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FABRICATION OF METAL ARTICLES

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2 Sheets-Sheet 1

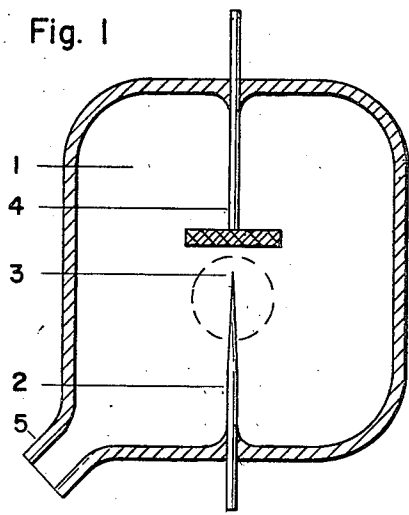
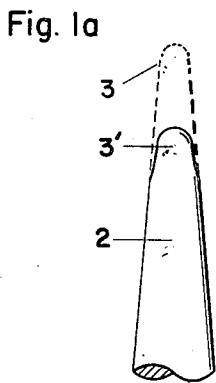
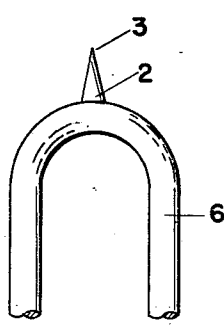


Fig. 2

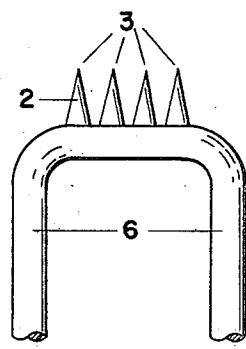


Fig. 3

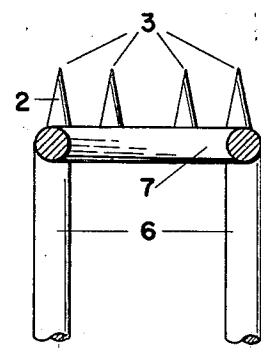


Fig. 4

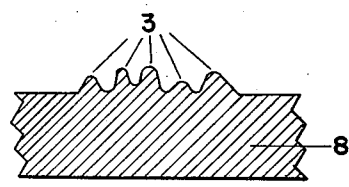


Fig. 5

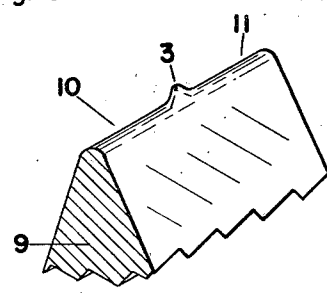


Fig. 6

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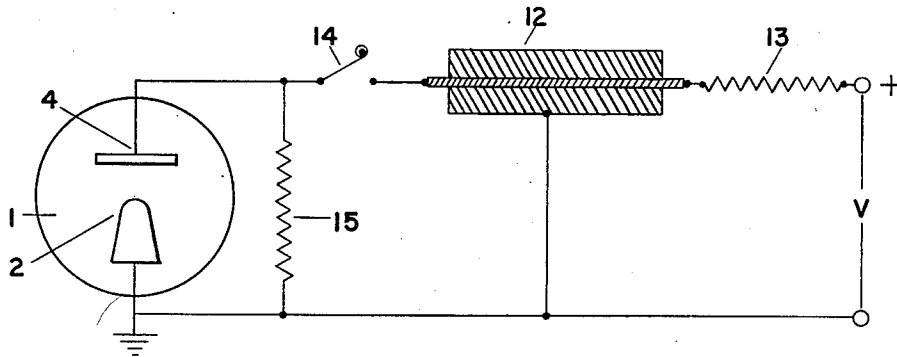


Fig. 7

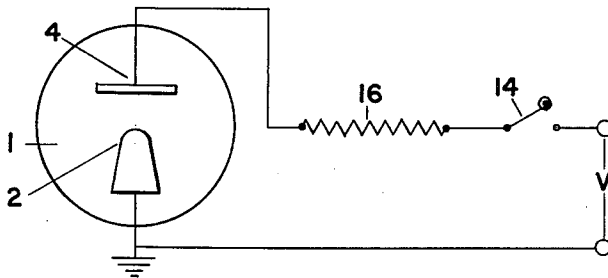


Fig. 8

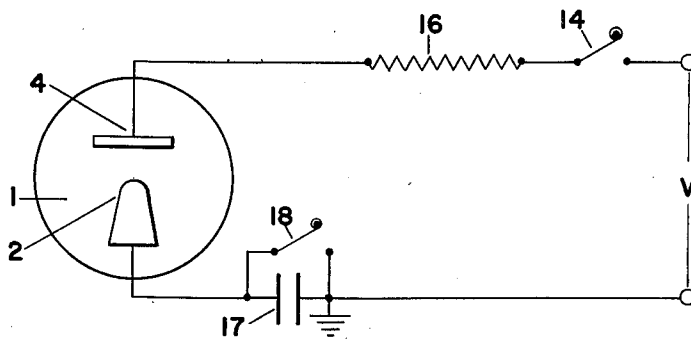


Fig. 9

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1

2,817,002

FABRICATION OF METAL ARTICLES

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7 Claims. (Cl. 219—121)

The invention relates to methods for fabricating metallic articles, a part of whose smooth surface has a small radius of curvature and to the articles thereby produced. The invention provides a method for controlling the radius of curvature of such surfaces. One use for such metallic articles is as field emission cathodes, i. e., sources of electrons, in vacuum tubes.

A field emission cathode generally consists of a small emitting surface area over which the radius of curvature has a small but relatively constant value. This surface, often approximately a hemisphere, is in many cases supported on a shank structure which resembles a cone of relatively small angle, including the limiting case of a cylinder. The field emission of electrons from such emitters occurs primarily from the hemispherical tip surface where a large electric field, usually between 10^7 and 10^8 v./cm., is maintained by a high and relatively positive potential in a nearby electrode. For many applications it is desired to have an approximately uniform electric field over an appreciable area of the emitter hemisphere. This arrangement achieves a corresponding uniformity of the emission current density, and hence maximum total current for a given hemisphere, and other benefits. For such purpose the hemispherical surface must be smooth.

The cone angle of the supporting emitter shank is advantageously (but not necessarily) chosen between 5° and 30° . Smaller angles favor a higher value of electric field at the emitter tip for a given value of the applied potential; however, very small cone angles provide poor conduction of heat from the support filament to the emitter tip, or vice versa, for example in the event of resistive heating of the tip by the emission current.

In the present invention, a small metallic object is deformed under the action of forces as described below as the result of thermal energy added during electrical discharge initiated by the field emission of large electron current densities from certain surfaces of the metallic object. The invention is selective, avoiding alteration of other surfaces where field current density is low. The invention includes methods for controlling the extent by which radius of curvature of the surface is altered and its direction of change, that is, increase or decrease.

The invention makes use of a large temperature increase at or near the field emitting surface during electrical discharge. Thermal agitation of the emitter material permits alteration of any or all of the following, hereinafter called "deformation": the emitter surface configuration, the surface and volume composition of the emitter, that is, crystallographic structure, chemically or physically adsorbed or absorbed materials etc., and the volume of the emitter.

Thermal energy may be added at or near localized field emitting surfaces by any processes during discharge in high vacuum, including resistive heating in the presence of large emission current densities, or "emission heating" (defined below).

As an alternate method, thermal energy may be added

2

at or near localized field emitting surfaces by several processes during discharge in gas, such as, ion bombardment, resistive heating, emission heating.

The invention will be more particularly described with reference to the accompanying drawings in which:

Fig. 1 is a sectional elevation of an arrangement for practicing the invention;

Fig. 1A is an enlarged fragmentary view of a field emitter cathode illustrating the principles of the invention;

Figs. 2-6 are enlarged fragmentary views of various forms of field emitter cathodes illustrating the principles of the invention; and

Figs. 7-9 are diagrammatic representations of several electrical circuits useful in practicing the methods of the invention.

In Fig. 1 is shown a discharge vessel 1 which contains a metallic cathode 2, a portion of whose surface 3 has a small radius of curvature, and a metallic anode 4. The discharge vessel is evacuated through the pump lead 5 which may be sealed off if desired. When the cathode 2 is grounded, a high positive potential applied to the anode 4 produces a large electric field at the cathode tip surface 3. As a result of that high field, electrons are emitted from the cathode tip surface 3, the emission process being well known as field emission. No appreciable emission will originate from other parts of the cathode surface 2 where the electric field is relatively low, if in order to simplify the following discussion it may be assumed that such surfaces are smooth and free from contaminants which condition may be achieved by the use of the invention as will be noted below. The average current density emitted at the tip surface 3 increases with increasing values of the applied potential difference between electrodes 3 and 4 in a manner expected for field emission until a critical current density is reached. At the critical current density the temperature in the immediate vicinity of the emitter tip is increased by heat from resistive generation or from emission heating or from both. Thermal agitation from these processes accompanying field emission may be used to effect emitter deformation. In addition, thermal energy may be added to the emitter tip at a much higher rate by forming a vacuum arc at the tip surface which arc is initiated by very large field current densities in the presence of a high emitter temperature. Total currents emitted during arc generally exceed the initiating field currents by a large factor and cause a corresponding increase in the thermal energy dissipated in the emitter.

The foregoing describes mechanisms by which thermal energy is added during a discharge in vacuum to the metal object to be deformed. Methods for determining the type of deformation and limiting its extent are described next.

Use of a short time duration discharge is fundamental to the invention in order both to control the total energy dissipated in the emitter during discharge and to minimize heat conduction and thus confine emitter deformation to localized regions in which thermal energy is dissipated.

In the case of emission heating, the corresponding thermal energy is liberated close to the emission surface, that is, within a few electron mean free path lengths. In the case of resistive heating, the cathode geometry is chosen so that both current density and the corresponding resistive heat generation are high only in regions in which cathode deformation is desired.

Consider for example a conical cathode 2 with a hemispherical tip 3 as shown in Fig. 1, which cathode is typical of those often used as field emitters. The same cathode is shown in enlarged view in Fig. 1A. It is desired to effect a deformation of the cathode tip 3 during a controlled electrical discharge in vacuum for which purpose field emission is obtained from the tip surface 3 as described

3

above. The procedure to be followed and the corresponding cathode deformation may take several forms.

Consider first the alteration of the original tip surface 3 into the final smooth surface 3' whose radius of curvature is increased in the process. Use is made of a short discharge time, and the voltage is applied between anode 4 and cathode 2 in the form of a voltage pulse by means described later. During the ensuing discharge in vacuum, the resistive generation of heat is appreciable only within the dashed surface 3 of Fig. 1A where current density is high; resistive heating is inappreciable in other regions such as 2 where current density is low. Emission heating is confined within an even smaller distance from the emitter tip. Use of a short discharge time minimizes heat conduction from the heated region 3 to cooler regions 2 and correspondingly limits the emitter deformation to the regions of high temperature under the dashed curve 3. If the material under the dashed curve 3 is melted during discharge by suitable current densities as a result of field emission and/or the vacuum arc, and if a portion of the melted emitter tip 3 is removed by large forces due to the applied electric field and/or to explosive thermal agitation, and if the remaining molten emitter material cools under the action of its own surface tension forces in the absence of electric field after discharge, then the final emitter tip surface is smooth and approximately hemispherical as shown in 3' in Fig. 1A. In this case the radius of curvature of the tip surface is increased slightly during discharge, a useful feature for several purposes noted below.

The extent of emitter deformation in the foregoing case, that is, the amount of tip material removed and the increase in tip radius, is controlled by limiting the time duration of the discharge and the energy dissipated in the emitter in the process. Discharge times between 10^{-10} and 10^{-4} seconds will generally be useful in the foregoing example of geometric deformation of a typical field emission cathode. However, for some cases noted later, particularly for voltage insulation, in which field emission is to be inhibited, more gross deformation achieved with longer discharge times may be useful.

If a very small increase in cathode tip radius is required in the foregoing example, for instance to clean or shape the surface without changing appreciably its radius of curvature or to increase the radius by a small amount to permit the parallel operation of two emitters, the following procedure will be useful. During a very short discharge time at high field current density, emission heating causes a high temperature and correspondingly increased resistivity near the emitting surface. Subsequent resistive generation of heat is concentrated in that surface layer of high resistivity which may be thus deformed, the extent of deformation depending on the extent to which such heating is conducted away from the surface, which is controlled by the time of discharge. In other words, by use of very short discharge times the emission heating further localizes the resistive heating and therefore effects the desired localization of the accompanying emitter deformation.

For example, when working with a tungsten cathode having a cone angle of about 10° and a radius of curvature at the tip of about 3×10^{-5} cm., the application of 15 kv. for about 1.0 microsecond will increase the radius of curvature by a factor of about 100, while the application of the same voltage for about 0.01 microsecond will increase the radius of curvature by a factor of 2 to 10.

In general, potentials of from 1 to 100 kv. are particularly useful although high potentials may be used. Typically the pressures in vacuum operation are less than 10^{-4} mm. of Hg.

In the foregoing example the emitter tip radius was increased and its surface smoothed when the molten metal cooled in the absence of field under the action of its own surface forces. The principles of the invention may also

4

be used to cause other types of deformation of the emitter in the solid phase. As one example, surface contaminants may be removed by evaporation, by surface migration, or may be incorporated in the metal by volume diffusion through thermal agitation produced by the method of the invention. These types of deformation may be accomplished in the absence of a field by use of a discharge time short compared to the time required for the emitter to cool.

The invention may also be useful when it is desired to decrease the radius of curvature of a metallic surface or a portion thereof. It is well known that such decrease in radius is observed in the combined presence of high electric field and high temperature. In the particular case of field emission cathodes the process is called build-up, and can proceed through growth of principal crystal faces on the cathode surface through temperature and field assisted plastic flow, surface migration or volume diffusion of atoms.

In a similar manner the method of the invention may be used to inhibit undesired field emission from certain surfaces, for example the cathode surfaces 2 of Fig. 1A. In practice it is often found that the undesired field current densities from small areas on such surfaces are larger than the desired field current density from the cathode tip surface 3, due to roughness and/or contaminants at the former surfaces. In order to inhibit such undesired field emission the method of the invention may be used to smooth and clean the corresponding cathode surfaces.

The procedure is similar to that described above, the cleaning and smoothing of such surfaces resulting from thermal, surface and other forces accompanying the localized resistive generation of heat during controlled discharge in vacuum. Other surfaces where field current density is below a critical value are not altered during the process.

The invention may be applied to cathodes of a variety of structures and for several useful purposes other than that illustrated by the specific and simplified structure of Fig. 1. In particular, the cathodes may be of the several forms shown in Figs. 2-6, or of other configurations. In Fig. 2, a needle shaped cathode 2 is mounted on a support filament structure 6 which may be heated by an external electrical current in order to supply thermal energy to the cathode. The method of the invention may be used to control the final geometry of the cathode tip 3 and/or to prevent field emission from undesired areas such as along the filament surface 6 by removing surface projections and/or increasing the radius of curvature of small areas on the surface.

The cathode may take the form of the structure shown in Fig. 3 in which several individual needle shaped cathodes 2 are mounted on a common support filament 6, the purpose of this filament being similar to that described for Fig. 2. The method of the invention may be used to alter the geometries of one or more of the cathode tips 3 and/or to prevent undesired emission from other surfaces such as the filament 6. In particular, if one or more of the cathode tips 3, emit higher current density than the other cathodes, the radii of curvature of the former may be selectively increased by use of the invention until all cathodes emit approximately a common value of the current density for a given value of the applied potential on a nearby electrode. The method of the invention is thus used to fabricate several individual field emission cathodes on a common support filament structure in such a manner that the cathodes may be simultaneously operated effectively in parallel.

In Fig. 4 is shown an alternate cathode form, namely a group of individual needle shaped cathodes 2 mounted on a common support ring 7 which is in turn mounted on the support filament structure 6. All portions of the cathode may be heated when a conduction current is drawn through the circuit 6-7-6. The method of the invention may be used as described above to effect parallel

5

field emission from the several cathode tips 3 and to prevent undesired field emission from other structures such as the surfaces 6 and 7 in a similar manner to that described in the preceding figures.

The cathode may take the form of any gross metallic surface 8 as shown in Fig. 5 upon which are regular or irregular surface projections 3 from which field emission is obtained. The several projections 3 may be geometrically altered to permit their operation as field emitters in parallel or may be altered and/or may be removed in order to prevent field emission by the use of the method of the invention as described above.

In Fig. 6 is shown a cathode of the form obtained by sharpening the edge of a sheet of metal. The method of the invention may be used as in Fig. 5 to provide the parallel operation of numerous field emission sources in the form of surface irregularities 3; or such irregularities may be removed and/or increased in radius to minimize their field emission. The method of the invention may be used to alter the radius of curvature of the portion of the edge 10 so that both the portions 10 and portions 11 and similarly other portions of the edge emit approximately the same value of the field current density for a common value of the applied potential on a nearby electrode. In other words, the invention may be used to achieve effectively parallel operation of all edge surfaces as field emission cathodes.

If field emission from the cathode tip surface 3 of Fig. 1 is obtained by the methods described above, except that the discharge vessel 1 is filled with gas at a suitable pressure, then positive gas ions are formed very near the cathode surface by the energetic electrons and these ions bombard the electron emitting surface of the cathode with sufficient energy to permit cathode deformation. Since ions formed near the emitting surface bombard primarily that surface and not others, and since ions formed far from electron emitting surfaces are prevented from bombarding the cathode in the present invention by use of a discharge time which is short compared to the transit times of these latter ions, it follows that the present invention provides a method for adding energy to, and only to, those surfaces 3 of the cathode where electron emission originates. Because of the high electric field at and near the cathode surface, the energy added to the surface by each impinging ion is relatively high. Sufficient energy may thus be selectively added to the cathode tip surface 3, for example, to permit the deformation of that surface, under the forces which have been described above.

An essential feature of the invention is the use of very short discharge times for which purpose the circuits shown in Figs. 7-9 and other equivalent circuits are applicable. As just noted, use of short discharge times limits cathode bombardment only of those surfaces from which the field emission of electrons was appreciable, namely the surfaces with small radius of curvature. However, use of a short discharge time has the additional advantage that the energy added to the emitter and therefore its corresponding geometric deformation are thereby limited and controlled.

During a short discharge time the heat conduction down the emitter shank is small and an appreciable temperature rise is therefore confined at and near the heated tip surface 3, correspondingly confining the cathode geometric alteration to such heated regions. For these reasons a discharge time of 10^{-6} seconds, or less, is desirable.

Since it is important to this form of the invention that copious positive ion production be maintained close to electron emitting surfaces, a relatively high gas pressure in the discharge vessel 1, such as atmospheric pressure or greater, may be used. Such relatively high gas pressures provide short electron mean free path, the significance of which is that electrons therefore collide with and ionize gas atoms close to the electron emitting surfaces.

6

To achieve various desired effects the gas pressure may be varied over a wide range. The gas used may be an inert gas such as argon or helium, or where chemical reaction with the surface of the article is desired, active gases, such as oxygen, may be provided.

If the field emission cathode is needle shaped, approximating a conical shank 2 with a hemispherical tip 3 as shown in Fig. 1A, use of the gaseous discharge may produce an altered cathode tip surface 3' whose radius of curvature is larger than that of the original surface 3, the result being similar to that achieved by the discharge in vacuum as disclosed above. The gaseous discharge has the advantage that energy is added at, and only at, electron emitting surfaces near which the emitter deformation is confined. In this respect the gaseous discharge method permits restriction of the heated portion of the emitter to a smaller volume than is possible in the case of resistive heating unless of course the latter is further localized by emission heating as noted above. The gaseous discharge method exposes the heated emitter surface to gas atoms and/or ions which may thus combine chemically or physically with the emitter material, thus providing means for fabrication of emitters with various surface and/or volume materials. On the other hand, the discharge in vacuum produces a final emission surface which is clean, a result which is an advantage in some cases.

During gaseous discharge involving the heated field emission surface it is necessary to limit the energy dissipated in the cathode in order to limit and control the cathode deformation. The several electrical circuits described in Figs. 7-9 may be used for this purpose as will be described.

In some cases it may be desirable to use a discharge in gas of the type described above during which there may be appreciable resistive and/or emission heating in the cathode. In fact the latter may be further enhanced by permitting an arc at the cathode with a corresponding increase in the cathode emission current. Cathode alteration may thus be achieved by a combination of the methods described herein.

Change in cathode geometry is limited and controlled by limiting and controlling the energy dissipated in the cathode during the discharge and by concentrating the energy dissipation within a small volume of the cathode, including its emitting surface. Consider for example the conical cathode 2 with a hemispherical tip 3 shown in Fig. 1A. During electron emission from the hemispherical tip 3, the current density conducted through the conical shank is large only in the immediate vicinity of the tip. The resistive generation of heat is large only within a distance of a few tip radii from the tip 3, and energy by positive ion bombardment during gaseous discharge is added primarily at the electron emitting surface 3. Use of discharge time which are short compared with the time required for the emitter to come to thermal equilibrium and in some cases mechanical equilibrium, for example a pulse duration of 1 microsecond or less, minimizes heat conduction down the shank and localizes the significant temperature rise to the small region at and near the cathode tip 3 (volume included in the dashed curve 3 of Fig. 1A). Since the emitter deformation is localized within the heated region, use of short discharge times therefore limits the extent of deformation.

A large current increase may accompany the transition from field emission to arc and causes a corresponding increase in the resistive generation of heat. The effect of this additional heat energy is to melt a relatively large volume of the emitter tip, unless the total energy available for discharge and for dissipation in the emitter is limited. Methods for controlling such energy dissipation and the corresponding alteration in cathode geometry are an important part of this invention for both the gaseous and the vacuum discharges.

In Fig. 7 is shown one method for limiting both the

time duration of the discharge and the energy dissipated thereby in the cathode. The discharge vessel 1 contains a cathode 2 and anode 4, all of which are intended to be equivalent to those shown in Fig. 1. The electrical arrangement shown in Fig. 7 provides a low impedance source of high voltage whose voltage output is in the form of an approximately rectangular pulse of short time duration. The coaxial cable 12 is charged to a source of positive potential V through the isolating resistor 13 whose value is large, for example, 5 megohms. The capacity and length of the coaxial cable 12 are chosen to give desired values of the stored total energy and voltage pulse length respectively. As an example, the cable may have an impedance of 70 ohms and a length of 10 feet. The cable 12 may be replaced by an artificial line (not shown) if desired. The cable 12 is electrically connected to the discharge vessel as indicated in Fig. 7 through the switch 14, which latter may be mechanical, a triggered air gap, a vacuum tube, or the like. The resistor 15 may have a value equal to the characteristic impedance of the cable, 70 ohms for example, or any value required to match electrically the cable to the discharge vessel. Closure of the switch 14 impresses an approximately rectangular voltage pulse of low impedance and short time duration between the cathode 2 and anode 4 of the discharge vessel 1. The discharge time is limited by choice of length of the cable, a short discharge time being desirable for the reasons noted above. The total energy available to the discharge is limited by choice of the total capacity of the cable 12 and the value of the applied potential V. In practice, successive voltage pulses of increasing amplitude may be applied to the discharge vessel 1 until the desired cathode alteration is obtained. The process may be repeated to achieve successive cathode alterations as desired. The cathode shown in Fig. 7 may take other forms, such as those shown in Figs. 2, 3, 4, 5 and 6, for example.

An alternate method for limiting the energy available to the discharge is illustrated in Fig. 8, which again includes the discharge vessel 1, cathode 2 and anode 4 as in Fig. 1. In Fig. 8, the applied potential V is connected by a switch 14 to the anode 4 through resistor 16. The latter has a large value, for example, 10 megohms, depending on the current to be drawn through the discharge vessel, and serves to limit the total current which is drawn by the discharge vessel after the initial current surge from cathode to anode which discharges the capacity of the vessel 1. The significant emitter deformation occurs during the latter initial discharge, after which the voltage drop across the resistor 16 is approximately equal to the applied potential V, thus reducing the voltage across the discharge vessel so that the discharge terminates. In this case the stored energy available to the discharge is determined by the effective electrical capacity of the discharge vessel 1 together with the value of the applied potential V, both of which may be chosen to give the desired cathode alteration. The capacity of the discharge vessel may be increased by use of a parallel capacity (not shown). The potential V may be in any desired form, i. e., static, alternating, including high frequency, pulsed, etc. Again, other cathode forms such as those shown in Figs. 2-6 for example, may be used.

A third method for limiting both the time of the discharge and the total energy available to the discharge is disclosed in Fig. 9. The applied voltage V is impressed

between cathode 2 and anode 4 of the discharge vessel 1 by closure of the switch 14. The discharge is terminated when the series condenser 17 becomes charged to or near the applied potential V, the time of discharge depending on the values of the series capacitance of the capacitor 17 and that of the discharge vessel 1, and the value of the total resistance of the circuit, that is, the resistor 16 plus the resistance of the discharge vessel. The latter is small during arcing, hence in that case the resistance 16 and the capacitance 17 may be effectively used to control the time duration of discharge. The resistance 16 may be chosen to limit the current during discharge. The process may be repeated after first opening switch 14 and closing switch 18 in order to discharge the capacitance 17. Other cathode forms, for example, those shown in Figs. 2-6 may be used. The circuits of Figs. 7-9 are intended to illustrate but not to limit the methods which may be used to control the cathode deformation.

We claim:

1. The method of treating metallic objects, a portion of which has a surface radius of curvature in the range of from about 10^{-7} to about 10^{-2} centimeters, which comprises applying between said object and an electrode positioned adjacent said portion of the object an electrical potential of at least about 1 kv. for periods of not more than about 10^{-4} seconds duration whereby an arc discharge is initiated from said portion thereof.

2. The method as defined in claim 1 wherein the said metallic object is maintained in a vacuum during said treatment.

3. The method as defined in claim 1 wherein the said metallic object is maintained in a gas during said treatment.

4. The method as defined in claim 1 wherein the said metallic object is maintained in an inert gas during said treatment.

5. The method as defined in claim 1 wherein the said metallic object is maintained in a gas reactive with said object during said treatment.

6. The method as defined in claim 1 wherein sufficient energy is supplied to said portion of the metallic object to cause fusion of at least the surface thereof.

7. The method of preparing a metallic article having a plurality of convex portions each of which emits a field emission current of approximately the same density under a common applied potential which comprises applying between a metallic object having a plurality of surface portions of small radius of curvature and an electrode positioned adjacent said surface portions a potential of at least about 1 kv. for periods of not more than about 10^{-4} seconds whereby an arc discharge is initiated from said portions thereof.

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