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(19)

(54) APPARATUS FOR ELECTROCHEMICALLY FORMING ARTICLES

(71) We, TRW INC., a corporation organized under the laws of the State of Ohio, U.S.A., of 23555 Euclid Avenue, Cleveland, Ohio 44114, U.S.A., do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement: —

The present invention relates to apparatus for electrochemically forming articles.

The apparatus of the present invention is particularly, but not exclusively applicable to the formation of airfoils.

The invention, the scope of which is defined in the appended claims, includes an apparatus for at least partially forming articles by electrolytically removing material from a workpiece having opposing sides and at least partially composed of an electrically conductive material, said apparatus comprising a working chamber for receiving at least a portion of the workpiece, means for holding at least a portion of the workpiece in said working chamber, first and second separately movable electrodes at least partially disposed in said working chamber for use in effecting the electrolytic removal of material from the opposing sides of the workpiece to at least partially form opposing side surfaces of an article, said first and second electrodes being movable toward each other through working strokes during which material is electrolytically removed from the opposing sides of the workpiece, said first and second electrodes being movable away from each other through return strokes after material has been electrolytically removed from the opposing sides of the workpiece, third and fourth separately movable electrodes spaced apart from said first and second electrodes and at least partially disposed in said working chamber for use in effecting the electrolytic removal of material from the opposing sides of the workpiece to at least partially form opposing side surfaces of an article, said third and fourth electrode being movable toward said first and second electrodes and toward each other through working strokes during which material is electrolytically removed from the opposing sides of the workpiece, said third and fourth electrodes being movable away from said first and second electrodes and away from each other through return strokes after material has been electrolytically removed from the workpiece, means for supporting each of said electrodes for movement relative to each of the other electrodes during movement of said electrodes through their working and return strokes, means for establishing an electrical potential between the workpiece and each of said electrodes during movement of each of said electrodes through its working stroke, means for establishing a flow of electrolyte between the workpiece and each of said electrodes during movement of each of said electrodes through its working stroke, and means for simultaneously moving each of said electrodes through working strokes toward each other while the electrical potential is established between each of said electrodes and the workpiece and during the flow of electrolyte between each of said electrodes and the workpiece to effect the electrolytic removal of material from the workpiece.

In order that the invention may be well understood two embodiments thereof will now be described, by way of example only, with reference to the accompanying drawing in which:

Fig. 1 is an illustration of an airfoil or turbine blade formed by the apparatus to be described;

Fig. 2 is a plan view (on a reduced scale) of a workpiece in which a plurality of airfoils have been formed by the electrolytic

removal of material from opposing sides of the workpiece;

Fig. 3 is a sectional view, taken along the line 3-3 of Fig. 2, illustrating the angular orientation of side surfaces of a plurality of airfoils formed adjacent to one minor side of the workpiece;

Fig. 4 is a sectional view, taken generally along the line 4-4 of Fig. 2, illustrating the angular orientation of side surfaces of airfoils formed adjacent to another minor side of the workpiece;

Fig. 5 is an illustration of a machine utilized in forming the air foils in the workpiece of Fig. 2;

Fig. 6 is an enlarged schematic view of a portion of the machine of Fig. 5, illustrating the relationship between a plurality of electrodes and a working chamber which receives the workpiece of Fig. 2;

Fig. 7 is a schematic illustration depicting the relationship of the electrodes of Fig. 6 to a workpiece during the simultaneous forming of a plurality of airfoils in the workpiece;

Fig. 8 is a sectional view, taken generally along the line 8-8 of Fig. 7, illustrating the relationship between a workpiece, a pair of cathode electrodes disposed in the working chamber, and a pair of anode electrodes disposed in a secondary chamber during the electrolytic removal of material from opposing sides of the portion of the workpiece in the working chamber;

Fig. 9 is a sectional view, taken generally along the line 9-9 of Fig. 7, illustrating the relationship between a second pair of cathode electrodes and the workpiece during the electrolytic removal of material from the workpiece;

Fig. 10 is a plan view illustrating the construction of an end portion of one of the cathode electrodes;

Fig. 11 is an elevational view, taken generally along the line 11-11 of Fig. 10, illusrating the twisted or angled configuration of a plurality of working surfaces formed on the end of the electrode of Fig. 10;

Fig. 12 is an elevational view, taken generally along the line 12-12 of Fig. 10, further illustrating the configuration of the working surfaces on the end of the electrode;

Fig. 13 is a fragmentary plan view of a workpiece having a frame in which a plurality of partially formed airfoils are mounted; and

Fig. 14 is a sectional view, taken generally along the line 14-14 of Fig. 13 and illustrating the manner in which a partially formed airfoil is mounted in the frame.

An airfoil 20 which, in the illustrated embodiment is a turbine blade, includes a twisted blade 22 having leading and trailing edge portions 24 and 26 which extend between the tip and root end portions 28 and 30 of the airfoil. Although only a single side surface 34 of the airfoil 20 is visible in Fig. 1, it should be understood that the airfoil has a pair of major side surfaces which have a twisted configuration to promote a desired flow of fluid. The airfoil 20 has a base portion 38 which, during use, is mounted in a fixture in a known manner to position the airfoil. Although it is contemplated that the airfoil 20 will be utilized in a turbojet engine, it is contemplated that an article formed with the apparatus to be described could be utilized in many different environments. It is also contemplated that the same apparatus could be utilized to form articles other than airfoils.

A plurality of articles, such as the airfoils 20, are simultaneously formed in a specific workpiece 42 (see Fig. 2) by a machine 44 (see Fig. 5). Prior to machining of the unitary steel workpiece 42, it has the configuration of a rectangular block with flat parallel opposing major sides 48 and 50 which are interconnected by a first pair of flat parallel opposing minor sides or first and second outer side surfaces 52 and 54 and a second pair of flat parallel opposing minor sides 56 and 58. However, it should be understood that workpieces having many different configurations could be utilized if desired. The workpiece 42 is composed of an electrically conductive material. On one specific instance it is contemplated that a nonrectangular workpiece may be utilized.

After a machining operation has been completed on the workpiece 42, a first series of turbine blades or airfoils 62, 64, 66, 68, 70 and 72 are formed in a linear array along the minor side 52 of the workpiece with their central axes extending parallel to each other and perpendicular to the minor side 52. Similarly, a second series of airfoils 74, 76, 78, 80, 82 and 84 are formed in a linear array along the opposite minor side 54. The airfoils 62-72 are formed with tip end portion 88 adjacent the first outer side surface 52 of the workpiece 42. Similarly, the airfoils 74-84 are formed with tip end positions 90 adjacent the second outer side surface 54 of the workpiece. The root end portions 92 of the airfoils 62-72 are disposed on one side of an unmachined central or body portion 94 of the workpiece 42 while the root portions 96 of the airfoils 74-84 are disposed on the other side of the body portion 94.

The airfoils 62-72 are oriented with their central axes 98 extending perpendicular to the minor side 52 and parallel to each other. The central axes 98 of the airfoils

62-72 intersect the minor side 52 at spaced apart locations therealong. Similarly, the airfoils 74-84 are oriented with their central axes 102 extending parallel to each other and perpendicular to the minor side 54. The central axes 102 of the airfoils 74-84 intersect the minor side 54 at spaced apart locations therealong. The two series of airfoils are disposed in alignment with each other so that the central axes 98 of the airfoils 62-72 are in general alignment with the central axes 102 of the airfoils 74-84. It should be understood that although the airfoils 62-84 are advantageously disposed in the spatial relationship described, certain types of airfoils and other articles may be disposed in a different spatial relationship.

During subsequent processing of the workpiece 42, the workpiece is split along a central axis 106 and the various airfoils are separated from arms or ribs 110 which extend parallel to each other and perpendicular to the minor sides 52 and 54 of the workpiece 42. Once the airfoils have been separated from the arms and the central portion of the workpiece has been split, base end portions of the airfoils 62-84 are formed to have a configuration similar to the base end portion 38 of the airfoil 20 of Fig. 1. Thus, twelve separate airfoils are formed from the single workpiece 42. However, a different number of airfoils or other articles could be formed in the workpiece 42.

The airfoils 62-72 have side surfaces which slope in a direction which is opposite to the slope of the airfoils 74-84. This is perhaps best seen by a comparison of Figs. 3 and 4. In Fig. 3 it can be seen tha the airfoils 74-84 have twisted side surfaces 114 and 116 which slope downwardly and rightwardly (as viewed in Fig. 3) from a leading edge portion 118 of the airfoil to a trailing edge portion 120. The airfoils 62-72 when viewed along a section line facing in the same direction, has side surfaces 114 and 116 which slope downwardly and leftwardly (as viewed in Fig. 4) from the leading edge portion 118 of the airfoils to a trailing edge portion 120. It should be noted that this difference in the angular orientation of the airfoils 62-72 enables the workpiece 42 to be split in half along a plane extending through the central axis 106 and perpendicular to the major side surfaces 48 and 50 to form a pair of identical workpiece sections. The upper (as viewed in Fig. 2) workpiece section can be pivoted about a vertical axis to a position in which the leading edge 118 of the airfoil 72 is immediately adjacent to the trailing edge of the airfoil 84 for machining purposes during the formation of the bases and tips of the airfoils.

The machine 44 (Fig. 5) is operable to electrolytically remove metal from the workpiece 42 to form the airfoils in the steel workpiece. The machine 44 has a base frame 130 with a rigid upstanding support section 134 upon which the fixture module or box assembly 136 (see Figs. 5 and 6) is mounted. The box assembly 136 includes a pocket assembly 138 (Fig. 6) which defines a machining or working chamber 140 in which a pair of guide members 142 and 144 are disposed to generally position the workpiece 42 (not shown in Fig. 6) at a 45° angle to a horizontal plane and with the central axis 106 of the workpiece extending perpendicular to a bottom or base surface 148 of the machining chamber 140. The workpiece 42 is accurately positioned and held in the chamber 140 with a central axis 106 of the workpiece extending along the line of intersection of a horizontal central plane indicated at 152 in Fig. 6 and a vertical central plate, indicated at 154 in Fig. 6.

The first pair of electrodes 160 and 162 are utilized to form airfoils along minor side 52 of the workpiece while a second pair of electrodes 164 and 166 are utilized to simultaneously form airfoils along the opposite minor side 54 of the workpiece. Each of the electrodes 160, 162, 164 and 166 is associated with motor means in the form of an hydraulic ram which is selectively operable to move the electrode through working and return strokes along a horizontal or vertical path extending at an acute angle to the major sides 48 and 50 of the workpiece 42. In the described embodiment the electrodes 160 through 166 are moved at an acute angle of 45° to the major sides 48 and 50 of the workpiece. However, other acute angles could be utilized to accommodate different articles.

Upon extension of a hydraulic ram 170, an electrode 160 is moved straight downwardly through a working stroke from the retracted position illustrated in Fig. 6 toward the fully extended position illustrated schematically in Fig. 7. Simultaneously with this movement of the electrode 160 from the retracted position to the extended position, a ram 174 is operated to move the electrode 162 horizontally through a working stroke from its retracted position (Fig. 6) to its extended position. It should be noted that the paths of movement of the two electrodes 160 and 162, that is the paths along which the end faces of the electrodes move, intersect at a location disposed above and to the right (as viewed in Fig. 6) of the center of the working chamber 140 and the center of the workpiece. Although the electrodes 160 and 162 simultaneously effect the re-

moval of metal from the workpiece 42, their working strokes could begin and/or end at different times.

During movement of the electrodes 160 and 162, the electrodes are at a negative potential relative to the workpiece 42 so that the electrodes 160 and 162 are cathodic and the workpiece 42 is anodic. The electrodes 160 and 162 are electrically connected with bus bars 175 (Fig. 5) which are connected with a negative polarity voltage source. The workpiece 42 is electrically connected with heavy duty cables 176 (Fig. 5) which are connected with a positive polarity voltage source.

In accordance with well known electrochemical machining practices, a flow of electrolyte is established between the electrodes 160 and 162 and the workpiece. This results in the electrolytic removal of metal from the workpiece 42 as the electrodes 160 and 162 move toward the workpiece. The flow of electrolyte is, at least partially, directed by the guide members 142 and 144.

The flow of electrolyte is directed from the minor side 52 (Fig. 7) of the workpiece toward the central portion 94 of the workpiece along a pair of flow paths which extend axially along the side surfaces 114 and 116 of the airfoil from the tip 88 to the root 92 of the airfoil. The electrolyte then flows outwardly toward the central portion 94 of the workpiece to drain. The direction of flow of the electrolyte is indicated schematically by arrows in Fig. 7. However, with certain types of airfoils or other articles, the direction of flow of the electrolyte may be reversed. It should be noted that a small gap is maintained between the electrodes 160 and 162 and the workpiece at all times so that there is no electrical shorting between the cathode electrode 160 and 162 and the workpiece which forms the anode electrode. Finishing gaps of between 0.002 inches and 0.005 inches are typically possible with this system to allow for a high degree of accuracy in reproduction of the cathode geometry.

Simultaneously with the formation of the plurality of airfoils in a first portion of the workpiece adjacent to the minor side 52 of the workpiece by the electrodes 160 and 162, a pair of rams 178 and 180 (Fig. 6) are operated to move the second pair of electrodes 164 and 166 from their retracted position (illustrated in Fig. 6) to their extended position (illustrated in Fig. 7) to form a plurality of airfoils in a second portion of the workpiece adjacent to the minor side 54 of the workpiece. It should be noted that the paths of movement of the two electrodes 164 and 166 intersect at a location disposed below and to the left (as viewed in Fig. 6) of the coincident centers of the working chamber 140 and workpiece 42. The electrodes 164 and 166 are at a negative potential relative to the workpiece 42 and electrolyte flows axially inwardly along the airfoil side surfaces 114 and 116 in the manner previously explained in connection with the electrodes 160, 162 and indicated schematically by the arrows in Fig. 7. Of course, other articles could have different electrolyte flow paths. Although all four electrodes 160, 162, 164 and 166 are moved through working strokes which start and end at the same time in order to effect the formation of airfoils in the workpiece 42, it is contemplated that the electrodes could have working strokes which start and/or end at different times and are of different durations.

To provide for the flow of electrolyte during the electrolytic removal of metal from the workpiece 42, a pair of conduits 184 and 186 (see Fig. 5) conduct electrolyte from a pump (not shown) to opposite sides of the fixture module 136. This flow is then conducted inwardly through passages 190 and 192 (Fig. 6) to the working chamber 140. It should be noted that the passages 190 and 192 are connected with relatively small passages extending through the guide elements 142 and 144 to openings which are aligned with the minor sides 52 and 54 of the workpiece. The flow of electrolyte is conducted from the central portion of the workpiece through passages indicated at 196, 198, 200 and 202 in Fig. 6 to drain conduits 204, 206, 208 and 210. The drain conduits 204 and 206 are connected with a single return conduit 214 (see Fig. 5) while the drain conduits 208 and 210 (Fig. 6) are connected with a second return conduit 216 (Fig. 5).

The workpiece 42 is formed with a length which is twice as great as the length which can be received in the working chamber 140. Thus during a machining operation, one end portion of the workpiece 42 is received in the working chamber 148 and the opposite end portion is received in a secondary chamber 220 (Fig. 8). The electrodes 164 and 166 are effective to form the airfoils 74, 76 and 78 extending in a linear array along the minor side 54 of the workpiece 42 during an initial machining operation in the manner illustrated in Fig. 8. Similarly, the electrodes 160 and 162 (see Fig. 9) are effective to form the airfoils 62, 64 and 66 in a linear array along the minor side 52 of the workpiece 42.

Since the airfoils 62-72 have side surfaces which slope in a direction opposite from the direction of slope of the side surfaces of the airfoils 74-84, offsetting operating forces are applied to the work-

piece 42 during the electrolytic removal of material from the workpiece. Thus as viewed in Fig. 8, reaction forces between the electrode 164 and the workpiece 42 tend to urge the workpiece upwardly and leftwardly. Similarly, reaction forces between the electrode 166 and the workpiece 42 tend to urge the workpiece downwardly and rightwardly (as viewed in Fig. 8). Similarly, the reaction forces between the electrode 160 and the workpiece 42 tends to urge the workpiece 42 upwardly and toward the right (as viewed in Fig. 9) while the reaction forces between the electrode 162 and the workpiece tend to urge it downwardly and toward the left.

To form the airfoils 62, 64 and 66 (Fig. 9) and the airfoils 74, 76 and 78 (Fig. 8), the two pairs of electrodes form recesses extending inwardly toward the central portion of the workpiece from minor sides and having openings in the opposing major sides of the workpiece 42 (see Figs. 2, 3 and 4). The recesses have bottom surfaces formed by the convex and concave slide surfaces 114 and 116 of the airfoils. Each recess has a relatively small opening in an associated minor side 52 or 54 of the workpiece. In addition, each recess has a relatively large opening in a smajor side 48 or 50 of the workpiece. Due to the twist of the airfoil side surfaces 114 and 116, the recess openings in the major sides of the workpiece 42 have a somewhat smaller area than the sides of the airfoils. Although this spatial relationship between the airfoils and the major and minor sides of the workpiece is advantageous, different articles could have different spatial relationships with the sides of the workpiece.

While the cathode electrodes 160, 162, 164 and 166 are forming the airfoils 74, 76, 78, 62, 64, 66 in the end portion of the workpiece 42 adjacent to the minor side 56, a pair of anode electrodes 224 and 226 (Fig. 8) grip the workpiece 42 and hold it against movement. Thus, the anode electrodes 224 and 226 are provided with end face surfaces 228 and 230 which abut the flat rectangular major side surfaces 48 and 50 of the workpiece 42 at the center of the workpiece to hold the workpiece against sidewise movement. In addition, a positioning element 234 engages a suitable hold formed in the center of the minor side 56 of the workpiece 42 to position the workpiece in the center of the working chamber 148. To facilitate positioning of the workpiece 42, the anode electrode 224 is fixedly positioned. The workpiece 42 is clamped against the accurately located reference surface 228 on the fixed anode electrode 224 by the movable anode electrode 226.

Upon completion of the formation of the airfoils 62, 64, 66, 74, 76 and 78 by the simultaneous movement of the electrodes 160, 162, 164 and 166 (see Figs. 8 and 9), the electrodes are moved through return strokes back to their retracted positions (Fig. 6) and the anode electrode 226 is retracted. The workpiece is then reinserted into the working chamber 148 with the minor side 58 leading so that the previously formed airfoils 62, 64, 66, 74, 76 and 78 are disposed outside of the working chamber 148 and the opposite end portion is positioned in the working chamber between the two pairs of cathode electrodes. After the workpiece has been firmly clamped in position by the anode electrodes 224 and 226, the rams 170, 174, 178 and 180 are simultaneously extended while flow of electrolyte is maintained between the workpiece and the cathode electrodes and while the cathode electrodes are maintained at a negative potential relative to the workpiece and the anode electrodes 224 and 226 to electrolytically remove material from the workpiece 42 and form the airfoils 68, 70, 72 adjacent to the minor side 52 and the airfoils 80, 82 and 84 adjacent to the minor side 54 in the manner previously explained. Although the workpiece 42 is stationary during the removal of material from the workpiece, it is contemplated that the clamping electrodes 224 and 226 could both be moved so as to move the workpiece 42 during a metal removing operation.

After forming the airfoils 62, 64, 66, 74, 76 and 78 and after removing the workpiece 42 from the working chamber 148, it is necessary to rotate the workpiece about a vertical axis extending perpendicular to the major side surfaces 48 and 50 of the workpiece before reinserting the workpiece in the working chamber. This results in the electrodes 160 and 162 being utilized to finish the formation of the airfoils along the minor side 54 while the electrodes 164 and 166 are utilized to finish the formation of the airfoils along the minor side 52. Thus, when the workpiece has been reinserted in the working chamber, a pair of cathode electrodes 160 and 162 are moved by the associated rams 170 and 174 to effect the formation of the airfoils 80, 82 and 84 while simultaneously therewith the cathode electrodes 164 and 166 are moved by the associated rams 178 and 180 to form the airfoils 68, 70 and 72 along the minor edge 52.

The construction of the cathode electrode 162 is more fully illustrated in Figs. 10, 11 and 12. The cathode electrode 162 includes a main body portion 242 to which a head end portion 244 is connected. The head end portion 244 has a plurality of spaced apart sections 246, 248 and 250 (see

Figs. 11 and 12). Each of the identical head end sections 246, 248 and 250 is provided with a working or face surface 254 which has a configuration corresponding to the configuration of the side surface 114 of the airfoil and forms the side surfaces 114 of the airfoils 62, 64 and 66 in the manner illustrated in Fig. 9. In addition, each of the sections 246, 248 and 250 of the cathode electrode 162 is provided with a face surface 258 (see Figs. 10 and 11) which is effective to form a shoulder surface 260 at the root end of the airfoil in the manner shown in Fig. 7.

The cathode electrode 160, which cooperates with the cathode electrode 162, has three head sections 264, 266 and 268 (Fig. 9). The head sections 264, 266 and 268 of the cathode electrode 160 have face or working surfaces which have configurations corresponding to the configuration of the side surface 116 of the airfoil and are complementary to and extend parallel to the face or working surfaces 254 on the head sections of the cathode electrode 162. The construction of the electrode 164 is exactly the same as the construction of the electrode 162. However, the orientation of the electrode 164 is offset by 180° from the orientation of the electrode 162. Similarly, the construction of the electrode 166 is the same as the construction of the electrode 160.

In the abovedescribed embodiment illustrated in Figs. 1-12 the apparatus 44 is utilized to form a plurality of articles, that is the airfoils 62-84 in a unitary workpiece 42. However, in the embodiment illustrated in Figs. 13 and 14 the workpiece is not unitary and includes a support frame in which a plurality of partially formed airfoils or other articles are disposed. Since the workpiece illustrated in Figs. 13 and 14 is somewhat similar to the workpiece 42, similar numerals will be utilized to designate similar components, the suffix letter "*a*" being associated with the numerals of Figs. 13 and 14 to avoid confusion.

A workpiece 42*a* is illustrated in Fig. 13 and includes a frame 280 in which a plurality of openings 282 are formed. A plurality of partially formed airfoils 286 are disposed in each of the openings 282 in the frame 280. In order to obtain a desired grain structure, the air foils 286 were forged to a size approaching the size of a completed airfoil. The partially formed airfoils 286 are finished to the desired size and configuration by the apparatus 44 in the manner previously explained in connection with the workpiece 42.

The frame 280 includes a pair of flat parallel major sides 48*a* and 50*a* (see Fig. 14) which are interconnected by a first pair of flat parallel minor sides 52*a* and 54*a* and a second pair of flat parallel minor sides, only one of which is illustrated in Fig. 13 and is designated by the numeral 56*a*. The partially formed airfoils 286 are disposed in two linear arrays along the minor sides 52*a* and 54*a* of the frame 280 in much the same manner in which the airfoils 62-72 and 74-84 are formed in linear arrays along the minor sides 52 and 54 of the workpiece 42. The partially formed airfoils 286 are disposed in the generally rectangular openings 282 with their central axes extending perpendicular to the minor sides 52*a* and 54*a* of the frame 280. It should be understood that although the airfoils 286 are advantageously disposed in the spatial relationship described, certain types of airfoils and other articles could be disposed in different spatial relationships.

The partially formed airfoils 286 disposed in linear array on one side of a central axis 106*a* of the frame 280 have side surfaces which slope in one direction while the partially completed airfoils disposed on the other side of the central axis 106*a* of the frame have side surfaces which slope in the opposite direction. This difference in the angular orientation of the side surfaces of the airfoils results in the application of offsetting reaction forces to the workpiece 42*a* during the electrolytic finishing of the partially formed airfoils 286.

The frame 280 includes a plurality of arms 110*a* which extend outwardly from a main or central body portion 94*a* of the frame 280. A pair of arms 110*a* enclose an airfoil 286 in the manner illustrated in Fig. 14.

Opposite longitudinally extending sides of each of the openings 282 are lined with a pair of optional polymeric isulating strips 290 and 292 (see Fig. 14). A pair of longitudinally extending conductor bars 294 and 296 are disposed inwardly of the insulating strips 290 and 292 and are electrically interconnected with the anode electrodes 224 and 226 (see Fig. 8) during the electrolytic machining of a partially completed airfoil 286. The conductor bars 294 and 296 firmly engage the opposite sides of the partially completed airfoil 286 to provide a solid electrical connection between the anode electrodes 224 and 226 (see Fig. 8) and the partially completed airfoil 286. To provide for tight abutting engagement of the conductor bars 294 and 296 with opposite sides of the partially completed airfoil 286, a wedge bar 298 is movable axially, that is longitudinally of the arms 110*a*, to press the conductor bar 294 toward the conductor bar 296 to thereby

clampingly engage opposite sides of the partially completed airfoil 286. Although the construction of only a portion of the frame 280 associated with one of the partially completed airfoils 286 has been illustrated in Fig. 14, it should be understood that the other partially completed airfoils 286 cooperate with similar conducting and wedge bars.

Although the frame 280 has been illustrated in connection with partially completed airfoils, it is contemplated that a frame similar to the frame 280 could be utilized in association with other articles. These articles could be partially formed to a greater or lesser extent. Thus, it is contemplated that an article associated with an opening in a frame similar to the frame 280 could be partially formed to its final configuration by merely cutting a piece of stock material to a length which corresponds to the desired length of the finished article.

Although the workpiece 42*a* has been shown in Figs. 13 and 14 apart from the apparatus 44, it should be understood that at least a portion of the frame 280 and the associated partially completed airfoils 286 are received in the working chamber 140 in the same manner as previously described in connection with the workpiece 42. The frame 280 is provided with electrically conductive sections (not shown) which are engaged by the anode electrodes 224 and 226 and are electrically connected with the conductor bars 294 and 296. Although only four openings 282 and partially formed airfoils 286 have been illustrated in Fig. 13, it is contemplated that any desired number of openings and airfoils could be provided in the frame. Of course, the size of the working chamber 140 would provide a limitation on the number of airfoils 286 which could be simultaneously operated on by electrode 160, 162, 164 and 166.

Although the operating relationship of these electrodes to the partially formed airfoils 286 has not been illustrated in the drawings, it should be understood that it is the same as the relationship of the electrodes 160-166 to the workpiece 42. Of course, the head end portions of the cathode electrodes 162-166 would have configurations corresponding to the spacing between the various partially formed airfoils 286 and the configuration of the major side surfaces of these airfoils. Thus, the workpiece 42*a* cooperates with the apparatus 44 during the electrolytic removal of material from opposing sides of the partially formed airfoils 286 in the same manner as in which the workpiece 42 cooperates with the various components of the apparatus 44. The principal difference between the workpieces 42 and 42*a* is that the workpiece 42*a* has a frame with openings which receive partially formed articles while the workpiece 42 has a unitary construction. Of course, if desired, the airfoils 62-84 could be partially formed in the workpiece 42 before the workpiece is operated on by the apparatus 44. This would have the advantage of reducing the time and energy required by the apparatus 44 to finish the workpiece.

In view of the foregoing it can be seen that an improved apparatus 44 for at least partially forming airfoils includes a plurality of pairs of electrodes 160, 162, 164 and 166 which are utilized to simultaneously effect the electrolytic removal of material from opposite sides of the workpiece 42 at spaced apart locations. The airfoils are formed in two separate groups each of which is disposed along an associated minor side surface 52 or 54 of the workpiece. This is accomplished by simultaneously moving each of the electrodes 160, 162, 164 and 166 relative to each other along separate paths extending at acute angles to the major and minor side surfaces 48, 50, 52 and 54 of the workpiece. As the electrodes 160, 162, 164 and 166 are moved toward the workpiece, electrolyte is directed along flow paths which extend axially along the surfaces 114 and 116 of the airfoils. The electrolyte flows from tip end portions 88 and 90 of the airfoils inwardly toward the central portion of the workpiece to the root portions 92 and 96 of the airfoils. The surface 114 and 116 of the airfoils 62-72 along one minor side 52 of the workpiece slope in one direction relative to the major side 48 of the workpiece while the surfaces 114 and 116 of airfoils 74-84 along the other minor side 54 of the workpiece slope in the opposite direction.

Although the workpiece 42 is disclosed herein as having a length which is twice as great as the length which can be received in the chamber 148, the length of the workpiece could be such that the entire workpiece would be enclosed in the chamber 148. In such a case, only three airfoils would be formed along each of the minor sides of the workpiece. Of course, the electrodes 160, 162, 164 and 166 could be sized so as to simultaneously form a greater or lesser number of airfoils along the minor sides of the workpiece. The airfoils 62-84 all have the same configuration. However, it is contemplated that the electrodes 160, 162, 164 and 166 could be shaped so as to form a plurality of airfoils having different configurations.

The workpiece utilized in associated with the apparatus can have many different forms. Thus, the workpiece 42 is integrally

formed by a single piece of metal. The workpiece 42*a* is formed by the securely interconnected frame 280 and partially formed airfoils 286. Partially formed airfoils can be mounted in the frame 280 to reduce the amount of material which must be electrolytically removed by the apparatus 44.

WHAT WE CLAIM IS:—

1. An apparatus for at least partially forming articles by electrolytically removing material from a workpiece having opposing sides and at least partially composed of an electrically conductive material, said apparatus comprising a working chamber for receiving at least a portion of the workpiece, means for holding at least a portion of the workpiece in said working chamber, first and second separately movable electrodes at least partially disposed in said working chamber for use in effecting the electrolytic removal of material from the opposing sides of the workpiece to at least partially form opposing side surfaces of an article, said first and second electrodes being movable toward each other through working strokes during which material is electrolytically removed from the opposing sides of the workpiece, said first and second electrodes being movable away from each other through return strokes after material has been electrolytically removed from the opposing sides of the workpiece, third and fourth separately movable electrodes spaced apart from said first and second electrodes and at least partially disposed in said working chamber for use in effecting the electrolytic removal of material from the opposing sides of the workpiece to at least partially form opposing side surfaces of an article, said third and fourth electrodes being movable toward said first and second electrodes and toward each other through working strokes during which material is electrolytically removed from the opposing sides of the workpiece, said third and fourth electrodes being movable away from said first and second electrodes and away from each other through return strokes after material has been electrolytically removed from the workpiece, means for supporting each of said electrodes for movement relative to each of the other electrodes during movement of said electrodes through their working and return strokes, means for establishing an electrical potential between the workpiece and each of said electrodes during movement of each of said electrodes through its working stroke, means for establishing a flow of electrolyte between the workpiece and each of said electrodes during movement of each of said electrodes through its working stroke, and means for simultaneously moving each of said electrodes through working strokes toward each other while the electrical potential is estabalished between each of said electrodes and the workpiece and during the flow of electrolyte between each of said electrodes and the workpiece to effect the electrolytic removal of material from the workpiece.

2. An apparatus as claimed in claim 1, wherein each of said electrodes includes a plurality of spaced apart working surface means for use in effecting the removal of material from the workpiece at a plurality of spaced apart areas without effecting the removal of material from portions of the workpiece disposed between the spaced apart areas.

3. An apparatus as claimed in claim 1, wherein said first electrode has a working surface with a configuration which corresponds to the configuration of a first side surface of a first article, said second electrode having a working surface with a configuration which is complementary to the configuration of said working surface of said first electrode and which corresponds to the configuration of a second side surface of the first article, said third electrode having a working surface with a configuration which corresponds to the configuration of a first side surface of a second article, said fourth electrode having a working surface with a configuration which is complementary to the configuration of said working surface of said third electrode and which corresponds to a second side surface of the second article, said first, second, third and fourth electrodes being ineffective to remove material from the workpiece in an area between the side surfaces of said first and second articles.

4. An apparatus as claimed in any one of the preceding claims, wherein said first and second electrodes are utilized in the removal of material from a first portion of the workpiece disposed on a first side of a plane extending through a longitudinal central axis of the workpiece in a direction perpendicular to the opposing sides of the workpiece, and said third and fourth electrodes are utilized in the removal of material from a second portion of the workpiece disposed on a second side of the plane extending through a longitudinal central axis of the workpiece in a direction perpendicular to the opposing sides of the workpiece, said second portion of the workpiece being spaced apart from said first portion of the workpiece by a central portion of the workpiece from which said first, second, third and fourth electrodes are ineffective to remove material.

5. An apparatus as claimed in any one of the preceding claims, wherein each of

the sides of the workpiece has a pair of opposite edge portions and a central portion disposed inwardly from the opposite edge portions at a location between spaced apart locations where material is removed, said means for establshing a flow of electrolyte including means for establishing a flow of electrolyte along a plurality of flow paths each of which extends between the central portion and one of the edge portions and across an associated one of the spaced apart locations where material is removed.

6. An apparatus as claimed in claim 1, wherein the opposing sides of the workpiece are opposing major sides which are interconnected by opposing minor sides, said first electrode including a working surface for use in forming a first recess extending inwardly toward a central portion of the workpiece from a first minor side of the workpiece, said first recess having an opening in a first major side of the workpiece, said second electrode including a working surface for use in forming a second recess extending inwardly toward the central portion of the workpiece from the first minor side of the workpiece, said second recess having an opening in the second major side of the workpiece opposite from the opening to the first recess in the first major side of the workpiece, said third electrode including a working surface for use in forming a third recess extending inwardly toward the central portion of the workpiece from the second minor side of the workpiece, said third recess having an opening in the first major side of the workpiece, said fourth electrode including a working surface for use in formng a fourth recess extending inwardly toward the central portion of the workpiece from the second minor side of the workpiece, said fourth recess having an opening in the second major side of the workpiece opposite from the opening to the third recess in the first major side of the workpiece, said first and second recesses being spaced apart from said third and fourth recesses by the central portion of the workpiece.

7. An apparatus as claimed in claim 6, wherein said means for establishing a flow of electrolyte includes means for causing electrolyte to flow along a first flow path extending between the first minor side and central portion of the workpiece through said first recess in a direction with at least a major portion of said first flow path extending generally perpendicular to the first minor side of the workpiece, means for causing electrolyte to flow along a second flow path extending between the first minor side and central portion of the workpiece through said second recess with at least a major portion of said second flow path extending generally perpendicular to the first minor side of the workpiece, means for causing electrolyte to flow along a third flow path extending between the second minor side and the central portion of the workpiece through said third recess with at least a major portion of said third flow path extending generally perpendicular to the second minor side of the workpiece, and means for causing electrolyte to flow along a fourth flow path extending between the second minor side and the central portion of the workpiece through said fourth recess with at least a major portion of said fourth flow path extending generally perpendicular to the second minor side of the workpiece.

8. An apparatus as claimed in any one of the preceding claims, wherein said means for simultaneously moving each of said electrodes includes means for moving each of said electrodes along a path which extends at an acute angle to the opposing side surfaces of the workpiece.

9. An apparatus as claimed in any one of the preceding claims, wherein said means for simultaneously moving each of said electrodes includes first motor means for moving said first electrode relative to each of the other electrodes along a first path, second motor means for moving said second electrode relative to each of the other electrodes along a second path, third motor means for moving said third electrode relative to each of the other electrodes along a third path extending transversely to the first path, and a fourth motor means for moving said fourth electrode relative to each of the other electrodes along a fourth path extending transversely to the second path.

10. An apparatus as claimed in any one of the preceding claims, wherein the workpiece has first and second end portions, said working chamber being effective to enclose one of the end portions of the workpiece with the other end portion of the workpiece disposed outside of said working chamber.

11. An apparatus for at least partially forming a plurality of articles by electrolytically removing material from a workpiece at least partially composed of an electrically conductive material and having opposing major sides interconnected by opposing minor sides, said apparatus comprising a working chamber for receiving at least a portion of the workpiece, means for holding at least a portion of the workpiece in said working chamber, a plurality of pairs of electrodes movable in said working chamber, a plurality of pairs of electrodes movable in said working chamber relative to each other and to the opposing

sides of the workpiece for use in effecting the electrolytic removal of material from the workpiece at each of a plurality of spaced apart locations to at least partially form opposing side surfaces of a plurality of articles, said plurality of pairs of electrodes including first and second pairs of electrodes said first pair of electrodes including a first electrode for use in forming a first recess extending inwardly toward a central portion of the workpiece from a first minor side of the workpiece said first recess having an opening in a first major side of the workpiece, and a second electrode for use in forming a second recess extending inwardly toward the central portion of the workpiece from the first minor side of the workpiece, said second recess having an opening in the second major side of the workpiece opposite from the opening to the first recess in the first major side of the workpiece, said second pair of electrodes including a third electrode for use in forming a third recess extending inwardly toward the central portion of the workpiece from the second minor side of the workpiece, said third recess having an opening in the first major side of the workpiece, and a fourth electrode for use in forming a fourth recess extending inwardly toward the central portion of the workpiece from the second minor side of the workpiece, said fourth recess having an opening in the second major side of the workpiece opposite from the opening to the third recess in the first major side of the workpiece, said first and second recesses being spaced apart from said third and fourth recesses by the central portion of the workpiece, means for establishing an electrical potential between the workpiece and said electrodes, means for establishing a flow of electrolyte between the workpiece and said electrodes at each of the plurality of spaced apart locations, and means for moving the electrodes of each pair of electrodes toward each other while the electrical potential is established between said electrodes and workpiece and during the flow of electrolyte between said electrodes and workpiece to effect the electrolytic removal of material at the plurality of spaced apart locations to at least partially form a plurality of articles.

12. An apparatus as claimed in claim 11, wherein said means for moving said electrodes includes means for moving each of said electrodes along a path which extends at an acute angle to the opposing major sides of the workpiece.

13. An apparatus as claimed in claim 11 or 12, wherein said means for establishing a flow of electrolyte includes means for establishing a flow of electrolyte in a first direction along a first plurality of flow paths which extend between the central portion and said first minor side of the workpiece through said first and second recesses and for establishing a flow of electrolyte in a second direction opposite to said first direction along a second plurality of flow paths which extend between the central portion and said second minor side of the workpiece through said third and fourth recesses.

14. An apparatus for electrochemically forming a plurality of series of article surface areas in a workpiece which is at least partially formed of an electrically conductive material, said apparatus comprising first and second electrodes for use in simultaneously forming opposite side surfaces of a first series of articles in a first portion of the workpiece, said first electrode including a first plurality of spaced apart working surfaces each of which has a configuration corresponding to the configuration of a first side surface of an article of the first series of articles, said second electrode including a second plurality of spaced apart working surfaces each of which has a configuration corresponding to the configuraion of a second side surface of an article of the first series of articles, third and fourth electrodes for use in simultaneously forming opposite side surfaces of a second series of articles in a second portion of the workpiece, said second portion of the workpiece being spaced apart from said first portion of the workpiece, said third electrode including a third plurality of spaced apart working surfaces each of which has a configuration corresponding to the configuration of a first side surface of an article of the second series of articles, said fourth electrode including a fourth plurality of spaced apart working surfaces each of which has a configuration corresponding to the configuration of a second side surface of an article of the second series of articles, means for establishing an electrical potential between the workpiece and said working surfaces of each of said electrodes, means for establishing a flow of electrolyte between the workpiece and said working surfaces of each of said electrodes, and means for simultaneously moving each of said electrodes relative to the workpiece while the electrical potential is established between the working surfaces of each of said electrodes and the workpiece and during the flow of electrolyte between the workpiece and the working surfaces of each of said electrodes to effect the simultaneous electrolytic removal of material from the first and second portions of the workpiece and the simultaneous formation of the opposite side surface of the first and second series of articles.

15. An apparatus as claimed in claim 14, wherein said means for simultaneously moving each of said electrodes relative to the workpiece includes first motor means connected with said first electrode for moving said first electrode along a first path, second motor means connected with said second electrode for moving said second electrode means along a second path extending transversely to said first path, third motor means connected with said third electrode for moving said third electrode along a third path extending transversely to said first path, and fourth motor means connected with said fourth electrode for moving said fourth electrode along a fourth path extending transversely to said second and third paths.

16. An apparatus as claimed in claim 14 or 15, wherein each of said articles is an airfoil, said working surfaces of said first and second electrode being disposed so as to effect the formation of the airfoils of the first series of articles with their tip end portions adjacent to a first outer side surface of the workpiece and their root end portions adjacent to a plane extending through the central axis of the workpiece, said working surfaces of said third and fourth electrode means being disposed so as to effect the formation of the airfoils of the second series of articles with their tip end portions adjacent to a second outer side surface of the workpiece and their root end portions adjacent to the plane extending through the central axis of the workpiece.

17. An apparatus as claimed in claim 16, wherein said means for establishing a flow of electrolyte includes means for directing a flow of electrolyte in a first direction along the opposite side surfaces of the first series of articles along flow paths extending between the root and tip end portions of the airfoils of the first series of articles and for directing a flow of electrolyte in a second direction opposite to the first direction along the opposite side surfaces of the second series of articles along flow paths extending between the root and tip end portions of the airfoils of the second series of articles.

18. An apparatus as claimed in any one of claims 14 to 17, wherein the workpiece has first and second end portions, a working chamber being effective to enclose one of the end portions of the workpiece with the other end portion of the workpiece disposed outside of said working chamber.

19. An apparatus as claimed in any one of claims 14 to 18, further including means for supporting each of said electrodes for movement relative to each of the other said electrodes during the electrolytic removal of material from the workpiece.

20. An apparatus for at least partially forming a plurality of articles by electrolytically removing material from the workpiece having opposing sides and at least partially composed of an electrically conductive material, said apparatus comprising a working chamber for receiving at least a portion of the workpiece, means for holding at least a portion of the workpiece in said working chamber, a plurality of pairs of separately movable electrodes at least partially disposed in said working chamber for use in effecting the electrolytic removal of material from the workpiece at each of a plurality of spaced apart locations to at least partially form opposing side surfaces of a plurality of articles, means for supporting each of said electrodes of said plurality of pairs of electrodes for movement relative to each of the other of said electrodes during the electrolytic removal of material from the workpiece, means for establishing an electrical potential between the workpiece and each of said electrodes, means for establishing a flow of electrolyte between the workpiece and each of said electrodes at each of the plurality of spaced apart locations, and a plurality of motor means each of which is connected with an associated one of said electrodes for simultaneously moving each electrode of said plurality of pairs of electrodes relative to each other and the workpiece while the electrical potential is established between each of said electrodes and the workpiece and during the flow of electrolyte between each of said electrodes and workpiece to effect the electrolytic removal of material at the plurality of spaced apart locations to at least partially form a plurality of articles.

21. An apparatus as claimed in claim 20, wherein each of said electrodes includes a plurality of spaced apart working surfaces for use in effecting the removal of material from the workpiece at the plurality of spaced apart locations, each of said spaced apart working surfaces of one electrode of a pair of electrodes being disposed opposite from a working surface of the other electrode of the pair of electrodes during the electrolytic removal of material from the workpiece to at least partialy form opposite side surfaces of an article.

22. An apparatus as claimed in claim 20 or 21, wherein said plurality of motor means for moving said plurality of pairs of electrodes includes means for moving each of said electrodes along a path which extends at an acute angle to the opposing sides of the workpiece.

23. An apparatus as claimed in claim 20 or 22, wherein each pair of electrodes in-

cludes a first electrode having a working surface with a configuration which corresponds to the configuration of one side of an article and a second electrode having a working surface with a configuration which is complementary to the configuration of said working surface of said first electrode and which corresponds to the configuration of a side of an article opposite from the one side.

24. An apparatus as claimed in any one of claims 20 to 23, wherein the workpiece has first and second end portions, said working chamber being effective to enclose one of the end portions of the workpiece with the other end portion of the workpiece disposed outside of said working chamber.

25. An apparatus as claimed in any one of claims 20 to 24, wherein one of said pairs of electrodes is utilized in the removal of material from a portion of the workpiece disposed on a first side of a plane extending through a longitudinal central axis of the workpiece and perpendicular to the opposing sides of the workpiece, and another of said pairs of electrodes is utilized in the removal of material from a portion of the workpiece disposed on a second side of said plane extending through a longitudinal central axis of the workpiece.

26. An apparatus for at least partially forming articles by electrolytically removing material from a workpiece substantially as herein described with reference to the accompanying drawings.

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1570733 COMPLETE SPECIFICATION

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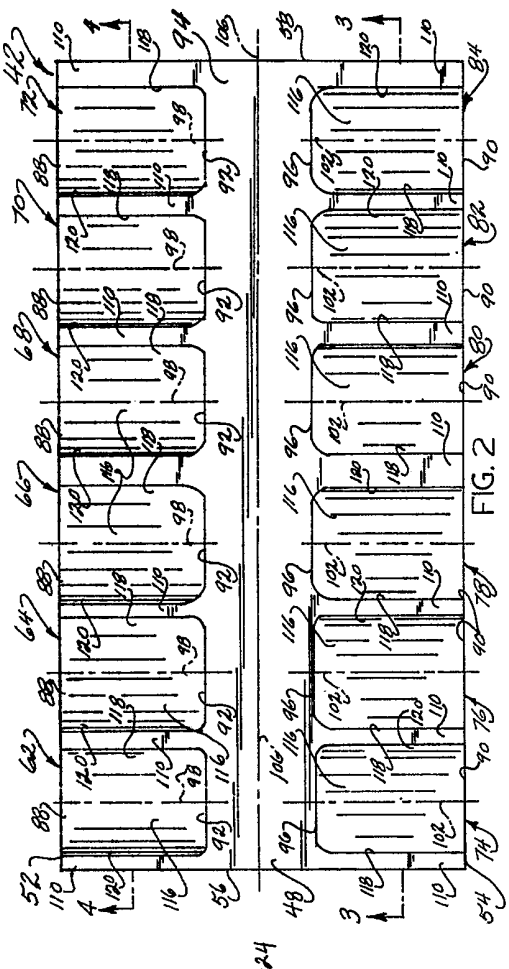

FIG. 2

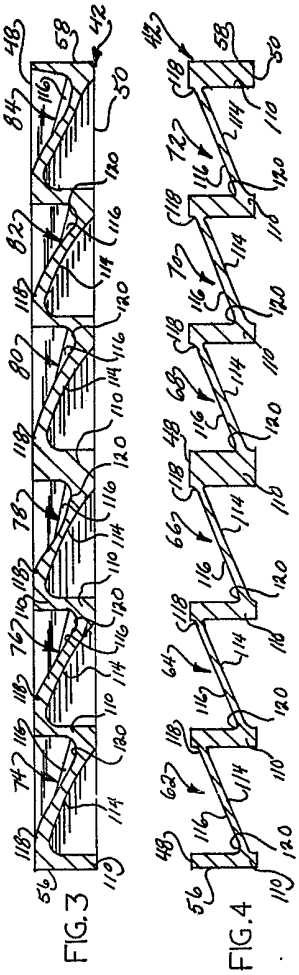

FIG. 3

FIG. 4

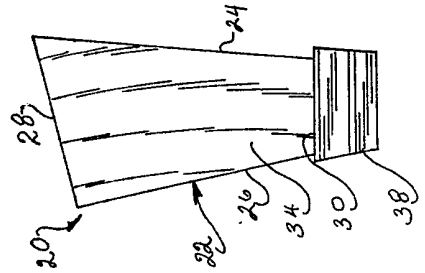

FIG. 1

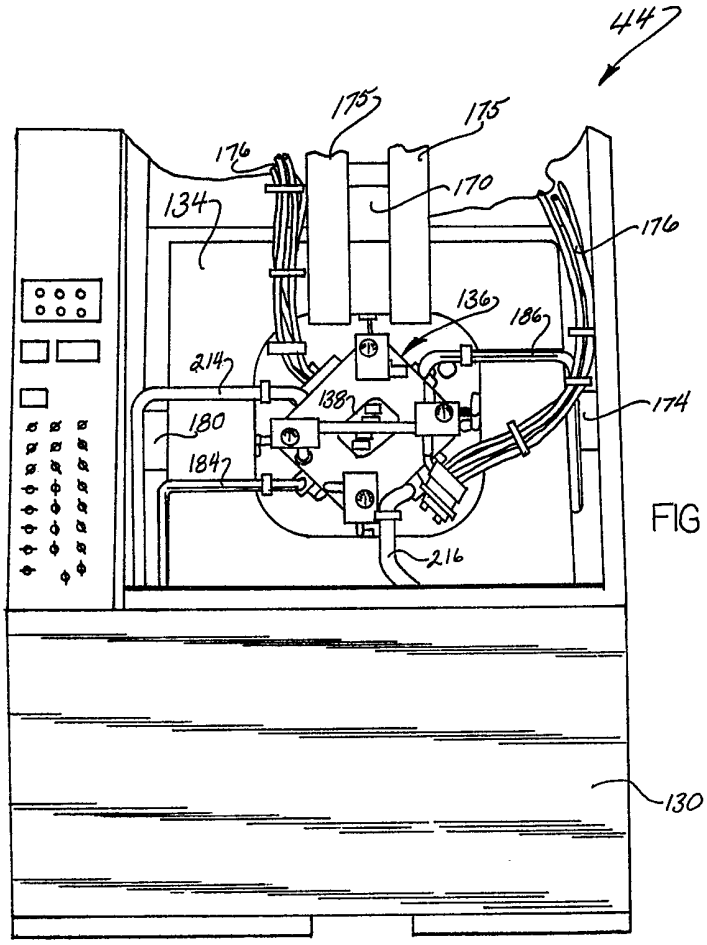

FIG 5

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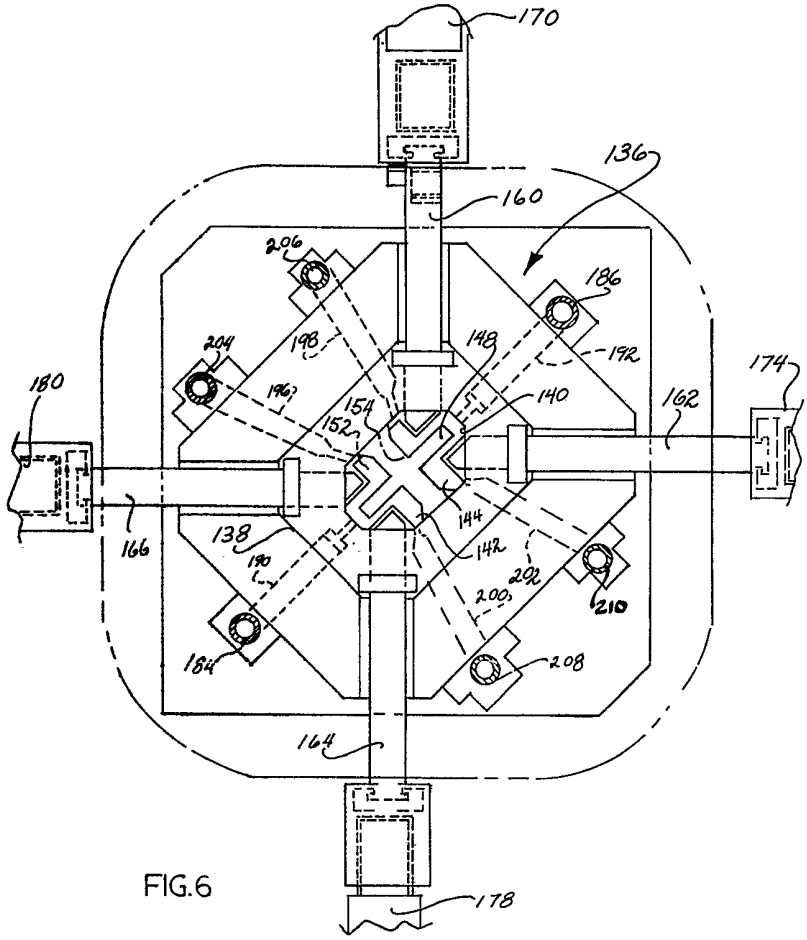

FIG.6

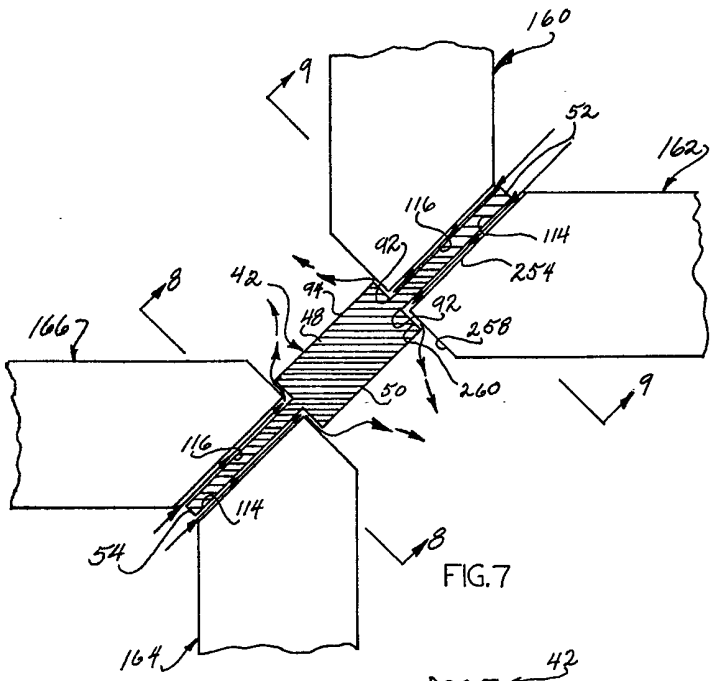
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FIG.7

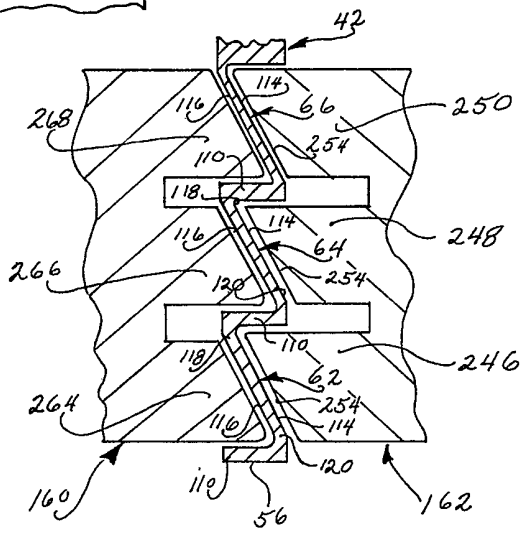
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FIG.9

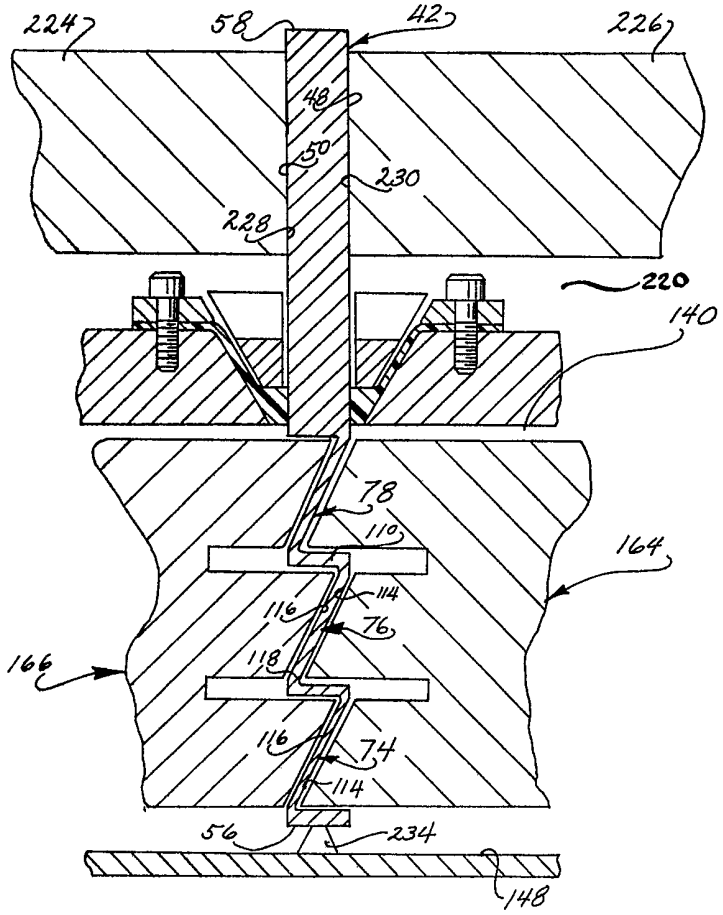
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FIG. 8

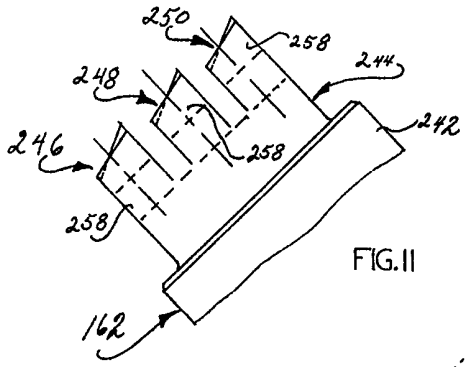

FIG. 11

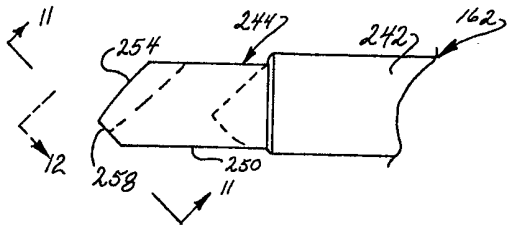

FIG. 10

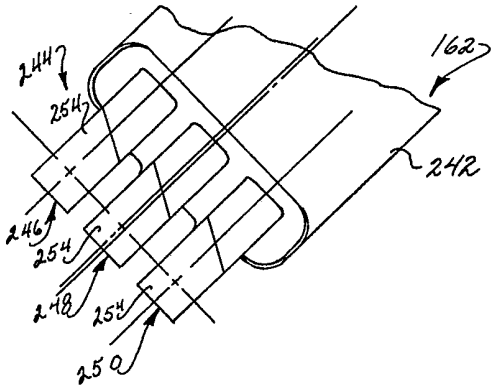

FIG. 12

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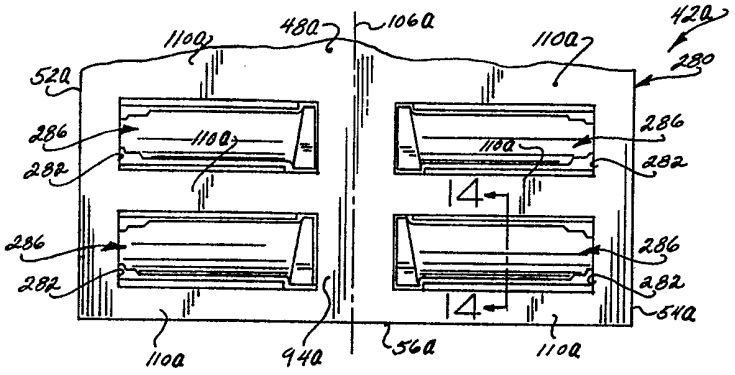
FIG,13



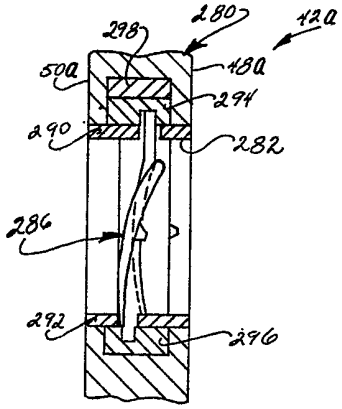


FIG. 14