June 30, 1964 P. A. OELGOETZ 3,139,394

METHOD AND APPARATUS FOR ELECTRO-CHEMICAL MILLING

Filed June 20, 1962 2 Sheets-Sheet 1

Fig. 2

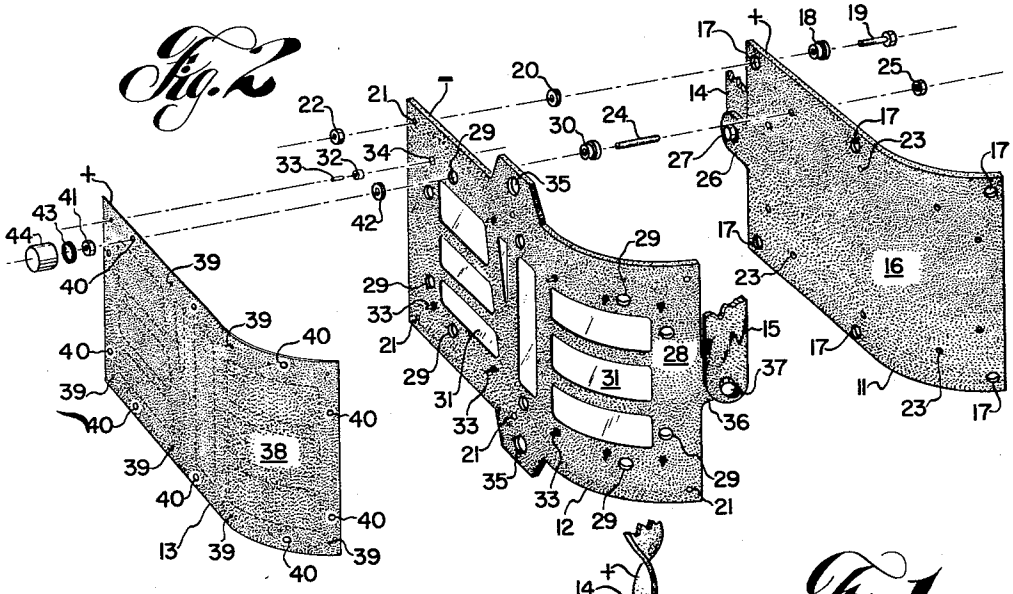


Fig. 1

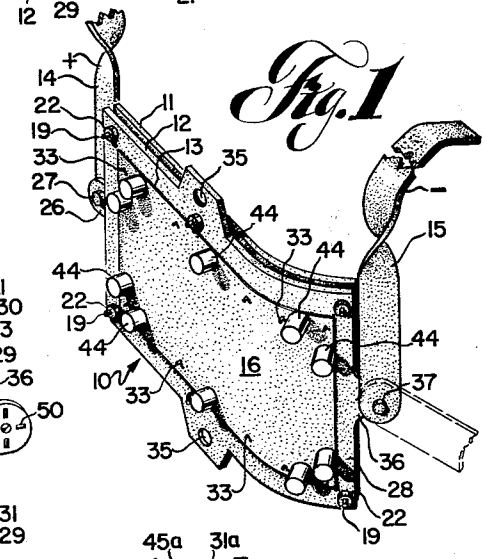


Fig. 3

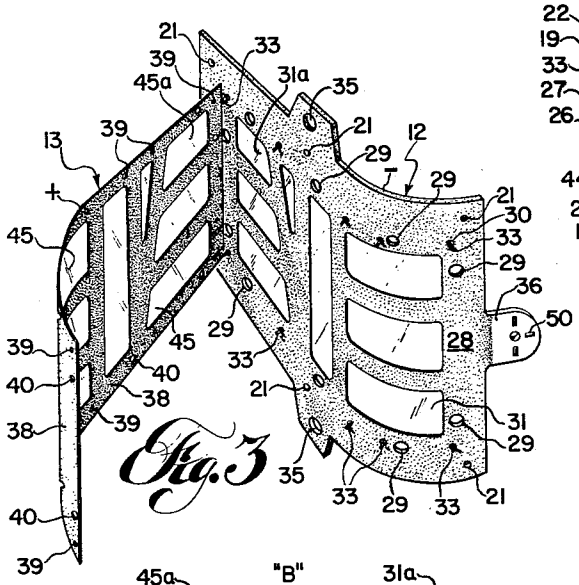


Fig. 4

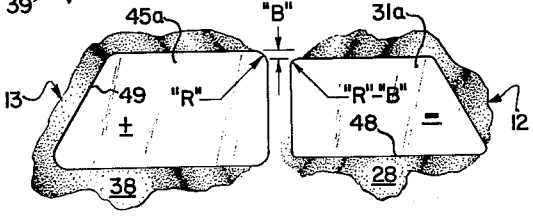
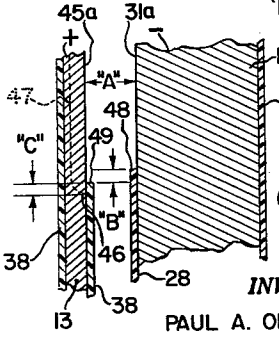


Fig. 5



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METHOD AND APPARATUS FOR ELECTRO-CHEMICAL MILLING

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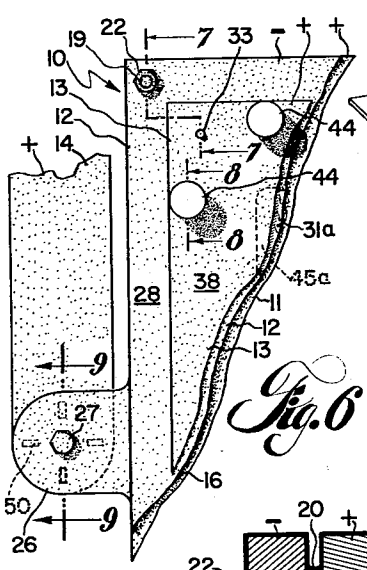


Fig. 6

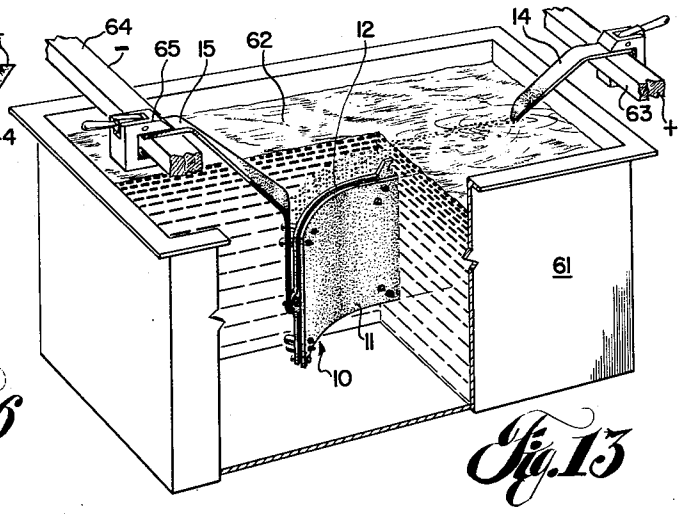


Fig. 13

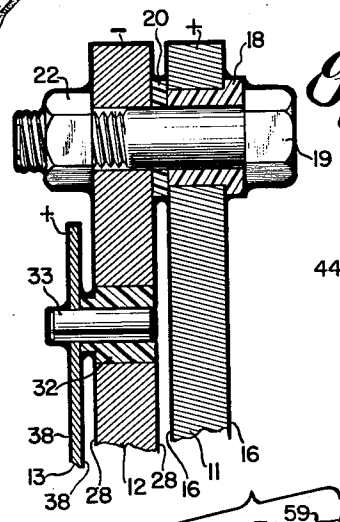


Fig. 7

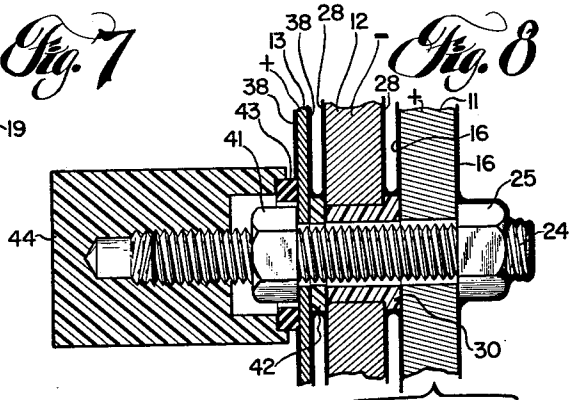


Fig. 8

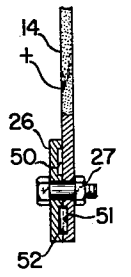


Fig. 9

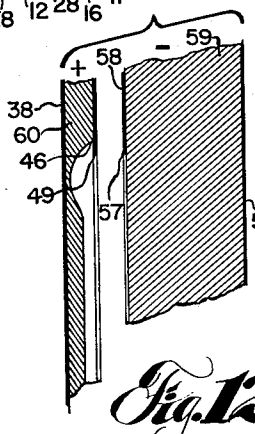


Fig. 12

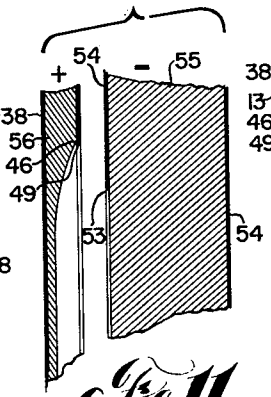


Fig. 11

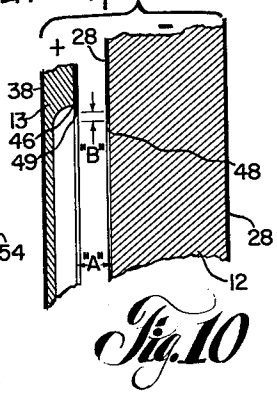


Fig. 10

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3,139,394

METHOD AND APPARATUS FOR ELECTRO-CHEMICAL MILLING

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Filed June 20, 1962, Ser. No. 203,956
12 Claims. (Cl. 204—143)

This invention pertains to method and apparatus for metal removal, and more particularly concerns method and apparatus for electro-chemically removing metal from regions adjacent selected inset surface areas of a steel panel or the like.

Numerous problems have been encountered in connection with attempts to uniformly remove metal from selected surface areas of relatively thin, panel-like, steel aircraft components which are typically contoured to either a flat, curved, or irregular configuration, or combinations thereof, prior to the metal removal operation. Generally, metal removal from panel surface areas is difficult in that it must be to a uniform depth with respect to the reference surface of the part, and further must be effected without introducing adverse stresses, as by machine-tool work-hardening, into the part. Also, it is important that metal removed from panel regions adjacent inset surface areas be carried out in a manner whereby properly proportioned fillets are provided to define the edges of the resulting milled surface areas.

Typical acid etching techniques have not proven acceptable for use in milling aircraft panel components fabricated of the highly-alloyed or heat-treatable steels because such materials are especially susceptible to hydrogen embrittlement. Similar steel parts subjected cathodically to an electrolytic acid etching treatment will also develop hydrogen embrittlement.

Conventional electro-chemical metal removal methods and apparatus have further proven deficient in that steel parts milled thereby have not been etched at uniform rates of metal removal throughout surface areas of substantial extent. Such unevenness in depth of metal removal is generally not acceptable when related to the production of aircraft components having stringent weight limitations and maximum stress conditions associated therewith.

Problems have also been encountered with respect to the intergranular corrosion introduced into certain steel workpieces when milled through use of known acid etching techniques. In addition, the practice of electro-chemical milling metal removal techniques using state-of-the-art apparatus has posed problems with respect to obtaining consistent tolerances of small magnitude substantially throughout surface areas of considerable extent. Further, the use of known methods and apparatus for the stated purpose of electro-chemically removing steel from surface areas of steel panels has required the use of more electrical energy than is comparatively required in connection with the practice of this invention. Apparatus heretofore developed for electro-chemically removing metal from regions adjacent selected inset surface areas of a steel-like panel have often employed a bleeder means member which is not required by this invention to obtain proper milled area edge fillet characteristics.

Accordingly, it is an object of this invention to provide apparatus for metal removal which will result in acceptably smooth final surface finishes and which further will not introduce work-hardening effects into steel parts subjected thereto.

Another object of this invention is to provide an electro-chemical milling equipment arrangement that does not expose worked-upon highly alloyed steel parts to the phenomenon of hydrogen embrittlement.

Another object of this invention is to provide electro-chemical milling tooling which is effective to remove metal from extended or substantial surface areas of steel materials at uniform metal-removal rates.

Another object of this invention is to provide apparatus which may be used for uniformly removing metal from pre-formed steel parts which have either flat, curved, or irregular surface configurations.

Another object of this invention is to provide apparatus which may be advantageously utilized to electro-chemically remove metal from regions adjacent selected inset surface areas of a steel panel or the like to a uniform depth substantially over the entire resulting milled area.

Another object of this invention is to provide improved apparatus for electro-chemically removing metal from selected inset regions of a steel-like panel in a manner which develops a properly proportioned fillet at the edge which defines the resulting milled surface area.

A still further object of my invention is to provide apparatus and equipment for removing metal from ultra-high-strength steel panels which does not subject such panels to the phenomenon of intergranular corrosion.

Another object of this invention is to provide apparatus for electro-chemically removing metal from selected regions of a steel-like panel with a reduced requirement as to total electrical energy.

Another object of this invention is to provide apparatus for electro-chemically removing metal from steel workpieces in a manner which obtains improved tolerances of greater consistency throughout surface areas of considerable size.

Another object of this invention is to provide apparatus which utilizes commercially-available materials and equipment for operation and construction. Additionally, the equipment utilized for the process of this invention is comparatively simple in construction, is operable by semi-skilled operating personnel, and is free of complex maintenance difficulties.

Other objects and advantages of this invention will become more apparent when consideration is given to the drawings and written description forming portions of this application.

In the drawings:

FIG. 1 illustrates component parts of the apparatus of this invention in assembled relation;

FIG. 2 illustrates component parts of the apparatus of FIG. 1 in exploded relation;

FIG. 3 illustrates masking details of the workpiece and cathode components of the apparatus of this invention;

FIG. 4 illustrates a detail shown in FIG. 3;

FIG. 5 is a sectional view which further illustrates the relation of opposed unmasked surface areas of the workpiece and cathode components of my invention;

FIG. 6 is an enlarged partial elevational view of the apparatus illustrated in FIG. 1;

FIG. 7 is a sectional view taken at line 7—7 of FIG. 6;

FIG. 8 is a sectional view taken at line 8—8 of FIG. 6;

FIG. 9 is a sectional view taken at line 9—9 of FIG. 6;

FIG. 10 illustrates the preferred workpiece milled surface area edge fillet condition which is obtained through practice of this invention; and

FIGS. 11 and 12 illustrate other workpiece milled surface area edge fillet conditions;

FIG. 13 illustrates an equipment arrangement employed with the apparatus components detailed in FIGS. 1 through 9.

FIG. 1 illustrates component parts of the apparatus of this invention in assembled relation. The assembly is referenced generally as **10** and is basically comprised of an anode member **11**, a cathode member **12**, and the workpiece designated **13**. Each of the components is provided in selected areas with an adhering dielectric film that is chemically-resistant to electrolyte and that

is preferably manually strippable from underlying component part surface areas. Such film is also frequently referred to herein as a protective coating, a mask, or a maskant. Support members 14 and 15 are mechanically coupled and electrically connected to anode member 11 and cathode member 12, respectively.

Details with respect to components 11, 12, and 13 and with respect to other components of assembly 10 are shown in exploded relation in FIG. 2. Anode member 11 is fabricated of metal and is coated with the maskant designated 16 (FIG. 7). Openings 17 are provided in anode member 11 for receiving insulating bushings 18 and the threaded screws designated 19 that mechanically couple anode member 11 to cathode member 12 but in electrically-insulated relation. Threaded screws 19 pass through the spacers designated 20 and through openings 21 in cathode member 12 and cooperate with the nuts designated 22. See FIG. 7. Bushings 18 and spacers 20 are preferably fabricated of a comparatively rigid chemically-resistant and electrically-resistant material such as methyl methacrylate. Openings 23 in anode member 11 are provided for receiving screws members 24 that electrically couple anode member 11 to workpiece 13. A portion of the maskant 16 provided on the rearmost surface of anode member 11 is removed from regions immediately adjacent each opening 23. This is accomplished in order that the nut 25 which cooperates with screw member 24 might make an electrically-conducting contact between nut member 25 and anode member 11. A portion of the maskant 16 provided on the rearmost surface of anode member 11 in the vicinity of the region designated 26 is also removed in order to establish an electrically-conducting contact between anode member 11 and support member 14. The fastener designated 27 is provided to removably couple support member 14 to anode member 11 at the region designated 26. Further details of this feature are provided in connection with the discussion of FIG. 9.

Cathode member 12 is also fabricated of a metal and is provided with the protective coating designated 28. Cathode member 12 is provided with openings 29 for receiving the insulating bushings designated 30. Each bushing 30 is provided to assure that a screw member 24 is not electrically-connected to cathode member 12 during its location within a hole 29 of cathode member 12. Open inset areas 31 are provided in coating 28 in prescribed locations to assist in obtaining the objectives of this invention. Cathode member 12 is also provided with a number of insulating bushings 32 and locating pins 33. Bushings 32 are preferably press-fit into the openings designated 34. Locating pins 33 may be either fixedly or removably located in bushings 32. Openings 35 are provided in cathode member 12 to facilitate immersion and removal of apparatus 10 in an electrolyte bath by use of a conventional hoist and hook. Support member 15 is connected to region 36 of cathode member 12 by fastener means 37 and in the manner of the attachment of support member 14 to anode member 11.

Workpiece 13 is provided with the protective film designated 38. Workpiece 13 contains the openings designated 39 for receiving locating pins 33 to establish the preferred proper positioning of workpiece 13 relative to cathode member 12. Openings 40 are provided in workpiece 13 for receiving screw members 24. Each screw member 24 projects through an opening 40 and cooperates with a nut designated 41. Because nut 41 constitutes a part of the circuit which electrically connects workpiece 13 to anode member 11, a portion of the mask 38 provided on workpiece 13 must be removed from adjacent each opening 40 to permit metal-to-metal contact between nut member 41 and workpiece 13. Spacer members 42 serve to maintain workpiece 13 a proper distance from cathode member 12. In the arrangement shown in FIG. 2, screw members 24 pass through spacer members 42. Seals 43 and cap members

44 are provided to develop chemical and electrical protection for the exposed end of screw member 24 projected beyond workpiece 13 and for nut 41.

Illustrations showing details of the manner in which anode member 11 and cathode member 12 are mechanically coupled to each other in electrically-insulated relation, of the manner in which workpiece 13 is located with respect to cathode 12, and of the manner for electrically connecting workpiece 13 to anode member 11 are shown in FIGS. 6 through 8. FIG. 9 discloses details of a preferred manner for securing support member 14 to anode member 11 in a manner which prevents rotation of such components relative to each other. The FIG. 9 arrangement employs individual elongated recesses 50 in region 26 of anode member 11 and one similar recess 51 in support member 14. A small key 52 cooperates with recess 51 and with a recess 50 in anode member 11 to prevent rotation of the components when fastener 27 is properly installed. Such arrangement is employed to facilitate repositioning of the support members to permit "upside-down" immersion of the tooling assembly in the electrolyte part-way through the metal removal operation.

Important advantages of my invention are achieved through the proper masking or coating of workpiece 13 and cathode member 12. To accomplish such advantages it is necesary to properly select, locate, size, and position various openings in the coatings 28 and 38 of components 12 and 13. Such openings are designated 31 and 45 (FIGS. 3 through 5) and are developed in the related component part by proper removal of selected portions. In applying the coatings to components 12 and 13 (and also coating 16 to anode member 11) it is preferred that such components first be cleaned using conventional degreasing equipment or the like. It is also preferred tht the component parts be subjected to moderate sand blasting in order that uniform adhesion of the subsequently-applied coating might be obtained. A precoating surface roughness of approximately 100 microinches R.M.S. generally proves entirely satisfactory for this purpose. Coatings 28 and 38 are preferably next applied over the entire exterior surface of each component through use of either a standard spraying or dipping technique. Commercially available materials suitable for the coating included modified vinyl polymers, cellulose acetate butyrate, polyethylene, or the like. One particularly effective air-drying maskant material is comprised of approximatley 18% polyvinyl chloride, 2% cellulose acetate butyrate modifier, and approximately 80% solvent such as methyl isobutyl ketone and methyl ethyl ketone, all percentages being on a weight basis. Adequate chemical and electrical resistance is generally obtained by applying three (3) wet cross-coats of the composition to the surfaces of the tooling assembly component parts. Sufficient time should be allowed between the application of each maskant coat to permit the solvents contained therein to sufficiently evaporate. The final coating is readily completely manually strippable and has a thickness generally approximating .003". Other comparable commercial coatings, such as those requiring a high-temperature baking step as distinguished from air-drying, may be used in the practice of this invention.

Particular details with respect to properly defining and locating specific coating openings in tooling assembly component parts 12 and 13 are shown in FIGS. 4 and 5; the details of FIG. 4 are especially directed to the areas designated 31*a* and 45*a* in FIG. 3. The details and the following comments also pertain to the other of the coating openings provided in the component parts. For the purpose of this discussion it is assumed that metal is to be removed from contoured panel-like workpiece 13 to a uniform depth throughout the extent of the area defined by the line or edge designated 46. The extent of the depth of planned metal removal is shown by the dotted line 47 of FIG. 5. It should be noted that a fillet of

nearly-constant radius equal to the depth of metal removal is desirably provided at the workpiece milled surface area edge region. In practicing this invention, inset portions of the maskant material separately provided on workpiece **13** are removed from area **45***a* to the edge designated **49**. Edge **49** is inset uniformly from edge **46** to a distance "C." Distance "C" typically is from ½ to 1 times the depth of metal removal. Maskant removal can be accomplished by using a hot, sharp stylus and a properly configured and contoured template to cut coating **38** coincident with edge **49**. After the edge is properly scribed in the coating, the inset coating portion may be removed from the component part readily by a manual stripping operation. FIG. 4 discloses that edge **49** includes parallel straight line portions, diverging straight line portions, and connection radii. One such radius defined by edge **46** has a preselected value designated "R."

Each coating opening provided in cathode member **12** for cooperation with a corresponding coating opening in workpiece **13** is of lesser extent in area than the area defined by edge **49** by a prescribed amount. Referring to the opening **31***a* in cathode member **12**, the defining edge **48** is shaped to be similar to edge **49** and is concentrically located with respect to edge **49**. The resulting unprotected surface area **31***a* of cathode member **12** has a similar contour to the contour of the unprotected surface area of corresponding opening **45***a* in FIG. 4. However, each portion of corresponding edge **48** of coating **28** is set inwardly the distance "B" from the related edge **49** of the opening **45***a*. Workpiece **13** and cathode member **12** are uniformly spaced-apart the distance designated "A" in FIG. 5. Distance 'B" is in the range of approximately ¼ to ½ of distance "A" with the lower limit being preferred. The offset relation between edges **49** and **48** is shown in FIG. 4. In the corner radii regions the cathode member inset surface area radius is of a dimension "B" less than the radius dimension for the corresponding part of inset surface area **45***a*. This offset relation is required to obtain the heretofore-mentioned desirable fillet characteristic at the workpiece milled area edge region.

The resulting preferred fillet condition at the edge region of the workpiece milled area is best shown in FIG. 10. It should be noted that the disclosed fillet has a nearly-uniformly radius corresponding to the depth of metal removal. The resulting condition is highly desired insfor as the design and manufacture of aircraft-quality parts are concerned. If the teachings of this invention are not adhered to, undesirable edge fillet conditions such as those illustrated in FIGS. 11 and 12 may result. In the FIG. 11 illustration, the edge **53** provided in maskant **54** for the cathode member designated **55** is positioned inwardly a substantial distance more than the preferred ¼ to ½ offset relation with respect to the edge **49** of coating **38** on the workpiece designated **56**. The resulting fillet condition does not have the desired nearly-uniform fillet radius that corresponds to the depth of metal removal; the edge fillet condition of workpiece **56** has an undesirably pronounced taper not present in the fillet condition of workpiece **13**. FIG. 12 also discloses an undesirable workpiece milled area edge fillet condition. In that figure, the edge **57** scribed in coating **58** on cathode member **59** is positioned directly opposite the edge **49** provided in maskant **38** to workpiece **60**. The resulting milled area edge fillet undercuts the depth of metal removal. This condition is unwanted insofar as aircraft-quality panels are concerned.

FIG. 13 discloses other component parts used in connection with the apparatus of this invention. Such other component parts include a process tank **61**, electrolyte acid solution **62**, and the anode and cathode bus bars respectively designated as **63** and **64**. Such bus bars are electrically connected to a source of electrical energy (not shown) and are each provided with a clamp member **65** for effecting an electrical connection between the bus bar and a support member **14** or **15** of tooling assembly **10** during operation of the apparatus. The source of electrical energy cooperating with bus bars **63** and **64** provides direct-type current and may take the form of a source of rectified alternating current electrical energy.

Process tank **61** is preferably constructed of, or lined with, a material that is chemically-resistant to the acid solution **62** contained therein. Material such as wood, polyvinyl chloride, natural or synthetic rubber, organic materials such as polytetrafluoroethylene, and the like have proved acceptable and are well-known to those familiar with the art. Acid solution **62** is electrically conducting and typically contains disassociated hydrogen ions. A solution comprised of 25%±5% sulfuric acid by weight and water is preferred in the practice of this invention. However, it is recognized that other single acids, such as phosphoric acid, and combination of acids will prove adequate when substituted for sulfuric acid. It is believed that minimum maintenance and control is required when single acid solutions, such as the above-referenced 25%±5% sulfuric acid solution, are employed. In practicing this invention it is desirable that the operating temperature of solution **62** be maintained at approximately 80° F.±10° F., and that the solution be continuously circulated as by air agitation.

During the processing of the workpiece in the equipment arrangement cathode member **12** and workpiece **13** are subjected to the electrical energy potential across bus members **63** and **64**. The tooling assembly (**10**), except for projecting portions of support members **14** and **15**, is immersed in acid solution **62**. Oxygen is given off at the face between uncoated anodic surface areas **45** and electrolyte solution **62**. Hydrogen gas is evolved at the uncoated surface areas **31** of cathode member **12**. The process must be continued a sufficient time to remove metal to the desired depth such as to the dotted line position **47** indicated in FIG. 5. To completely avoid hydrogen embrittlement, electrical current should be flowed to and from tooling assembly **10** as it is being both immersed in and removed from the solution bath **62** in process tank **61**.

The following information is provided to describe specific apparatus that has been employed to selectively remove metal from flat, uncoated panel surface areas having maximum dimensions of approximately 4" x 6". The workpiece test panel from which the metal was removed was comprised of PH 15–7 Mo alloy steel 0.060" thick. Metal was removed to a nominal depth of 0.052" leaving a remaining metal thickness of 0.008". The specific apparatus has also been used to selectively remove metal from workpiece panels fabricated of Type H–11 alloy steel and of metals such as Inconel X, René 41, H–25, and N–155 with equally good results. The anode member was fabricated of Type 61S aluminum alloy approximately ½" thick. The cathode member employed in the specific apparatus was also fabricated of Type 61S aluminum alloy approximately ½" thick. The various bushing and spacer devices employed in such apparatus were fabricated of methyl methacrylate and the coatings provided over the major exterior surface areas of the anode member and of the cathode member corresponded to the above-described air-drying polyvinyl chloride maskant material. Screw members employed to connect the cathode member to the anode member and to connect the workpiece to the anode member were made of an aluminum alloy. Locating pins employed in the apparatus were manufactured of titanium.

Openings provided in the coating on the cathode member for cooperation with coating openings in the workpiece were developed following the previously-described principles. The workpiece was spaced-apart from the opposing similarly contoured surface of the cathode member a uniform distance of approximately 1/16" and the inward offset of the edge **48** to the cathode member coat-

ing opening was approximately 1/32". The same relation was provided for all coating opening corner radii.

The current density maintained over the uncoated surface areas of the workpiece was approximately 8 amperes per square inch of to-be-milled surface. Other current densities in the range of from 5 to 10 amperes per square inch may be successfully employed. The direct current voltage established as between the workpiece and the cathode member varies, depending on size and thickness of the workpiece panel; in the case of the herein-described specific apparatus the voltage was established at approximately 4 volts. Other voltages in the range of from 4 volts to 6 volts have been used for the purpose of carrying out this invention. The acid solution employed in the specific apparatus consisted of 25% sulfuric acid by weight and water. The milled surface of the panel workpiece was examined subsequent to immersion in the acid solution at the prescribed current density and voltage for approximately 3 hours. Rate of metal removal varies with workpiece composition. The dimensional tolerance of the milled area was to within ±0.001" as to uniformity of metal removal. Surface roughness of the milled area was 30 to 40 microinches R.M.S. or better. Neither hydrogen embrittlement or intergranular corrosion characteristics were present in the finished product. In addition, the workpiece milled area was provided with an edge fillet condition of desirable characteristic. More specifically, the milled area edge fillet condition was of nearly-uniform radius corresponding to the depth of metal removal and without metal undercutting.

It is to be understood that the form of the invention herewith shown and described is to be taken as the preferred embodiment of the same; various changes in shape, size and arrangement of component parts, as for removing metal from workpiece panels of different configuration, may be effected without departing from the spirit of the invention or from the scope of the claims.

I claim:

1. Apparatus to be connected to an electrical energy supply for electro-chemically removing metal to a uniform depth from and substantially throughout an anodic workpiece surface area which is defined by a prescribed edge and which is immersed in an acid electrolyte solution, and comprising:

(*a*) A metal cathode member having a surface area which is spaced-apart from said workpiece surface area a uniform distance and which is contoured similarly to said workpiece surface area,

(*b*) A dielectric coating which is chemically-resistant to said electrolyte solution and which is adhered over the exterior of said workpiece but with an inset opening that is defined by an edge set inwardly from said workpiece surface area prescribed edge a uniform distance, and

(*c*) A dielectric coating which is chemically-resistant to said electrolyte solution and which is adhered over the exterior of said cathode member but with an inset opening that is located at said cathode member surface area and that is defined by an edge,

said cathode member coating inset opening being concentrically positioned with respect to said workpiece coating inset opening and having said cathode member coating inset opening edge set inwardly with respect to said workpiece coating inset opening edge.

2. The invention defined by claim 1, wherein said cathode member surface area is spaced-apart from said workpiece surface area a uniform preselected distance, said cathode member coating inset opening edge being set inwardly from said workpiece coating inset opening edge a uniform distance which is approximately ¼ to ½ of said preselected distance.

3. The invention defined by claim 1, wherein said cathode member surface area is spaced-apart from said workpiece surface area a uniform preselected distance, said cathode member inset opening edge being set inwardly from said workpiece coating inset opening edge

a uniform distance which is approximately ¼ of said preselected distance.

4. Apparatus for use with a metal removal electrolyte and with a source of electrical energy to remove metal to a uniform depth from and throughout an anode workpiece precontoured surface area which is defined by a prescribed protective coating edge, and comprising

metal cathode means having a surface area contoured to match said workpiece precontoured surface area and having an adhering protective dielectric coating which is provided at said cathode means surface area and which is provided with an inset opening defined by an edge that conforms in configuration to and is of lesser extent than said workpiece protective coating edge,

said cathode means surface area being spaced apart from said workpiece surface area a uniform distance with said cathode means protective coating edge located concentrically with respect to said workpiece protective coating edge.

5. The invention defined by claim 4, wherein said cathode means surface area is spaced apart from said workpiece surface area a preselected distance in a direction transverse to said cathode means surface area, said preselected distance being approximately 2 to 4 times the inward offset distance of said cathode means protective coating edge relative to said workpiece protective coating edge.

6. The invention defined by claim 4, wherein said cathode means surface area is spaced apart from said workpiece surface area preselected distance in a direction transverse to said cathode means surface area, said preselected distance being approximately 4 times the inward offset distance of said cathode means protective coating edge relative to said workpiece protective coating edge.

7. In a method of removing metal from an anodic workpiece and to a predetermined depth uniformly throughout an uncoated surface area which is defined by an acid-resistant dielectric coating edge and which is immersed in an acid electrolyte with a cooperating cathode member, the steps of:

(*a*) Covering a cathode member which has a surface area contoured to correspond to the workpiece uncoated surface area with an adhering acid-resistant dielectric coating,

(*b*) Providing said cathode member coating with a scribed line having a configuration which corresponds to the workpiece coating edge but which is uniformly set inward a first predetermined distance in a direction parallel to the workpiece uncoated surface area,

(*c*) Removing said cathode member coating from said cathode member within said cathode member coating scribed line, and

(*d*) Afterwards locating the cathode member in fixed relation with respect to the workpiece whereby the uncoated surface area defined by said cathode member scribed line is concentric with the workpiece uncoated surface area but is uniformly spaced-apart from the workpiece uncoated surface area a second predetermined distance in a direction normal thereto.

8. The method defined by claim 7, wherein said second predetermined distance is from 2 to 4 times said first predetermined distance.

9. The method defined by claim 7, wherein said second predetermined distance is 4 times said first predetermined distance.

10. In a method of removing metal from an anodic workpiece and to a predetermined depth uniformly throughout an uncoated surface area which is defined by an acid-resistant dielectric coating edge and which is immersed in an acid electrolyte with a cooperating cathode member, the steps of:

(*a*) Providing a cathode member having a surface contoured to correspond to the workpiece uncoated

surface area with an uncoated surface area portion which is defined by an acid-resistant dielectric coating edge that corresponds in configuration to the workpiece coating edge but that is uniformly set inward from the workpiece coating edge in a direction parallel to the workpiece uncoated surface area, and

(*b*) Locating said cathode member in fixed relation with respect to the workpiece whereby said cathode member uncoated surface area is concentric with the workpiece uncoated surface area but is uniformly spaced-apart from the workpiece uncoated surface area a second predetermined distance in a direction normal thereto.

11. The method defined by claim 10, wherein said second predetermined distance is from 2 to 4 times said first predetermined distance.

12. The method defined by claim 10, wherein said second predetermined distance is 4 times said first predetermined distance.

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