Voltage $V_1$ less than $V_2$.

Voltage signal from Transformer $X_2$ at $T_8$.

Voltage signal at $T_7$ to grids of $V_3$ and $V_4$.

Anode current of tubes $V_3$ and $V_4$.

Current in $W-1$ windings of motor.

Current in $W-2$ windings of motor.

Currents in both windings of motor.

Voltage $V_2$ less than $V_1$.

A-c timing wave at Comp-Term X&Y.

Fig. 10
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 for 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 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 or wear 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 diamond reduces 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-
in full described and particularly pointed out in the
claims, the following description and the annexed draw-
ing s setting forth in detail certain illustrative embodi-
ments 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, sub-
stantially 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.

The term "electrolytic dissolution" as used through-
out this description and in the claims is meant the sub-
stantial 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
procedures as electrolytically conducting, 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 volt-
age above which further increase will not cause the re-
quired 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 electroplating, metal dis-
solution rates do not exceed 0.05 to 0.1 inch per hour.

Other investigators have increased electrolytic dissolu-
tion by means of mechanical assistance given by elec-
trically conducting abrasive wheels in contact with the
article being electrolytically ground so as to continuously
scrape away insulating salt or oxide coatings, and there-
by, provide for continuous high current density and
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 shap-
ging. 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
rates by the conditions of relative rate of film formation
and removal by scraping.

A significant and greater increase in electrolytic grind-
ing 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 accoun-
talment 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 metals are accomplished with out
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-re-
moval rate of 0.057 inch per minute at 1550 ampere-cen-
square inch at 76 percent metal anode current efficiency, or of
0.040 inch per minute at 100 percent anode efficiency.

It is not unexpected that technical and patent litera-
ture described processes in which scraping or abrasive
assistance is required for electrolytically grinding

cemented tungsten carbide. Most usually, the consum-
ing metal is cobalt. Tungsten oxide is well-known to be
soluble in alkaline solutions and insoluble in acid solu-
tions. 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 elec-

trolytic grinding rates without scraping to remove either
tungsten oxide or cobalt oxide, depending on whether the
electrolyte is acid or alkaline. By the methods of the
present invention which depend on scraping of the anode face, the dis-
advantage exists in that control is difficult and critical for
maintaining light weight 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
soluteing anion for removing cobalt very soluble. A
suitable electrolyte contains sodium tartrate, sodium
hydroxide and sodium chloride.

Providing an electrolyte with capacity to accept tung-
sten 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 re-
placed at a high rate at the anode face. Such replace-
ment can be effected in a satisfactory manner by dis-
tributing the electrolyte in a layer less than 0.020 inch
and usually less than 0.006 inch in thickness on a rotat-
ing cathode disc as heretofore 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 assembly illustrated in Fig. 2 showing in greater

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
grounding cemented tungsten carbide;

Fig. 6 is a similar graph when the object electrolytically
ground is made of high carbon 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 system 299,895.

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 circulation 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. The spindle on which the cathode disc 2 is carried. 2. The system for circulating the electrolyte and 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 toward the gap control 9 and is supported 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 amperemeter and the control 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 suitable 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 a means of adjustment 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 Figs. 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 adjusting the angle 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 20, although any other suitable means may be employed for adjusting the anode in any desired position with respect to the upper surface of the cathode disc 2. 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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 in 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 is 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 the passage of the grinding machine, 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 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.

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.

- For tungsten carbide:
  - Sodium tartrate (Na₂C₄H₄O₆) 150
  - Sodium hydroxide (NaOH) 150
  - Sodium chloride (NaCl) 20

- For composite articles:
  - A. Triethanolamine (HOCH₂CH₂OH)₃N 197
  - Sodium hydroxide (NaOH) 50
  - Sodium chloride (NaCl) 100
  - Sodium cyanide (NaCN) 25
  - Sodium carbonate (Na₂CO₃) 25
  - B. Sodium tartrate (Na₂C₄H₄O₆) 105
  - Sodium hydroxide (NaOH) 60
  - Sodium cyanide (NaCN) 25
  - C. Sodium tartrate (Na₂C₄H₄O₆) 168
  - Sodium hydroxide (NaOH) 60
  - Sodium chloride (NaCl) 50

- For vanadium steel:
  - Sodium hydroxide (NaOH) 200
  - Boric acid (H₃BO₃) 25

75 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 impurity often 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 metal 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 permits 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 electrolyte 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 60% 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 limiting current density by disturbing the naturally-forming diffusion layer so that the products of dissolution are swept away and fresh dissolution 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 plunged ground electrolytically in the following aqueous electrolyte:

<table>
<thead>
<tr>
<th>Composition</th>
<th>Concentration (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium tartrate (Na₂C₂H₄O₄)</td>
<td>150</td>
</tr>
<tr>
<td>Sodium hydroxide (NaOH)</td>
<td>150</td>
</tr>
<tr>
<td>Sodium chloride (NaCl)</td>
<td>20</td>
</tr>
</tbody>
</table>

The cutting rate in inches 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.

<table>
<thead>
<tr>
<th>Current Density Range (amperes per square inch)</th>
<th>Appearance of Cemented Carbide Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 to 30</td>
<td>Dull, gray anode film; uneven surface.</td>
</tr>
<tr>
<td>30 to 60</td>
<td>Very gray anode film; duller than 10 to 30.</td>
</tr>
<tr>
<td>60 to 100</td>
<td>Good edge and smooth surface (55.8 to 7.2 R.M., 8. microns).</td>
</tr>
<tr>
<td>1,151 to 1,600</td>
<td>Good edge, but less smooth than surface at 100 to 1,150 amp./sq. ft.</td>
</tr>
</tbody>
</table>

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 engines 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 electrolytic 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 tool 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 (HOC$_2$H$_2$NH$_2$) 197
   Sodium hydroxide (NaOH) 50
   Sodium chloride (NaCl) 100
   Sodium cyanide (NaCN) 25
   Sodium carbonate (Na$_2$CO$_3$) 25
   Sodium tartrate (Na$_3$C$_6$H$_5$O$_7$) 105
   Sodium hydroxide (NaOH) 50
   Sodium chloride (NaCl) 25
   Sodium cyanide (NaCN) 25

Current density .................................... gpl. 300
Cathode wheel speed ..................................... ft/min. 6000
Anode area ........................................ sq. in. 0.2
Anode-to-cathode space ................................... sq. 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 rounded; 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 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:

<table>
<thead>
<tr>
<th>Component</th>
<th>G./l.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium tartrate (Na$_3$C$_6$H$_5$O$_7$)</td>
<td>60</td>
</tr>
<tr>
<td>Sodium hydroxide (NaOH)</td>
<td>60</td>
</tr>
<tr>
<td>Sodium chloride (NaCl)</td>
<td>50</td>
</tr>
</tbody>
</table>

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 salt 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 0.101 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 anion 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 of 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 or a surface such as results from the rippling, shearing, tearing, and nonuniform cutting by abrasives and contact tools; 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. 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 55 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 values of gap spacing 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 contour, by using a constant voltage source, the electrolytic current's flow is a measure of the gap between the tool and the disc. This phenomenon 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 filament of tubes V3, V4, V5 and V6 causing them to heat, and activates the metal reed of converter CON-1. Voltage induced in secondary 2 in SEC. 2 is applied between the right hand plate of V5 and bus B-1 by means of wires A and B. The right hand section of V2 and connected as a rectifier and a D.C. voltage is caused to appear between terminals T1 and T2. T1 is positive in polarity with respect to T2.

Resistor R2 and capacitor C5 are part of a filtering network which smooths the fluctuations from the rectified D.C. voltage. In the phase sensitive amplifier, Rg, R3 and R4 are series resistors placed in the cathode placemats of V1, V2 and V4 respectively. C3 and C4 are cathode by-pass capacitors to reduce degeneration. C15 and C16 are decoupling capacitors.

In the electrolysis circuit, current I1 flows from the voltage source E1 through wire E to the brushes by means of a brush. This 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 E2 by means of wire D and resistor R4 and wire E. A voltage V1 is developed across transformer X1 between terminals T1 and T2 by the passage of the electrolysis current. The magnitude of this current and voltage V1 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 I2 passes from the source E2 through resistors R5 and R6 and back to the source E2.

This current I2 is controlled in magnitude by fixed resistors R5 and R6, and variable resistor R7. R4 is present to control the maximum of current which flows when R5 is at a minimum. In operation, R5 is adjusted so that the proper current I2 flows through R6, establishing an A.C. induction in T1 and T2, equal to V2 between terminals T1 and T2 when the desired amount of electrolysis current is flowing. When the desired amount of electrolysis current is flowing, V1 is equal to V2.

The polarities of V1 and V2 are so arranged that when V1 and V2 are equal in magnitude, no net voltage appears between terminals T1 and T2.

Converter 1 operates in conjunction with transformer X4 in such a manner that a 60 cycle alternating voltage V9 appears at terminals T3 and T4 when a D.C. voltage occurs at terminals T5 and T6. This 60 cycle voltage V9 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 T5 and T7.

When the desired electrolysis current I1 is flowing, a net voltage of zero appears between terminals T3 and T7. Whatever voltage appears between terminals T2 and T5 is transmitted through wires F and G, through reversing switch SW-3 to terminals T6 and T8, thence by wires H and I to converter CON-1. Since the voltage between T2 and T5 is zero, the voltage V9 that appears between terminals T3 and T6 is also zero. V9 also has zero net voltage at T6, the grid G24 of the left hand section of tube V1 is at the same potential as cathode K24. This lets the left hand section of tube V1 pass current. These electronics flow from bus B-1 through R5, through the left section of tube V1, R4, R13 and R14 to terminal T1. A voltage V9 appears across R5 which is positive at K24 and negative at B-1. This makes cathode K24 more positive than grid G24, decreasing the current in the left hand side of tube V1. This voltage V9 across R5 is the grid bias of the left hand side of tube V1. Hence, with no grid signal, the left hand side of V1 passes a small steady current, producing also a voltage across R13 and R14. However, no matter what steady voltage appears between points T5 and T6, capacitor C5 charges to this voltage, and no voltage remains across R13 and R14. Similarly the anode current which passes through the right hand side of tube V6 develops a voltage across R7 which is a biasing voltage. This limits the anode current in the right hand side of tube V1 to a small steady flow. This has no effect on the left hand side of V2, for capacitor C6 has charged to the voltage between points T5 and bus B-1, so that no voltage remains across R6. The left hand side of V2 has voltage and passes some anode current. Similarly, C7 has charged to the voltage T4 to bus B-1, and grids G23, G24, G25, G26 and G27 of both tube V2 and V4 are at the same potential as bus B-1.

Although in all sections of V3 and V4, the cathodes are tied together, and the grids are tied together, the tubes are not in parallel. Anodes P34 and P35 are connected by wire J to terminal T35, one side of transformer X1 secondary 3. Anodes P34 and P35 are connected by wire K to terminal T36, the other side of secondary 3 of transformer X1. The left hand section of V3 and V4 is in phase with the wire of M4, during one half cycle. The right hand section of V3 and the left hand section of V4 may fire during the next half cycle. Never do all four sections of V3 and V4 pass current at the same time. While their grids, attached to terminal T37, remain at B-1 potential, the tubes V3 and V4 act as a two tube full wave rectifier, producing a small direct current. These electronics flow from terminal T6, the center tap of SEC. 3, transformer XI through wire L, through one set of windings (W-1) in the two-phase motor, through wire M to bus B-4, through R4 to cathodes K34, K35, K36 and K37 and through the left and right sections of V3 and V4, in turn. The voltage developed across R4 makes cathodes K34, K35, K36 and K37 more positive than grids G34, G35, G36 and G37 attached to terminal T7, thus acting as grid bias. This limits the amount of anode current of V3 and V4. This direct current through the motor windings does not turn the motor, since it is an A.C. induction in T1 and T2, but it does tend to make it move more stable. So, until a signal voltage appears at T6, all tubes pass current steadily but the motor does not turn.

In Fig. 9, suppose that the electrolysis current I1 decreases, lowering the voltage V1 developed across R5 to a value less than V9 developed across R5. A voltage thus appears between terminals T3 and T7, which is positive at T3 and negative at T7. With switch SW-3 in the down position this voltage appears between terminals T6 and T9,
and is carried by wires H and I to the converter CON-1. Consequently a 60 cycle signal voltage appears at $T_9$ as shown in curve 2, Fig. 10. During the half wave $X$, grid $G_5\beta$ becomes more positive, increasing the anode current of the left hand section of $V_4$. This reduces the potential at terminal $T_{39}$. Since capacitor $C_9\alpha$ cannot change its charge instantly, the potential at $G_{39}\beta$ is forced more negative. Since the grid voltage of the right hand side of $V_4$ becomes negative, its anode current decreases. When the current decreases in the right hand side of $V_4$, the potential at terminal $T_{39}$ increases. Since capacitor $C_9\alpha$ cannot change its charge instantly, the potential at terminal $T_{39}$ also increases. When the potential at terminal $T_{39}$ increases, the anode current through the left hand side of $V_4$ decreases, decreasing the potential at terminals $T_{19}$ and $T_{29}$. The slider on resistor $R_1\alpha$ is a sensitivity control. When it is moved toward the lower end, less of the voltage developed across $R_1\alpha$ is used to change the current in the left hand side of $V_4$, so the whole amplifier has less output at terminal $T_{19}$.

During the half wave $X$ when current increases in the left hand side of $V_4$, decreases in the right hand side of $V_4$, and increases in the left hand side of $V_5$, the potential at terminal $T_{49}$ decreases. Coupled through capacitor $C_{19}$, the potential at terminal $T_{49}$ is more negative than bus $B-I$. Curve 3 of Fig. 10 shows this change at $T_{49}$, which is the grid voltage of tubes $V_3$ and $V_4$. During half cycle $X$, anodes $P_{24}$ and $P_{25}$ are positive, and anodes $P_{24}$ and $P_{25}$ 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 $P_{24}$ and $P_{24}$ are now negative. The amount of this current increases as 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 $V_3$ is less than voltage $V_4$. These current pulses (curve 4, Fig. 10) are changed into an alternating current by adding capacitor $C_9\beta$, which is the proper size to resonate at 60 cycles with the motor windings $W-I$. Current flows back and forth through windings $W-I$ and is out of capacitor $C_{19}$. This current is reversed and kept flowing by the pulses of current (curve 4, Fig. 10) from the electrolyte with of $V_3$ and the right hand section of $V_4$. Since the current lags by $90^\circ$ when flowing through an inductive coil, the current wave form through coil $W-I$ will lag by $90^\circ$ (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 $C_{19}$ back to the mains. Since the current in an Inductive coil lags the applied voltage, capacitor $C_1\beta$ is added to bring the current wave form in phase (curve 6, Fig. 10) more nearly in phase with the applied voltage.

When the left side of $V_4$ and the right side of $V_4$ alone pass current, the current in the motor $W-I$ windings is shown by curve 5. This is also shown in curve 7, which includes curve 6 (current in the $W-2$ windings). The $W-I$ 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 $I_{19}$, tive. As current $I_{19}$ increases, so that voltage $V_1$ is larger than voltage $V_2$, there will again be a voltage between terminals $T_8$ and $T_9$. 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 $T_9$ is like curve 9, Fig. 10, or shifted 180 degrees from the previous signal as shown in curve 2, Fig. 10. Since $T_9$ is negative during the first half cycle to be removed, the current in the left hand side of $V_4$ decreases, and the current in the right hand side of $V_4$ increases, the current in the left hand side of $V_4$ decreases, and the signal at terminal $T_9$ 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 first tube $P_{24}$ and $P_{24}$ are negative during this half cycle and the left hand section of $V_4$ and the right hand section of $V_4$ will not pass current. Anodes $P_{24}$ and $P_{24}$ are positive during this half cycle so the left hand section of $V_4$ and the right hand section of $V_4$ may pass pulses of current (curve 11, Fig. 10). These pulses cause an alternating current to flow in winding $W-I$ of the motor and resonating capacitor $C_{19}$ 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 $V_4$ (curve 11, Fig. 10). Since these tube currents (curvelli) occur a half cycle later than currents illustrated in curve 4, the wave of current in the $W-I$ windings is also later. In the combined curves 14 we see that the $W-I$ 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, changes 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 conducting 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 conductivity supported film of electrolyte within the range of from about 0.001 to about 0.008 inch moving rapidly in a 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 across the body as an anode and the conducting 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 conductivity supported film of 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 the first half cycle, the current being in 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 electrolytically 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 the thickness of a layer of electrolyte, 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 carbide body by electrolytically 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, maintaining 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 conducting 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 conducting 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 body as an anode and the 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 conducting 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 motion 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 conducting 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 so as to form 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 discharge 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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