounting base **125** having an entrance opening **125I** for electrolyte.

Here, an additional modification has been discovered as a means of improving the accuracy or conformation between the workpiece and the electrode. The work surface is widened as the diameter of the work increases following the principle described above. However, wherever the contour of the electrode departs from a plane parallel to that of the work surface; that is to say, transverse to the line of advance of the electrode; the effective width of the electrode is narrowed so that its projected area is what it ought to be in accordance with the diametric linear increase. Thus, at **126D** in FIG. 15 and, also, at **126B**, where the contour is parallel to the work surface the width of the working area is precisely in the proportion of the radial distance from the center of rotation of the workpiece. However, where there is a slope to the contour, as at **126A** or again at **126C**, the width of the effective surface is narrowed in accordance with the trigonometric tangential function.

This may be understood by supposing that the slope at **126A** was 45°. Here, as the electrode advances a given increment of distance into the work, the sloped portion of the electrode at **126A** may be taken as the hypotenuse of a 45° triangle and, accordingly, the area is approximately 1.4 times the area which would be available if the surface were normal to the line of advance. To offset this, the width at this point should be reduced by multiplying its width computed for diametric adjustment by the factor of approximately 0.7. Similar adjustments must be made for every other slope, and where, as indicated here, the contour is curved, the adjustments in width will follow a curve established by taking a closely spaced series of points and determining the slope at each point. Thus, wherever the slope is steep and more nearly in line with the linear advance of the electrode, the working surface will be narrowed, and, wherever the contour approaches parallelism with the work surface, the adjustment for contour will approach zero.

The same technique of electrode design is illustrated in FIGS. 16, 16A, 17, 17A, 18 and 18A.

In FIG. 16 there is shown a frontal view of the working surface of an electrode **130** intended for straight machining on the periphery of a cylindrical workpiece such as is carried out in the apparatus of FIGS. 6 to 8. Feed passages **130P** are shown opening into a central feed slot **130G** (see FIG. 16A).

In FIGS. 17 and 17A, an electrode **131** is shown which is intended to be advanced from the exterior periphery of a cylindrical workpiece toward its center. As seen in FIG. 17A, the electrode is arranged to impart a simple contour to the workpiece so that it is to cut deeper and approach near the center of the workpiece at its right-hand end **131R** than at its left-hand end **131L**. As seen in FIG. 17, the right-hand end **131R** has its working surface reduced in width as compared with the left-hand end **131L**, the amount of reduction being related to be proportionate difference in the diameters of the workpiece at the deepest part and the shallowest part of the cut. As shown here, it is assumed that the diameter at the deepest part of the cut is only about one-half that at the largest diameter. Accordingly, the working surface at the right-hand end is reduced to about one-half that at the left-hand end. The electrode **131** is also shown with a central feed slot **131G** supplied through passages **131P**. In the central area **131C**, there is shown a slope that may be assumed to be a 45° slope, then at the left-hand end the effective working area is approximately .7 times that of the flat surface to the left, and similarly at the right-hand side. The working surface of the sloped portion tapers on account of the change in diameter between the opposite extremities of the sloped portion.

Thus, it is a principle of my invention to proportion the working area in two ways: First, to increase the working area proportionately to the diameter of the workpiece which is engaged by the electrode at the finish of the work, and, second, to proportion the width of the working area, reducing the working area as a trigonometric function of the slope of the electrode in its contour.

With contoured electrodes of the kind shown, for example, in FIG. 15, difficulty may be encountered when the electrode is first advanced toward the work as there is a natural tendency for all of the electrolyte which is being pumped through the electrode to escape through that part of the electrode which is remote from the work surface. When and as this happens, there is an inadequate supply of electrolyte flowing between the working face of the electrode and the work at the very part of the electrode which is nearest the work and where it is most important that electrolytic action occur. To overcome this, a dam of insulating material is arranged to surround the electrode and to have a face which engages the work lightly, the face of the electrode being contoured to accord with the face of the work as it is first approached.

This arrangement is shown in FIG. 19. The contoured electrode **125** of FIG. 15 is shown for the most part in dotted outline and it has a mounting base **125J** equipped with an electrolyte inlet **125I**. Surrounding the electrode **125** is a dam of insulating plastic material; for example, an epoxy resin. In this case the dam is shown as having a flat face F to engage the work, on the assumption that the surface of the work part is substantially flat before initiation of the operation of contouring it. The plastic dam is identified generally as **D125**. The dam completely surrounds the electrode proper, and element **125A**, as shown in FIG. 15, should be regarded as being spaced sufficiently away from the electrode proper so as not to interfere with the placement of the plastic dam **D125**. The dam has an opening passing all the way through it which accords with the generally segmental shape of the electrode **125**. However, this opening is larger than the electrode by about .015" to .025". This clearance is provided for two purposes, the first being to permit some exit of electrolyte from the work area and the second to assure that there is no accidental binding between the dam and the electrode. The dam is guided by a number of guide pins **P125** on which the dam is free to move toward or away from the work. Around the pins **P125**, there are springs **S125** which urge the dam toward the work.

In the starting position, the dam extends slightly beyond the electrode proper, and, as the electrode is advanced toward the work, the dam first engages it, and, as the electrode assembly is advanced, the dam slides back on the guide pins **P125**. By this arrangement, the free exit of electrolyte from the electrode surface area generally designated as **126D** is prevented, and instead some amount of electrolyte is forced to exit at the deepest protrusion of the electrode, thus assuring a flood of electrolyte at this point. As the electrode enters the work, forming the contour, the electrode itself running in close proximity to the work prevents free escape of electrolyte at such a point, and the plastic dam continues to serve as a restriction to unintended free exit in the unengaged portion of the electrode until the entirety of the electrode surface has entered the work.

The dam and contoured electrode assembly of FIG. 19 is useful both in the machining of rotating workpieces and in cavity sinking in stationary workpieces.

In FIGS. 18 and 18A, there is shown an electrode **132** intended to produce a square step or groove. Here, the projecting portion **132K** has a working surface of the shape shown in FIG. 18 which is reduced because it extends to a smaller diameter in the workpiece. As shown in FIG. 18A, the projection **132K** has sidewardly extending lips **132L** and the sides of the electrode are covered with insulation **132I** in order to prevent sideward erosion.

While I have described this invention in illustrative terms and have indicated the best modes of carrying the invention into practice, it will be understood that many departures in detail are permitted without departing from the spirit and intention. It is, therefore, desired by the following claims to include within the scope of the invention all such variations and modifications by which substantially the results of this invention may be obtained through the use of substantially the same or equivalent means.

What I claim as new and desire to secure by Letters Patent is:

1. In a device for removing material from an electrically conductive and electro-chemically erodible workpiece by electrolytic action, the combination of an electrode having a conductive working face, said workpiece being mounted and rotated about its longitudinal axis, means for moving said electrode face toward the workpiece at a predetermined rate, control means operable in conjunction with said means for moving said electrode for establishing and maintaining a predetermined gap between said face and the workpiece as said face is advanced toward the same, said working face defining a sector generated about an axis coincident with the axis of rotation of said workpiece, said sector having an arcuate width at any given radial distance which is inversely proportional to the angular velocity of a point on said workpiece at the same radial distance, so that the time required for any point on the workpiece to traverse the width of said sector will be the same, a source of electrical power connected between said electrode and the workpiece so as to establish the former as a cathode, and the latter an anode, and means for pumping fluid electrolyte to and through said gap so as to provide a high density current carrying path between said face and a portion of the rotating workpiece immediately adjacent thereto, whereby material is removed from said workpiece in accordance with the contour of said face, the rotation of said workpiece, and to a depth corresponding to the travel of said electrode toward said workpiece once said gap has been established.

2. A device as set forth in claim **1** wherein a portion of said working face slopes relative to the axis of generation thereof and said slope portion has an arcuate width such that the area of said portion projected on said workpiece is equal to the projected area of all other portions of said sector relative to the speed of rotation of said workpiece.

3. In an electrolytic apparatus for removing material from a workpiece of electrically conductive material, an electrode having a conductive working face, a spacer providing a contact face having a surface contour like that of said working face, means for rotating the workpiece relative to said electrode and said spacer for sweeping a circular surface path thereof past the working face of said electrode and past the contact face of said spacer, means for moving said spacer and said electrode jointly toward said workpiece to bring said spacer into contact with a workpiece region within said surface path and to bring said working face adjacent another workpiece region within said surface path to establish a gap therebetween, circuit means for impressing an electric potential between the electrode and the workpiece in a sense to make the electrode a cathode, means for supplying electrolyte through said gap to provide a high density current carrying path and remove a circular portion of the workpiece to a depth corresponding to the relative travel of the electrode toward the workpiece and to provide a finish surface contour corresponding substantially to the surface contour of the working face, a motor for rotating said workpiece, having an electric power supply circuit, and means responsive to power variations in said supply circuit for controlling said moving means and therefore regulating the advance of said spacer toward said workpiece in accordance with the drag effect resulting from contact between said spacer and said workpiece.

4. Apparatus as set forth in claim **3** wherein said means is provided mounting said spacer in fixed relation to and alongside said electrode to lie within the sweep of said circular path, said spacer having a surface contour like the working face of said electrode and projecting slightly therebeyond to contact the end face of the workpiece.

5. The apparatus as set forth in claim **3** wherein the face of said electrode defines a flow passage opening therein, and means for supplying electrolyte to said opening including a length of tubing jointly movable with said electrode and extending parallel to the direction of the electrode movement, a casing having a chamber bordered by aligned guideways at its opposite ends, with said tubing projecting through said guideways in freely slidable sealing relation, and having an opening at a portion thereof located within said chamber, means for supplying electrolyte through said casing and into said chamber for passage through said openings and along said tubing.

6. Apparatus as set forth in claim **3** including means mounting a dam having an insulated contact face with a surface contour like that of said workpiece in relatively movable loose surrounding relation about said electrode, and including yieldable means biasing said dam toward said workpiece, the face of said dam adapted to contact the face of said workpiece when said electrode and spacer are moved into contact therewith, said dam adapted to restrict electrolyte flow to thereby produce flooding throughout the gap between said workpiece and electrolyte during initial travel of said electrode through said dam and into said workpiece.

7. In an electrolytic apparatus for removing material from a cylindrical face of a workpiece, an electrode having a curved conductive working face adjacent and facing the cylindrical face of the workpiece, means for rotating the workpiece about its longitudinal axis for sweeping a path past the working face of said electrode, said working face having a radius of curvature in a range between that of the workpiece prior to and after removal of material is completed, means for moving said electrode toward said workpiece so as to bring an optimum amount of working face area within a predetermined distance from an arcuate portion of said surface path, control means for regulating the rate of advance of said electrode by the last named moving means to establish and maintain a predetermined gap between said working face and the surface portion of said workpiece that is facing said working face, means for progressively swinging said electrode about an axis parallel to said axis of rotation of said workpiece to compensate the gap configuration for the changing workpiece curvature during removal of material therefrom, circuit means for impressing an electric potential between the electrode and the workpiece in a sense to make the electrode a cathode, and means for supplying electrolyte through said gap to provide a high density current carrying path and remove a circular portion from the cylindrical face of the workpiece to a depth corresponding to the relative travel of said electrode toward said workpiece and to provide a finished surface contour corresponding substantially to the surface contour of said working face.

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