June 7, 1960 C. L. FAUST ET AL 2,939,825

SHARPENING, SHAPING AND FINISHING OF ELECTRICALLY CONDUCTIVE MATERIALS

Filed April 9, 1956

5 Sheets-Sheet 1

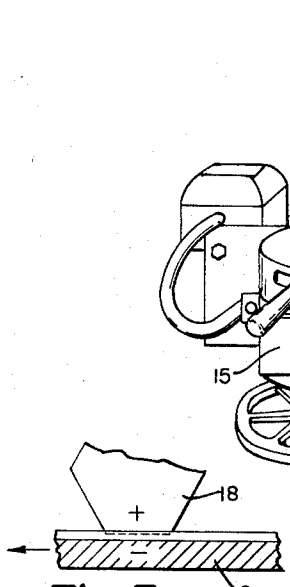


Fig. 3

Fig. 1

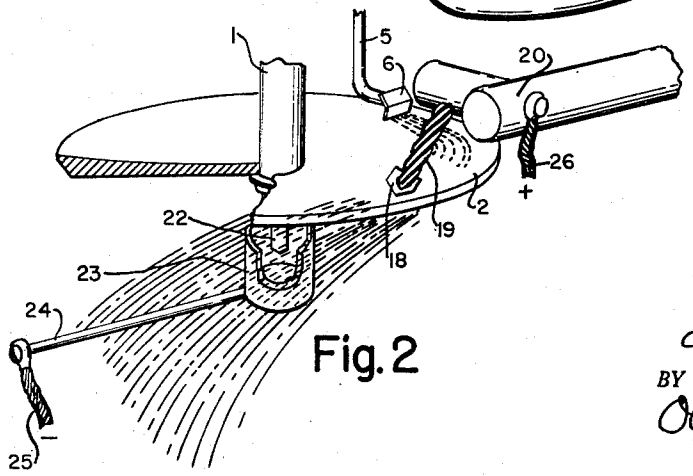


Fig. 2

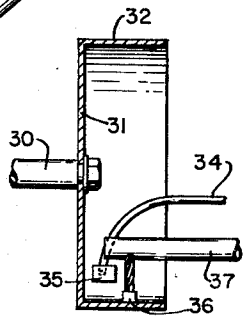
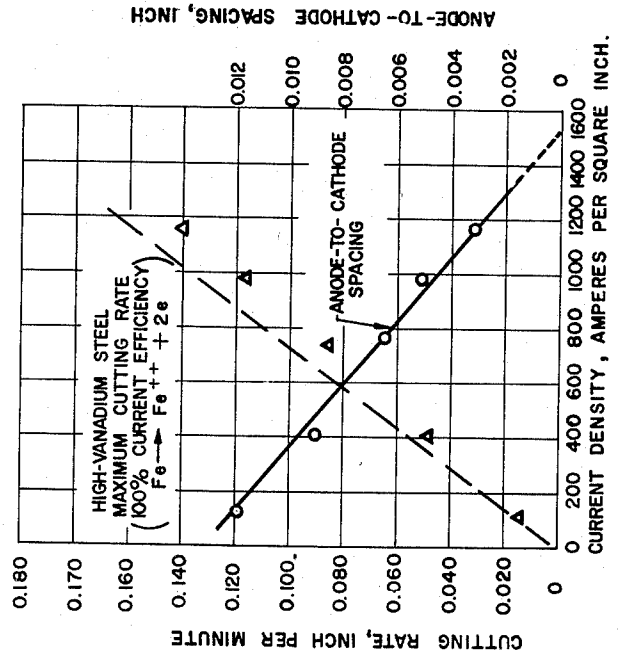


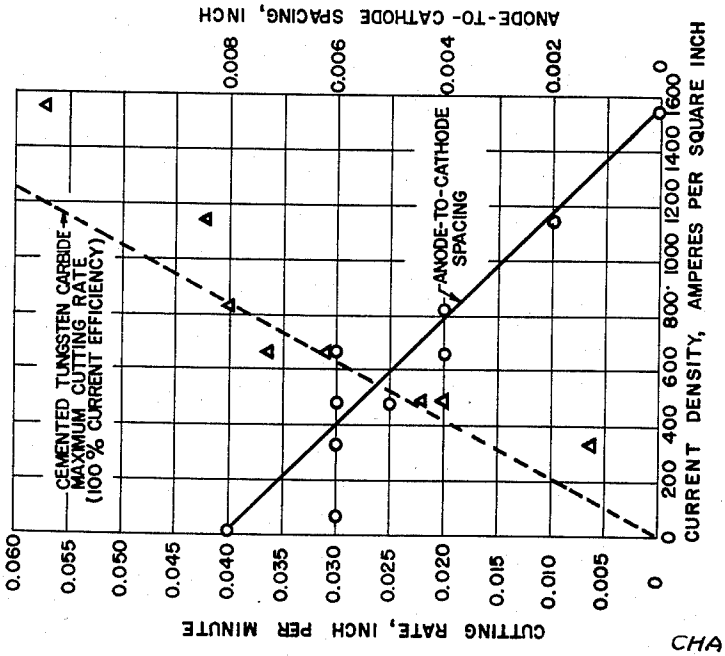
Fig. 4

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EFFECT OF ANODE-TO-CATHODE SPACING ON CURRENT DENSITY AND CUTTING RATE FOR ELECTROLYTIC GRINDING OF HIGH-VANADIUM STEEL WITH A NEUTRAL ELECTROLYTE (pH 7) AT 25 VOLTS
ANODE AREA - 0.1725 SQ. IN.
Na Cl - 200 GRAMS PER LITER
$H_3 BO_3$ - 25 GRAMS PER LITER

Fig. 6



EFFECT OF ANODE-TO-CATHODE SPACING ON CURRENT DENSITY AND CUTTING RATE FOR ELECTROLYTIC GRINDING OF CEMENTED TUNGSTEN CARBIDE WITH AN ALKALINE TARTRATE ELECTROLYTE AT 25 VOLTS
ANODE AREA - 0.062 SQ. INCH
$Na_2 C_4 H_4 O_6$ - 150 GRAMS PER LITER
Na OH - 150 GRAMS PER LITER
Na Cl - 20 GRAMS PER LITER

Fig. 5

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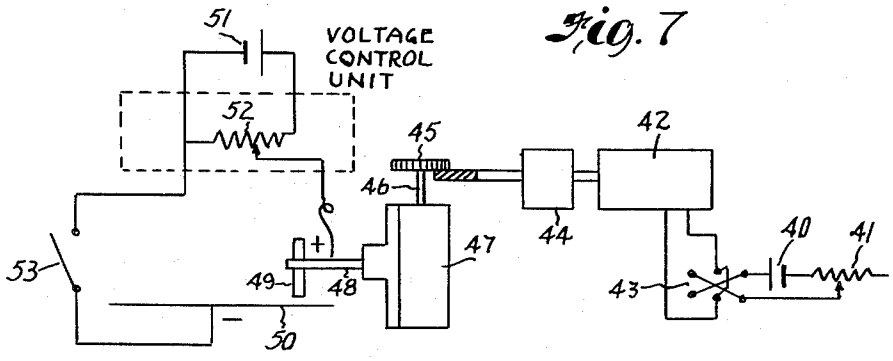


Fig. 7

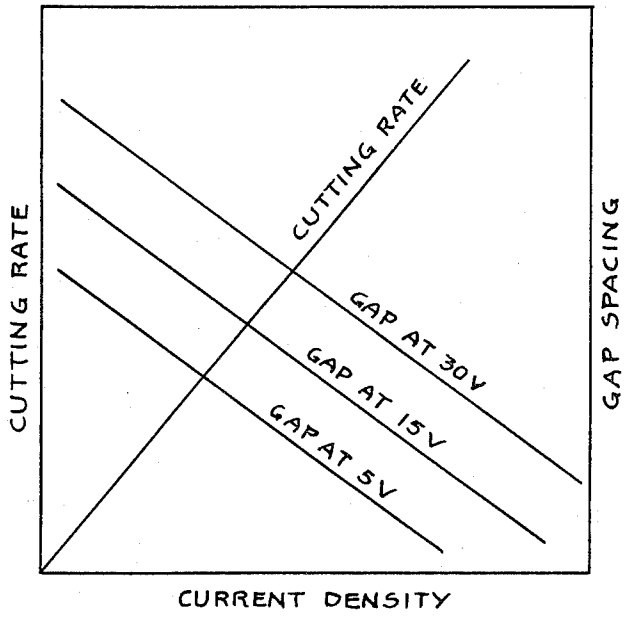


Fig. 8

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SHARPENING, SHAPING AND FINISHING OF ELECTRICALLY CONDUCTIVE MATERIALS

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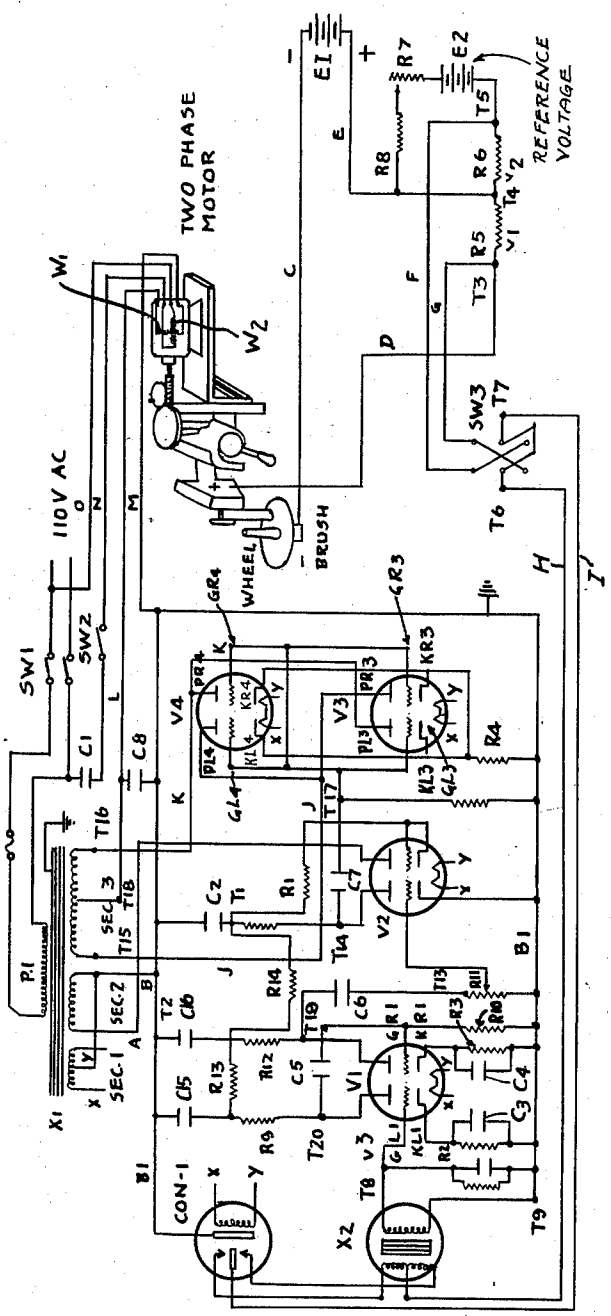


Fig. 9

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SHARPENING, SHAPING AND FINISHING OF ELECTRICALLY CONDUCTIVE MATERIALS

Filed April 9, 1956 5 Sheets-Sheet 5

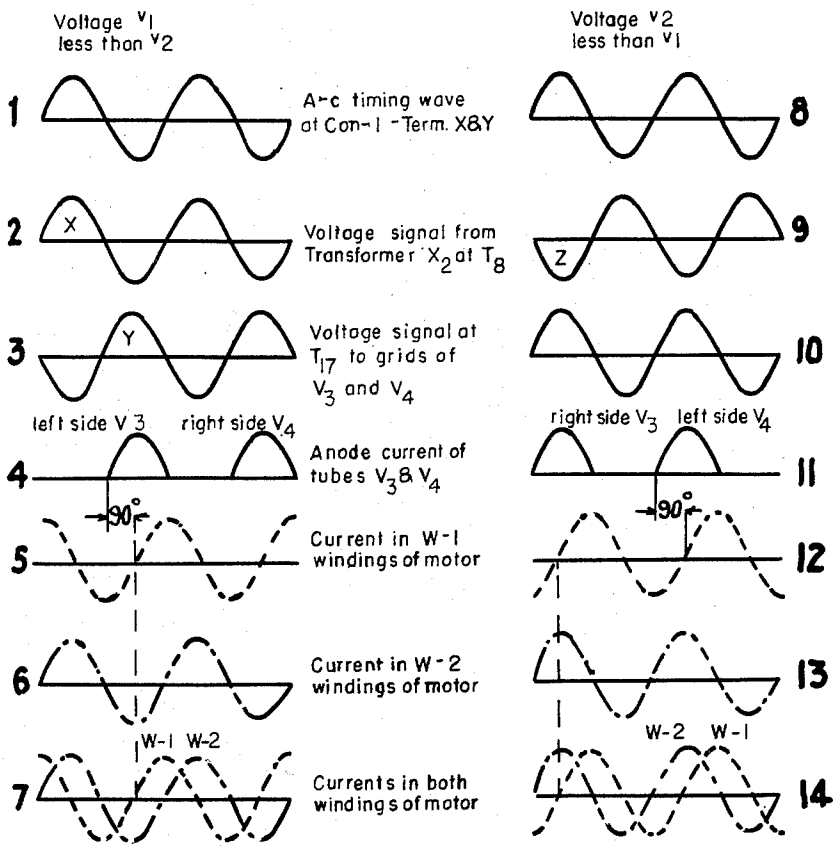


Fig. 10

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United States Patent Office 2,939,825 Patented June 7, 1960

2,939,825

SHARPENING, SHAPING AND FINISHING OF ELECTRICALLY CONDUCTIVE MATERIALS

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Filed Apr. 9, 1956, Ser. No. 577,015

12 Claims. (Cl. 204—142)

This invention relates as indicated to methods of and apparatus for sharpening, shaping and finishing materials having electrical conductivity. In particular, the invention relates to sharpening, shaping and finishing such materials by electrolytic dissolution of them as anodes without physical and mechanical contact with another solid and without either electric spark or electric arc discharge.

In the art of shaping, sharpening and finishing, several non-mechanical (meaning free from pressure cutting, smearing, and tearing as caused by tools and abrasive wheels or belts) methods have been developed and are in limited commercial use. They are: the electric discharge processes that erode away a metal surface by arc or spark discharge from the metal to another electrode in a di-electric medium; electrolytic process in which the metal item to be ground is made anodic in contact with diamonds or other non-metallic abrasive on a metal cathode or in contact with a metal as cathode; and sonic or ultrasonic processes that cut by high frequency vibration of a metal with abrasive powder between it and the material to be cut.

All the above-mentioned non-mechanical processes have advantages and limitations. The electric discharge, sonic and ultrasonic methods are especially adapted to drilling small holes or forming small cavities in materials hard to pierce, drill or form by conventional methods of piercing with twist drills or for forming cavities with routers, reamers, etc. These methods have been explored for shaping and finishing, and are meeting with some industrial successes, but their limitations prevent them from fully meeting the extensive needs cor grinding and shaping hard-to-grind materials that now can be cut or ground only by diamond wheels or cannot be cut without damage with abrasive wheels of any type now known.

Certain of the electric discharge processes, for example, operate at 25 volts or higher, cut at practical speeds that cause rough surfaces; or produce smooth surfaces at impractically slow cutting speeds; do not produce sharp edges at reasonable rates of metal removal; and have best application for drilling or producing cavities. Sonic and ultrasonic methods have found very limited uses other than in drilling and in forming of cavities. For the electric discharge, sonic and ultrasonic methods, the electrode disc or drilling tool wears away at a rate almost the same as that at which the work piece is cut away by the electrogrinding or the drilling action or the cavity forming action. The attritional action on the important part of the machine adds to the cost through need for replacement because of change in contour and/or wearing away of the cutter, and for shut-down time to make such changes.

The so-called electrolytic grinding process requires the use of a diamond (or other inert non-metallic, non-conducting abrasive or metal) in contact with the work made anodic in an electrolytically conducting, but substantially neutral solution, such as a solution of sodium silicate, or of sodium nitrate and sodium nitrite in water. The prior art teaches the need for diamond (or other

abrasive) wheels or discs for two major reasons: (1) the protruding diamonds act as "spacers" touching the surface of the article to be finished so as to automatically maintain spacing that fixes the thickness of electrolyte film; and (2) to scrape away from the surface the insoluble salts or oxides that form on and adhere to the surface of the article being finished. By these two requirements, the prior art limits the cutting rate (rate of metal removal) because: the non-conducting diamonds reduce the active cathode area and the maximum current is limited to correspond to a lower anode current density than if the diamonds were absent and the conducting area were increased by the amount of area occupied by the diamonds; the diamonds further decrease the maximum operating current by restricting electrolyte flow over the cathode surface so there is polarization in the electrolyte-filled valleys and electrolysis current flow is limited; or the metal-removal rate is limited to the current flow that forms solid adhering anode products at a rate just equal to that at which the products are scraped away by the diamonds.

The present invention has shown that cutting or metal-removal rates by anodic electrolysis can greatly exceed those reached by the aforementioned non-mechanical methods, without mechanical action by or physical contact with the article being electrolytically ground or machined. This is electrolytic grinding in its true coulombic meaning without mechanical contact and/or action. Consequently, surfaces are smooth, no stresses of any kind are induced into the surface of the article being shaped or finished, and hardness or composition of the metal or electrically conducting material has no significance, and voltages are 25 volts or less and are usually 4 to 8 volts, which are so low as to be without danger to machine operators. As is described hereinafter, it has been shown that metals and electrically conducting materials can be electrolytically ground at speeds at least twice those at which diamond wheels can grind such materials as cemented tungsten carbide; i.e., up to 0.05 inch per minute; and vanadium tool steels at speeds up to 0.14 inch per minute, metal-removal depth. This latter speed and more can be attained for mild steel, tool steels, etc., and non-ferrous metals and alloys, without wear on the "cathode or cutting disc" which is inexpensive but is properly designed as to form. This feature of no wear is immediately recognized as a significant fact for automation in shaping operations with contour wheels, for example, as well as for flat surface shaping, sharpening and finishing. Savings in operating costs accrue from long runs without costly down time for re-dressing wheels or for ultimately replacing them.

It is a primary object of this invention, therefore, to provide methods and apparatus for electrolytically grinding metals and other electrically conducting materials without mechanical action or physical contact of any kind.

It is a further object of this invention to provide methods of and apparatus for shaping, sharpening and finishing metals and electrically conducting materials without generation of damaging heat, introduction of stresses from pressure, mechanical work, or electric discharge.

It is still a further object of this invention to provide methods of and apparatus for the simultaneous grinding of combinations of metals presenting very hard and relatively soft metals to the grinding operation; for example, cemented tungsten carbide inserts, silver solder, and tool steel.

Other objects and advantages of the present invention will become apparent as the following description proceeds.

To the accomplishment of the foregoing and related ends, the invention, then, comprises the features here-

inafter fully described and particularly pointed out in the claims, the following description and the annexed drawings setting forth in detail certain illustrative embodiments of the invention, these being indicative, however, of but a few of the various ways in which the principle of the invention may be employed.

This invention may be broadly defined as the method of electrochemically eroding the surface of an electrically conductive body which comprises:

(*a*) Providing an electrolyte in which said body is electrolytically soluble;

(*b*) Relatively moving said body, as an anode, substantially in surface contact with a continuous layer of said electrolyte, which is supported on a cathode which is in spaced relation to said anode;

(*c*) While maintaining a direct current flow between said body and electrolyte;

(*d*) Said method characterized further in that said anode and cathode are at all times in physical spaced relation.

By the term "electrolytic dissolution" as used throughout this description and in the claims is meant the substantial complete dissolution progressively of the surface of a material according to Faraday's law.

When metals or electrically conducting materials are made anodic in electrolytic solutions in such conventional processes as electroplating and electropolishing, dissolution rate depends on the current density that can be maintained without polarization of the anode or the cathode. Polarization increases resistance to flow of electric current so that electrolysis current decreases and dissolution rate falls off, or a higher applied voltage is required. For any electrolyte, there is a maximum voltage above which further increase will not cause the required electric current flow for a given metal anode and indeed may even cause current to cease to flow because of the formation of an insoluble film of oxide or salt on the metal anode surface. Because of polarization, dissolution rates of anodes are slow relative to the metal removal rate needed for practical grinding and shaping of metals in machine shop practices. By electrolysis as in plating, electroetching, or electropolishing, metal dissolution rates do not exceed 0.05 to 0.1 inch per hour. Other investigators have increased electrolytic dissolution by means of mechanical assistance given by electrically conducting abrasive wheels in contact with the article being electrolytically ground so as to continuously scrape away insulating salt or oxide coatings, and thereby, provide for continuous high-current density anodic dissolution. For example, Keeleric, and others using his process, using neutral solutions of sodium salts in water, passed direct current through cemented tungsten carbide and achieved substantial metal removal rates but only because of scraping action of an electrically conducting diamond grinding wheel touching the surface of the cemented carbide. Thus, Keeleric effected a significant improvement in anodic dissolution for grinding and shaping. But, the Keeleric method, as do others known as electrolytic grinding, depends on physical contact and scraping or even actual abrasive cutting simultaneously and requires costly diamond wheels which are electrically conductive and of special design. Any process which depends upon physical contact or abrasive cutting may result in a damaging heating of the work. Furthermore, effectiveness of such a process, depending on scraping and/or abrasive cutting, is limited in maximum cutting rate to those conditions of relative rate of film formation and removal by scraping.

A significant and greater increase in electrolytic grinding rate would be attained if solid film formation was avoided and the need for scraping or physical contact with abrasive or rubbing surface accordingly eliminated. By the method of the present invention such an accomplishment is realized by very accurate control of the film thickness of electrolyte supplied at very high flow rate

across the surface of a metal as an anode to be ground or shaped. By this method commercially practical grinding or cutting rates of metal-removal are accomplished without spark or arc discharge. The dissolution is strictly electrolytic in the coulombic meaning.

By the use of the method of the present invention, cemented tungsten carbide has been cut at a metal-removal rate of 0.057 inch per minute at 1550 amperes per square inch at 76 percent anodic current efficiency, or of 0.040 inch per minute at 100 percent anode efficiency.

It is not unexpected that technical and patent literature described processes in which scraping or abrasive assistance is required for electrolytically grinding cemented tungsten carbide. Most usually, the cementing metal is cobalt. Tungsten oxide is well-known to be soluble in alkaline solutions and insoluble in acid solutions. Cobalt oxide is insoluble in alkaline and soluble in acid solutions. Oxides of both metals are insoluble in neutral solutions. Polarization causes metal oxide films to form on anodes when limiting current densities are exceeded. Limiting current densities are much too low for tungsten carbide cemented with cobalt in simple acid, neutral or alkaline solutions for practical electrolytic grinding rates without scraping to remove either tungsten oxide or cobalt oxide, depending on whether the electrolyte is acid or alkaline. When utilizing methods which depend on scraping of the anode face, the disadvantage exists in that control is difficult and critical for maintaining light wheel contact, yet avoiding pressure that introduces cutting by the abrasive and, thus, wheel wear as well as a damaging heating of the work.

By the method of the present invention cobalt-cemented tungsten carbide can be electrolytically ground or cut at high metal-removal rate without abrasive wheel or other wheel contact by using an alkaline electrolyte in which tungsten oxide is very soluble and which contains a solubilizing anion for rendering cobalt very soluble. A suitable electrolyte contains sodium tartrate, sodium hydroxide and sodium chloride.

Providing an electrolyte with capacity to accept tungsten and cobalt at high rates by anodic dissolution of cemented tungsten carbide is not alone sufficient for high-speed electrolytic grinding. The electrolyte must be replaced at a high rate at the anode face. Such replacement can be effected in a satisfactory manner by distributing the electrolyte in a layer less than 0.020 inch and usually less than 0.008 inch in thickness on a rotating cathode disc as hereinafter described.

Apparatus for carrying out the novel method of the present invention is illustrated in the drawings.

In the annexed drawings:

Fig. 1 is a perspective view of one form of apparatus which may be used in carrying out the process of my invention;

Fig. 2 is a perspective view partially in section and drawn to an enlarged scale of a portion of the apparatus illustrated in Fig. 1 showing in greater detail the cathode disc on which the electrolyte is supported and to which is presented the body to be electrolytically ground;

Fig. 3 is an enlarged fragmentary view of a portion of the assemblage illustrated in Fig. 2 showing in greater particularity the physical relationship between the cathode, anode and the electrolyte film therebetween;

Fig. 4 is an illustration of an alternative form of apparatus by which the method of this invention may be carried out;

Fig. 5 is a graph showing the effect of anode-to-cathode spacing on the current density and cutting rate when the method of this invention is used for electrolytically grinding cemented tungsten carbide;

Fig. 6 is a similar graph when the object electrolytically ground is made of high vanadium steel;

Fig. 7 is a diagrammatic representation of one method of controlling the spacing between the anodic work piece and the cathode.

Fig. 8 is a graph showing the general relationship between current density, cutting rate and spacing between the anode and cathode at various voltages;

Fig. 9 is a diagrammatic representation of another method of controlling the spacing between the anodic work piece and the cathode; and

Fig. 10 shows a list of schematic wave-form diagrams illustrating phase relationship associated with the functioning of the gap control system of Fig. 9.

Fig. 1 is a drawing of a machine for electrolytic grinding employing a cathode disc rotatable in a horizontal plane. The cathode disc is affixed to a rigid electrically insulated spindle driven by a suitably powered motor, preferably having variable speed so that the spindle can be rotated at speeds up to 10,000 r.p.m. or more. A universal vise is mounted in position so that the part to be ground and held thereby can be advanced toward or retracted from the surface of the disc and can be moved in a direction parallel with a radius of the disc and in addition can be moved in a direction substantially parallel with the plane of the disc. The machine is also provided with a liquid circulating system for introducing the electrolyte to the surface of the disc and for collecting the overflow so it can be kept in continuous circulation by means of a suitable pump. The machine has a hood enclosing the grinding area in a manner that enables the operator to observe the operations. Having thus described in general terms the principal components of the machine and their respective functions, the following description will now identify, in detail, by appropriate reference characters, the various elements of the machine as illustrated in Figs. 1, 2 and 3.

1 is the spindle on which the cathode disc 2 is carried. 3 is the system for circulating the electrolyte and it comprises a pump 4, a delivery conduit 5 which is terminally provided with a dam 6 held in a predetermined spaced relation with the upper acting face of the cathode disc 2.

While in the preferred embodiment of the invention appropriate means may be provided for the purpose of regulating the gap between the lower edge of the dam and the upper surface of the cathode disc, such adjusting means have been omitted from Fig. 1 for purposes of clarity in the drawing.

The housing 7 has its bottom 8 arranged to slope centrally to a discharge opening 9 which is covered by a baffle plate 10 in spaced relation to the bottom in which the discharge opening is formed. The discharge opening has a return conduit 11 connected therewith, by which the electrolyte is fed back to the pump 4. If desired, a drain connection generally indicated at 12 may be provided in the return conduit 11 for the purpose of draining the electrolyte from the system. Suitable means may be provided such as a float in the tank or housing for the purpose of maintaining a proper level of electrolyte, i.e., supply of electrolyte in the system.

The electrical panel 13 contains the ampere-minute meter, ammeter and rheostat necessary for adjusting and maintaining the operation by automatic means based on voltage control as hereafter more fully explained.

Spindle 1 extends upwardly from the cathode disc into a drive housing 14 where it is rotatably supported for high-speed operation. In view of the close tolerances necessary to be maintained between the work which is anodic and the active face of the cathode disc, it is essential that the spindle 1 be so supported that it will not wobble during operation. In the illustrated embodiment of the apparatus, the spindle is driven by means of a remotely mounted motor 15 through a flexible belt 16.

The spindle, at its upper end, may have associated therewith any suitable means such as that illustrated at 17 by which the rotational speed in terms of revolutions per minute of the spindle may be indicated.

Referring now more specifically to Fig. 2 it will be noted that the work piece or anode indicated at 18 is actually a hard metal alloy insert in a drill, the body of which, indicated at 19, is at its opposite end held in a universal vise generally indicated at 20, although any other suitable means may be employed for adjustably supporting the anode in any desired position with respect to the upper surface of the cathode disc 2. The external controls generally indicated at 21 by which the universal vise is adjusted are as illustrated in Fig. 1 conventional, but these may vary also as referred to above.

In order to insure proper circuit characteristics for the electrochemical grinding circuiting, the spindle 1 at its lower end below the disc 2 is provided with a projection generally indicated at 22 which dips into and rotates in a mercury bath contained in cup 23 from which extends a conductor member 24 which terminally carries a lead 25 which will be connected in the same circuit as the lead 26 on the vise member 20.

The cathode disc 2 may have any desired physical dimensions as for example in the machines which have been operated successfully thus far, the cathode disc has had diameters of 8 and 12 inches respectively. The only difference which exists when using discs of different diameters is that correspondingly different spindle speeds are necessary in order to maintain the same surface speed on that area of the disc with which the work is adjacent.

The upper surface of the disc may be planar, but preferably it is slightly conical. Preferably, it is the surface of a very flat right cone. When a conical surface is thus used the elements of the cone should slope upwardly at an angle of about 1°. For certain purposes such as when employing an electrolyte of certain viscosity or when forming a surface on the work which is other than flat, that is, contour grinding or for a variety of other reasons, the shape of the upper surface of the cathode may vary from that of a right cone.

It is essential for most purposes that the electrolyte supporting surface of the cathode be as smooth as practical in order that the film may be distributed thereover with a minimum turbulence.

Since the path of the electrolyte film issuing from beneath the dam 6 is a resultant of its circumferential and radial progression, for certain types of operations it is desirable to orient in a particular way the surface of the work piece contacting the electrolyte film. Thus, it has been found that when operating at the higher voltages such as in the vicinity of 25 volts, and if a sharp cutting egde is desired, the work should be oriented so that such edge occurs on that side of the tool facing upstream and that the line representing the cutting edge be substantially at right angles to the direction of relative movement between the film and work piece.

The present method is characterized by the employment of current densities considerably higher than the prior art processes referred to previously. For the purpose of maintaining such current density different voltage levels are required depending on the thickness and other characteristics of the electrolyte film. When utilizing electrolytes of the character referred to herein, it has been found that for the purpose of utilizing 25 volts, the electrolyte film has a thickness such that whereas there is substantially no turbulence in the area where the film meets the work and that edge is accordingly made sharp, in the area where the film leaves the work there is sufficient turbulence so that the edge is less sharp.

When, however, the film thickness is reduced so as to require only 5 volts for the same current density, the film becomes so thin that the turbulence thereof is very substantially reduced and under such conditions of operation the leading edge of the work is made even more sharp than when utilizing a thicker film and a higher voltage and the trailing edge of the work, at the lower voltage level conditions of operation, is also relatively sharp, that is, the trailing edge of the work under 5

volt operative conditions has been found to be sharper than the leading edge under 25 volt operative conditions

The factors just discussed signify the essential difference between the present process and the processes of the prior art, for example, those wherein the cathode carries projections which extend into or through the film in substantial contact with the work for the purpose of for example, removing from the work surfaces the films formed thereon by the electrochemical action.

In view of the fact that the cutting speeds which can be achieved by the use of this method are substantial, and the further fact that for best operations, the space between the cathode and anode are relatively small, it becomes important to provide some means for adjusting such spacing. It is possible to effect such adjustment manually by means of the controls illustrated, for example, at 21 in Fig. 1 for the reason that under fixed operating conditions a definite relationship exists between the current density, cutting rate and gap distance. The anode feed rate is the independent variable which determines the gap distance, current density and cutting rate. At equilibrium grinding conditions, the cutting rate is equal to the anode feed rate and the current density and gap distance have fixed values. If the anode-feed rate is increased slightly above the cutting rate, the gap decreases, the current density increases, and the cutting rate increases until it equals the increased anode-feed rate. When equilibrium conditions have been re-established at the higher anode-feed rate, the gap is smaller and the current density is higher. If the anode-feed rate is decreased slightly below the cutting rate, the gap increases, the current density decreases and the cutting rate decreases until it equals the reduced anode-feed rate. When equilibrium conditions have thus been re-established at the lower anode-feed rate, the gap is larger and the current density is smaller. The above examples show that once the anode-feed rate is set, the electrolytic process is inherently self-correcting. It is thus possible to operate the present method by controlling the feed rate manually after some experience has been had along this line. The self-correcting tendency just explained will tolerate rates of feed which, when controlled manually, are either not at the maximum or are of a varying nature within limits. For most consistent results, however, it is desirable that some means be provided which are functionally responsive to one of the variables referred to and which will automatically maintain a feed rate which bears a predetermined proportional relation to such variable. For example, since the thickness of the film or more accurately the space between the anode and cathode when varied is reflected in substantial changes in current values at a uniform voltage, means, presently to be described in greater detail, which are functionally responsive to variations in current can be used for the purpose of maintaining the feed at a constant rate.

Simply pouring the electrolyte at the not-quite touching conjunction of the rotating disc cathode and the article being ground, as is done by pumping the oil-emulsion coolant and lubricant out of a tube so a stream strikes the grinding wheel where it touches the article being ground in conventional abrasive wheel grinding machines and in electrolytically assisted grinding wheels described in the literature, is not suitable for electrolytic grinding when performing the method of the present invention.

In the machine shown in Fig. 1, a thin coating of electrolyte is metered onto the disc surface by a deflecting dam. The clearance of the dam above the disc and the rotational speed of the disc are such that the electrolyte is firmly impacted against the disc by centrifugal force until after it has passed under the article being electrolytically ground or cut. This force is believed to so condition the film of electrolyte on the disc that substantially no turbulence occurs in the electrolyte film as it passes through the gap between the disc and the article being ground. Such absence of turbulence is believed confirmed by the fact that flat surfaces without waviness and with sharp edges result from the anodic dissolution that effects anodic grinding. Turbulence, if present in the electrolyte film, would be accompanied by waviness or flow patterns formed in the ground surface. Fig. 1 shows the disc in a substantially horizontal position, but the useful apparatus is not limited to such an arrangement. The plane of the disc may be vertical or at an angle.

An important part of the novelty in the method of the present invention resides in this demonstration that an electrolyte having sufficient degree of solubility for metal oxides can be deposited, practically rigidized in streamline, non-turbulent flow on a rotating disc, and that a metal or other electrically conducting article brought into the outermost layer of this electrolyte can be made anodic with direct current at low voltage and much higher-than usual current density known in the art as a result of which highly effective and efficient electrolytic grinding can be done at rates at least equal to and usually exceeding the rates of electrolytically assisted abrasive methods, electric discharge methods, and of conventional abrasive methods.

Since no metal removal occurs until the article to be ground contacts the electrolyte film, easy and simple operation results. Since the right gap is adjusted by metering the electrolyte film, the article is automatically spaced correctly when electrolysis current flows since no action can occur until the electrolyte is contacted upon advancing the article toward the electrolyte.

Although a rotating cathode disc having a flat surface radially from center to outer rim can be used in performing the method of this invention, the preferred apparatus utilizes a rotating cathode disc that is concave at the center. The preferred concavity is provided with 0.002 to 0.100 inch thinner in section at the center than at the outer rim of the grinding face, decreasing radially in a straight line to zero at the outer rim or with a 5 to 40 degree bevel at the outer edge. This concavity adds a component of centrifugal force in a better manner to impact the electrolyte against the disc surface. By the means provided according to Fig. 1 and described hereinbefore, non-turbulent electrolyte films can be easily maintained in thicknesses less than 0.008 inch. At a given applied voltage, the amperage that can pass is greater per unit of area the thinner the electroylte film and thus the closer the article is to, but not, touching the cathode disc.

ELECTROLYTE COMPOSITIONS

The following are various electrolyte compositions useful in carrying out the present invention. They will be referred to more particularly later in this description and are here set forth together for ready comparison.

	G./l.
For tungsten carbide:	
Sodium tartrate ($Na_2C_4H_4O_6$)	150
Sodium hydroxide (NaOH)	150
Sodium chloride (NaCl)	20
For composite articles:	
A. Triethanolamine ($HOCH_2CH_2)_3N$	197
Sodium hydroxide (NaOH)	50
Sodium chloride (NaCl)	100
Sodium cyanide (NaCN)	25
Sodium carbonate (Na_2CO_3)	25
B. Sodium tartrate ($Na_2C_4H_4O_6$)	105
Sodium hydroxide (NaOH)	60
Sodium chloride (NaCl)	50
Sodium cyanide (NaCN)	25
C. Sodium tartrate ($Na_2C_4H_4O_6$)	168
Sodium hydroxide (NaOH)	60
Sodium chloride (NaCl)	50
For vanadium steel:	
Sodium chloride (NaCl)	200
Boric acid (H_3BO_3)	25

pH 7 or higher preferred range 1.8–10 or higher.

Electrolyte compositions for carrying out the process defined herein have the chemical ability to dissolve the oxides of the metals and the metallic elements being processed. For example, electrolytically grinding a part consisting of cemented tungsten carbide, silver solder and tool steel requires that tungsten oxide, cobalt oxide, silver oxide and iron oxides be dissolved. Tungsten oxide is well-known to be soluble in alkaline solutions and insoluble in acid solutions. Cobalt oxide and iron oxide are insoluble in alkaline solutions and are soluble in acid solutions. Oxides of all three metals are insoluble in neutral solutions. In electrolytes of this invention, the oxides of all the metals named are soluble because special improvements are present in an alkaline solution. The electrolyte of Example B contains sodium hydroxide to dissolve the tungsten electrolytically, sodium tartrate to make the cobalt soluble and sodium tartrate plus sodium chloride to make the iron soluble. The sodium cyanide in this example provides solubility for silver solder when the operating voltage is high enough to cause polarization of the silver. When the operating voltage is low enough to avoid polarization, the cyanide is not needed and the electrolyte of the composition C will electrolytically carry out the process described for a combination of the three metallic components.

For metallic elements that are substantially steel with minor alloying constituents, chloride solutions provide sufficient solubility for the oxides and are, therefore, useful for electrolytic grinding as described herein.

Or, in the case of an alloy, the electrolyte can be selected for dissolving characteristics of the major constituent and by dissolving it permit the alloying elements to fall free without need for electrolytic solubility or mechanical scraping.

In the absence of the oxidizing effect of the electric current passed through the metallic components as anodes, these electrolytes are without substantial attack upon the metallic components. With the passage of the electric current as described herein, the metallic components are dissolved at substantial current efficiencies according to Faraday's law. While the operations are technically feasible at any current efficiency for metal dissolution, we prefer to operate at values above 40% current efficiency. The balance of the electro process which makes the current efficiency total to 100 is believed to be consumed in dissociating water with the discharge of oxygen simultaneously with the metal dissolution that brings about the electrolytic grinding. For the most practical operations, current efficiencies will exceed 80% for metal dissolution.

Generally, electrolytic processes have limiting current densities, such that increase in current density beyond this point effects no further increase in the rate of metal dissolution. This condition is reached when the rate of metal dissolution just equals the rate at which the dissolved metal ion can be accepted by the solubilizing ions and the product can diffuse away while at the same time new acceptor ions can diffuse to the metal surface. This limiting current density condition involves a diffusion layer at the anode surface that has a thickness in the range of about 0.005 inch. The only way to speed up the anodic dissolution is to exceed the limting current density by disturbing the naturally-forming diffusion layer so that the products of dissolution are swept away and fresh dissolving solution is supplied at a rate faster than normal diffusion can maintain. Thus, by flowing electrolyte under forced pressure into the gap between the two electrodes, the products of dissolution are swept out and fresh solution is supplied at the high rate necessary for maintaining high-speed anodic dissolution. Thus, there is a minimum speed of fresh flow in the gap between the electrodes that will correspond with or be greater than the normal diffusion film thickness. There can be an excessive amount of turbulence at the metal surface such that the diffusion film is broken up into globules of liquid and

does not maintain a continuous liquid layer in contact with the anode surface. The rate of anodic dissolution will be decreased approximately by the amount that the contact area of anode to liquid is decreased. In flowing electrolyte through the gap in the process described herein, the maximum flow rate or conditions of flow will be that which causes excessive turbulence within the reaction zone equivalent to the diffusion film thickness.

The efficiency of this novel electrolyte grinding method is shown by Example I.

Example I

Cemented tungsten carbide was plunge ground electrolytically in the following aqueous electrolyte:

	G./l.
Sodium tartrate ($Na_2C_4H_4O_6$)	150
Sodium hydroxide (NaOH)	150
Sodium chloride (NaCl)	20

The cutting rate in inch per minute as shown in Fig. 5 was substantially directly proportional to the anode (the article being ground) current density, which also was substantially indirectly proportional to the anode-to-cathode spacing which is the effective thickness of electrolyte film. These linear relationships are to be expected only if electrode polarizations are zero or nearly zero at the cathode (rotating disc) and the anode (the article being ground). The dotted line shows the theoretical cutting rate at 100 percent coulombic efficiency. At current density above 1000 amperes per square inch, the actual efficiency appears slightly less than 100 percent, indicating that some polarization did occur; but even so, the high coulombic anode efficiencies shown by this example have not heretofore been attained at current densities over a few hundred amperes per square foot, thus attesting to a novel accomplishment by the present invention.

The importance of establishing very high current density is shown by the appearance of the carbide surface at several levels of the current density range covered by Fig. 5.

Current Density Range (amperes per square inch)	Appearance of Cemented Carbide Surface
0 to 325	Dull, gray anode film; uneven surface.
326 to 500	Shiny surface, but uneven.
501 to 1,150	Good edges and smooth surface (5.5 to 7.5 R.M.S. microinches).
1,151 to 1,600	Good edges, but less smooth than surface at 501 to 1,150 amp./sq. in.

For some applications, very sharp edges are desired such as those resulting from diamond-wheel grinding to sharpen cutting tools. The very high current densities shown in Fig. 5 for Example I can only occur because cathode polarization is essentially eliminated because the high rate of electrolyte flow through the cutting gap sweeps away the hydrogen (principal product at the cathode disc surface) at the instant it forms. The slight fall off in efficiency at the high current density end of the range shown in Fig. 5 indicates that some anode polarization may have occurred. Clearly also at the 25-volt operation, polarization at the edges was slightly less than at the rest of the surface being dissolved, so some edge rounding occurred. This is desirable for the smooth running of some engine and other mechanism parts, but is not desirable when a very sharp edge is desired as in sharpening a cutting tool.

Since the agitation for anodic dissolution in the electrolysis gap clearly reached heretofore unheard-of agitation rate by streamline flow, permitting exceptionally high current densities, electrolysis at some lower voltage should take place so that a slight decrease in agitation should cause a relatively large decrease in current density, and thus a large decrease in metal-removal rate. Because of the "firmness" of the electrolyte film on the cathode disc, there is no pile-up of electrolyte on the leading edge

of the article being ground. Thus, in the absence of turbulence, the agitation effect is slightly less on a part of the article not substantially parallel to electrolyte flow. This slight difference in agitation at an edge is not enough to cause the decreased current density resulting from less agitation to offset the greater current at edges caused by normal current distribution at 25 volts. In the electrolyte film, as provided by the present method, it was found that at 5 volts direct current, the slightly less agitation at the edges caused lesser current density that offset the increase that configuration would give current distribution to effect greater current density and metal removal at edges. So with conditions the same as for Example I except at 5 volts applied E.M.F., the edges were as sharp as those produced by diamond-wheel grinding.

The process described herein for electrolytic grinding is eminently suitable for grinding materials other than cemented carbide. Since the process does not remove metal by mechanically cutting it away, hardness is no factor in electrolytic grinding. Thus, metals of widely different hardness can be electrolytically ground simultaneously; for example, cemented tungsten carbide, silver solder, and tool steel. Such a combination now requires tedious and careful grinding with diamond wheels and with wheels of less costly abrasives. Care must be taken not to grind silver solder and steel with the diamond wheels, and the wheel of other abrasives used to cut the silver solder and steel is worn excessively if it contacts the cemented tungsten carbide.

Example II

Since it is not practical to use a diamond wheel or an abrasive wheel of other type for the complete grinding and shaping of cemented tungsten carbide, silver solder and tool steel, a method for grinding all three at once is both novel and practical. All three metals were simultaneously electrolytically ground in thin-film electrolytes of the following composition in the electrolytic grinding unit shown in Fig. 1.

A.	Triethanolamine ($[HOCH_2CH_2]_3N$) ____g./l__	197
	Sodium hydroxide (NaOH) _____g./l__	50
	Sodium chloride (NaCl) _____g./l__	100
	Sodium cyanide (NaCN) _____g./l__	25
	Sodium carbonate (Na_2CO_3) _____g./l__	25
B.	Sodium tartrate ($Na_2C_4H_4O_6$) _____g./l__	105
	Sodium hydroxide (NaOH) _____g./l__	60
	Sodium chloride (NaCl) _____g./l__	50
	Sodium cyanide (NaCN) _____g./l__	25

Current density _____amp./sq. in__	300
Cathode wheel speed _____ft./min__	6000
Anode area _____sq. in__	0.2
Anode-to-cathode space _____in__	0.002

Both electrolytes gave approximately the same results for electrolytic grinding at 25 volts. Cutting rate was 0.020 inch per minute; the carbide surface was smooth (5 to 10 R.M.S. microinches), but was slightly wavy and the edges were slightly round; and the steel had a surface finish of 70 to 100 microinches.

Electrolytic grinding at 5 volts produced a flat, non-wavy tungsten carbide surface with sharp edges and a smooth "polished" finish on the steel and silver solder.

The electrolyte flow system and rotating disc remain the same for presenting a thin, electrolyte film to the article to be ground. Because the electrode reaction of different metals differs at high current densities, and the solubilities of metal oxides and salts differ, the best electrolytic grinding results will require some changes in electrolyte for different metals. Note that electrolytes A and B of Example II differ in composition from the electrolyte of Example I. The cyanide in A and B effects dissolution of the silver solder and the chloride prevents anodic polarization of the steel, solubilization of which in alkaline solution is effected by the triethanolamine or the tartrate, both of which are equally effective in allowing high current density, high efficiency dissolution of the cobalt.

For simultaneously electrolytic grinding cemented tungsten, carbide, silver solder and tool steel at 5 volts applied E.M.F., the cyanide can be omitted from the electrolyte. For example, the electrolyte can comprise:

	G./l.
Sodium tartrate ($Na_2C_4H_4O_6$) _____	168
Sodium hydroxide (NaOH) _____	60
Sodium chloride (NaCl) _____	50

At 300 amperes per square inch, 6000 feet per minute disc speed, and lowest electrolyte flow that gave uniform film, metal-removal rate was 0.020 inch per minute and surface finish was 10 R.M.S. microinches on both the steel and the cemented tungsten carbide. At the low voltage of 5 volts the "throwing power" of the electrolyte is less than at 25 volts, so edges are sharper.

The electrolytes shown in Examples I and II are for electrolytic grinding of the grade of carbide containing 6 percent cobalt. The concentrations of tartrate, hydroxide and chloride in the electrolyte will vary somewhat as the percent cobalt is different or as nickel or other cementing metals are used.

The cation is not a factor in the process described herein and may be any other that forms very soluble tartrates such as potassium and ammonium. In place of tartrate, any of the following may be used: triethanolamine, citrate, tetrasodium ethylene diamine tetraacetate, ammonium hydroxide, etc.

Example III

High carbon vanadium steel was also electrolytically ground at high rates by the method of this invention. An electrolyte consisting of an aqueous solution of 200 g./l. sodium chloride and 25 g./l. boric acid was used. At cathode disc speed of 6000 feet per minute, 25 volts applied E.M.F., cutting rates of 0.010 to 0.140 inch per minute were attained depending on the anode-to-cathode gap (i.e., the electrolyte film thickness) as shown in Fig. 6. Projection of the line for "anode-to-cathode spacing" shows an electrolytic cutting rate of about 0.165 inch per minute at 0.001 inch spacing.

Low-alloy steels, high and low carbon steels, and stainless steels can be electrolytically ground under the conditions cited for Example III. Cutting rates are substantially the same for all. Very little difference is seen in cutting rates as pH varies from 1.8 to 10. Finish appearance is slightly better at pH of 7 and higher.

At 5 volts, electrolytic cutting rate is slightly slower than at 25 volts, but surface finish is better for some metals. Thus, a roughing cut can be taken at the higher voltage for speed and finishing can be done for appearance at the low voltage. The only change is in voltage regulation, whereas, for abrasive wheel grinding either the wheel must be changed or the work must be reset-up on a second machine for finishing after rough cutting.

The aspect of variability of voltage is a characteristic of electrolytes having good conductance and high solubility for metal oxides and anodic oxidation of metal compounds with non-metals such as represented by tungsten carbide. Thus, a feature of the present process is the use of an electrolyte composition giving good electrical conductance and having high solubility for metal oxides and for salts of the anions in the electrolyte and the metal dissolved during the electrolytic grinding.

For accomplishing electrolytic grinding as disclosed herein, wheel speeds (cathode disc speed) are those at which a uniform uninterrupted smooth film of electrolyte is formed at point of discharge of the electrolyte from the circulating pump to the location behind the metering dam. Generally, wheel speeds will be in the range of 2000 to 15,000 feet per minute, depending on the viscosity of the electrolyte. More specifically, speeds of 6000 to 10,000 feet per minute are preferred.

In general, current density on the article (as anode) to be electrolytically ground will be 100 to 2000 amperes per square inch. More specifically, 500 to 1600 amperes per square inch are preferred.

Electrolyte film thickness (anode-to-cathode gap) will be 0.0001 to 0.020 inch. More specifically, film thickness in the range of 0.001 to 0.008 inch are preferred, depending on the composition of electrolytic solution being used, the metal being electrolytically ground, and the voltage being used, as for rough cut or fine finishing.

Operating voltages will generally be in the range of 2 to 30 volts. More specifically, voltages of 5 to 25 volts should be used for practical electrolytic grinding rates.

The material of the cathode disc is not important so long as it has adequate electrical conductance and resistance to chemical attack in the electrolyte and is not damaged by hydrogen discharge.

Other advantages of the method of this invention will be apparent to those skilled in the art of electrolysis and of metal grinding, machining and shaping. For example, electrolytic grinding is accomplished without generation of damaging heat in the article to be ground or pressure on the article to be ground and, being in addition without physical contact, cannot introduce damaging stresses in the surface of hardened steels; cannot leave torn, fragmented, damaged metal on a surface such as results from the ripping, shearing, tearing and smearing by which abrasives and contact tools cut; cannot deform thin-section metal parts; and is not hampered by plastic flow of soft metals that fill abrasive wheels and smear under contact-cutting tools.

Throughout the preceding description reference has been made to the employment of a disc **2** as the cathode on which the electrolyte is supported and to which electrolyte film the work to be electrolytically formed is presented. In Fig. 4 there is shown an alternative arrangement wherein a rotating spindle **30** carries a disc **31** having a substantially cylindrical flange **32** integral therewith. The electrolyte is introduced through conduit **34** and distributed by the dam or baffle **35** on the end of the conduit. The work piece to be electrolytically formed is indicated generally at **36** and is held by a suitable arm **37** by which it may be presented to the electrolyte film in the manner previously described in connection with Figs. 1, 2 and 3.

ADJUSTMENT OF ANODE-CATHODE SPACING

One simple means by which this can be accomplished is illustrated in Fig. 7 wherein **40** designates the direct current control circuit power source, **41** is a rheostat for the control of the speed of a variable speed reversing motor **42**, the direction of rotation of which is controlled by the reversing switch **43**. The shaft of the motor **42** is connected through a gear box **44** to a gear **45** on the adjusting stem **46** of the universal vise **47**, the arm **48** of which carries the work piece **49** in the proper spaced relation to the disc **50**. **51** denotes the D.C. power source for the work circuit, **52** is the rheostat by which that circuit is controlled and **53** is the switch by means of which the circuit is energized and de-energized.

Electrolytic grinding without the arcing, sparking or scraping as in the prior art is inherently self-adjusting. If the feed rate tends to exceed the cutting rate, the gap will decrease, causing the current density to increase, and the cutting rate will increase to a value equal to the feed rate. Conversely, if the cutting rate tends to exceed the feed rate, the gap will increase causing the current density to decrease, and the cutting rate will decrease to a value equal to the feed.

Anode feed can be accomplished by the variable speed motor **42** with the gear reduction train **44** to allow feed rates covering the range of cutting rates achieved in electrolytic machining (i.e., 0 to 0.2 inch or more per minute). The reversing switch **43** is provided to withdraw the work **49** from the cathode disc **50** when the metal removal operation is completed. This reversing switch can be manually controlled by the operator or can be operated by an electric timer with variable settings, or by other means, according to need for timing the duration of the electrolytic grinding, as described below. As shown in Fig. 7, a separate switch **53** is provided for the electrolysis grinding circuit. Alternatively, the reversing switch mechanism could be arranged to simultaneously open or close the electrolysis grinding circuit.

There are several methods of terminating the cutting action after the desired amount of metal removal. The choice will depend on the requirements of the machining operation. The following examples illustrate the unique control features possible for electrolytic machining with present-anode-feed-rate control:

(1) Cutting action can be terminated by an adjustable limit switch which is mechanically activated by the anode feed holder. The limit switch would simultaneously open the electrolysis circuit and reverse the feed direction. The advantage of this method is that the limit switch can be set with reference to the cathode disc. No further adjustment of the limit switch setting would be required in repetitive machining operations, since there is no wear on the cathode disc. In conventional machining or other electrolytic processes, tool wear or cathode-disc wear must be continually compensated by some means in order to achieve reproducible accuracy.

(2) An electric timer could be set in conjunction with the preselected feed rate, so as to terminate the cutting action after the desired anode feed travel from the initial position. At the end of a specified time, the electric timer can activate the mechanism for opening of the electrolysis circuit and reversing of the feed direction.

(3) Similar to 2, except that the start of the electric timer would be activated by the start of the electrolysis current. In this manner, the timing of the depth of cut can be started when the anode entered the electrolyte. The advantage of this method is that by suitable choice of time and feed rate, a definite depth of cut can be obtained independent of the initial positioning of the anode in the holder.

(4) For precision work on a production basis of a number of similar parts of known anode area, an ampere-minute meter connected in the electrolysis circuit will control and limit the electrolytic grinding. The cutting action can be terminated after a predetermined number of ampere minutes of electricity have passed. As an example, assume an anode area of 0.1 square inch and a cutting rate of about 0.050 inch per minute at 1000 amperes per square inch. In cutting 0.050 inch, 100-ampere minutes will pass. With an ampere-minute meter sensitive to the nearest tenth of an ampere minute, the precision of cut will be 0.00005 inch.

In operation, the desired anode-feed rate and electrolysis voltage are selected. The electrolysis circuit is closed, and the anode feed toward the cathode disc is begun. As the work enters the electrolyte, current flows, and metal removal begins. At the gap distance set, the cutting rate will be less than the anode-feed rate; therefore, the gap will tend to decrease, the current density will increase, and the cutting rate will increase, until the cutting rate equals the feed rate.

It is also contemplated to provide a voltage-control unit. This consists of a voltage divider to select from the line voltage the desired electrolysis voltage. During electrolysis, the equilibrium gap spacing that exists when the feed rate equals the cutting rate can be controlled by the electrolysis voltage. The gap for electrolytic grinding, as described herein, is directly proportional to the electrolysis voltage. The electrolysis voltage is selected so that the equilibrium gap distance is less than the electrolyte film thickness on the cathode disc, but large enough to prevent arcing or sparking.

Figure 8 shows the general relationship between cur-

rent density, cutting rate and gap spacing at various voltages, as characteristic of electrolytic machining as described herein. The exact numeral values and relationships will depend on many factors, i.e., the type of anode material, the electrolyte, etc. In Fig. 8, a straight-line relationship between gap distance and current density is shown for simplicity. The important factor is that the current density is inversely proportional to the gap spacing for the purposes of gap control during electrolytic machining. A straight-line relationship is not essential.

This control system, based on a preselected cutting rate, is advantageous because the method is independent of the anode area being machined. This control system does not require auxiliary electronic equipment. It is apparent that such a simple control system can only be used for electrolytic machining without scraping, sparking or arcing. Such a control system would not be feasible if continual contact of the anode and cathode were required during electrolysis.

In Figs. 9 and 10 are shown modes for electronically controlling the gap or spacing between the anode and cathode when the thickness of the electrolyte film on the cathode is at least as great as such spacing.

The purpose of this electronic equipment is to provide an automatic control of the gap between the tool and the cathode disc. When machining surfaces of essentially constant areas using a constant voltage source, the electrolytic current flowing is a measure of the gap between the tool and the disc. This phenomena is used as a basis of control in the circuit shown in Fig. 9.

When SW1 is closed, current from the power mains flows through the primary PI of transformer X1. Voltage induced in secondary 1 is applied to the filaments of tubes V_1, V_2, V_3 and V_4 causing them to heat, and activates the metal reed of converter CON–1. Voltage induced in SEC. 2 is applied between the right hand plate of V_2 and bus B–1 by means of wires A and B. The right hand section of V_2 is connected as a rectifier and a D.C. voltage is caused to appear between terminals T_1 and T_2. T_1 is positive in polarity with respect to T_2. Resistor R_1 and capacitor C_2 are part of a filtering network which smooth the fluctuations from the rectified D.C. voltage. In the phase sensitive amplifier, R_2, R_3 and R_4 are bias resistors placed in the cathode circuits of V_1, V_3 and V_4 respectively. C_3 and C_4 are cathode by-pass capacitors to reduce degeneration. C_{15} and C_{16} are decoupling capacitors.

In the electrolysis circuit, current I_1 flows from the voltage source E_1 through wire C to the wheel by means of a brush. The current then passes through the gap between the wheel and the work by means of an electrolyte, removing material from the work. Said current then passes from the specimen back to the source E_1 by means of wire D and resistor R_5 and wire E. A voltage v_1 is developed across resistor R_5 between terminals T_3 and T_4 by the passage of the electrolysis current. The magnitude of this current and voltage v_1 will depend upon the area of the specimen and the size of the gap between the wheel and the specimen. In the reference voltage circuit, current I_2 passes from the source E_2 through resistors R_6, R_8 and R_7 and back to the source E_2. This current I_2 is controlled in magnitude by fixed resistors R_6 and R_8, and variable resistor R_7. R_8 is present to control the maximum of current which flows when R_7 is at a minimum. In operation, R_7 is adjusted so that the proper current I_2 flows through R_6, establishing a voltage v_2 between terminals T_4 and T_5, equal to v_1 between terminals T_3 and T_4 when the desired amount of electrolysis current is flowing. When the desired amount of electrolysis current is flowing, v_1 is equal to v_2. The polarities of v_1 and v_2 are so arranged that when v_1 and v_2 are equal in magnitude, no net voltage appears between terminals T_3 and T_5.

Converter 1 operates in conjunction with transformer X_1 in such a manner that a 60 cycle alternating voltage v_3 appears at terminals T_8 and T_9 when a D.C. voltage occurs at terminals T_6 and T_7. This 60 cycle voltage v_3 is either in phase or 180° out of phase with the voltage that drives converter CON–1, depending upon the polarity of the voltage appearing between terminals T_6 and T_7.

When the desired electrolysis current I_1 is flowing, a net voltage of zero appears between terminals T_3 and T_5. Whatever voltage appears between T_3 and T_5 is transmitted through wires F and G, through reversing switch SW–3 to terminals T_6 and T_7, thence by wires H and I to converter CON–1. Since the voltage between T_3 and T_5 is zero, the voltage v_3 that appears between terminals T_8 and T_9 is also zero. When there is no voltage at T_8, the grid G_{L1} of the left hand section of tube V_1 is at the same potential as cathode K_{L1}. This lets the left hand section of tube V_1 pass current. These electrons flow from bus B–1 through R_2, through the left section of tube V_1, R_9, R_{13} and R_{14} to terminal T_1. A voltage v_3 appears across R_2, which is positive at K_{L1} and negative at B–1. This makes cathode K_{L1} more positive than grid G_{L1}, decreasing the current in the left hand side of tube V_1. This voltage v_4 across R_2 is the grid bias of the left hand side of tube V_1. Hence, with no grid signal, the left hand side of V_1 passes a small steady current, producing also a voltage drop across R_9, R_{13} and R_{14}. However, no matter what steady voltage appears between points T_{20} and T_1, capacitor C_5 charges to this voltage, and no voltage remains across resistor R_{10}. Similarly the anode current which passes through the right hand side of tube V_1 develops a voltage across R_3 which is a biasing voltage. This limits the anode current in the right hand side of tube V_1 to a small steady flow. This has no effect on the left hand side of V_2, for capacitor C_6 has charged to the voltage between points T_{13} and bus B–1, so that no voltage remains across R_{11}. The left hand side of V_2 also has zero grid voltage and passes some anode current. Similarly, C_7 has charged to the voltage T_{14} to bus B–1, and grids G_{L3}, G_{R3}, G_{L4} and G_{R4} of both tube V_3 and V_4 are at the same potential as bus B–1.

Although in all sections of V_3 and V_4, the cathodes are tied together, and the grids are tied together, the tubes are not in parallel. Anodes P_{L4} and P_{R3} are connected by wire J to terminal T_{15}, one side of transformer X_1 secondary 3. Anodes P_{R4} and P_{L3} are connected by wire K to terminal T_{16}, the other side of secondary 3 of transformer X_1. The left hand section of V_3 and the right hand section of V_4 may fire during one half cycle. The right hand section of V_3 and the left hand section of V_4 may fire during the next half cycle. Never do all four sections of V_3 and V_4 pass current at the same time. While their grids, attached to terminal T_{17}, remain at B–1 potential, tubes V_3 and V_4 act as a two tube full wave rectifier, producing a small direct current. These electrons flow from terminal T_{18}, the center tap of SEC. 3, transformer X1 through wire L, through one set of windings (W–1) in the two-phase motor, through wire M to bus B–1, through R_4 to cathodes K_{L3}, K_{R3}, K_{L4}, and K_{R4} and through the left and right sections of V_3 and V_4 in turn. The voltage developed across R_4 makes cathodes K_{L3}, K_{R3}, K_{L4} and K_{R4} more positive than grids G_{L3}, G_{R3}, G_{L4} and G_{R4} attached to terminal T_{17}, thus acting as grid bias. This limits the amount of anode current of V_3 and V_4. This direct current through the motor windings does not turn the motor, which is an A.C. induction motor, but tends to make it more stable. So, until a signal voltage appears at T_8, all tubes pass current steadily but the motor does not turn.

In Fig. 9, suppose that the electrolysis current I_1 decreases, lowering the voltage v_1 developed across R_5 to a value less than v_2 developed across R_6. A voltage thus appears between terminals T_3 and T_5 which is positive at T_3 and negative at T_5. With switch SW–3 in the down position this voltage appears between terminals T_6 and T_7,

and is carried by wires H and I to the converter CON–1. Consequently a 60 cycle signal voltage appears at T_8 as shown in curve 2, Fig. 10. During the half wave X, grid G_{L1} becomes more positive, increasing the anode current of the left hand section of V_1. This reduces the potential at terminal T_{20}. Since capacitor C_5 cannot change its charge instantly, the potential at G_{R1} is forced more negative. Since the grid voltage of the right hand side of V_1 becomes negative, its anode current decreases. When the current decreases in the right hand side of V_1, the potential at terminal T_{19} increases. Since capacitor C_6 cannot change its charge instantly, the potential at terminal T_{13} also increases. When the potential at terminal T_{13} increases, the anode current through the left hand side of V_2 increases, decreasing the potential at terminals T_{14} and T_{17}. The slider on resistor R_{11} is a sensitivity control. When it is moved toward the lower end, less of the voltage developed across R_{11} is used to change the current in the left hand side of V_2, so the whole amplifier has less output at terminal T_{17}.

During the half wave X when current increases in the left hand side of V_1, decreases in the right hand side of V_1, and increases in the left hand side of V_2, the potential at terminal T_{14} decreases. Coupled through capacitor C_7, the potential at terminal T_{17} is more negative than bus B–1. Curve 3 of Fig. 10 shows this change at T_{17}, which is the grid voltage of tubes V_3 and V_4. During half cycle X, anodes P_{L4} and P_{R3} are positive, and anodes P_{L3} and P_{R4} are negative. No tube section passes current since the voltage of all grids of tubes V_3 and V_4 is negative. However, during the next half cycle, all the grids of V_3 and V_4 are positive. Although all grids are positive, only the left hand section of V_3 and the right hand section of V_4 will pass current, for P_{L4} and P_{R3} are now negative. The amount of this current increases if the voltage signal (curve 2, Fig. 10) becomes larger.

From the above we see that the left hand section of V_3 and the right hand section of V_4 pass half cycle pulses of current whenever voltage v_1 is less than voltage v_2. These current pulses (curve 4, Fig. 10) are changed into an alternating current by adding capacitor C_8, which is the proper size to resonate at 60 cycles with the motor windings W–1. Current flows back and forth through windings W–1 and in and out of capacitor C_8. This current is started and kept flowing by the pulses of current (curve 4, Fig. 10) from the left hand section of V_3 and the right hand section of V_4. Since the current lags by 90° when flowing through an inductive coil, the current wave form through coil W–1 will lag by 90° (curve 5) the pulses of current from the left side of V_3 and the right side of V_4.

The two phase motor requires an alternating current in each winding. When switch SW–2 is closed, SW–1 having been closed, 60 cycle current flows from the mains through wire O, motor windings W–2, wire N, switch SW–2 and capacitor C_1 back to the mains. Since the current in an inductive coil lags the applied voltage, capacitor C_1 is added to bring the current wave form in the coil (curve 6, Fig. 10) more nearly in phase with the applied voltage.

When the left side of V_3 and the right side of V_4 alone pass current, the current in the motor W–1 windings is shown by curve 5. This is also shown in curve 7, which includes curve 6 (current in the W–2 windings). The W–1 winding current is to the left of the W–2 winding current and leads by 90 degrees (curve 7, Fig. 10). These combined currents make this induction motor turn so as to move the specimen holder toward the cathode wheel, decreasing the gap and increasing the current I_1.

When the current I_1 increases, so that voltage v_1 is larger than voltage v_2, there will again be a voltage between terminals T_6 and T_7. However, this voltage will have a polarity opposite that which occurred in the previous discussion. When this signal voltage is applied to converter CON–1 the resultant 60 cycle signal at terminal T_8 is like curve 9, Fig. 10, or shifted 180 degrees from the previous signal as shown in curve 2, Fig. 10. Since T_8 is negative during the first half cycle, the current in the left hand side of V_1 decreases, the current in the right hand side of V_1 increases, the current in the left hand side of V_2 decreases, and the signal at terminal T_{17} becomes more positive, as shown in curve 10. During half wave Z, the grids of tubes V_3 and V_4 are all positive. However, the anodes P_{L3} and P_{R4} are negative during this half cycle and the left hand section of V_3 and the right hand section of V_4 will not pass current. Anodes P_{L4} and P_{R3} are positive during this half cycle so the left hand section of V_4 and the right hand section of V_3 may pass pulses of current (curve 11, Fig. 10). These pulses cause an alternating current to flow in winding W–1 of the motor and resonating capacitor C_8. This alternating current curve (curve 12, Fig. 10) lags 90 degrees behind the wave of current through the left section of V_4 and the right section of V_3 (curve 11, Fig. 10). Since these tube currents (curvell) occur a half cycle later than currents illustrated in curve 4, the wave of current in the W–1 windings is also later. In the combined curves 14 we see that the W–1 winding current is to the right of the W–2 winding current, and lags by 90 degrees. These combined currents make the induction motor turn so as to retract the specimen from the wheel and cause the gap to increase and decrease the current.

Thus, by tapping off a voltage developed by the electrolysis current, it is possible to control the gap present between the specimen and the cathode wheel. The two-phase motor responds immediately and accurately to keep the current and gap constant.

Other modes of applying the principle of the invention may be employed, change being made as regards the details described, provided the features stated in any of the following claims or the equivalent of such be employed.

We, therefore, particularly point out and distinctly claim as our invention:

1. The method of sharpening, shaping and finishing an electrically conductive body by removing stock therefrom, which comprises metering a thin layer of electrolyte onto a smooth electrically conducting surface moving at high speed to form a conductively supported film of the electrolyte within the range of from about 0.001 to about 0.008 inch moving rapidly in streamline, non-turbulent flow, thereafter disposing the surface of said body from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the body as an anode and the conductive film-supporting surface as a cathode to remove stock from the body, and maintaining such surface of said body in contact with the electrolyte film but spaced from the conducting surface supporting the same during such stock removal operation.

2. The method of sharpening, shaping and finishing a metallic body by removing stock therefrom, which comprises metering a thin layer of electrolyte onto a smooth electrically conducting surface moving at high speed to form a conductively supported film of the electrolyte of a thickness within the range of from about 0.001 to about 0.008 inch moving rapidly in streamline, non-turbulent flow, thereafter disposing the surface of said body from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the body as an anode and the conducting film-supporting surface as a cathode to remove stock from the body, said electrolyte having high solubility for the metal oxides produced by the electrolytic dissolution, and maintaining such surface of said body in contact with the electrolyte film but spaced from the conducting surface supporting the same during such stock removal operation.

3. The method of sharpening, shaping and finishing an electrically conductive body by removing stock therefrom, which comprises metering a thin layer of electrolyte onto a smooth electrically conducting surface moving at high speed to form a conductively supported film of the electrolyte of a thickness within the range of from about 0.001 to about 0.008 inch moving rapidly in streamline, non-turbulent flow, thereafter disposing the surface of said body from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the body as an anode and a conductive film-supporting surface as a cathode to remove stock from the body, and advancing the body during such stock removal operation at a predetermined uniform rate of feed, such surface of said body being maintained in contact with the film of electrolyte but spaced from the conducting surface supporting the same.

4. The method of sharpening, shaping and finishing a metallic body by removing stock therefrom, which comprises metering a thin layer of electrolyte, having high solubility for the metal oxides produced by the electrolytic dissolution, onto a smooth electrically conducting surface moving at high speed to form a conductively supported film of the electrolyte of a thickness within the range of from about 0.001 to about 0.008 inch moving rapidly in streamline, non-turbulent flow, thereafter disposing the surface of said body from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the body as an anode and the conductive film-supporting surface as a cathode to remove stock from the body, and advancing the body during such stock removal operation at a predetermined uniform rate of feed, such surface of said body being maintained in contact with the film of electrolyte but spaced from the conducting surface supporting the same.

5 The method of sharpening, shaping and finishing a metallic body by removing stock therefrom, which comprises metering a thin film of electrolyte, in which the metallic oxides produced in the electrolytic dissolution of said body are soluble, onto a smooth rapidly moving electrically conductive surface in streamline, non-turbulent flow, the thickness of said film of electrolyte being within the range of from about 0.001 to about 0.008 inch, thereafter disposing the surface of said body from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the body as an anode and the conductive film-supporting surface as a cathode to remove stock from the body, and advancing the body during such stock removal operation at a predetermined uniform rate of feed, such surface of said body being maintained in contact with the film of electrolyte but spaced from the conductive surface supporting the same.

6. The method of sharpening, shaping and finishing a metallic carbide body including metallic cementing material by electrolytically removing stock therefrom, without formation thereon of a solid polarizing film of oxide, which comprises discharging an electrolyte in which the oxides of the carbide and the metallic cement of said body are soluble onto a smooth rapidly moving electrically conductive surface, such discharge being metered to form a thin non-turbulent film of the electrolyte of a thickness within the range of from about 0.001 to about 0.008 inch on said surface, thereafter disposing the surface of said body from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the body as an anode and the conductive film-supporting surface as a cathode to remove stock from the body, and maintaining such surface of said body in contact with the electrolyte film but spaced from the conductive surface supporting the same during such stock removal operation.

7. The method of sharpening, shaping and finishing a cobalt-cemented tungsten carbide body by electrolytically removing stock therefrom, without formation thereon of a solid polarizing film of oxide, which comprises discharging an electrolyte in which tungsten oxides are soluble and which contains a cobalt solubilizing group onto a smooth rapidly moving electrically conductive surface, such discharge being metered to form a thin non-turbulent film of the electrolyte of a thickness within the range of from about 0.001 to about 0.008 inch on said surface, thereafter disposing the surface of the body from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the body as an anode and the conductive film-supporting surface as a cathode to remove stock from the body, and advancing the body during such stock removal operation at a predetermined uniform rate of feed, such surface of said body being maintained in contact with the film of electrolyte but spaced from the conducting surface supporting the same.

8. The method of electrolytically sharpening, shaping and finishing simultaneously all three components of a composite workpiece in which cobalt-cemented tungsten carbide is brazed to a steel body, without formation of a polarizing film of oxide, which comprises discharging an alkaline cyanide-amine chloride electrolyte onto a smooth rapidly moving electrically conductive surface, such discharge being metered to form a thin non-turbulent film of the electrolyte of a thickness within the range of from about 0.001 to about 0.008 inch on said surface, thereafter disposing the surface of said workpiece from which stock is to be removed in contact with the thus preformed film of electrolyte, applying direct current voltage across the workpiece as an anode and a conductive film-supporting surface as a cathode to remove stock from the workpiece, and maintaining such surface of the workpiece in contact with the electrolyte film but spaced from the conductive surface supporting the same during such stock removal operation.

9. The method of sharpening an electrically conductive body by electrolytically removing stock from a selected surface of said body to produce a sharp edge thereon, which comprises metering a thin layer of electrolyte onto a smooth electrically conductive surface, while moving such surface at high speed to form thereon a conductively supported film of the electrolyte of a thickness within the range of from about 0.001 to about 0.008 inch moving rapidly in streamline, non-turbulent flow, thereafter disposing the surface of said body from which stock is to be removed in contact with the thus preformed film of electrolyte, with the edge of the selected surface to be sharpened facing upstream and substantially at right angles to the direction of movement of the film of electrolyte, applying direct current voltage across the body as an anode and the conductive film-supporting surface as a cathode to remove stock from such selected surface of the body, and maintaining such surface of the body in contact with the electrolyte film but spaced from the conductive surface supporting the same during such stock removal operation.

10. Apparatus for sharpening, shaping and finishing conductive bodies electrolytically, comprising a rotatable cathode disc having a smoothly dished surface, an electrolyte delivery conduit having its discharge opening closely spaced adjacent such surface of the cathode disc, baffle means at such discharge opening of the delivery conduit arranged generally transversely thereof and having a bottom margin in close-spaced relation to such surface, whereby electrolyte flowing from such opening is deflected by said baffle means under such bottom margin thereof and deposited on the cathode surface, upon rotation of the same, as a thin layer, drive means for rotating the cathode disc at high speed thereby to impact the electrolyte thereagainst by centrifugal force and form a thin, rigidized film of electrolyte on such surface, support means spaced from and independent of said baffle means

for mounting a conductive workpiece in contact with said film of electrolyte, and means for applying electrolysis voltage across said cathode and said workpiece as an anode.

11. Apparatus for sharpening, shaping and finishing conductive bodies electrolytically, comprising a rotatable cathode disc having a smooth surface, an electrolyte delivery conduit having its discharg opening closely spaced adjacent such surface of the cathode disc, baffle means at such discharge opening of the conduit arranged generally transversely thereof and having a bottom margin in close-spaced relation to such surface, whereby electrolyte flowing from such opening is deflected by said baffle means under said bottom margin thereof and deposited on the cathode surface, upon rotation of the same, as a thin layer, drive means for rotating the cathode at high speed to form a thin, non-turbulent film of the electrolyte on such surface, support means spaced from and independent of said baffle means for mounting a conductive workpiece in contact with said film of electrolyte, and means for applying electrolysis voltage across said cathode and said workpiece as an anode.

12. Apparatus for sharpening, shaping and finishing conductive bodies electrolytically, comprising a cathode having a smooth surface, electrolyte delivery means so constructed and located adjacent the cathode as to discharge electrolyte on such cathode surface with negligible turbulence in a thin wide stream, means supporting said cathode for movement relative to said electrolyte delivery means, drive means for thus relatively moving said cathode at high speed, thereby to form a thin non-turbulent film of the electrolyte on the smooth cathode surface, support means spaced from and independent of the electrolyte delivery means for mounting a conductive workpiece in contact with the thus formed film of electrolyte, and means for applying electrolysis voltage across said cathode and said workpiece as an anode.

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