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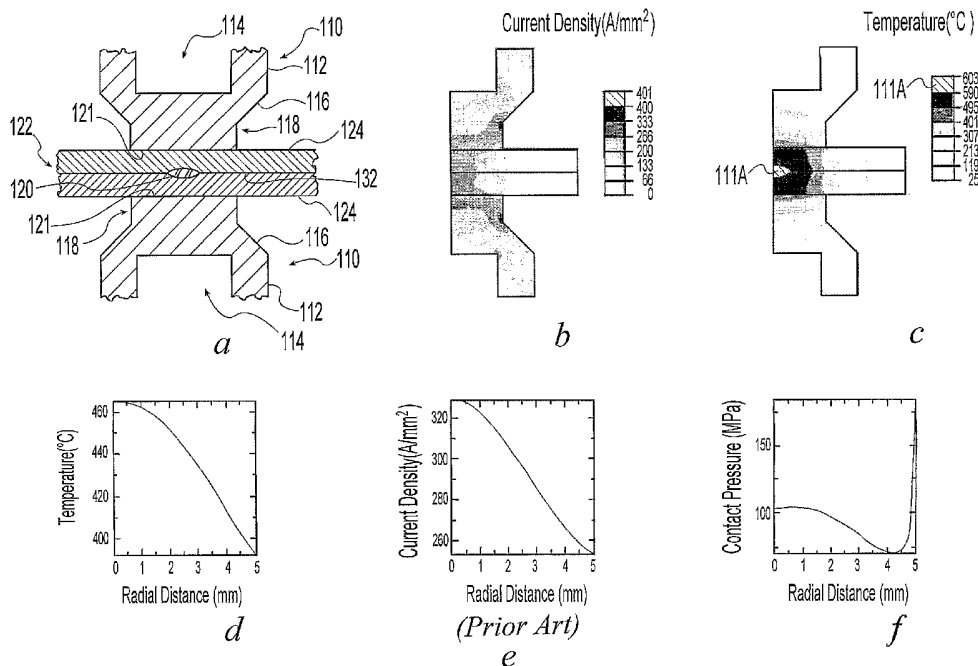
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(54) Title: RESISTANCE WELDING ELECTRODE



(57) Abstract: A composite resistance spot welding electrode is disclosed which comprises a co-axial annular neck ring, a co-axial insert, a co-axial annular sleeve, or combinations there of. The electrode provides improved nugget formation and longer electrode life. A composite resistance seam welding electrode is also disclosed which can include a ring, an insert, and/or a sleeve. A resistance welding machine according to the invention can operate using a reduced current level compared to a conventional machine.



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RESISTANCE WELDING ELECTRODE

FIELD OF THE INVENTION

5 This invention relates to electrodes for use in resistance welding, in particular to resistance spot welding of aluminum and aluminum alloys, and, in further particular, to composite electrodes having improved useful life and providing improved nugget formation when used to weld aluminum and alloys thereof.

BACKGROUND OF THE INVENTION

10 Resistance spot welding (RSW) is characterized by placing two workpieces of base metal, for example, low-, medium-, and high-carbon steels, alloy steels, stainless steels, nickel and nickel-based alloys, copper and copper alloys, aluminum, magnesium, titanium, and other alloys, including dissimilar metals or similar metals with the same or different sheet thicknesses, adjacent to one another, forcing the tip of
15 at least one electrode against at least one of the workpieces, and passing a finite number of current cycles via the at least one electrode through the two workpieces. Metals with higher electrical resistivity and lower thermal conductivity are considered to be more amenable to RSW since it is possible to use a more-desirable lower welding current. When the base metals exhibit high thermal expansion, warping and buckling of the welded assembly can be a problem. In addition, hardness is a factor.
20 Soft metals will be marked easily by the electrodes unless low electrode forces are used. Conversely, hard, strong metals require greater force to ensure adequate contact between the electrode and the workpiece. Finally, other factors such as oxide formation and plastic range can have significant effects on RSW.

25 In operation, resistance to the current melts the base metal at the interface between the two workpieces (the faying surface), thereby creating a lenticular-shaped zone of initially molten base metal which, when fused, forms a nugget which secures the two workpieces together. The current is typically short-time-pulsed, low-voltage, and high-amperage.

30 The electrodes used in RSW must exhibit the ability to conduct electricity to the workpiece efficiently, effectively transmit the necessary pressure to the workpiece, and rapidly transfer heat away from the interface between the electrode and the workpiece. Therefore, the most desirable electrodes will have high electrical and

thermal conductivities, high hardness at elevated temperatures, and sufficient structural strength and stiffness to withstand the rigors of the weld process.

RSW is the most widely used joining method for thin sheet metals, particularly in the automotive industry. There is, particularly in the automotive industry, growing
5 interest in the use of aluminum and aluminum alloys in automobile structures. (It is to be understood herein that any reference to aluminum, unless otherwise indicated, refers also to aluminum alloys.) It is recognized, further, that RSW is a key technology in the volume production of aluminum sheet structures. While conventional RSW is quite satisfactory for joining, for example, steels, other metals,
10 particularly aluminum, present unique problems. First, aluminum has a high chemical affinity for oxygen and, therefore, forms a film of oxide when exposed to air. This oxide film not only presents a barrier of high electrical resistance which must be overcome to supply current to the workpiece, it also exhibits high heat transfer which conducts heat away from the workpiece so quickly that a nugget may not form properly. In addition, the oxide layer has a high melting point – an important
15 consideration also at the interface between the two sheets. These attributes result in the need for higher current densities and associated higher electrode temperatures to produce a satisfactory weld. Second, aluminum itself has high thermal and electrical conductivities as well as a high heat of fusion. To overcome these properties and generate enough heat at the weldsite to create a satisfactory nugget, a higher welding
20 current is required in a relatively shorter period of time. Finally, aluminum has a narrower plastic temperature range and a larger thermal expansion coefficient. These properties necessitate a high electrode force in order to avoid inner stress-induced cracking during the nugget formation process. In addition, the required electrode
25 force for aluminum, relative to surface hardness, is much higher than, for example, steel. However, since contact resistance is inversely proportional to electrode force, a higher current density is required to create the necessary heat to form a satisfactory nugget when a higher electrode force is used. The force is generally of such a magnitude that, along with the increased temperature of the electrode due to high
30 current densities, a mushrooming effect is observed around the periphery of the electrode tip. The combination of these properties imposes a severe working environment of high mechanical and thermal stresses upon the electrodes. The

electrodes are run hotter and, at the same time, subjected to higher forces. This, in turn, results in shorter electrode life, reduced productivity, and higher cost operations.

As an example of the difficulty of using RSW on a metal like aluminum, consider the following comparison shown in Table 1 below.

5

Table 1

<u>Parameter</u>	<u>Galvanized Steel [1]</u>	<u>Aluminum [2]</u>
Base Metal Thickness (mm)	2.0	2.0
Current (KA)	16.7	25
Force (pounds-force)	1400	1573
Weld Time (cycles)	19	8
Life (welds) [1]	5,000	500

Sources: [1] Updated Technology, Resistance Welding Course – 2000, 4-22 (2000).

Basis: Flat-tip Cu-Zr electrode and low-carbon galvanized steel.

[2] M. Hao, et al., Developments in Characterization of Resistance Spot
 10 Welding of Aluminum, Welding J., vol. 75, no. 1, 1s-8s (1996). Basis: Dome- or
 spherical-shaped tip Cu-Zr electrode and 5XXX aluminum.

The reason the indicated electrodes function at all with aluminum is the fact that a dome-shaped tip is used so that more concentrated contact is achieved and mushrooming is minimized. As the electrodes are used, however, the mushrooming
 15 effect, noted above, causes a degradation in the quality of the nugget. As shown, after
 a limited number of welds, the electrodes must be replaced.

These and other problems have been approached in several ways. It is known, for example, to include a thick annular sleeve of high strength and high electrical resistivity material around the tip of a copper electrode as well a co-axial insert at the
 20 center of the tip surface. For example, U.S. Pat. No. 4,514,612 to Nied teaches such a configuration to control and improve both thermal and mechanical conditions. The Nied configuration is said to minimize the mushrooming that can occur around the periphery of the electrode tip as the result of high temperature and high forces and help channel current flow into the central region of the electrode. When applied to
 25 aluminum, however, the Nied electrode exhibits unacceptably high current densities and resultant higher temperatures in the vicinity of the sleeve and unacceptably low temperatures at the faying surface. Similarly, U.S. Pat. No. 3,689,731 to Miller

teaches the use of a high electrical resistivity washer offset from the tip face. When used in aluminum applications, the configuration of the Miller electrode directs the majority of the current flow around a slot formed to receive the washer and only a very small portion of the current flows to the center of the electrode. In addition, the current tends to "bleed back" around the slot resulting in insufficient current at the interface between the electrode and the workpiece. The result is poor or no weld formation. In addition, stress concentration in the Miller electrode at the interface between the relatively soft electrode and the workpiece directly below the relatively hard washer can damage the electrode and shorten its life.

Thus, there is a need for an improved electrode, particularly for welding aluminum and similar metals, which forms satisfactory nuggets with lower energy requirements and which electrode exhibits a longer useful life.

Resistance seam welding (RSEW) is characterized by moving two adjacent metal workpieces between rotating wheel electrodes. The wheel electrodes usually apply a constant force to the workpieces and rotate at a controlled speed. The welding current is normally pulsed to make a series of overlapping spot welds and thereby form a continuous seam weld. A continuous welding current may be used for certain high speed applications where gaps could otherwise occur between individual spot welds. Some other types of resistance welding processes include projection welding, flash welding, upset welding, percussion welding, and high frequency resistance welding. There is also a need for improved electrodes for resistance seam welding and other types of resistance welding processes.

BRIEF DESCRIPTION OF THE INVENTION

It is, therefore, an object of the present invention to provide an improved electrode for resistance welding, and particularly for resistance welding of aluminum.

It is a further object of the present invention to provide an RSW electrode which effects improved welds, offers increased electrode life, and has lower electrical energy requirements.

It is yet a further object of the present invention to provide an RSW electrode comprising a composite tip, which electrode comprises, individually or in combination, a high-strength, low thermal- and electrical-conductivity insert co-axial with the tip, a high-strength, low thermal- and electrical-conductivity annular sleeve

co-axial with the tip, and a high-strength, low thermal- and electrical-conductivity ring co-axial with the tip in a spaced-apart relation to a face of the tip.

It is yet a further object of the present invention to provide an RSW electrode comprising an insert and a sleeve of proportions relative to the electrode whereby the
5 current flow path is confined and whereby a comparably-sized nugget is formed with fewer welding cycles, reduced peak welding current values, or both, relative to welding utilizing traditional electrodes.

It is yet a further object of the present invention to provide RSW electrodes which offer improved electrode pressure distribution and reduced electrode tip heating and
10 plastic deformation of the electrode.

Examples of empirical results, together with results from incrementally-coupled finite element analysis (FEA) models, are used to illustrate the new design.

It is yet a further object of the present invention to provide improved RSEW electrodes.

15 It is yet a further object of the present invention to provide a resistance welding machine that can operate using a reduced current level compared to a conventional machine.

The above and other objects, features, and advantages of the present invention will be made more apparent from the following specification taken in conjunction with the
20 accompanying drawings which illustrate preferred embodiments of the present invention by way of example.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a is a cross-section of a pair of prior art electrodes and also showing a
25 workpiece as well as a nugget.

Fig. 1b is an FEA graphic of the type of prior art electrodes and workpiece shown in Fig. 1a showing the current density profile during operation.

Fig. 1c is an FEA graphic of the type of prior art electrodes and workpiece shown in Fig. 1a showing the temperature profile during operation.

30 Fig. 1d is a plot of the temperature during operation at the interface between the type of prior art electrodes and the workpiece shown in Fig. 1a.

Fig. 1e is a plot of the current density during operation at the interface between the type of prior art electrodes and the workpiece shown in Fig. 1a.

Fig. 1f is a plot of the contact pressure at the interface between the type of prior art electrodes and the workpiece shown in Fig. 1a.

Fig. 2a is a cross-section of a pair of prior art composite copper electrodes comprising a heavy-duty annular sleeve and a center insert and also showing a workpiece.

Fig. 2b is an FEA graphic of the type of prior art electrodes and workpiece shown in Fig. 2a showing the current density profile during operation.

Fig. 2c is an FEA graphic of the type of prior art electrodes and workpiece shown in Fig. 2a showing the temperature profile during operation.

Fig. 3a is a cross-section of a pair of prior art composite copper electrodes comprising an offset support washer and also showing a workpiece.

Fig. 3b is an FEA graphic of the type of prior art electrodes and workpiece shown in Fig. 3a showing the current density profile during operation.

Fig. 3c is an FEA graphic of the type of prior art electrodes and workpiece shown in Fig. 3a showing the temperature profile during operation.

Fig. 3d is a plot of the contact pressure at the interface during operation between the type of prior art electrodes and the workpiece shown in Fig. 3a.

Fig. 4a is a cross-section of a pair of electrodes comprising an insert, a sleeve, and a ring according to the present invention and also showing a workpiece as well as a nugget.

Fig. 4b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 4a showing the current density profile during operation.

Fig. 4c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 4a showing the temperature profile during operation.

Fig. 4d is a plot of the temperature during operation at the interface between type of the electrodes and the workpiece shown in Fig. 4a.

Fig. 4e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 4a.

Fig. 4f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 4a.

Fig. 5a is a cross-section of a pair of electrodes comprising an insert, a sleeve, and a ring according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 5b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 5a showing the current density profile during operation.

Fig. 5c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 5a showing the temperature profile during operation.

5 Fig. 5d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 5a.

Fig. 5e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 5a.

10 Fig. 5f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 5a.

Fig. 6a is a cross-section of a pair of electrodes comprising a sleeve according to another aspect of the present invention and also showing a workpiece as well as a nugget.

15 Fig. 6b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 6a showing the current density profile during operation.

Fig. 6c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 6a showing the temperature profile during operation.

Fig. 6d is a plot of the temperature at the interface during operation between the type of electrodes and the workpiece shown in Fig. 6a.

20 Fig. 6e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 6a.

Fig. 6f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 6a.

25 Fig. 7a is a cross-section of a pair electrodes comprising a sleeve according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Figs 7b-7e are FEA graphics of nugget formation with varying sleeve dimensions according to the aspect of the present invention shown in Fig. 7a.

30 Fig. 8a is a cross-section of a pair of electrodes comprising an insert according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 8b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 8a showing the current density profile during operation.

Fig. 8c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 8a showing the temperature profile during operation.

Fig. 8d is a plot of the temperature at the interface during operation between the type of electrodes and the workpiece shown in Fig. 8a.

5 Fig. 8e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 8a.

Fig. 8f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 8a.

10 Fig. 9a is a cross-section of a pair of electrodes comprising an insert according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Figs 9b-9e are FEA graphics of nugget formation with varying insert dimensions according to the aspect of the present invention shown in Fig. 9a.

15 Fig. 10a is a cross-section of a pair of electrodes comprising a ring according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 10b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 10a showing the current density profile during operation.

20 Fig. 10c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 10a showing the temperature profile during operation.

Fig. 10d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 10a.

Fig. 10e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 10a.

25 Fig. 10f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 10a.

Fig. 11a is a cross-section of a pair of electrodes comprising a ring according to another aspect of the present invention and also showing a workpiece as well as a nugget.

30 Figs 11b-11d are FEA graphics of nugget formation with varying ring dimensions according to the aspect of the present invention shown in Fig. 11a.

Fig. 12a is a cross-section of a pair of electrodes comprising an insert, a sleeve, and a ring according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 12b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 12a showing the current density profile during operation.

Fig. 12c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 12a showing the temperature profile during operation.

Fig. 12d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 12a.

Fig. 12e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 12a.

Fig. 12f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 12a.

Fig. 13a is a cross-section of a pair of electrodes comprising an insert and a sleeve according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 13b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 13a showing the current density profile during operation.

Fig. 13c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 13a showing the temperature profile during operation.

Fig. 13d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 13a.

Fig. 13e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 13a.

Fig. 13f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 13a.

Fig. 14a is a cross-section of a pair of electrodes comprising an insert and a sleeve according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 14b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 14a showing the current density profile during operation.

Fig. 14c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 14a showing the temperature profile during operation.

Fig. 14d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 14a.

Fig. 14e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 14a.

5 Fig. 14f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 14a.

Fig. 15a is a cross-section of a pair of electrodes comprising an insert and a sleeve according to another aspect of the present invention and also showing a workpiece as well as a nugget.

10 Fig. 15b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 15a showing the current density profile during operation.

Fig. 15c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 15a showing the temperature profile during operation.

15 Fig. 15d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 15a.

Fig. 15e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 15a.

Fig. 15f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 15a.

20 Fig. 16a is a cross-section of a pair of electrodes comprising an insert and a sleeve according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 16b is an FEA graphic the type of electrodes and workpiece shown in Fig. 16a showing the current density profile during operation.

25 Fig. 16c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 16a showing the temperature profile during operation.

Fig. 16d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 16a.

30 Fig. 16e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 16a.

Fig. 16f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 16a.

Fig. 17a is a cross-section of a pair of electrodes comprising an insert, a sleeve, and a ring according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Fig. 17b is an FEA graphic of the type of electrodes and workpiece shown in Fig. 17a showing the current density profile during operation.

Fig. 17c is an FEA graphic of the type of electrodes and workpiece shown in Fig. 17a showing the temperature profile during operation.

Fig. 17d is a plot of the temperature during operation at the interface between the type of electrodes and the workpiece shown in Fig. 17a.

Fig. 17e is a plot of the current density during operation at the interface between the type of electrodes and the workpiece shown in Fig. 17a.

Fig. 17f is a plot of the contact pressure during operation at the interface between the type of electrodes and the workpiece shown in Fig. 17a.

Fig. 18a is a cross-section of a pair of electrodes comprising an insert according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Figs 18b-18d are FEA graphics of nugget formation with varying insert dimensions in combination with a sleeve according to the aspect of the present invention shown in Fig. 18a.

Fig. 19a is a cross-section of a pair of electrodes comprising an insert, a sleeve, and a ring according to another aspect of the present invention and also showing a workpiece as well as a nugget.

Figs 19b-19d are FEA graphics of nugget formation with varying insert dimensions in combination with both a sleeve and a ring according to the aspect of the present invention shown in Fig. 19a.

Figs 20a, 21a, 22a, and 23a are duplicate cross-sections of a pair of electrodes comprising an insert and a sleeve according to another aspect of the present invention and also showing a workpiece, and, in the case of Figs 22a and 23a, a nugget.

Figs 20b-20f, 21b-21f, 22b-22f, and 23b-23f are FEA graphics and plots showing current densities, contact pressures, and temperatures at varying current cycles according to the aspect of the present invention shown in Figs 20a, 21a, 22a, and 23a, respectively.

Figs 24a and 24b are FEA graphics of current densities and temperatures, respectively, showing nugget formation according to an aspect of the present invention comprising an insert and a sleeve.

5 Figs 25a and 25b are FEA graphics of current densities and temperatures, respectively, showing nugget formation according to an aspect of the present invention comprising an insert and a ring.

Figs 26a and 26b are FEA graphics of current densities and temperatures, respectively, showing nugget formation according to an aspect of the present invention comprising an insert, a sleeve, and a ring.

10 Figs 27a and 27b are plots of nugget sizes versus weld time (cycles) for FEA computer program-predicted values compared with experimental values.

Figs 28a-28d are cross-sections of electrodes in which the insert and the co-axial cavity have a protrusion and a corresponding recess according to another aspect of the present invention.

15 Fig. 29 is a cross-section of a pair of different electrodes according to the present invention, and also showing a workpiece as well as a nugget, the first electrode comprising an insert, a sleeve, and a ring, and the second electrode comprising a sleeve.

20 Fig. 30 is a side elevational view of a resistance seam welding process in which rotating wheel electrodes create a continuous seam weld between adjacent metal workpieces, where the electrodes are composite wheel electrodes according to the present invention.

Fig. 31 is a front view, partly in cross-section, of one of the composite wheel electrodes according to the present invention.

25 Fig. 32 is a front view, partly in cross-section, of another embodiment of a composite wheel electrode according to the present invention.

Fig. 33 is a front view, partly in cross-section, of another embodiment of a composite wheel electrode according to the present invention.

30 Fig. 34 is a front view, partly in cross-section, of another embodiment of a composite wheel electrode according to the present invention.

Fig. 35 is a front view, partly in cross-section, of another embodiment of a composite wheel electrode according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION AND BEST MODE

Turning first to Fig. 1a, a pair of conventional prior art copper electrodes 110 of the indicated design is shown. Each electrode 110 comprises first a shank portion 112 which, for purposes of comparison, has a diameter of 16 mm which is formed to include a coolant channel 114 having a diameter of 9 mm in which cold water or other suitable coolant circulates to help cool the electrode 110 during use. (In the FEA analyses presented herein, the coolant is water at ambient temperature (20 deg. C).) Second is a tapered section 116, adjacent to, and integral with, the shank portion 112. For purposes of comparison, the tapered portion 116 has a height in the axial direction of 3 mm and an angle relative to the radius of 45 degrees. Third is a tip portion 118, adjacent to, and integral with, the tapered portion 116. Again, for purposes of comparison, the tip portion 118 has a height in the axial direction of 2.4 mm and a diameter of 10 mm. The tip portion 118 is formed to include a flat face 121. The flat face 121 was chosen for consistency and to provide a proper comparison with the electrodes of the present invention. While a particular electrode shape is shown using pure copper, those skilled in the art will recognize that there are many different shapes used in RSW applications and that various copper alloys may be used for the electrode 110. Furthermore, those skilled in the art will also recognize that each of the pair of electrodes 110 need not be identical.

During operation, the pair of electrodes 110 are arranged in a facing, spaced-apart relationship, a workpiece 122, comprising two pieces of sheet metal 124 is interposed between the electrodes 110, the workpiece 122 is then squeezed between the electrodes 110 with a specified force, and a current of specified amperage is applied for a specified number of electrical cycles. The current flow causes the temperature of the faying surface 132 between the two pieces of sheet metal 124 to rise causing the metal to melt and, when fused, to form a solid nugget 120.

Turning next to Figs 1b-1f, the conditions during operation for the configuration of Fig. 1a are illustrated. In all FEA examples shown herein, the conditions shown in Table 2 below were used unless otherwise specified.

Table 2

<u>Parameter</u>	<u>Value</u>
Base Metal Type	5XXX Al
Base Metal Thickness (mm)	2
Total Workpiece Thickness (mm)	4
Electrode Material	Cu
Current (KA)	22
Force (pounds-force)	1550
Weld Time (cycles)	10
Squeeze Time (cycles)	60

Fig. 1b shows the current density profile throughout the electrodes 110 and the workpiece 122. The current density profile shows that the current is distributed over the entire interface between the electrode face 121 and the workpiece 122. In addition, the current is concentrated near the faying surface 132. Similarly, Fig. 1c shows the temperature profile. The highest temperature range 111A is between 590-603 deg. C and indicates the formation of a nugget 120. In this example, however, the nugget 120 is too small to be effective. For a nugget 120 to be effective, it must have a vertical coverage, the percent of the thickness of the nugget 120 to the total thickness of the workpiece 122 of between 20 and 80 percent and preferably about 40 percent and have a diameter as large as possible. For example, if the nugget 120 is too thin, the weld will have insufficient strength, if the nugget 120 is too thick, however, the high temperature can cause the electrode 110 to become overheated. The nugget 120 in the example shown in Figs 1a and 1c, however, is only 0.96 mm thick, or 24 percent of the total 4 mm thickness of the workpiece 122. This dimension is acceptable, but at the lower end of the desired range and well below the preferred value of 40 percent. The diameter of the nugget 120 is 3.1 mm.

Fig. 1d shows the temperature profile (deg. C) along the interface between the electrode face 121 and the workpiece 122. As shown, the peak temperature of 470 deg. C is at the center of the electrode face 121 and steadily decreases to 390 deg. C at the periphery of the face 121. This temperature range is well below the melting point of copper (1080 deg. C) to avoid deformation of the electrode.

Fig. 1e shows the current density profile (A/mm^2) along the same interface described in Fig. 1d. As with the temperature, the current density is higher at the center of the interface between the electrode face 121 and the workpiece 122 and steadily decreases toward the periphery of the face 121. This last phenomenon is undesirable since, in order to form a large-diameter nugget, the current should be distributed radially as far as possible.

Fig. 1f shows the contact pressure profile (MPa) along the same interface described in Fig. 1d. Both the center of the interface (0 mm Radial Distance) and the periphery (5 mm Radial Distance) experience the highest contact pressures. The periphery, in fact, experiences a significantly higher contact pressure which can cause degradation and mushrooming of the electrode face 121 at the periphery.

Turning now to Figs 2a-2c, a pair of prior art electrodes 210 according to Nied, above, is shown. Each electrode 210 comprises a shank portion 212 having a diameter of 16 mm, which is formed to include a coolant channel 214 having a diameter of 9 mm, an annular sleeve 226 having a thickness in the radial direction of 2.3 mm, and a co-axial insert 228 having a diameter of 2 mm. Also shown is a workpiece 222 comprised of two aluminum sheets 224. As shown in Fig. 2b, using an insert 229 and a sleeve 226 of 304 stainless steel (SS), the current load necessary to weld aluminum creates high current densities and higher-than-desirable electrode temperatures in some locations and lower-than-desirable electrode temperatures in other locations (Fig. 2c). For example, the current densities 210A, 210B in the undesirable location between the sleeve 226 and the coolant channel 214, produces higher-than-desirable electrode temperatures 211D, 211E back in the shank portion 212 and lower-than-desirable temperatures 211F at the interface between the face 221 and the workpiece 222. More importantly, however, the temperature 211E at the faying surface 232 is insufficient to create a nugget.

Turning next to Figs 3a-3d, a pair of prior art electrodes 310 comprises first a shank portion 312, a tapered portion 316, and a tip portion 318. In addition, an annular washer 330 is inserted into an annular slot 334. Drawing from information disclosed in Miller, the diameter of the tip portion 318 is one-half inch (12.7 mm), the annular washer 330 is one thirty-second inch thick (0.8 mm) in the axial direction and offset from the tip face one thirty-second inch (0.8 mm). The horizontal depth of the slot 334 in the radial direction is one-eighth inch (0.3 mm). As shown in Fig. 3b,

during operation, the nature of the 304 SS annular washer 330 so positioned causes a region of high current density 310A and a “bleed back” of current attempting to ground to the workpiece 322 along the path of least resistance. In addition, the indicated conditions fail to produce a nugget because the temperature at the faying surface 332 is too low. Finally, as shown in Fig. 3d, the interaction of the high-strength (Miller at 2:7) 304 SS annular washer 330 with the relatively soft copper and the force required to clamp the workpiece 322 causes an undesirable spike in the contact pressure which will, over time, deteriorate the electrode 310. Table 3 below summarizes the properties of interest.

Table 3

Property	Yield Strength (MPa)	Brinell Hardness	Melting Point (deg. C)
Copper (Cu)	110	75	1080
304 SS	240	150	1430

Source: Marks' Standard Handbook for Mechanical Engineering 6.66 Eugene A. Avallone and Theodore Baumeister III eds., 9th ed. (1987).

Turning now to an embodiment of the present invention, Fig. 4a shows a pair of electrodes 410 comprising first a shank portion 412, which, for purposes of comparison, has a diameter of 16 mm, but which can vary from 8-24 mm depending upon the application, which is formed to include a coolant channel 414 having a diameter of 9 mm. The coolant channel 414 diameter may vary depending upon the diameter of the shank 412. In addition, the coolant channel 414 shape may vary depending upon the application. Second is a tapered section 416, adjacent to, and integral with, the shank portion 412. Again, for purposes of comparison, the tapered portion 416 has a height in the axial direction of 3 mm and an angle relative to the radius of 45 degrees, but which can vary from 0 mm (no tapered section 416) to about 10 mm and have an angle of 20-90 degrees relative to the radius depending upon the application. Third is a tip portion 418, adjacent to, and integral with, the tapered portion 416. Again, for purposes of comparison, the tip portion 418 has a height in the axial direction of 2.4 mm and a diameter of 10 mm. For consistency and comparison purposes, the tip portion 418 is formed to include a flat face 421. Alternatively, the tip face could be spherical or any other shape with a smooth and

continuous surface. Each electrode 410 also comprises first an annular sleeve 440. Preferably, the sleeve 440 is relatively thin compared to the radius of the tip 418. The sleeve 440 preferably has a thickness in the radial direction between 0.5-3 mm, more preferably between 0.5-1 mm, and most preferably about 0.75 mm, or, more generally, between 10-60 percent of the radius of the tip 418, preferably between 10-20 percent of the radius of the tip 418, and more preferably about 15 percent of the radius of the tip 418 and a height in the axial direction between 1-5 mm, preferably between 2-3 mm, and more preferably 2.4 mm, or, more generally, between 20-80 percent of the distance from the face 421 to the bottom of the coolant channel 414, preferably between 40-50 percent of the distance from the face 421 to the bottom of the coolant channel 414, and more preferably 45 percent of the distance from the face 421 to the bottom of the coolant channel 414. Second, the electrode 410 includes a co-axial insert 444. The insert 444 is preferably relatively large in diameter compared to the diameter of the tip face 421. A large size insert 444 with low conductivity makes current flow more efficient. The insert 444 usually conducts minimum electrical current, but still provides necessary cooling effects to maintain low temperature at the interface between the electrode and the welded sheet. Preferably, the insert comprises no more than about 50% of the area of the tip face 421, so that the tip face has sufficient surface area for current to get through to cause a weld. In one embodiment, the insert comprises about 36% of the area of the tip face. When the tip face 421 has a diameter of 10 mm, the insert 444 preferably has a diameter between 1-7 mm, more preferably between 3-6 mm, and most preferably 5 mm, or, more generally, between 10-70 percent of the diameter of the tip 418, preferably between 30-60 percent of the diameter of the tip 418, and more preferably 50 percent of the diameter of the tip 418 and a height in the axial direction between 1-5 mm, preferably between 2-3 mm, and more preferably 2.4 mm, or, more generally between 20-80 percent of the distance from the face 421 to the bottom of the coolant channel 414, preferably between 40-50 percent of the distance from the face 421 to the bottom of the coolant channel 414, and more preferably 45 percent of the distance from the face 421 to the bottom of the coolant channel 414. Third, an annular ring 442 having a thickness in the radial direction of between 0.5-3 mm, preferably between 1-3 mm, and more preferably 1.5 mm, or, more generally, between 10-60 percent of the radius of the tip 418, preferably between 20-40 percent of the radius of the tip 418, and more preferably 30 percent of

the radius of the tip 418 and a height in the axial direction of between 0.5-2 mm, preferably between 0.75-1.5 mm, and more preferably 1 mm, or more generally, between 10-40 percent of the distance from the tip face 421 to the bottom of the coolant channel 414, preferably between 15-30 percent of the distance from the tip face 421 to the bottom of the coolant channel 414, and more preferably 20 percent of the distance from the tip face 421 to the bottom of the coolant channel 414.

In the example shown in Figs 4b-4f, the electrode 410 is copper and the sleeve 440 (0.75 mm thick in the radial direction and 2.4 mm high in the axial direction), the insert 444 (2 mm diameter and 2.4 mm high in the axial direction), and the ring 442 (1.5 mm thick in the radial direction and 1 mm high in the axial direction) are 304 SS. Other stainless steels and other materials with high strength and low thermal and electrical conductivities will also work satisfactorily. For example, tungsten can be a good choice for the insert, sleeve, and/or ring.

Fig. 4b shows the current density profile throughout the electrodes 410 and the workpiece 422. The effects of the sleeve 440, the insert 444, and the ring 442 on the current density are shown as greatly improved flow of current through the electrodes 410 to the workpiece 422. More importantly, an improved, larger nugget 420 is formed as shown by the 590 deg. C-plus temperature zone 411A. (Fig. 4c.) In the example shown, the nugget 440 is 3.34 mm thick, or 84 percent of the total 4 mm thickness of the workpiece 422. The diameter of the nugget 420 is 4.5 mm. Welding parameters, insert/sleeve dimensions, and nugget sizes can vary with significant magnitudes.

Fig. 4d shows the temperature distribution along the interface of the electrode tip face 421 and the workpiece 422. The temperature at the center is relatively high due to the presence of the low thermal conductivity SS insert 444. The copper portion of the electrode face 421 experiences a temperature (500 deg. C), only slightly higher than that of a plain copper electrode (Fig. 1d).

Fig. 4e shows the current density distribution along the interface of the electrode tip face 421 and the workpiece 422. As shown, the current density along both the insert 444 and the sleeve 440 is very low, but it is high and nearly uniform throughout the copper portion of the electrode tip face 421 which indicates that the current flows more efficiently in that area. (Compare Fig. 1e.)

Fig. 4f shows the contact pressure distribution along the interface of the electrode tip face 421 and the workpiece 422. Both the center and the periphery have relatively higher contact pressures which enables the insert 444 and the sleeve 440 to minimize any excess pressure on the copper portion of the tip face 421. (Compare Fig. 1f.)

5 The electrode 410 of the present invention can be advantageously used for welding aluminum, but it can also be used for welding any other suitable materials. For example, galvanized steels have short electrode lives with conventional electrodes. The electrode 410 of the invention should have a longer life when used for welding galvanized steels.

10 A modification of the embodiment shown in Figs 4a-4f is shown in Figs 5a-5f. Reference numerals are analogous to those used in Figs 4a-4c. Dimensions of the electrodes 510 are the same with the exception of the insert 544 which is 3 mm (versus 2 mm in Figs 4b-4f) in diameter. The composition of all components is the same as that shown in Figs 4a-4f.

15 Fig. 5b shows a somewhat enlarged current density profile compared with that shown in Fig. 4b. The nugget 520 (shown in Fig. 5c as temperature zone 511A) is 3.34 mm thick, or 84 percent of the total 4 mm thickness of the workpiece 522. The diameter of the nugget 520 is 5 mm. Thus, compared with the nugget 420 shown in Fig. 4c, the nugget 520 shown in Fig. 5c is the same thickness but slightly wider.

20 As in Figs 4d-4f, the plots shown in Figs 5d-5f are somewhat different from those of Figs 1d-1f, respectively. Note that the peak current density in Fig. 5e is higher than the comparable value in Fig. 4e because of the narrower current flow path caused by the wider diameter insert 544. In turn, the higher current density leads to a larger weld nugget 520.

25 Another embodiment of the instant invention is shown in Fig. 6a. Reference numerals are analogous to those used in Figs 4a-4c. Dimensions of analogous structures of the electrodes 610 are the same as those in the electrodes 410 shown in Fig. 4a. The electrode 610 shown in Fig. 6a, however, comprises only an added sleeve 640.

30 In the example shown in Figs 6b-6f, the sleeve 640 has a thickness in the radial direction of 0.75 mm and a height in the axial direction of 2.4 mm. The nugget 620 (shown in Fig. 6c as temperature zone 611A) is 2.12 mm thick, or 53 percent of the

total 4 mm thickness of the workpiece 622. The diameter of the nugget 640 is 3.6 mm.

Referring now to Figs 6d-6f, temperature, current density, and contact pressure are nearly uniform along the interface between the tip face 621 and the workpiece 622. The sleeve 640 takes the high pressure at the periphery of the electrode tip 610. Overall, this electrode 610 produces a smaller weld nugget 620 than the electrodes 410, 510 shown in Figs 4a and 5a respectively but provides a larger nugget 620 than the plain copper electrode 110 and more desirable mechanical conditions (i.e., reduced mushrooming).

Figs 7a-7e (Fig. 7a is referenced as above.) illustrate the effects of changing SS sleeve 740 thickness on the size and proportions of the nugget 720. All basic dimensions are the same as the earlier versions. Table 4 below compares the proportions of the nugget 720.

Table 4

Annular Ring Thickness (mm)	0.0	0.5	0.75	1.0
Nugget Thickness (mm)	0.96	0.66	2.12	3.2
Nugget Diameter (mm)	3.1	2.76	3.60	5.16
Nugget Vertical Coverage (%)	24	17	53	80

Thus, with the annular ring 740 alone, a larger thickness effects a larger nugget 720 in both thickness as well as the diameter. The apparent anomaly for the 0.5 mm thickness appears to be caused by the sleeve 740 being thinner and farther away from the axis and tracking much of the current near its inner surface. (Compare Fig. 7c for a thickness of 0.5 mm with Fig. 7e for a thickness of 1.5 mm.)

Another embodiment of the instant invention is shown in Fig. 8a. Reference numerals are analogous to those used in Figs 4a-4c. Dimensions of analogous structures of the electrodes 810 are the same as those in the electrodes 410 shown in Fig. 4a. The electrode 810 shown in Fig. 8a, however, comprises only an added insert 844.

In the example shown in Figs 8b-8f, the insert 840 has a diameter of 2 mm and a height in the axial direction of 2.4 mm. In this example, the insert 840 is tungsten, not 304 SS. The nugget 820 (shown in Fig. 8c as temperature zone 811A) is 2 mm thick,

or 50 percent of the total 4 mm thickness of the workpiece 822. The diameter of the nugget 840 is 3.6 mm.

Figs 8d and 8e show how the insert 844, which is stronger and has a higher melting temperature than copper, withstands higher temperatures and stresses. However, as shown in Fig. 8f, the periphery of the electrode tip face 821 experiences high contact pressure which can cause mushrooming.

Figs 9a-9e (Fig. 9a is referenced as above.) illustrate the effects of changing tungsten insert 944 diameter on the size and proportions of the nugget 920. All basic dimensions are the same as earlier versions. Table 5 below compares the proportions of the nugget 920.

Table 5

Co-axial Insert Thickness (mm)	0	1.5	2	3
Nugget Thickness (mm)	0.96	1.54	2	3.34
Nugget Diameter (mm)	3.10	3.5	3.6	3.76
Nugget Vertical Coverage (%)	24	39	50	84

Thus, with the insert 944 alone, a larger diameter effects a much thicker nugget 920 with a proportionally smaller increase in diameter. As the diameter of the insert 944 increases, the nugget 920 is increased primarily in the thickness dimension, which, as noted above, can cause the electrode 910 to experience higher temperatures which can cause the electrode 910 to soften and mushroom at the periphery. Thus, the diameter of the insert 944 can be too large, and an optimum may exist for a particular application.

Another embodiment of the present invention is shown in Fig. 10a. Reference numerals are analogous to those used in Figs. 4a-4c. Dimensions of analogous structures of the electrodes 1010 are the same as those in the electrodes 410 shown in Fig. 4a. The electrode in 1010 shown in Fig. 10a, however, comprises only an added ring 1042.

In the example shown in Figs 10b-10f, the ring 1042 has a thickness in the radial direction of 1.5 mm and a height in the axial direction of 1 mm. In this example, the ring 1042 is SS. The nugget 1020 (shown in Fig. 10c as temperature zone 1011A) is 1.66 mm thick, or 42 percent of the total 4 mm thickness of the workpiece 1022. The diameter of the nugget 1040 is 4 mm.

Figs 10d-10f show plots of temperature, current density, and contact pressure similar to those in Figs 1d-1f. Again, the periphery of the electrode 1010 experiences high pressure, which may cause mushrooming.

5 Figs 11a-11d (Fig. 11a is referenced as above.) illustrate the effects of changing the thickness of the ring 1142 on the size and proportions of the nugget 1120. All basic dimensions are the same as earlier dimensions. Table 6 below compares the proportions of the nugget 1120.

Table 6

Neck Ring Thickness (mm)	0	1	1.5
Nugget Thickness (mm)	0.96	1.20	1.66
Nugget Diameter (mm)	3.1	3.5	4
Nugget Vertical Coverage (%)	24	30	42

10 Thus, with the ring 1142 alone, an increase in the thickness of the ring 1142 in the radial direction tends to enlarge the nugget 1120 in both the thickness as well as the diameter directions. The role of the ring 1142 is limited, however, since if its thickness is too large, the current will be restricted or sufficiently blocked to interfere with the formation of a satisfactory nugget 1120.

15 Another modification of the embodiment shown in Figs 4a-4f is shown in Fig. 12a-12f. Reference numerals are analogous to those used in Figs 4a-4c. Dimensions of analogous structures of the electrodes 1210 are the same. The insert 1244 shown in Fig. 12a, however, is tungsten instead of SS. The nugget 1220 (shown in fig. 12c as temperature zone 1211A) is 2.7 mm thick, or 68 percent of the total 4 mm thickness of workpiece 1222. The diameter of the nugget 1220 is 4 mm. Compared with Figs
20 6c (sleeve 640 alone), 8c (insert 844 alone), and 10c (ring 1042 alone), the size of the nugget 1220 (temperature zone 1211A in Fig. 12c) is increased primarily in the thickness direction when the three elements are incorporated into the same electrode.

Figs 12d shows the insert 1244 experiencing the highest temperature while the sleeve 1240 takes the high pressure at the periphery of the electrode 1210.

25 Another embodiment of the present invention is shown in Fig. 13a. Reference numerals are analogous to those used in Figs 4a-4c. Dimensions of analogous structures of the electrodes 1310 are the same as those in the electrodes 410 shown in

Fig. 4a. The electrode 1310 shown in Fig. 13a, however, comprises only an added tungsten insert 1344 and an added SS sleeve 1340.

In the example shown in Figs 13b-13f, the insert 1344 has a diameter of 2mm and a height in the axial direction of 2.4 mm. The sleeve 1340 has a thickness in the radial direction of 0.75 mm and a height in the axial direction of 2.4 mm. In this example, the insert 1344 is tungsten and the sleeve 1342 is SS. The nugget 1320 (shown in fig. 13c as temperature zone 1311A) is 3.3 mm thick, or 82 percent of the total 4 mm thickness of the workpiece 1322. The diameter of the nugget 1320 is 4.25 mm.

Another embodiment of the instant invention is shown in Fig. 14a. Reference numerals are analogous to those used in Figs 4a-4c. Dimensions of analogous structures of the electrodes 1410 are the same as those in the electrodes 410 shown in Fig. 4a. The electrode 1410 shown in Fig. 14a, however, comprises only an added insert 1444 and an added sleeve 1440.

In the example shown in Figs 14b-14f, the insert 1444 and the sleeve 1440 are the same dimensions as those in the example shown in Figs 13b-13f. In the instant example, however, the insert is 304 SS. The nugget 1420 (shown in fig. 14c as temperature zone 1411A) is 2.8 mm thick, or 70 percent of the total 4 mm thickness of the workpiece 1422. The diameter of the nugget 1440 is 4.26 mm. The electrode 1410 creates a nugget 1440 of about the same diameter as the nugget 1340 from the electrode 1310 (4.25 mm versus 4.26 mm) but with a more satisfactory thickness (70 percent versus 82 percent) due, at least in part, to the lower thermal and electrical conductivities of SS versus tungsten.

A modification of the embodiment shown in Figs 14a-14f is shown in Fig. 15a. Reference numerals are analogous to those used in Figs. 14a-14c. Dimensions of analogous structures of the electrodes 1510 are the same as those in the electrodes 1410 shown in Fig. 14a with the exception of the insert 1544. As in Fig. 14a, the electrode 1510 comprises both an added insert 1544 and an added sleeve 1540.

In the example shown in Figs 15b-15f, the insert 1544 is SS as it is in the example shown in Figs 14b-14f but the diameter is 3 mm (versus 2 mm). The dimensions and composition of the sleeve 1540 are the same as the sleeve 1440 in the example shown in Figs 14b-14f. The nugget 1520 (shown in Fig. 15c as temperature zone 1511A) is 3.2 mm thick, or 78 percent of the total 4 mm thickness of the workpiece 1522. The diameter of the nugget is 4.76 mm.

Another modification of the embodiment shown in Figs 14a-14f is shown in Fig. 16a. Reference numerals are analogous to those used in Figs. 14a-14c. Dimensions of analogous structures of the electrodes 1610 are the same as those in the electrodes 1410 shown in Fig. 14a with the exception of the insert 1644. As in Fig. 14a, the electrode 1610 comprises both an added insert 1644 and an added sleeve 1540.

In the example shown in Figs 16b-16f, the insert 1644 is SS as it is in the example shown in Figs 14b-14f but the diameter is 4 mm. The dimensions and composition of the sleeve 1640 are the same as the sleeve 1440 in the example shown in Figs 14b-14f. The nugget 1620 (shown in Fig. 16c as temperature zone 1611A) is 2.66 mm thick, or 67 percent of the total 4 mm thickness of the workpiece 1622. The diameter of the nugget 1620 is 5.1 mm. This electrode 1610 not only produces a nugget 1620 with an improved diameter (5.1 mm versus 4.76 mm), but produces a thickness which is more desirable (67 percent versus 78 percent) which minimizes overheating of the electrode 1610.

A preferred modification of the embodiment shown in Figs 4a-4f is shown in Fig. 17a. Reference numerals are analogous to those used in Figs 4a-4c. Dimensions of analogous structures of the electrodes 1710 are the same as those in the electrodes 410 shown in Fig. 4a with the exception of the insert 1744. As in Fig. 4a, the electrode 1710 comprises an added insert 1744, an added sleeve 1740, and an added ring 1742. The insert 1744 in the examples shown in Figs 17b-17f is 4 mm in diameter. The nugget 1720 (shown in Fig. 17c as temperature zone 1711A) is 2.86 mm thick, or 72 percent of the total 4 mm thickness of the workpiece 1722. The diameter of the nugget 1720 is 5.5 mm.

Figs 18a-18d (Fig. 18a is referenced as above.) illustrate the effects of changing the diameter of the insert 1828 of SS on the size and proportions of the nugget 1820. The electrode 1810 also includes a sleeve 1840 of 304 SS. All other basic dimensions are the same as earlier versions. Table 7 below compares the proportions of the nugget 1820.

Table 7

Co-axial Insert Thickness (mm)	0	2	3	4
Nugget Thickness (mm)	0.96	2.80	3.20	2.66
Nugget Diameter (mm)	3.10	4.26	4.76	5.01
Nugget Vertical Coverage (%)	24	70	80	67

Thus, as the diameter of the co-axial insert 1844 increases from 2 mm to 3 mm, the nugget 1820 increases in both thickness and diameter. When the diameter of the co-axial insert 1844 is further increased to 4 mm, however, the diameter of the nugget 1820 increases but the thickness decreases. As shown in Table 8 below, it is known that the electrical and thermal conductivity of the 304 SS, particularly compared with tungsten, is low enough that the larger-diameter SS insert 1844 prevents current from directly flowing beneath the electrode 1810, thus forming a thinner nugget 1820. This phenomenon also causes more current to be shifted radially outward, which produces a larger-diameter nugget 1820.

Table 8

Property/Material	304 SS	Tungsten
Thermal Conductivity (J/s-mm-°C)	0.014	0.13
Electrical Conductivity ($\Omega^{-1}\text{mm}^{-1}$)	0.138E+4	1.81E+4

Source: Marks' Standard Handbook for Mechanical Engineering 14 Eugene A. Avallone and Theodore Baumeister III eds., 9th ed. (1987).

Figs 19a-19d (Fig. 19a is as referenced above.) illustrate the effects of changing the diameter of a SS insert 1928 on the size and proportions of the nugget 1920. The electrode 1910 also comprises a SS sleeve 1940 having a thickness in the radial direction of 0.75 mm and a SS ring 1942 having a thickness in the radial direction of 1.5 mm. All other basic dimensions are the same as earlier versions. Table 9 below compares the proportions of the nugget 1920.

Table 9

Co-axial Insert Thickness (mm)	0	2	3	4
Nugget Thickness (mm)	0.96	3.34	3.34	2.86
Nugget Diameter (mm)	3.1	4.5	5.0	5.5
Nugget Vertical Coverage (%)	24	84	84	72

Thus, adding the ring 1942, in addition to the insert 1944 and the sleeve 1940, effects a significant increase in the diameter of the nugget 1920 and only a slight increase in the thickness of the nugget 1920. The ring 1942 effects a redistribution of the current flow in an outward radial direction, which increases the diameter of the nugget 1920.

Figs 20a-23e illustrate the dynamic process of the development of a weld nugget by examining temperature, current flow, and contact pressure at the interface between the electrode tip and the workpiece. The embodiment used comprised a 4 mm diameter SS insert (e.g., 2044) and a SS sleeve (e.g., 2040) having a dimension in the radial direction of 0.75 mm. Figs 20b-20f show the results with two and one-half current cycles. As shown in Figs 20b and 20c, although there is good current density, the workpiece 2022 does not reach the temperature necessary to form a nugget. Figs 21b-21f show the results with five current cycles. As with the previous version, no nugget is formed (Figs 21b and 21c). Figs 22a-22f show the results with seven and one-half current cycles. A small, but insufficient, nugget 2220 is formed. The nugget 2220 has a thickness of 0.67 mm and a diameter of 3.5 mm. Finally, Figs 23a-23f show the results with ten current cycles. A satisfactory nugget 2320 is formed with a thickness of 2.66 mm and a diameter of 5.1 mm.

Figs 24a and 24b show the results of an FEA for an electrode of the present invention. The electrode has a tungsten insert with a diameter of 2 mm and a SS sleeve with a thickness in the radial direction of 0.75 mm. As shown by the temperature zone 2411A in Fig. 24b, a nugget is formed with a thickness of 3.34 mm (vertical coverage of 84 percent) and a diameter of 4.26 mm.

Figs 25a and 25b show the results of an FEA for another electrode of the present invention. The electrode has tungsten insert with a diameter of 2 mm and a SS ring with a thickness in the radial direction of 1.5 mm. As shown by the temperature zone

2511A in Fig. 25b, a nugget is formed with a thickness of 2.54 mm (vertical coverage of 64 percent) and a diameter of 4.06 mm.

Figs 26a and 26b show the results of an FEA for another electrode of the present invention. The electrode has a tungsten insert with a diameter of 2 mm, a SS ring with a thickness in the radial direction of 1.5 mm, and a SS sleeve with a thickness in the radial direction of 0.75.

Figs 27a and 27b show the results of evaluations of the accuracy of FEA for use in predicting nugget formation. The basis for both Figs 27a and 27b is two sheets of 2.0 mm galvanized steel as the workpiece and a pair of dome-shaped electrodes. To conform to the FEA analyses, the results as reported herein are for half-dimensions. Actual nugget sizes are double those shown. Fig. 27a shows the results of experimental and predicted nugget size versus weld cycles at 26 KA and a weld force of 800 pounds-force. Fig. 27b shows results at 29.5 KA and 1100 pounds-force. As Figs 27a and 27b show, there is good agreement.

Figs 28a-28d are cross-sections of electrodes in which the insert and the co-axial cavity are modified according to another aspect of the present invention. Apart from these modifications, the electrodes are similar to the electrode 810 shown in Fig. 8a, and analogous reference numerals are used to describe analogous structures. The electrode 2810 shown in Fig. 28a includes a co-axial cavity 2846, and an insert 2848 contained within the cavity 2846. The insert 2848 has an axially extending recess 2852 in the form of a step in its end that is proximal to the transition portion 2816 of the electrode 2810. The electrode 2860 shown in Fig. 28b is like the electrode 2810 of Fig. 28a, except that the insert 2866 has an axially extending protrusion 2868 in the form of a step on its proximal end.

In the electrode 2870 shown in Fig. 28c, the insert 2878 has an axially extending recess 2880 in the form of a series of steps 2882 in its proximal end. In an alternate embodiment (not shown), the insert could have an axially extending protrusion in the form of a series of steps on its proximal end.

In the electrode 2890 shown in Fig. 28d, the insert 2894 has an axially extending recess 2895 including sloped sides 2896 in its proximal end. In an alternate embodiment (not shown), the insert could have an axially extending protrusion including sloped sides in its proximal end. In another alternate embodiment (not shown), the recess or the protrusion could be curved instead of stepped or sloped.

Preferably, the recess or the protrusion in the above embodiments is co-axial, i.e., centered on the axis of the electrode. Also, if the diameter of the insert is "D", preferably the diameter of the recess or protrusion is within a range of from about 20% to about 90% of D, and more preferably about 50% of D. For example, in
5 Fig.28b, preferably the diameter "d" of the protrusion 2868 is from about 20% - 90% of the diameter D of the insert2866.

The axially extending recess or protrusion is believed to improve the heat transfer properties of the electrode along its axis. At the same time, the insert is still effective for blocking current flow sufficiently to provide a more uniform current density
10 throughout the electrode tip face.

Fig. 29 shows another aspect of the present invention, in which different types of electrodes are used on different sides of the workpiece. The electrode 510 is the type of electrode 510 shown in Fig. 5a and described above. The electrode 510 comprises an insert 544, a sleeve 540, and a ring 542. The electrode 610 is the type of electrode
15 610 shown in Fig. 6a and described above. The electrode 610 comprises only a sleeve 640, without an insert or a ring. The electrodes could be any other different types of electrodes according to the invention. The use of different types of electrodes on different sides of the workpiece allows the electrode to be tailored for the particular type of metal being welded on each side of the workpiece, in the event that two
20 different types of metals are being welded together, or in the event that workpieces having different sheet thicknesses are being welded together. For example, in Fig. 29 a sheet 524 of a first type of metal is being welded to a sheet 624 of a second type of metal. The use of different types of electrodes on different sides of the workpiece can also allow the structure of the nugget 550 to be tailored.

Fig. 30 is a simplified illustration of a resistance seam welding process. A pair of
25 composite wheel electrodes 10 according to the present invention are mounted for rotation on axes 12. Two adjacent metal workpieces 22 and 24 are moved between the rotating wheel electrodes 10. A welding current to the electrodes 10 is provided to make a series of overlapping spot welds that form a continuous seam weld between
30 the workpieces.

One of the composite wheel electrodes 10 according to the invention is shown in Fig. 31. The composite wheel electrode 10 includes a circular disk-shaped body 14, including a circumferential surface 11 and opposing side surfaces 13 and 15. The

electrode body 14 is formed from any suitable electrically conductive material, such as a copper alloy. The composite wheel electrode 10 also includes an annular insert 16. The insert 16 is positioned in an annular groove 17 that extends around the circumferential surface 11 of the electrode body 14. Preferably, the insert 16 is centered in the circumferential surface 11. The composite wheel electrode 10 also includes a pair of annular sleeves 18 and 18'. The sleeves 18 and 18' are positioned in annular grooves 19 and 19' that extend around the sides surfaces 13 and 15 of the electrode body 14, adjacent to the circumferential surface 11. The composite wheel electrode 10 further includes a pair of annular rings 20 and 20'. The rings 20 and 20' are positioned in annular grooves 21 and 21' that extend around the sides surfaces 13 and 15 of the electrode body 14, radially inward from and adjacent to the grooves 19 and 19'. The insert 16, sleeves 18 and 18', and rings 20 and 20' are analogous to those described above with respect to the resistance spot welding electrode, and it is believed that they will provide similar benefits in a wheel electrode for resistance seam welding. These structures are made from any suitable material, such as stainless steel.

Although the composite wheel electrode 10 shown in Fig. 31 includes the combination of the insert 16, sleeves 18 and 18', and rings 20 and 20', the invention is not limited to including all of these structures. The composite wheel electrode can include any one or more of these structures, and any combination of structures. For example, Fig. 32 shows another embodiment of a composite wheel electrode 30 that includes the insert 16 and the sleeves 18 and 18'. Fig. 33 shows another embodiment of a composite wheel electrode 40 that includes just the insert 16. Fig. 34 shows another embodiment of a composite wheel electrode 50 that includes just the sleeves 18 and 18'. Lastly, Fig. 35 shows another embodiment of a composite wheel electrode 60 that includes just the rings 20 and 20'.

The invention also relates to a resistance welding machine that is effective to weld materials such as aluminum using a reduced current level. The components of a conventional resistance welding machine are well known in the art. The welding machine includes at least one electrode for conducting welding current to the workpiece, and typically at least two opposing electrodes. For high-volume production work such as subassemblies in the automotive industry, usually the welding machine includes a plurality of robotic welding guns carrying electrode tips.

The welding machine also includes a welding transformer for supplying current to the electrode. Typically, the welding machine includes an electrical circuit consisting of the welding transformer and a secondary circuit including the electrode(s) which conducts the welding current to the workpiece. The welding machine also includes a means of applying welding pressure to the workpiece. The pressure means usually includes a mechanical system consisting of a machine frame and associated mechanisms to hold the workpiece and apply the welding pressure. The welding pressure is usually applied by pressing the workpiece between a pair of opposing electrodes. The welding machine also includes a means to control the welding current, which is typically a controller or a contactor. The control equipment may be used to initiate the welding current and to control the duration and magnitude of the current flow.

Advantageously, a resistance welding machine according to the invention is effective to weld aluminum and other metals using a reduced current level. A major problem with conventional resistance welding of aluminum is that it is necessary to use a very high welding current to achieve an effective weld. The required welding current is usually at least about 30-40 KA for 2 mm aluminum sheets, and sometimes from about 50-60 KA for thicker sheets. Cost is a major issue, because a high capacity welding machine is much more expensive than a machine that operates at a lower current level, and because the cost of energy (electricity) is much higher. For purposes of comparison, under the same welding conditions except for the current level (e.g., the same thickness and composition of the workpiece), a resistance welding machine according to the present invention is effective to weld using a current that is usually at least about 20% less than the conventional welding current, often at least about 30% less, and sometimes up to about 40% less. For example, the current used during the welding process can be between about 20 KA and about 30 Ka, and typically about 20 KA for 2 mm aluminum workpieces. A low capacity welding machine can be used instead of a high capacity machine, thereby saving money on the cost of the machine. For example, a low capacity welding machine that is typically used to weld steel can instead be used to weld aluminum. Previously, in order to weld aluminum, a much bigger capacity welding machine was required. The welding machine can be used to weld both steel and aluminum. The welding machine can be used to weld two different materials at a single amperage, so that, for example,

a steel workpiece could be first welded and then an aluminum workpiece brought to the machine for welding at the same amperage. The resistance welding machine may achieve these benefits through the use of a composite welding electrode according to the invention. The electrode may offer great potential for welding different materials, such as magnesium (and its alloys), copper (and its alloys), galvanized steels, and even very thick low carbon steels (4-12 mm) since they all require high welding current like aluminum.

The resistance welding machine of the invention may be useful for welding, at reduced cost, in many different industries. Some nonlimiting examples of applicable industries include automotive, boating, aerospace, construction, and packaging. In an industrial setting, the resistance welding machine is typically located in a welding station that includes the machine and any other conventional equipment necessary for carrying out the welding operation and handling the workpiece(s).

Although the invention has been described in detail with reference to certain preferred embodiments, variations and modifications exist within the scope and spirit of the invention as described and defined in the following claims. For example, the same principles can be operative in a non-circular design for a spot welding electrode.

CLAIMS

We claim:

1. A composite resistance spot welding electrode comprising:
 - 5 (a) a shank portion;
 - (b) a transition portion integral with the shank portion, the transition portion comprising:
 - (i) an annular groove co-axial with the transition portion; and
 - (ii) a co-axial neck ring contained within the annular groove; and
 - 10 (c) a tip portion integral with the transition portion, the tip portion including a tip portion end distal to the transition portion, and the tip portion comprising:
 - (i) a co-axial insert having an end co-terminus with the distal tip portion end; and
 - 15 (iii) a co-axial annular outer sleeve, the sleeve having an end co-terminus with the distal tip portion end, the tip portion end, the insert, and the sleeve end cooperating to form a face; wherein
 - (d) the insert comprises no more than about 50 percent of the area of the face; and
 - 20 (e) the sleeve has a thickness in the radial direction of about 10-60 percent of the radius of the face.
2. The electrode of claim 1, wherein the ring, the insert, and the sleeve are formed from a material selected from the group consisting of steel and tungsten.
- 25 3. The electrode of claim 2, wherein the steel is stainless steel.
4. The electrode of claim 3, wherein the insert comprises about 36 percent of the area of the face.
- 30 5. The electrode of claim 3, wherein the sleeve has a thickness in the radial direction of about 15 percent of the radius of the face.

6. A first and a second electrode, each electrode according to claim 1, wherein when:
- (a) the first and second electrodes are placed in a facing, spaced-apart relationship;
 - 5 (b) a workpiece comprising two sheets of 2 mm-thick 5XXX aluminum are placed therebetween;
 - (c) the first and second electrodes compress the workpiece with a force of about 700-2000 pounds-force; and
 - (d) a 60-Hz current of about 20-30 KA is passed through the workpiece
10 for 8-12 cycles;
 - (e) a nugget is formed with a thickness of between 0.8-3.4 mm and a diameter of between 2-6 mm.
7. The electrodes of claim 6, wherein:
- 15 (a) the compressive force is about 1550 pounds-force;
 - (b) the current is about 22 KA; and
 - (c) the nugget thickness is about 2.7-3.4 mm.
8. A composite resistance spot welding electrode comprising:
- 20 (a) a shank portion;
 - (b) a tip portion integral with the shank portion, the tip portion comprising a co-axial annular outer sleeve, the sleeve having an end co-terminus with a tip portion end distal to the shank portion, the tip portion end and the sleeve end cooperating to form a smooth, continuous tip face;
 - 25 wherein
 - (c) the sleeve has a thickness in the radial direction of about 10-30 percent of the outside radius of the sleeve.
9. The electrode of claim 8, wherein the sleeve is formed from a material selected
30 from the group consisting of steel and tungsten.
10. The electrode of claim 9, wherein the steel is stainless steel.

11. The electrode of claim 10, wherein the sleeve has a thickness in the radial direction of about 15 percent of the outside radius of the face.

12. A first and a second electrode, each electrode according to claim 8, wherein
5 when:

(a) the first and second electrodes are placed in a facing, spaced-apart relationship;

(b) a workpiece comprising two sheets of 2 mm-thick 5XXX aluminum are placed therebetween;

10 (c) the first and second electrodes compress the workpiece with a force of about 700-2000 pounds-force; and

(d) a 60-Hz current of about 20-30 KA is passed through the workpiece for 10 cycles;

15 (e) a nugget is formed with a thickness of between 0.8-3.4 mm and a diameter of between 2-6 mm.

13. The electrodes of claim 12, wherein:

(a) the compressive force is about 1550 pounds-force;

(b) the current is about 22 KA; and

20 (c) the nugget thickness is about 2.7-3.4 mm.

14. A composite resistance spot welding electrode comprising:

(a) a shank portion

25 (b) a tip portion integral with the shank portion, the tip portion including a tip portion end distal to the shank portion, and the tip portion comprising a co-axial insert having an end co-terminus with the distal tip portion end, the tip portion end and the insert cooperating to form a smooth, continuous tip face; wherein

(c) the diameter of the insert is no more than about 70 percent of the diameter of the tip.

30

15. The electrode of claim 14, wherein the insert is formed from a material selected from the group consisting of steel and tungsten.

16. The electrode of claim 15, wherein the steel is stainless steel.

17. A first and a second electrode, each electrode according to claim 14, wherein when:

5 (a) the first and second electrodes are placed in a facing, spaced-apart relationship;

(b) a workpiece comprising two sheets of 2 mm-thick 5XXX aluminum are placed therebetween;

10 (c) the first and second electrodes compress the workpiece with a force of about 700-2000 pounds-force; and

(d) a 60-Hz current of about 20-30 KA is passed through the workpiece for 10 cycles;

(e) a nugget is formed with a thickness of between 0.8-3.4 mm and a diameter of between 2-6 mm.

15

18. The electrodes of claim 17, wherein:

(a) the compressive force is about 1550 pounds-force;

(b) the current is about 22 KA; and

(c) the nugget thickness is about 2.7-3.4 mm.

20

19. The electrode of claim 14, the tip portion further comprising:

(a) a co-axial annular outer sleeve, the sleeve having an end co-terminus with the distal tip portion end, the tip portion, the insert, and the sleeve end cooperating to form a smooth, continuous tip face; wherein

25 (b) the annular sleeve has a thickness in the radial direction of about 5-15 percent of the outside diameter of the sleeve.

20. The electrode of claim 19, wherein the insert and the sleeve are formed from a material selected from the group consisting of steel and tungsten.

30

21. The electrode of claim 20, wherein the steel is stainless steel.

22. A first and a second electrode, each electrode according to claim 19, wherein when:

(a) the first and second electrodes are placed in a facing, spaced-apart relationship;

5 (b) a workpiece comprising two sheets of 2 mm-thick 5XXX aluminum are placed therebetween;

(c) the first and second electrodes compress the workpiece with a force of about 700-2000 pounds-force; and

10 (d) a 60-Hz current of about 20-30 KA is passed through the workpiece for 10 cycles;

(e) a nugget is formed with a thickness of between 0.8-3.4 mm and a diameter of between 2-6 mm.

23. The electrodes of claim 22, wherein:

15 (a) the compressive force is about 1550 pounds-force;

(b) the current is about 22 KA; and

(c) the nugget thickness is about 2.7-3.4 mm.

24. A method of resistance spot welding comprising:

20 (a) providing a first and a second electrode, each electrode according to claim 1;

(b) placing the first and second electrodes in a facing, spaced-apart relationship;

(c) placing a workpiece comprising two sheets of metal therebetween;

25 (d) urging the first and second electrodes together to compress the workpiece; and

(e) passing a 60-Hz current of about 20-30 KA through the workpiece; whereby

(f) a nugget is formed.

25. A composite resistance spot welding electrode comprising:
- (a) a shank portion;
 - (b) a transition portion integral with the shank portion; and
 - 5 (c) a tip portion integral with the transition portion, the tip portion including a tip portion end distal to the transition portion, and the tip portion comprising a co-axial insert having a distal end co-terminus with the distal tip portion end, and the insert having a proximal end including an axially extending recess or protrusion.
- 10
26. A composite resistance seam welding electrode comprising:
- (a) a circular disk-shaped body made from an electrically conductive first material, the body including a circumferential surface and opposing side surfaces; and
 - 15 (b) at least one structure selected from the following group which are made from a second material different from the first material:
 - (i) an annular insert positioned in an annular circumferential groove that extends around the circumferential surface of the electrode body;
 - 20 (ii) a pair of annular sleeves positioned in annular sleeve grooves that extend around the side surfaces of the electrode body adjacent to the circumferential surface; and
 - (iii) a pair of annular rings positioned in annular ring grooves that extend around the side surfaces of the electrode body, radially inward
- 25 from and adjacent to the sleeve grooves.

27. A resistance welding machine comprising:

- (a) at least one electrode for conducting welding current to a workpiece;
- (b) a welding transformer for supplying the current to the electrode;
- 5 (c) a means of applying welding pressure to the workpiece; and
- (d) a means to control the welding current;

the welding machine being effective to weld using a current level that is at least about 20% less than the current level of a conventional resistance welding machine under the same welding conditions.

10

28. The welding machine of claim 27, wherein the welding machine is effective to weld at least one of the following materials using the reduced current level: magnesium, copper, galvanized steel, low carbon steel, and alloys thereof.

15 29. The welding machine of claim 27, wherein the welding machine is effective to weld both aluminum and steel using the reduced current level.

30. The welding machine of claim 27, wherein the welding machine is suitable for welding in at least one of the following industries: automotive, boating,
20 aerospace, construction, and packaging.

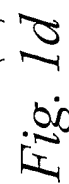
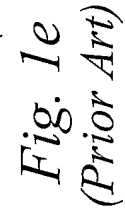
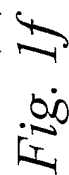
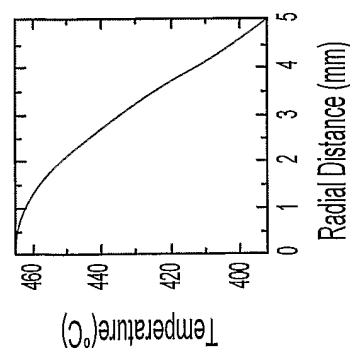
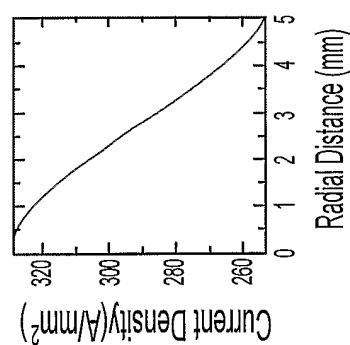
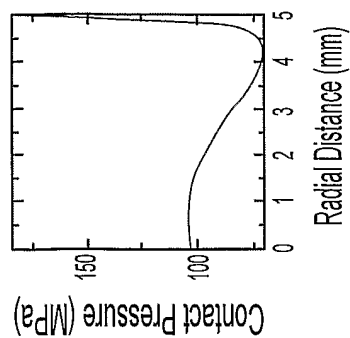
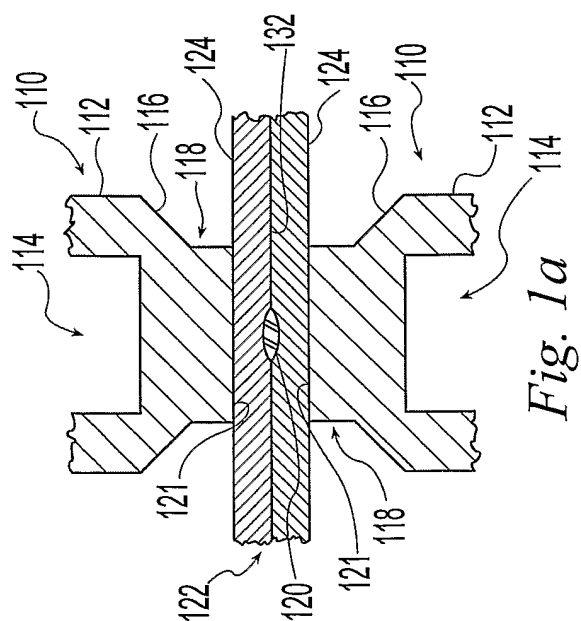
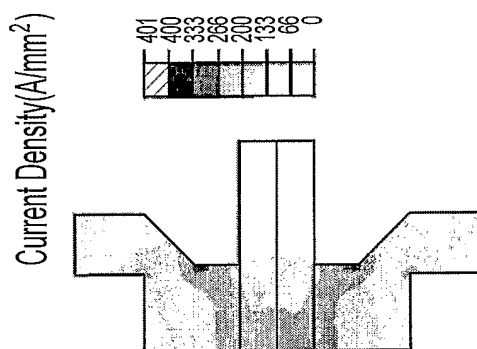
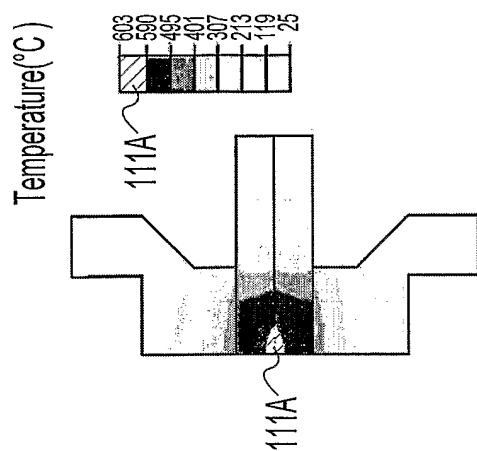
31. The welding machine of claim 27, wherein workpieces made from different materials can be welded one after the other using the same current level.

32. A resistance welding machine comprising:

- (a) at least one electrode for conducting welding current to a workpiece, the welding electrode comprising a shank portion and a tip portion integral with the shank portion, the tip portion including a tip portion end distal to the shank portion, and the tip portion comprising a co-axial insert having an end co-terminus with the distal tip portion end, the tip portion end and the insert cooperating to form a smooth, continuous tip face wherein the insert comprises no more than about 50 percent of the area of the face;
- (b) a welding transformer for supplying the current to the electrode;
- (c) a means of applying welding pressure to the workpiece; and
- (d) a means to control the welding current.

33. A composite resistance spot welding electrode comprising:

- (a) a shank portion;
- (b) a tip portion integral with the shank portion, the tip portion including a tip portion end distal to the transition portion, and the tip portion comprising:
 - (i) a co-axial insert having an end co-terminus with the distal tip portion end; and
 - (iii) a co-axial annular outer sleeve, the sleeve having an end co-terminus with the distal tip portion end, the tip portion end, the insert, and the sleeve end cooperating to form a face; wherein
- (d) the insert comprises no more than about 50 percent of the area of the face; and
- (e) the sleeve has a thickness in the radial direction of about 10-60 percent of the radius of the face.



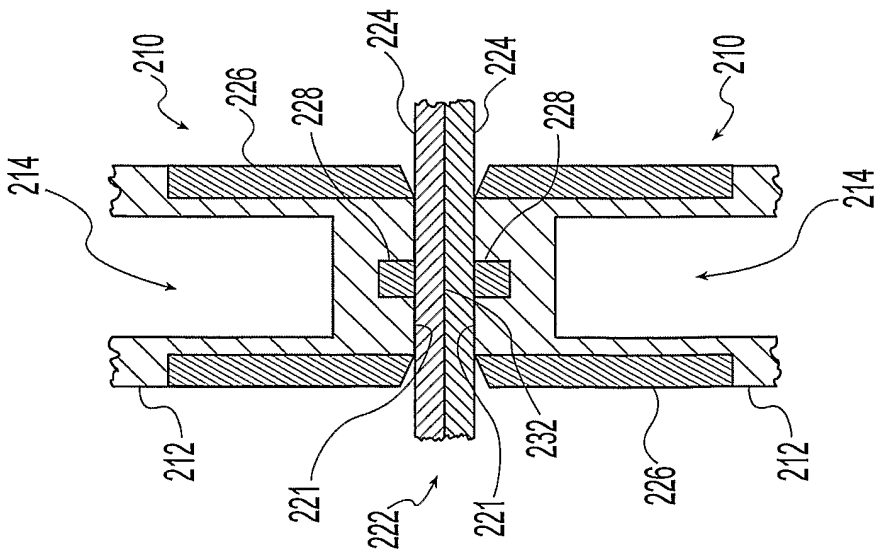


Fig. 2a

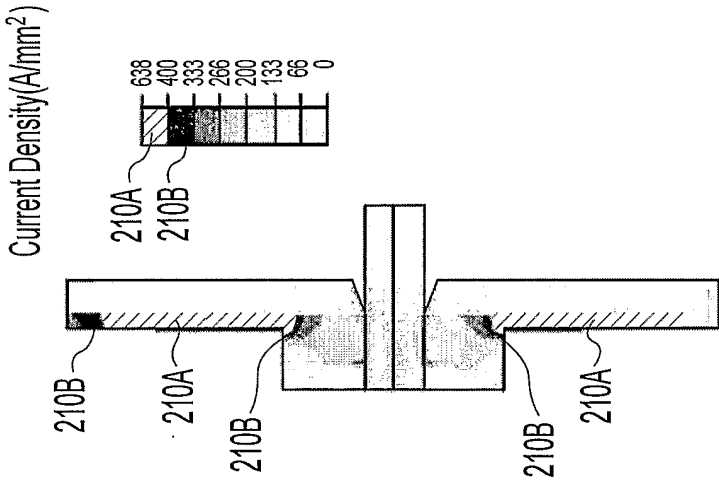


Fig. 2b

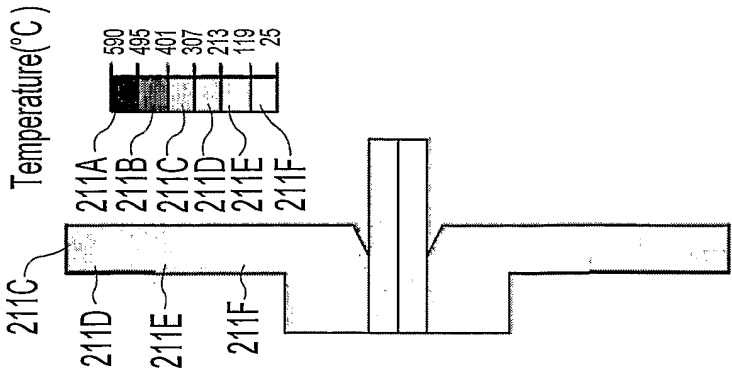
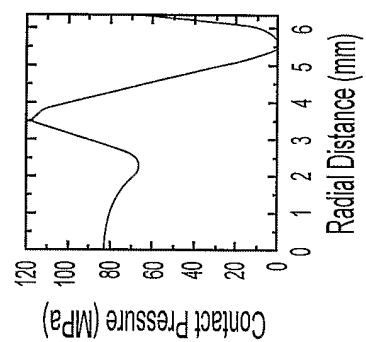
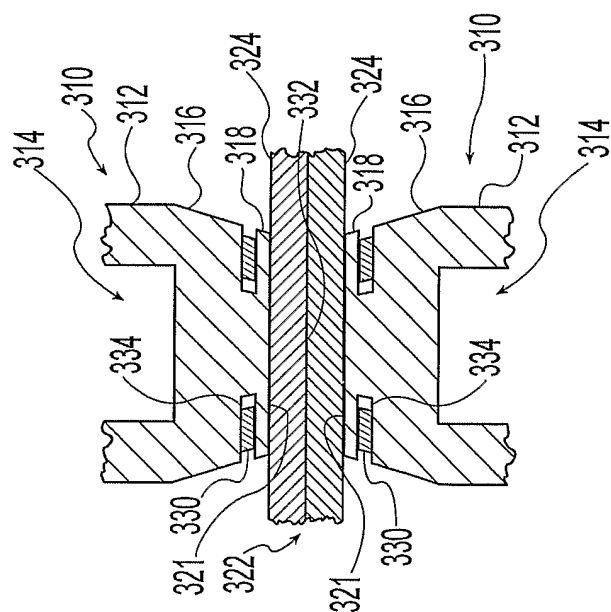
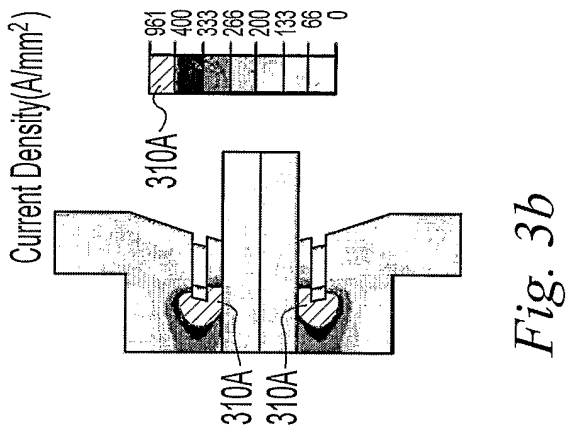
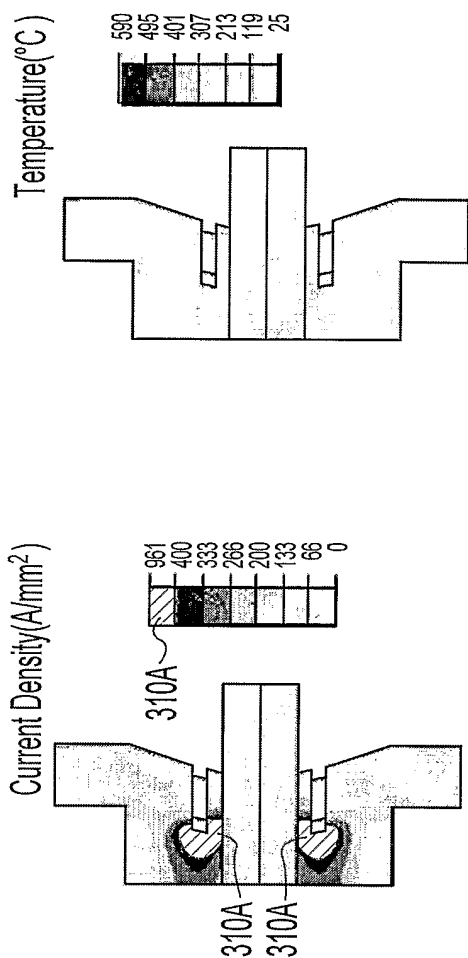


Fig. 2c

(Prior Art)



(Prior Art)

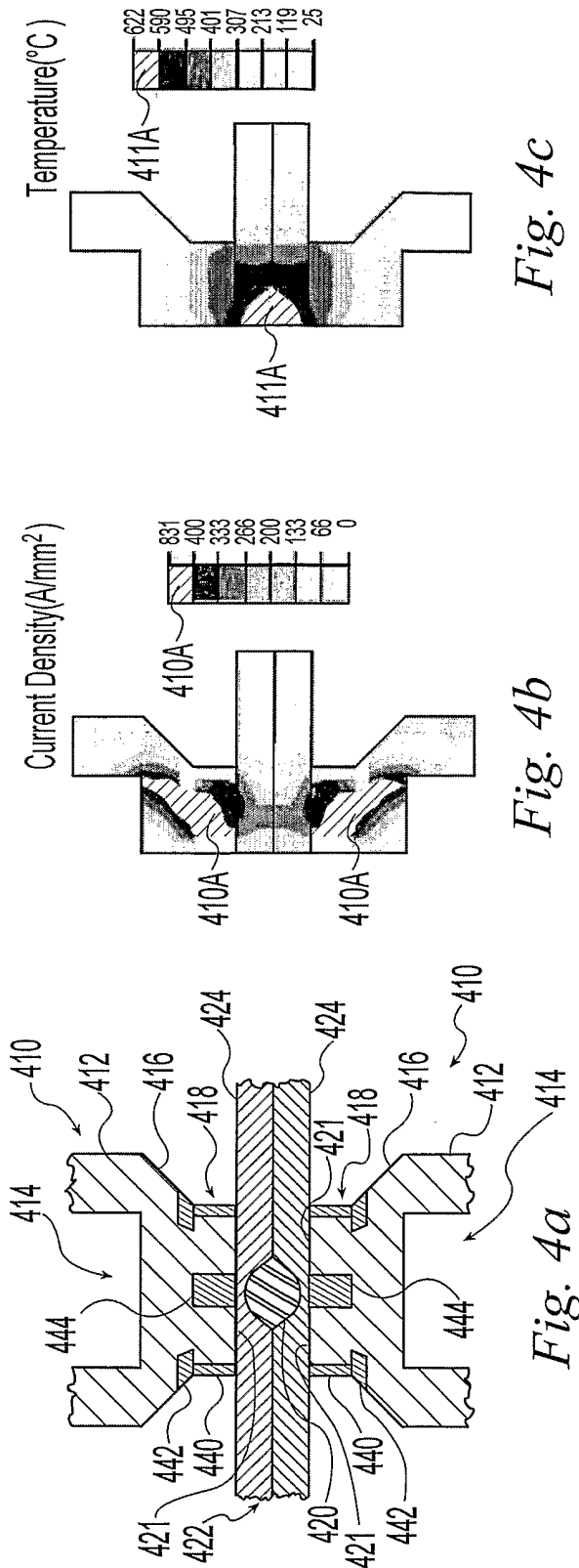


Fig. 4c

Fig. 4b

Fig. 4a

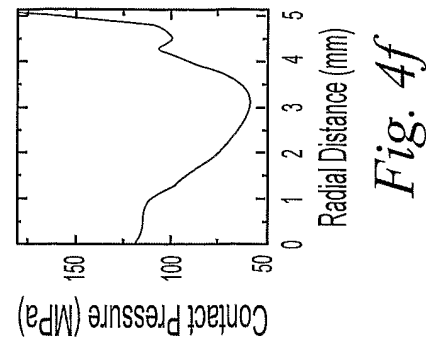


Fig. 4f

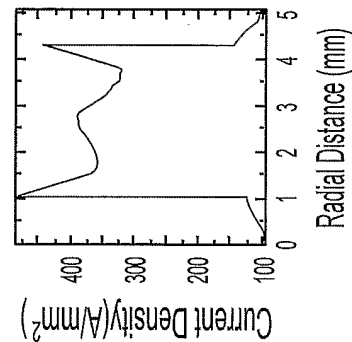


Fig. 4e

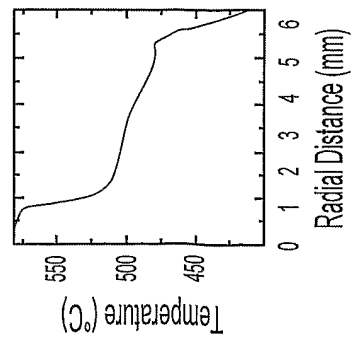


Fig. 4d

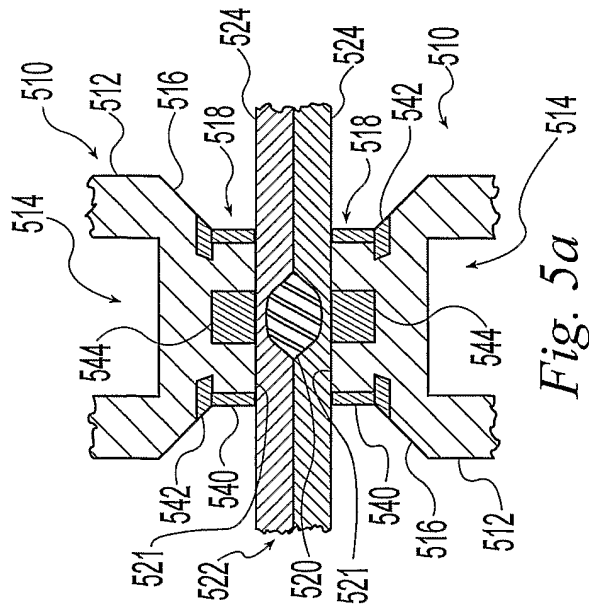


Fig. 5a

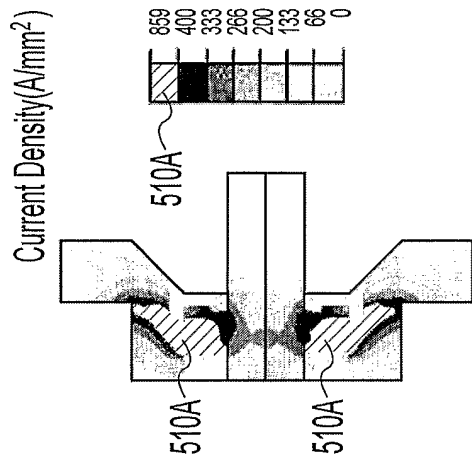


Fig. 5b

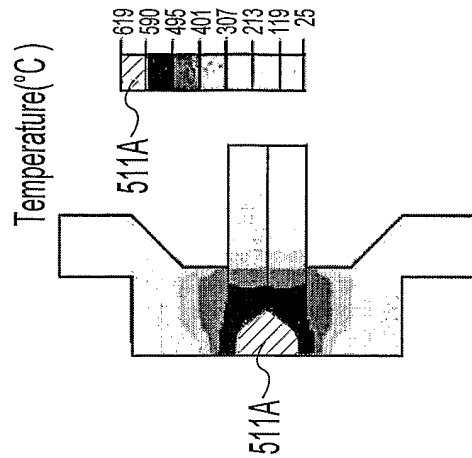


Fig. 5c

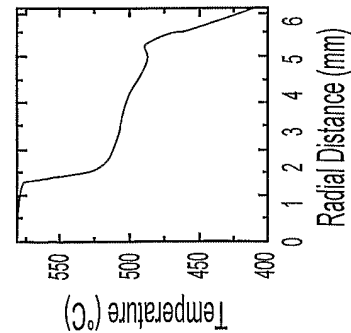


Fig. 5d

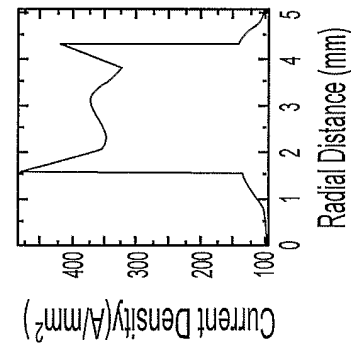


Fig. 5e

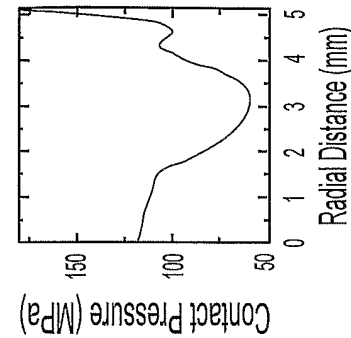


Fig. 5f

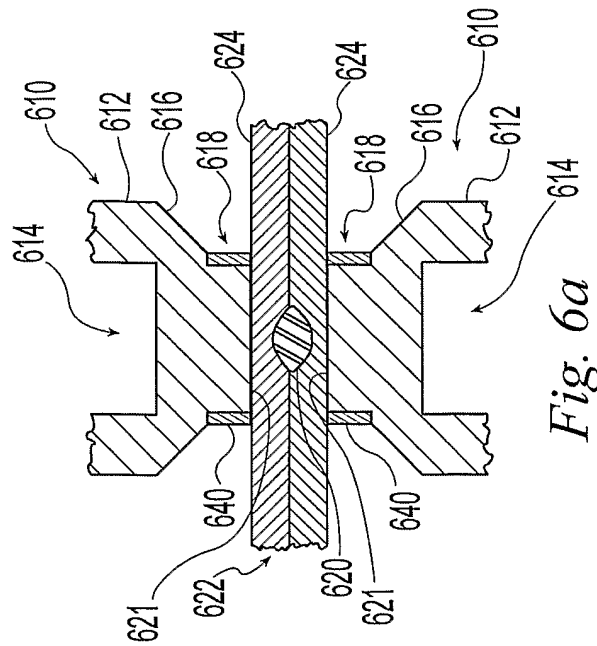


Fig. 6a

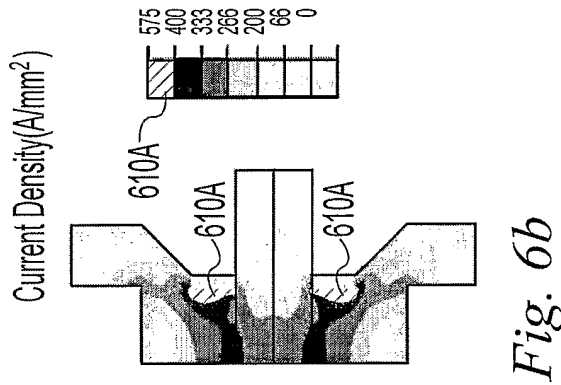


Fig. 6b

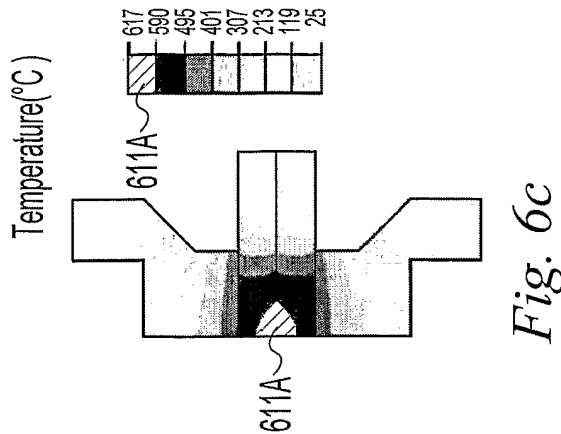


Fig. 6c

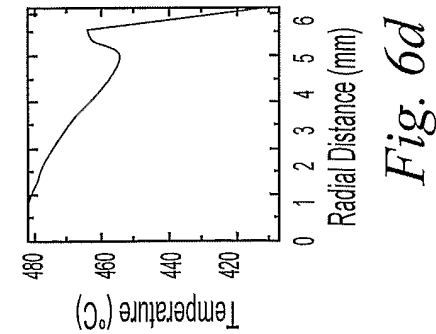


Fig. 6d

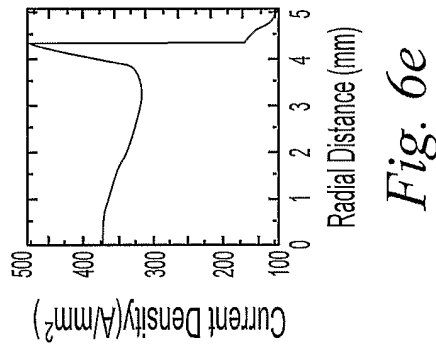


Fig. 6e

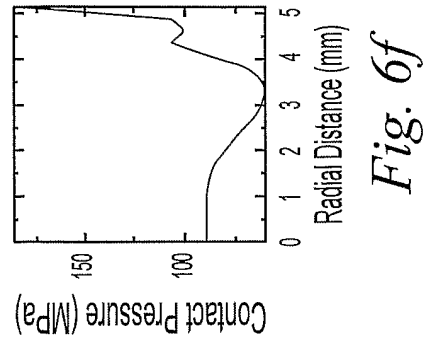


Fig. 6f

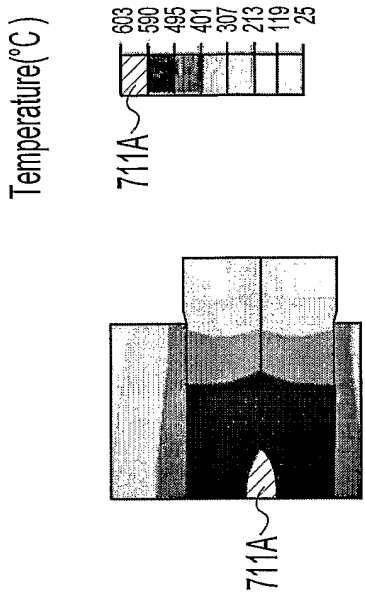


Fig. 7c

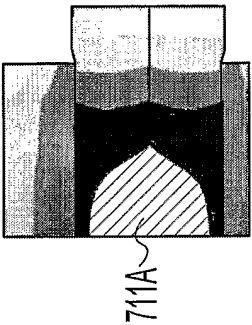


Fig. 7e

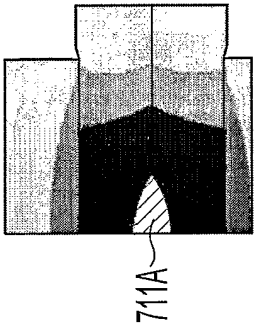


Fig. 7b

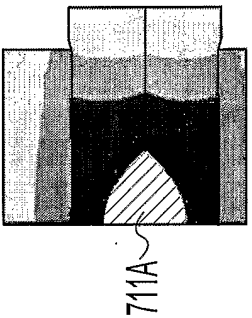


Fig. 7d

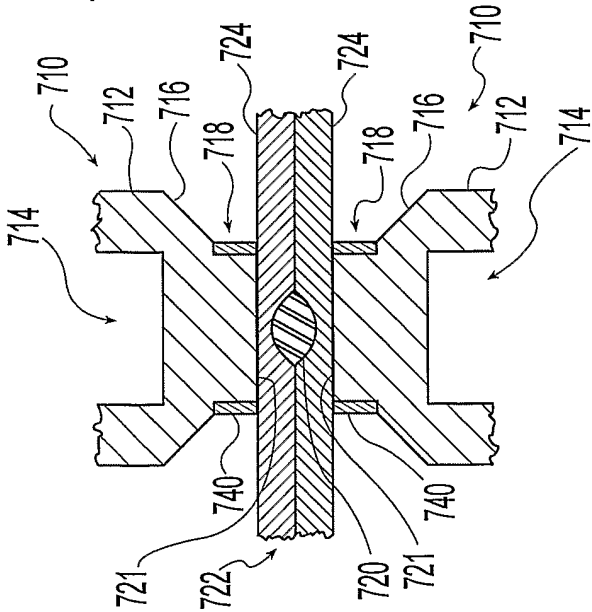
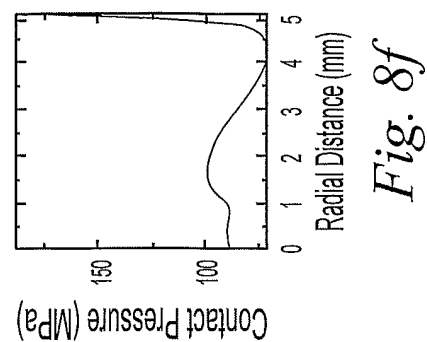
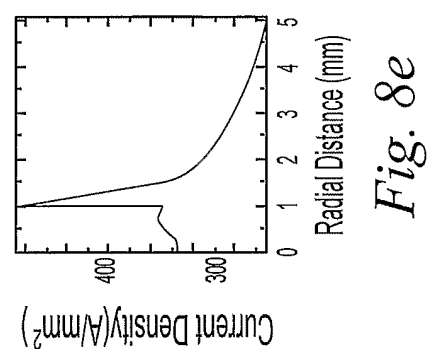
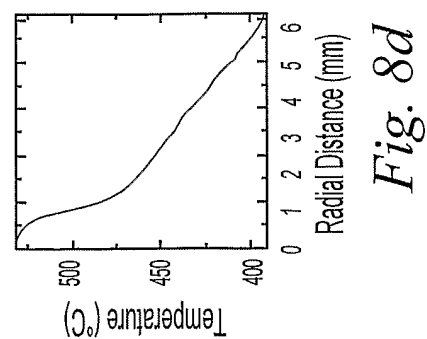
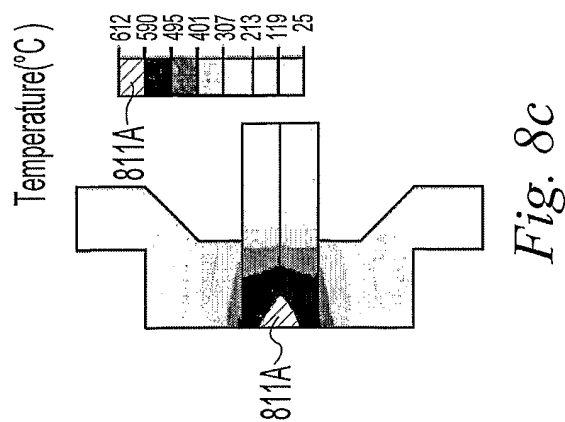
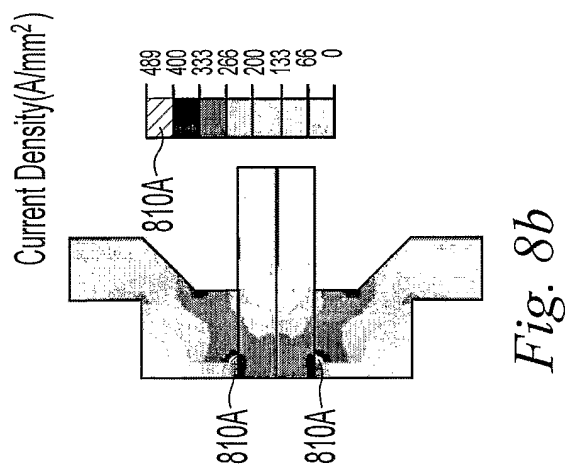
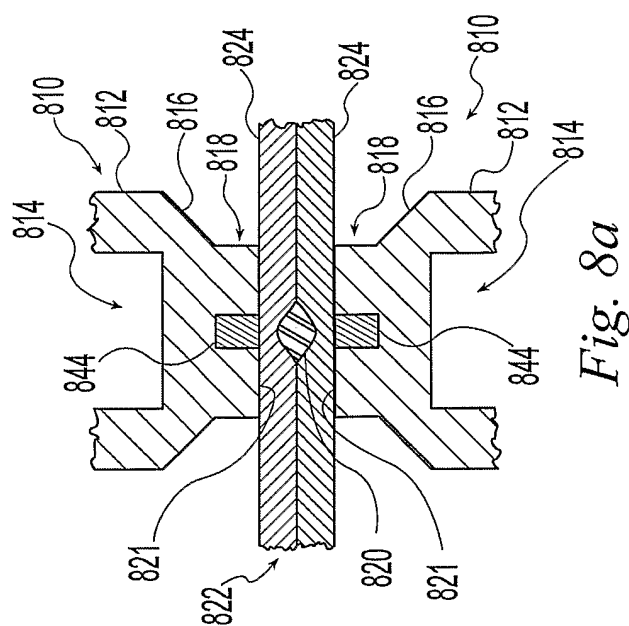


Fig. 7a



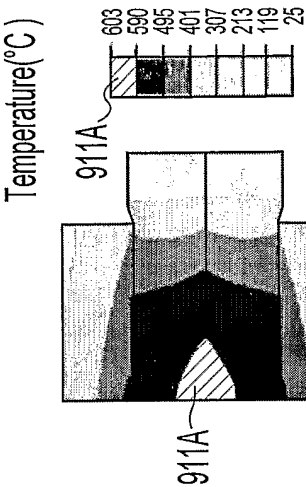


Fig. 9c

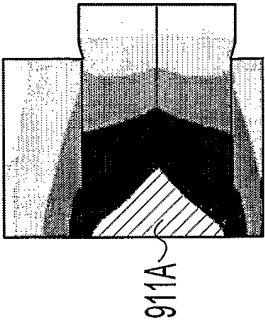


Fig. 9e

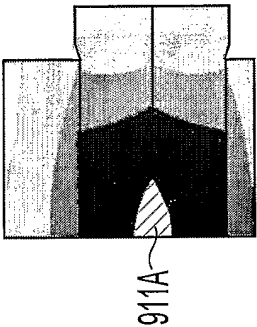


Fig. 9b

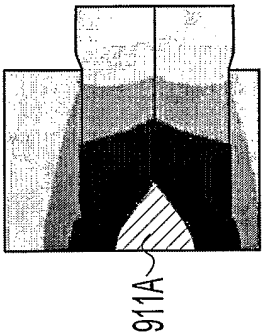


Fig. 9d

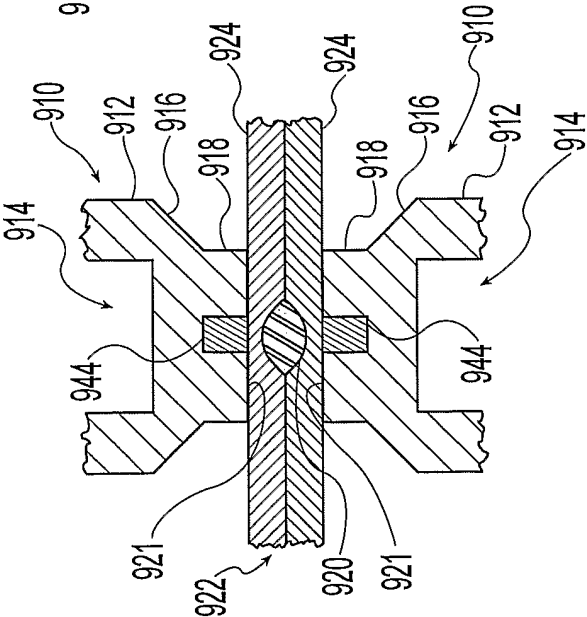


Fig. 9a

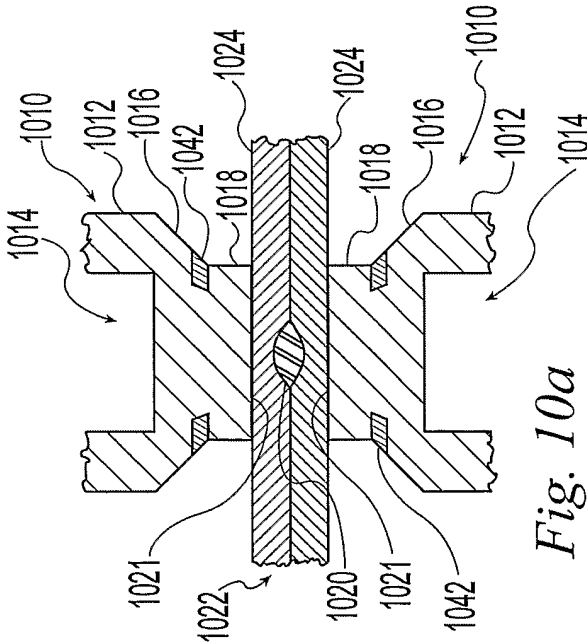


Fig. 10a

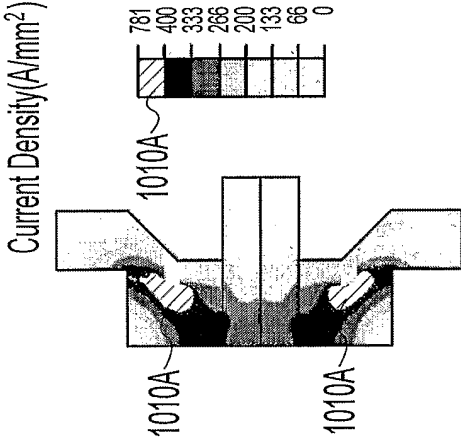


Fig. 10b

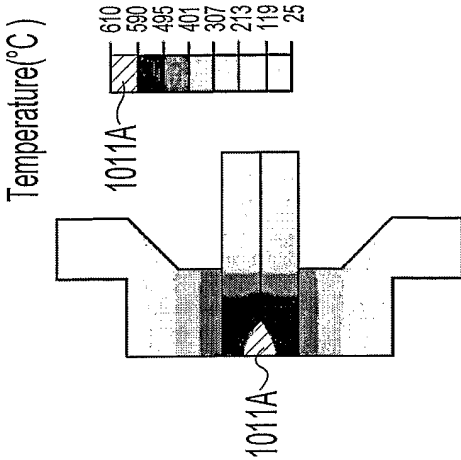


Fig. 10c

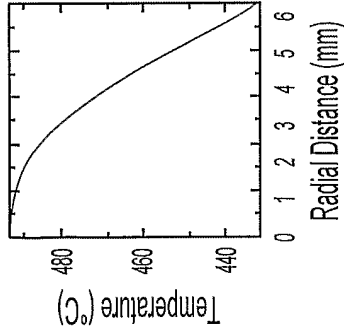


Fig. 10d

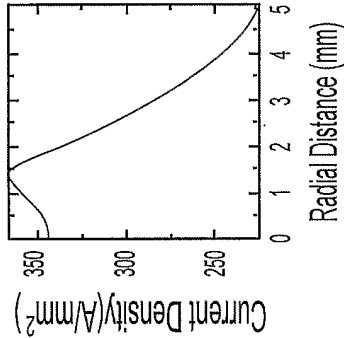


Fig. 10e

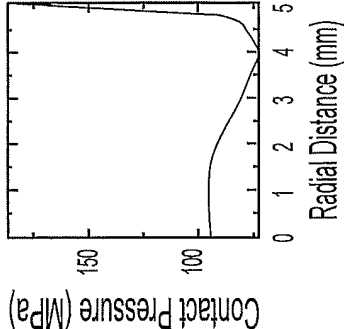


Fig. 10f

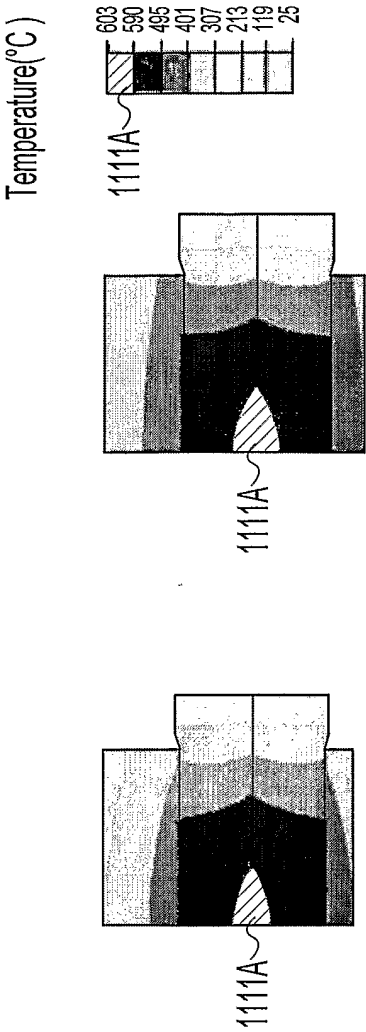


Fig. 11c

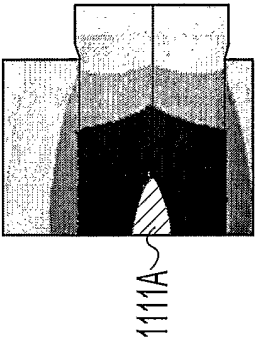


Fig. 11b

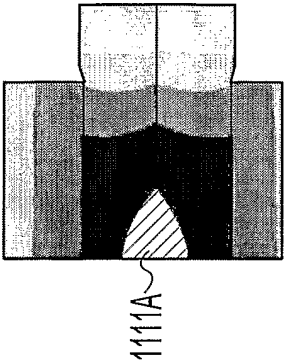


Fig. 11d

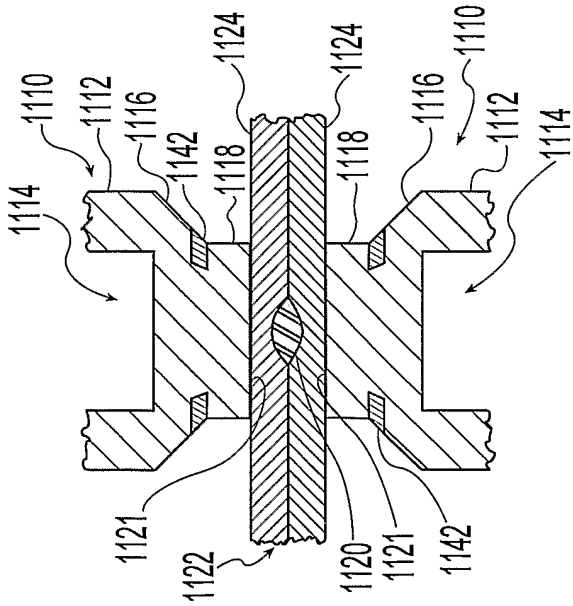
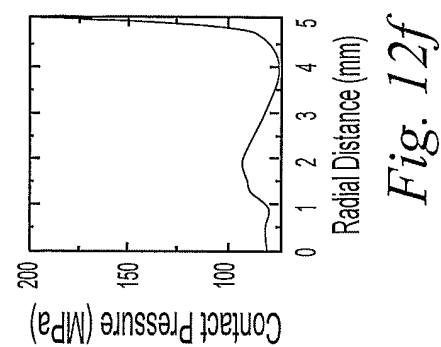
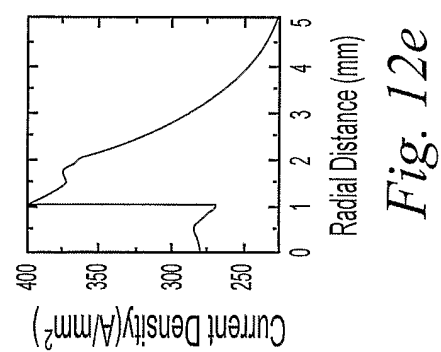
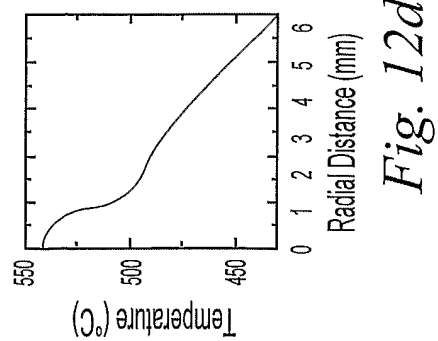
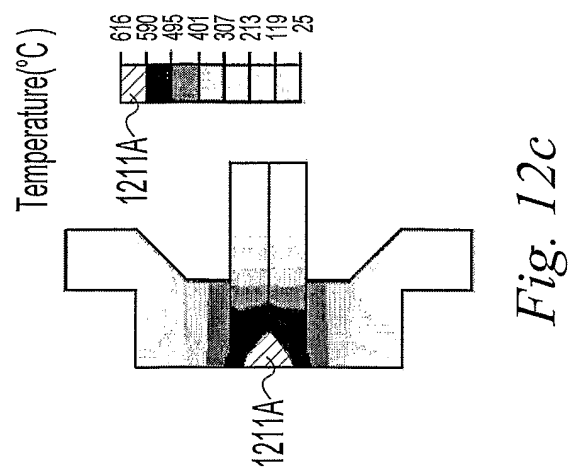
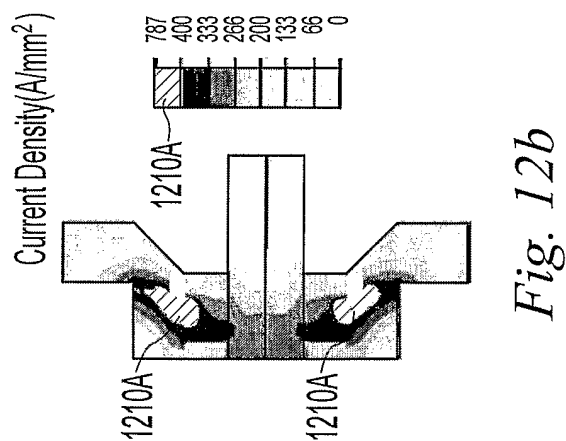
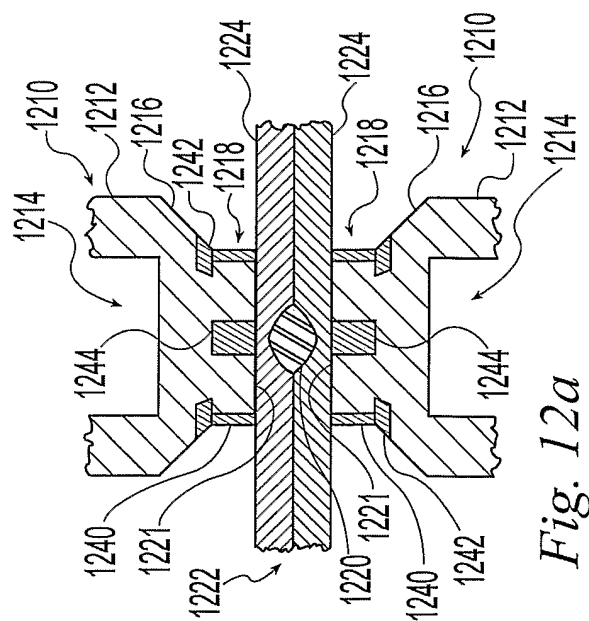


Fig. 11a



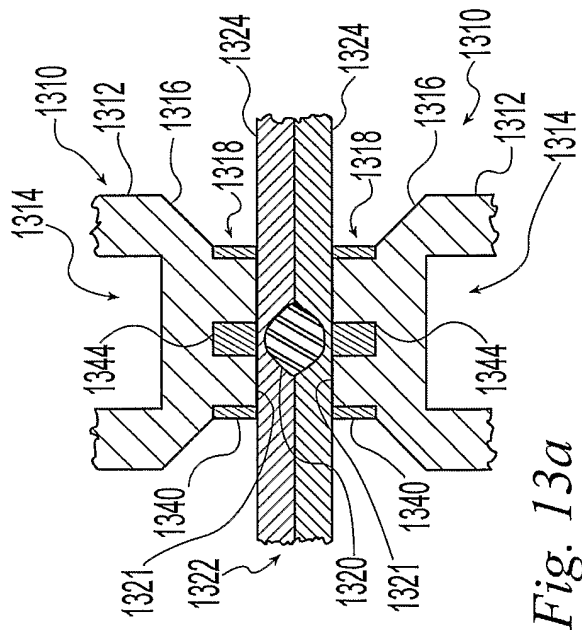


Fig. 13a

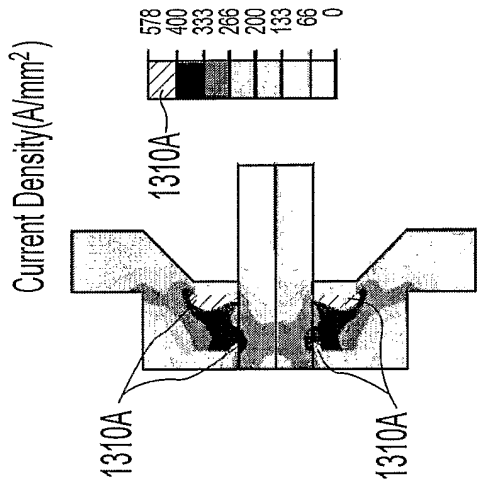


Fig. 13b

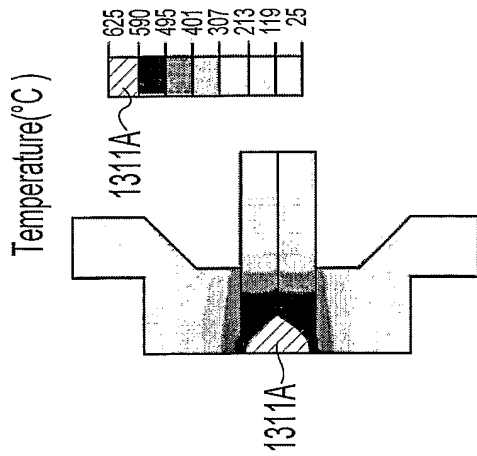


Fig. 13c

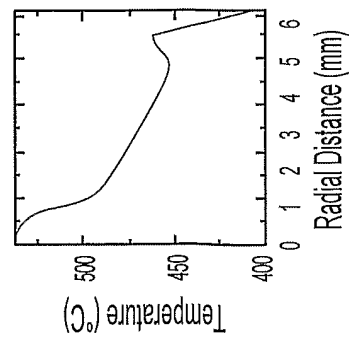


Fig. 13d

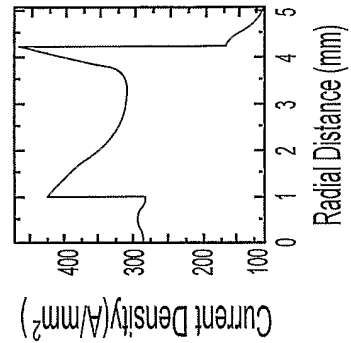


Fig. 13e

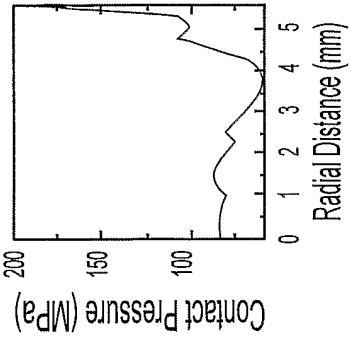


Fig. 13f

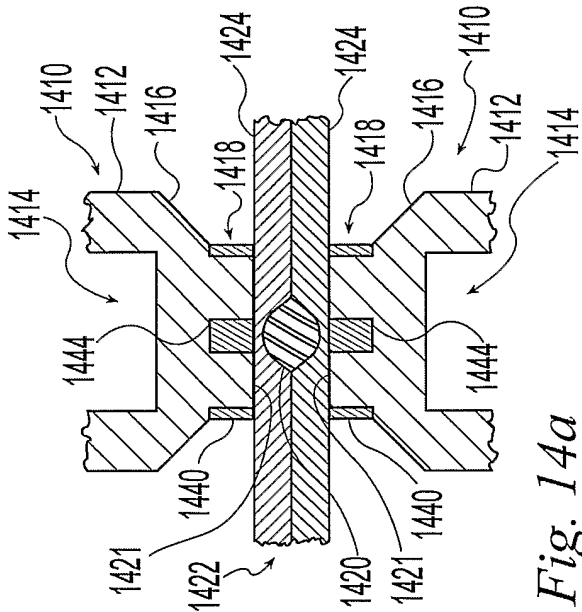


Fig. 14a

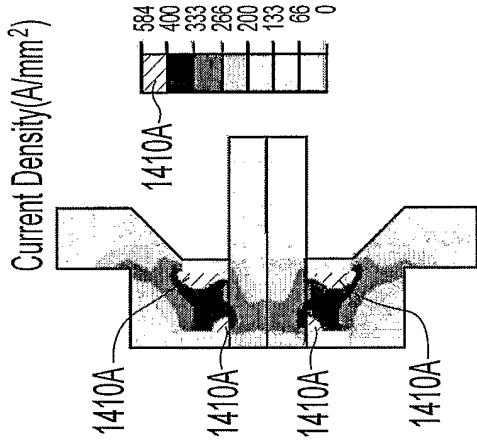


Fig. 14b

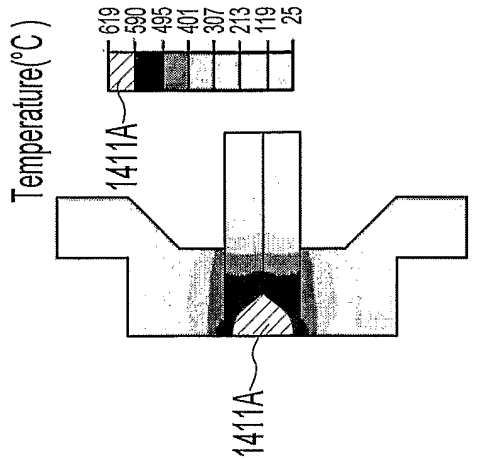


Fig. 14c

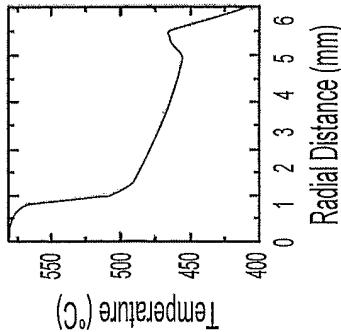


Fig. 14d

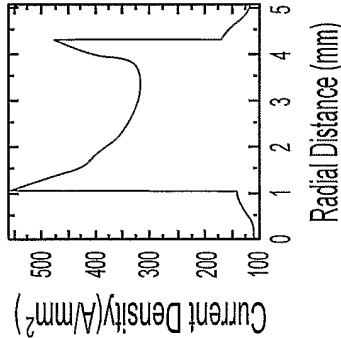


Fig. 14e

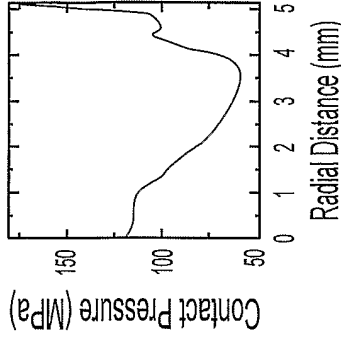


Fig. 14f

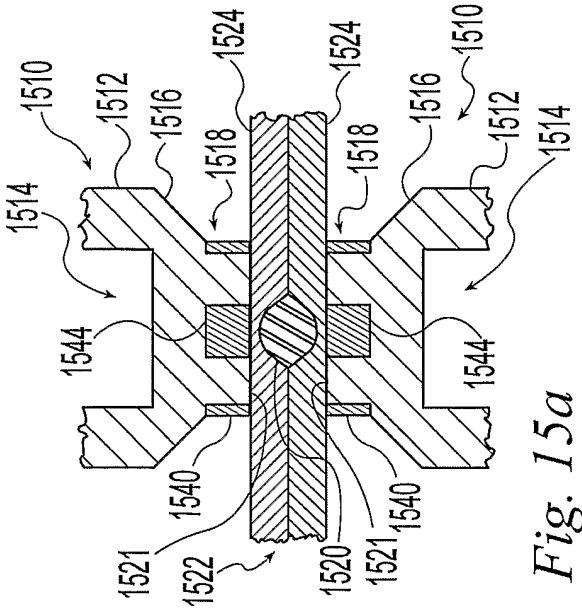


Fig. 15a

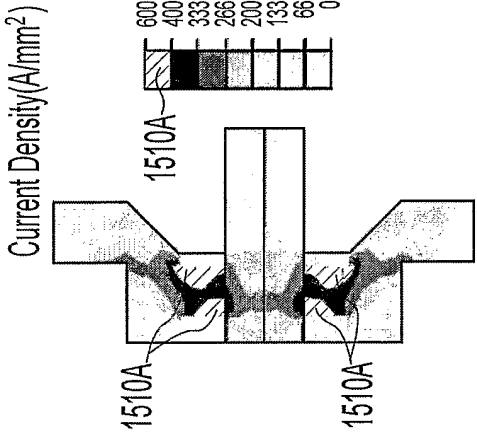


Fig. 15b

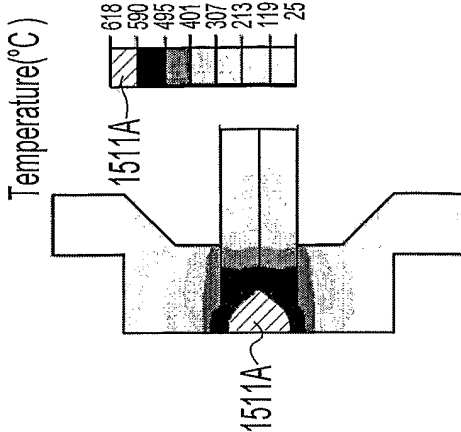


Fig. 15c

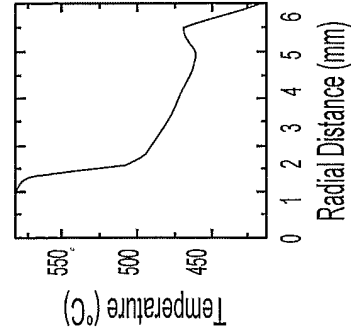


Fig. 15d

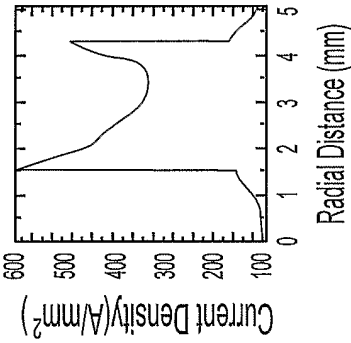


Fig. 15e

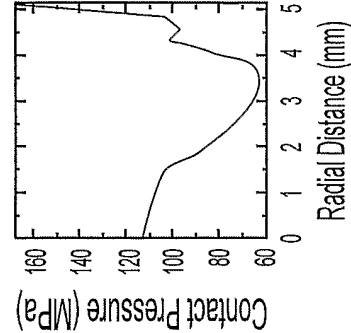


Fig. 15f

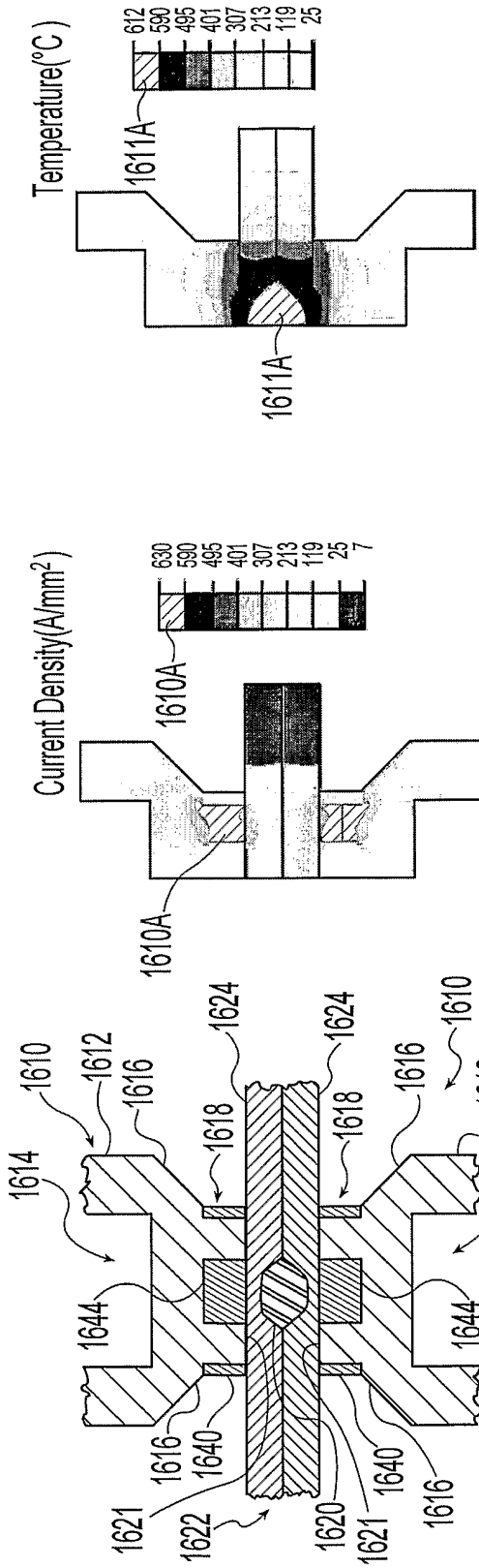


Fig. 16c

Fig. 16b

Fig. 16a

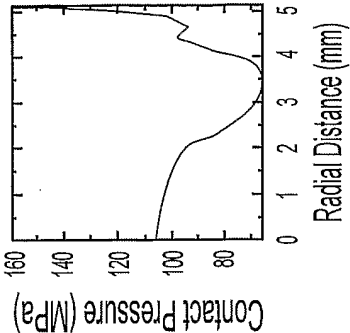


Fig. 16f

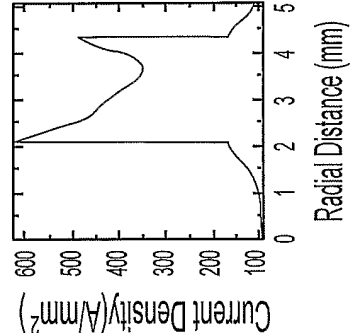


Fig. 16e

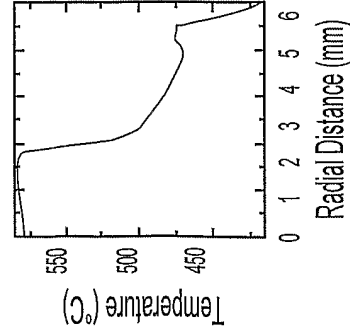


Fig. 16d

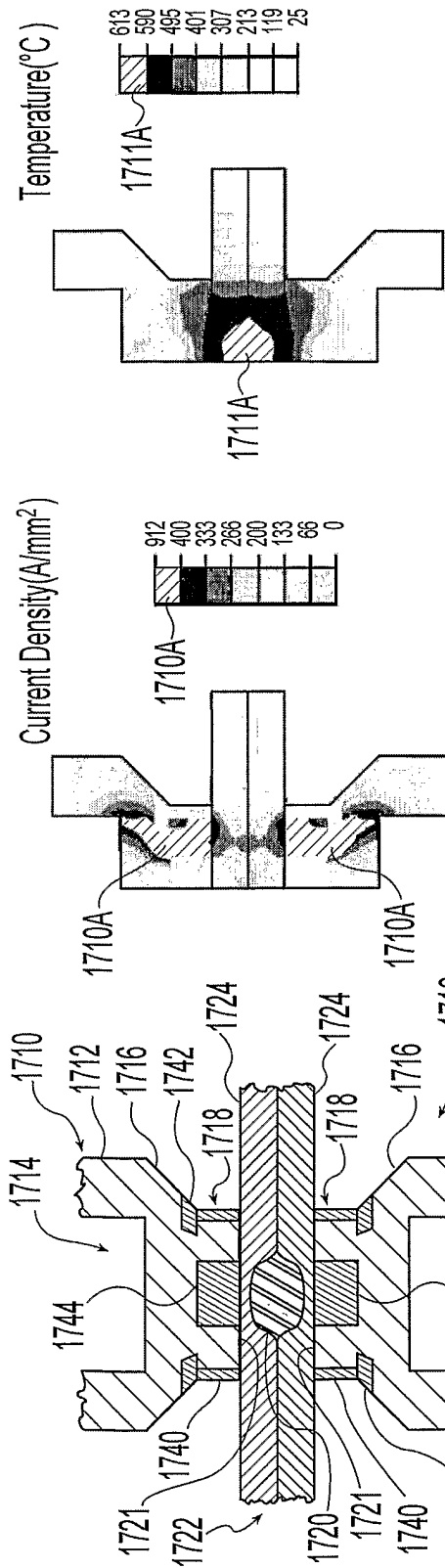


Fig. 17b

Fig. 17c

Fig. 17a

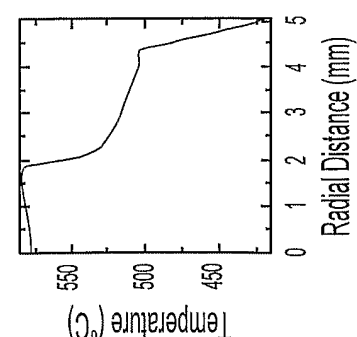
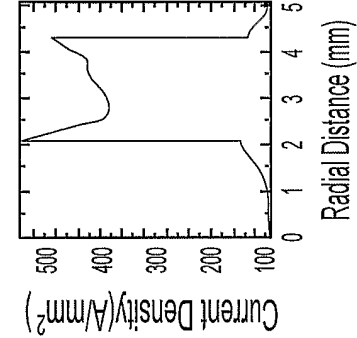
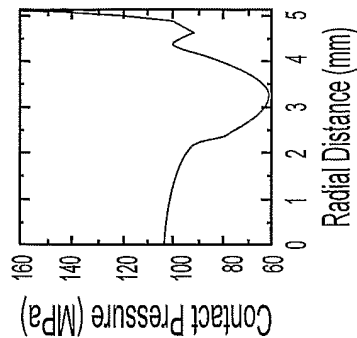


Fig. 17e

Fig. 17f

Fig. 17d

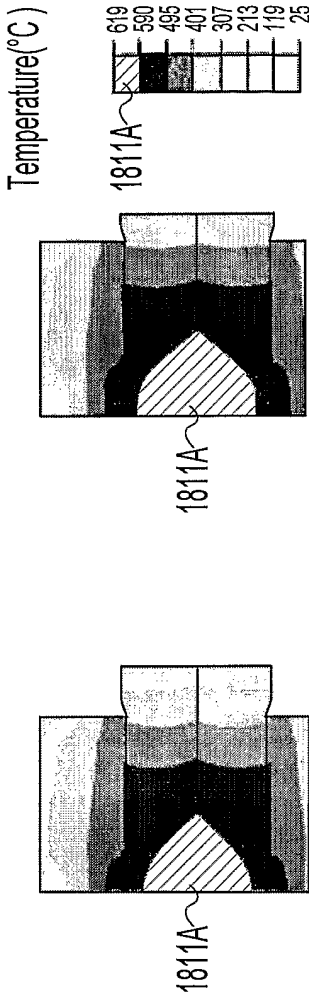


Fig. 18c

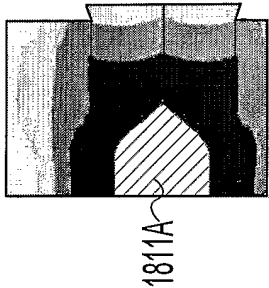


Fig. 18d

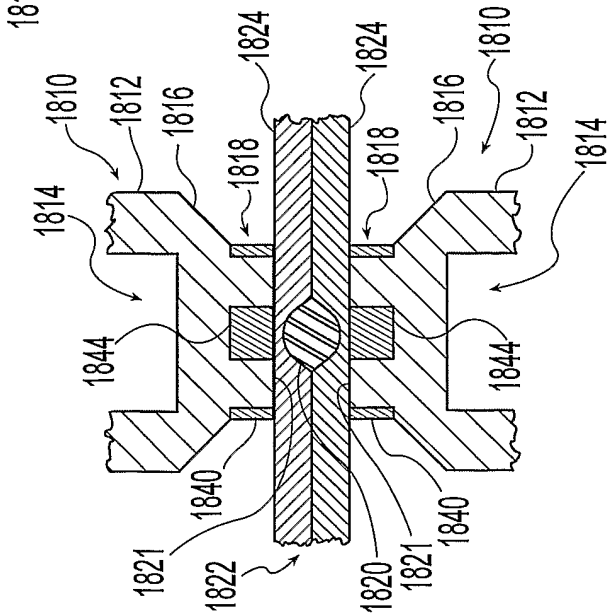


Fig. 18a

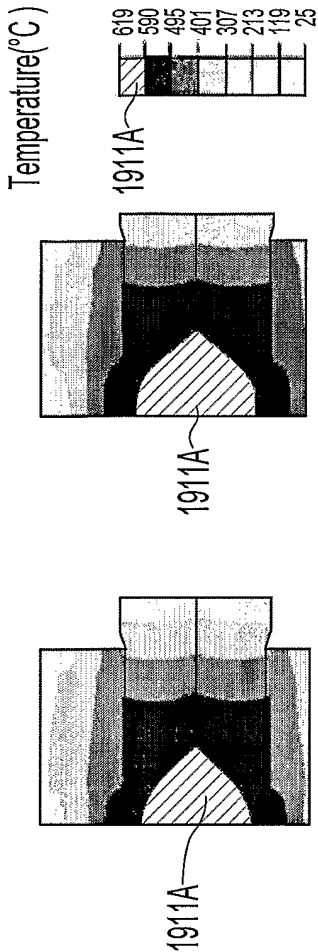


Fig. 19c

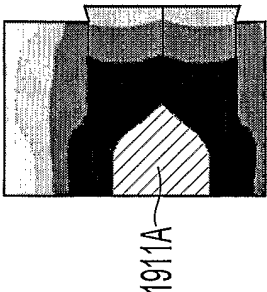


Fig. 19d

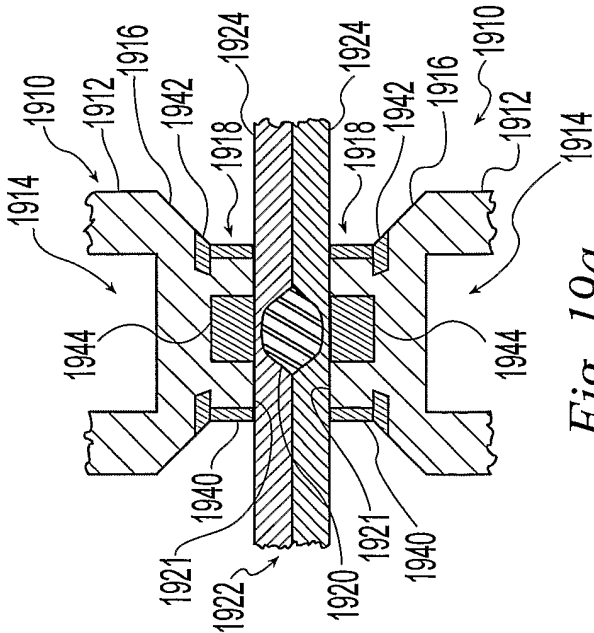


Fig. 19a

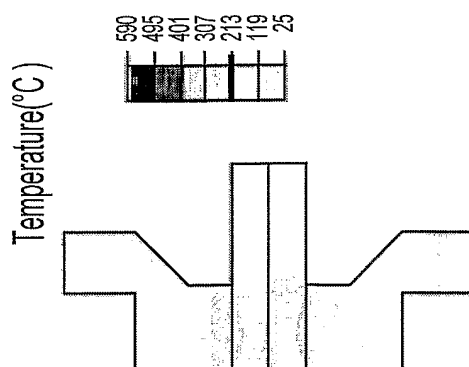


Fig. 20c

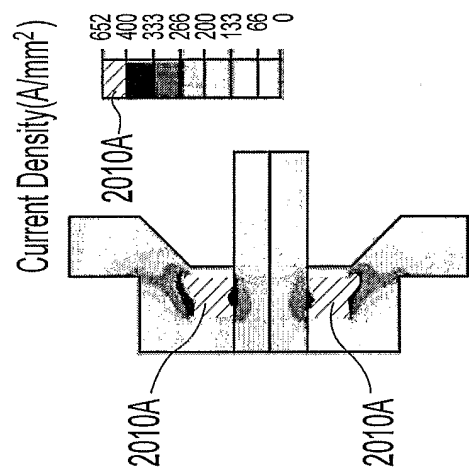


Fig. 20b

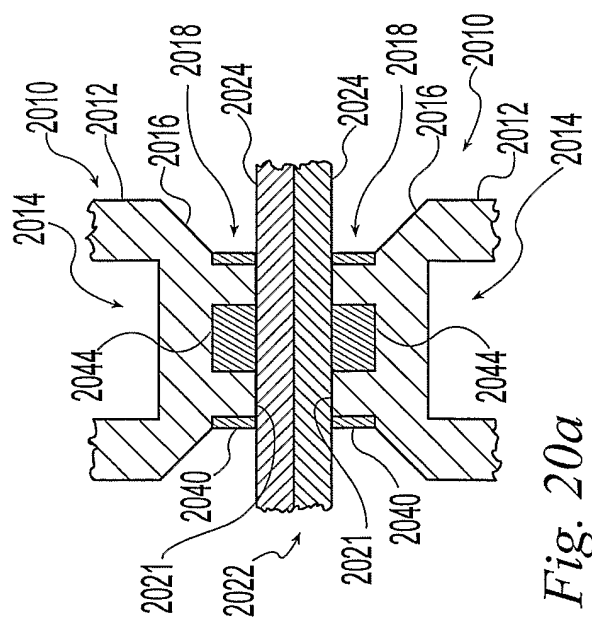


Fig. 20a

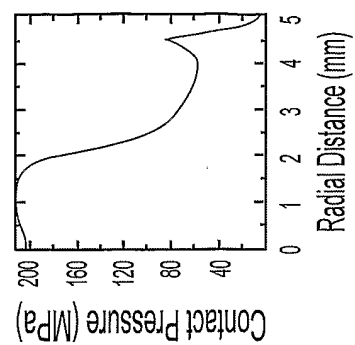


Fig. 20f

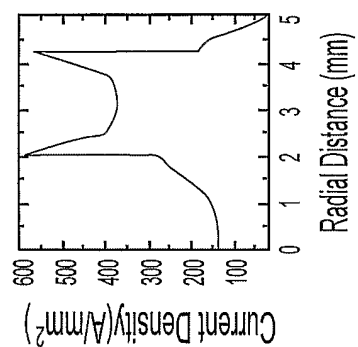


Fig. 20e

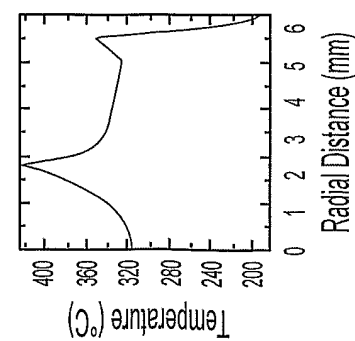


Fig. 20d

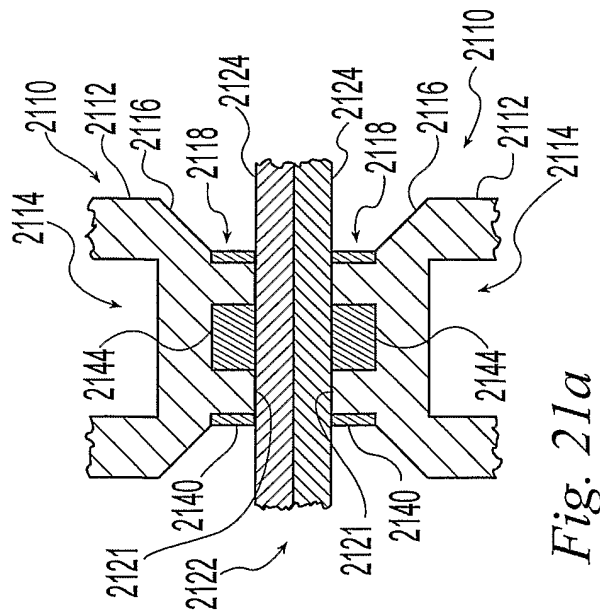


Fig. 21a

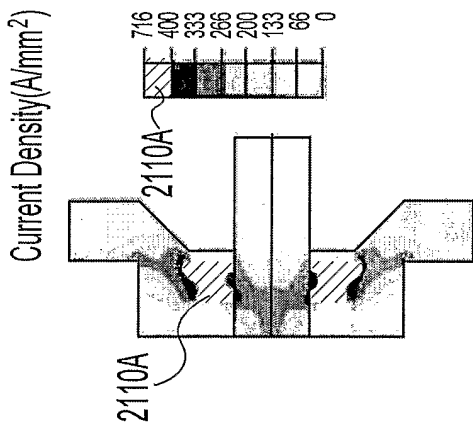


Fig. 21b

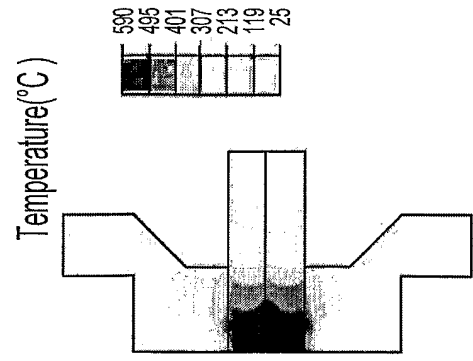


Fig. 21c

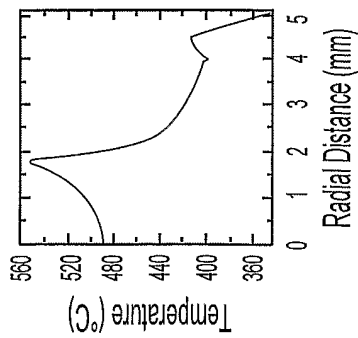


Fig. 21d

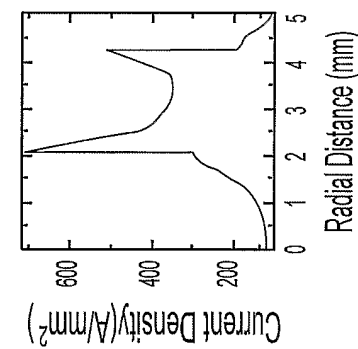


Fig. 21e

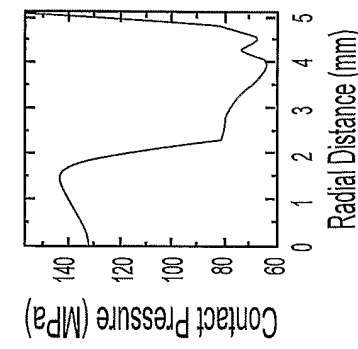
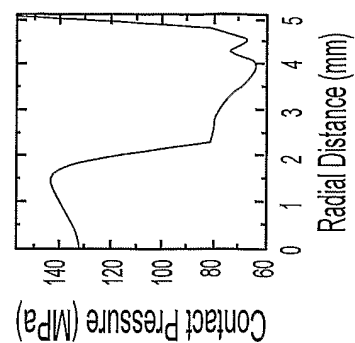
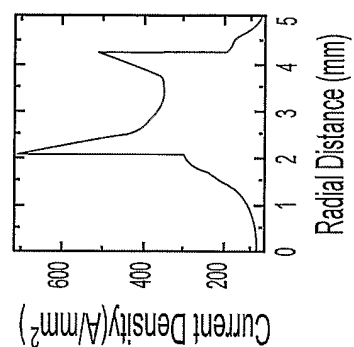
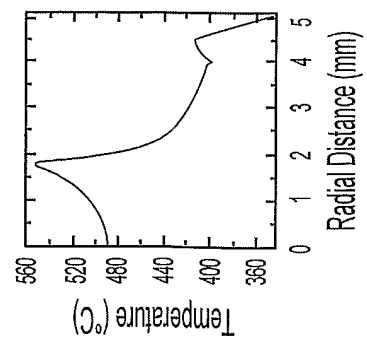
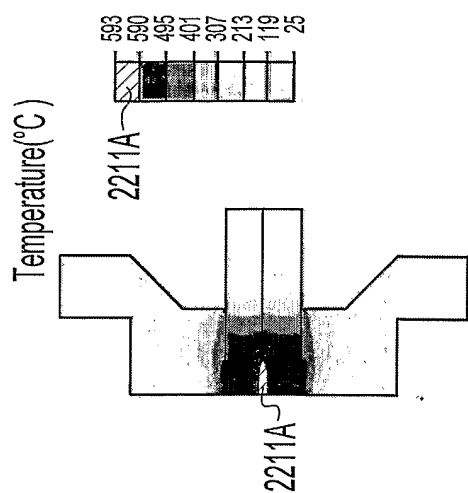
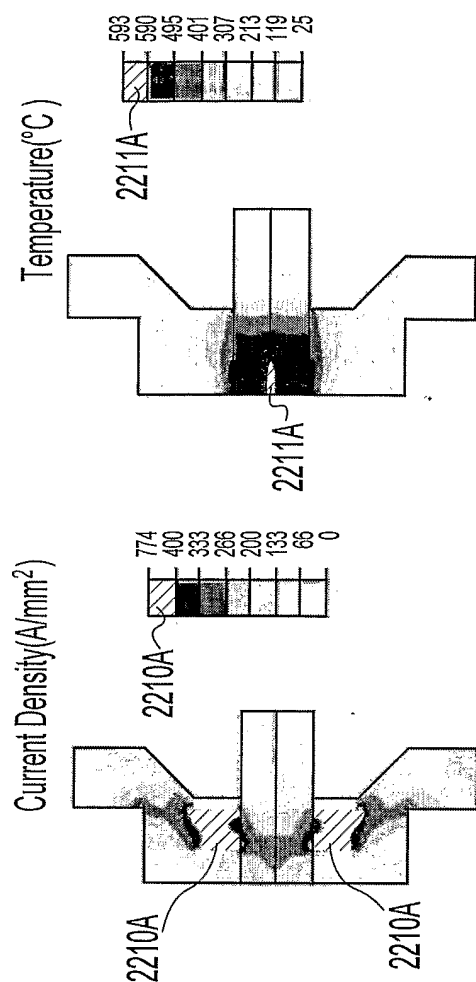
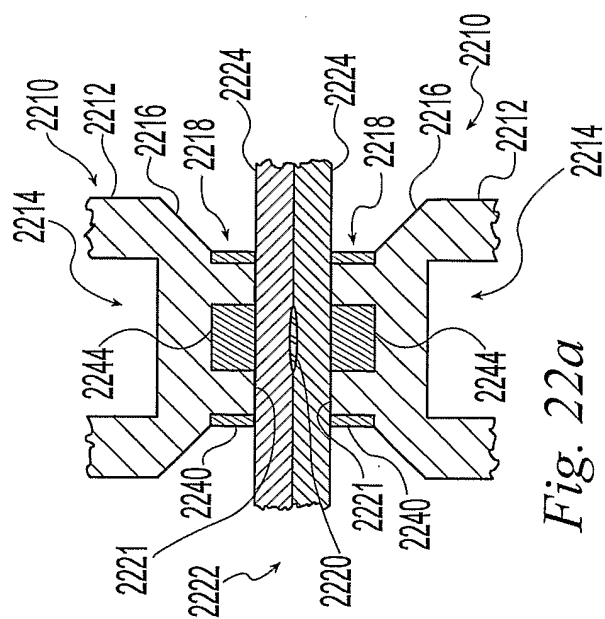


Fig. 21f



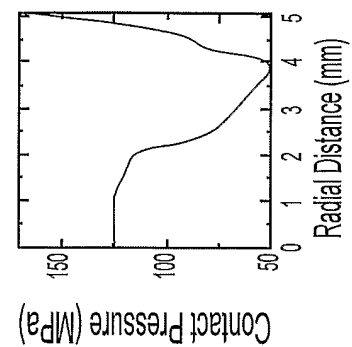
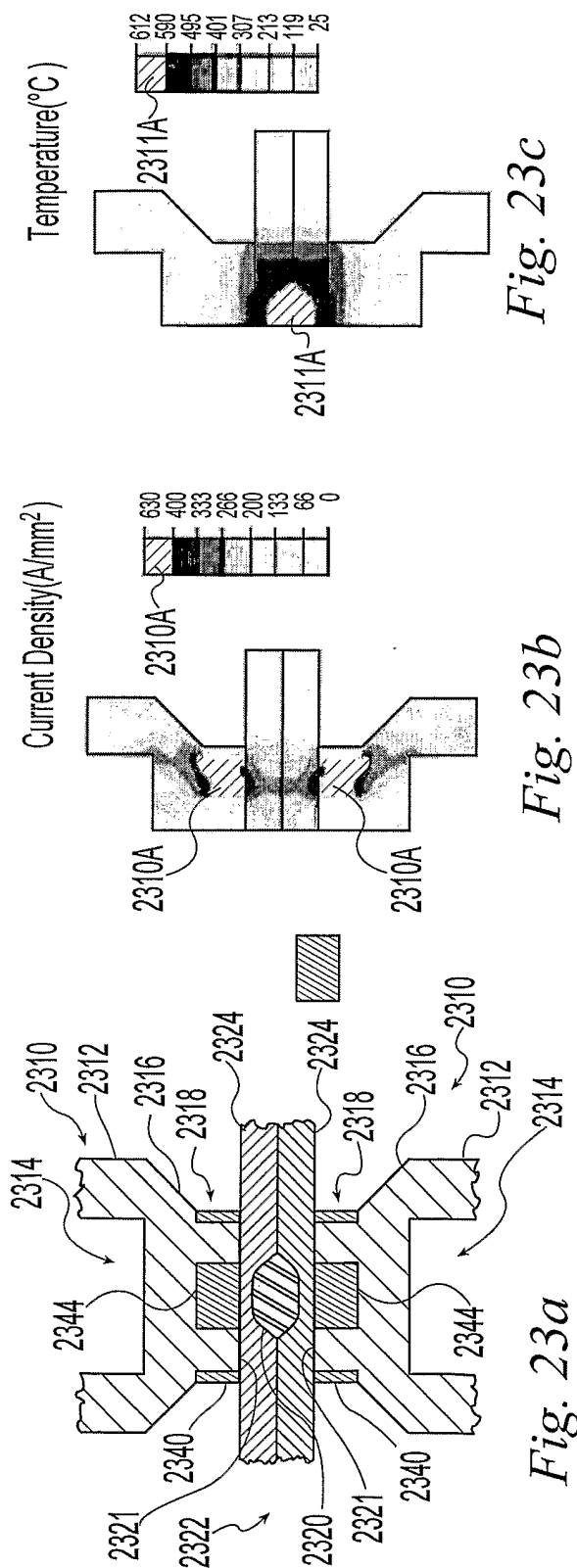


Fig. 23f

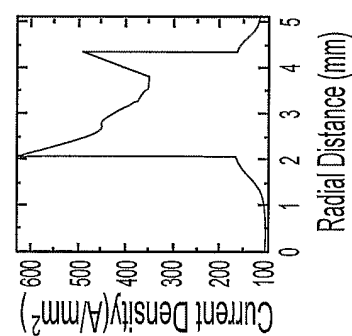


Fig. 23e

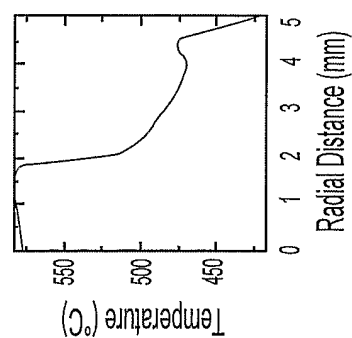


Fig. 23d

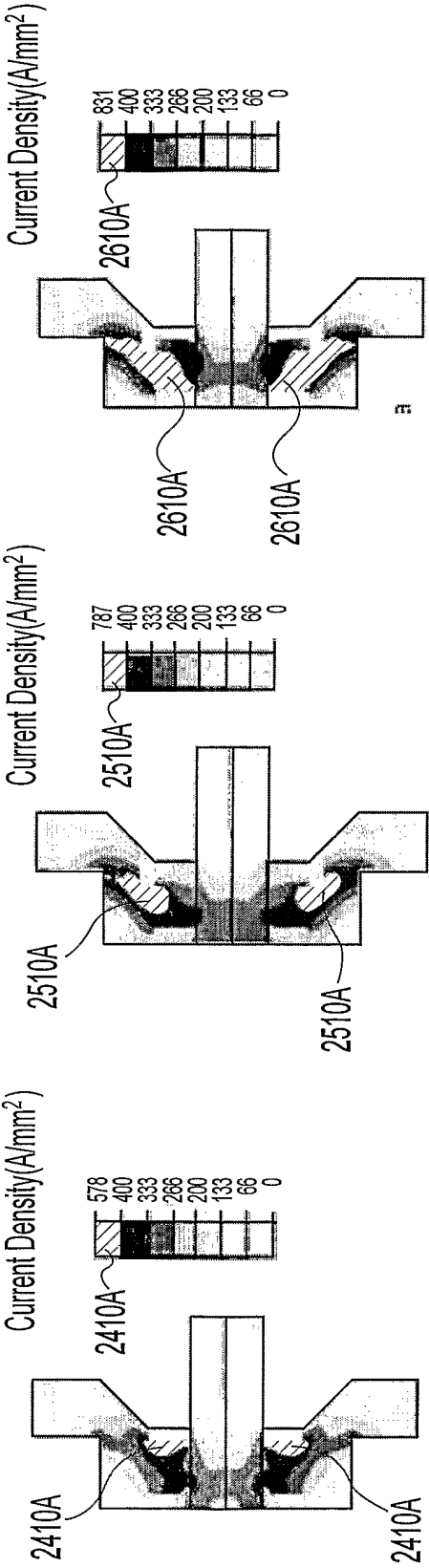


Fig. 24a

Fig. 25a

Fig. 26a

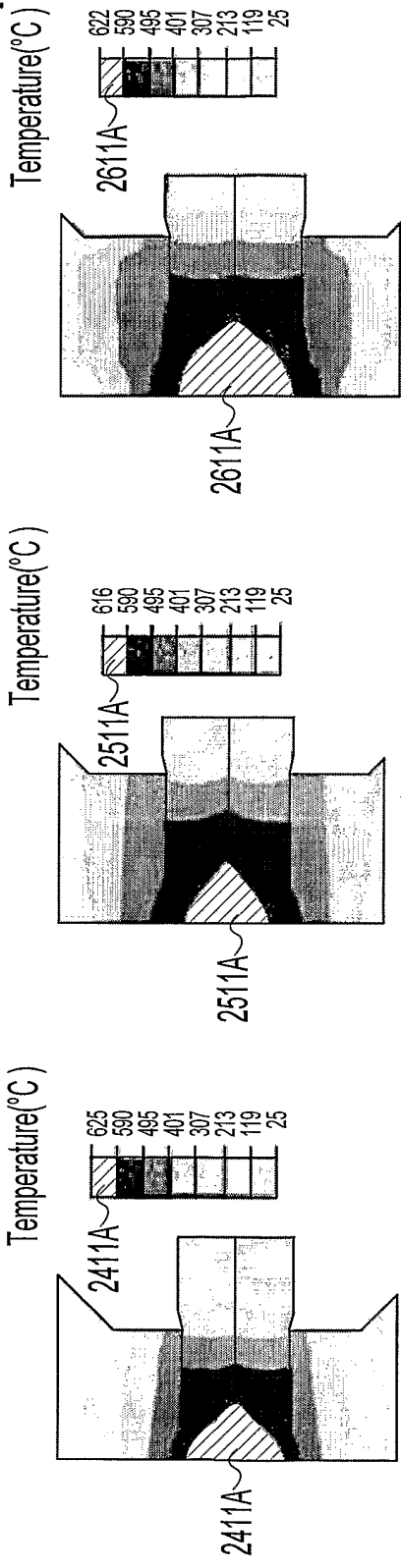


Fig. 24b

Fig. 25b

Fig. 26b

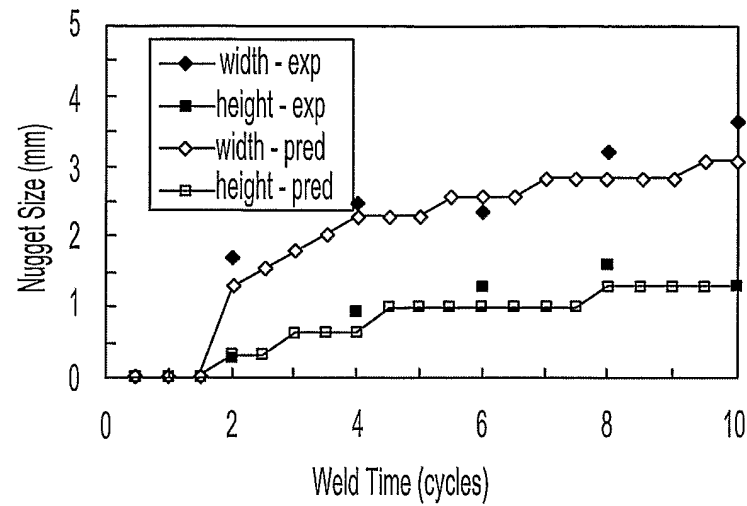


Fig. 27a

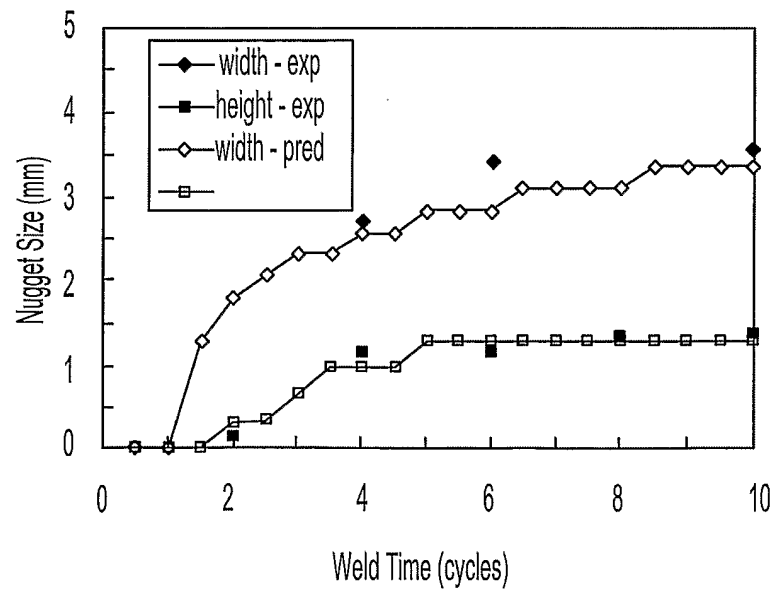
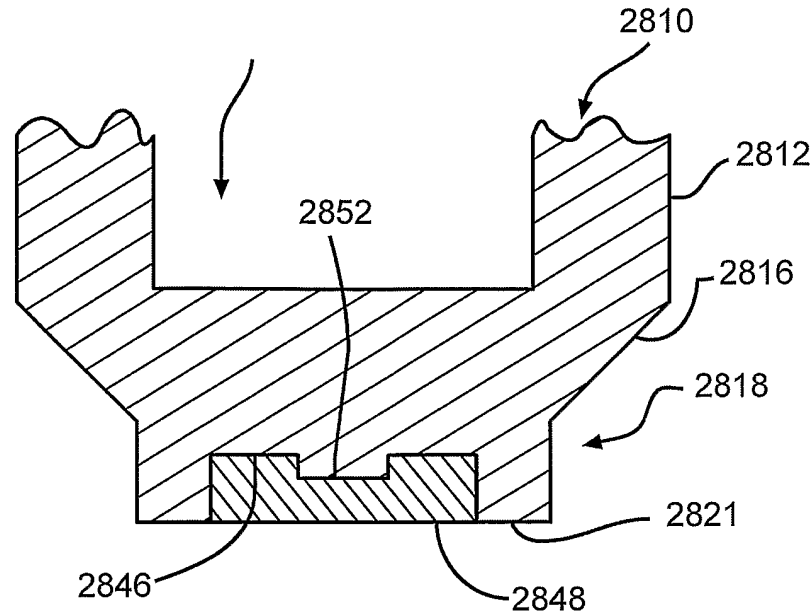
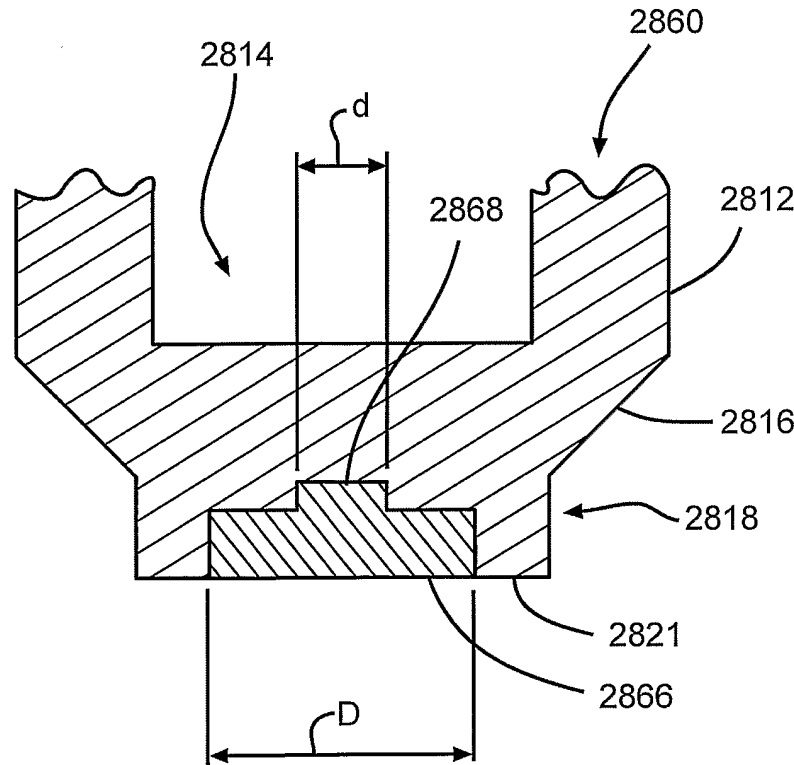


Fig. 27b

┌



—FIG. 28a



—FIG. 28b

└

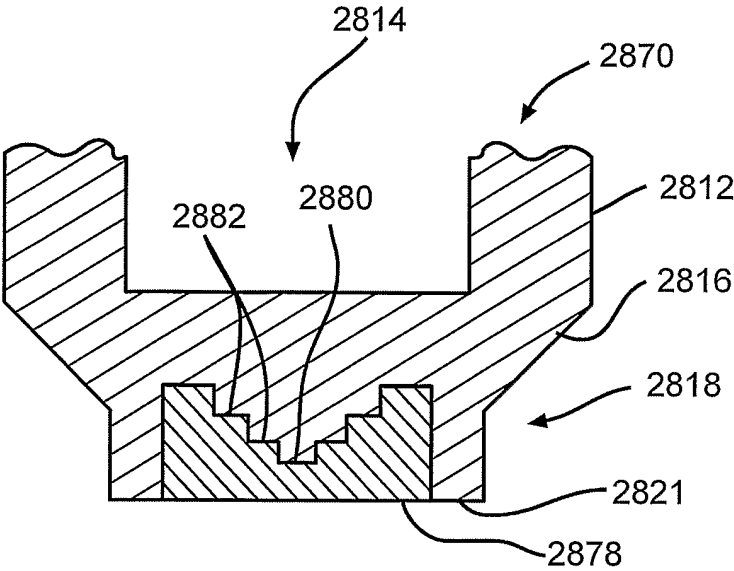


FIG. 28c

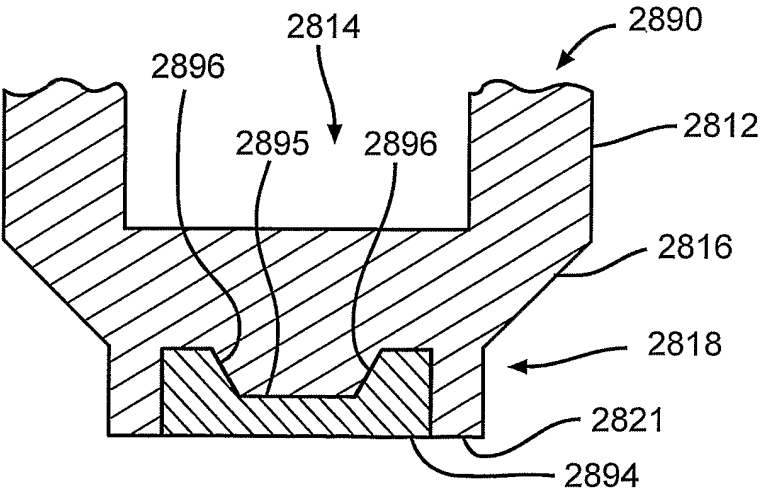


FIG. 28d

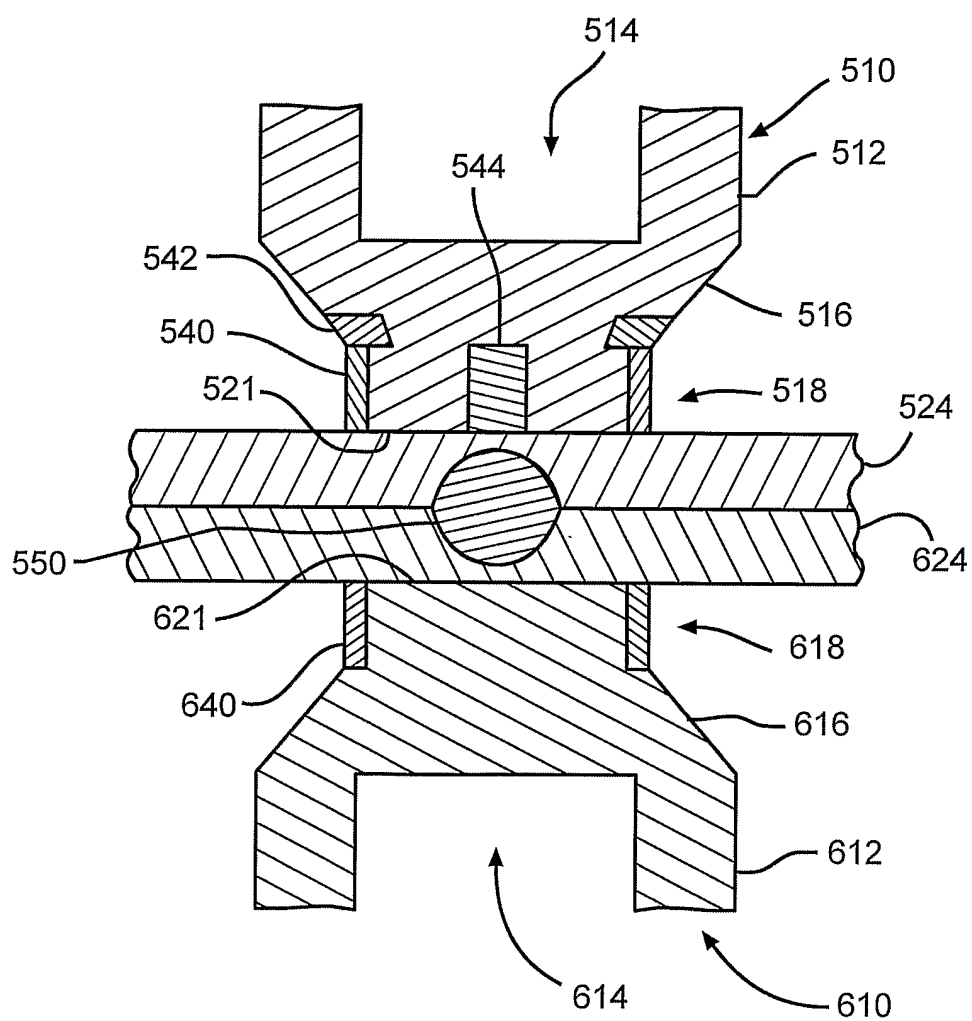
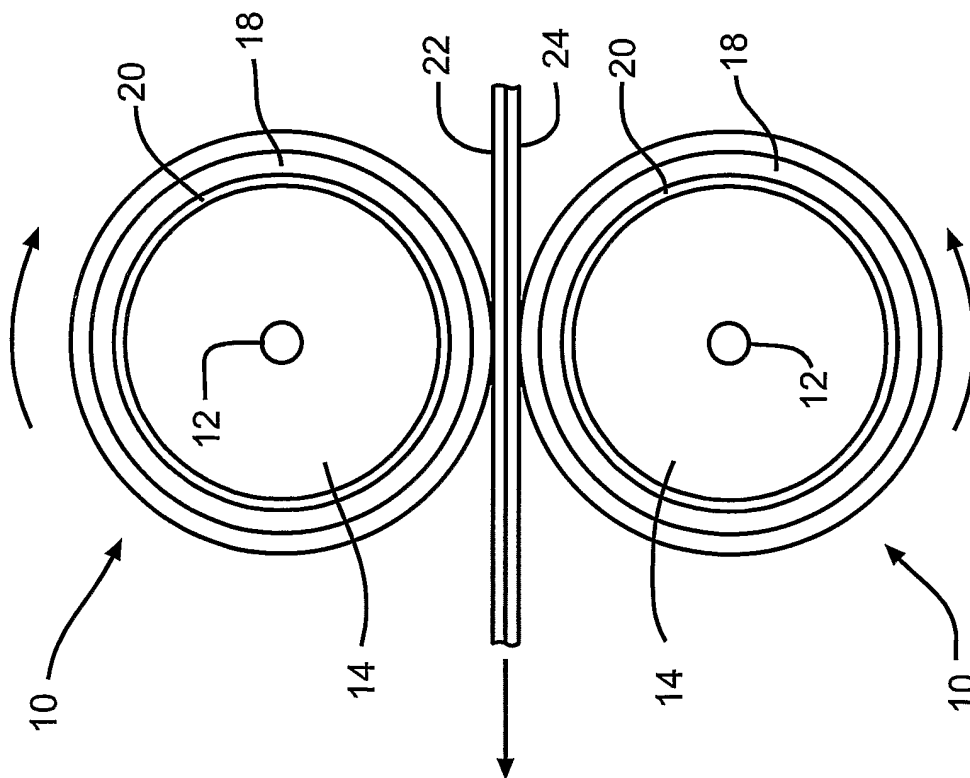
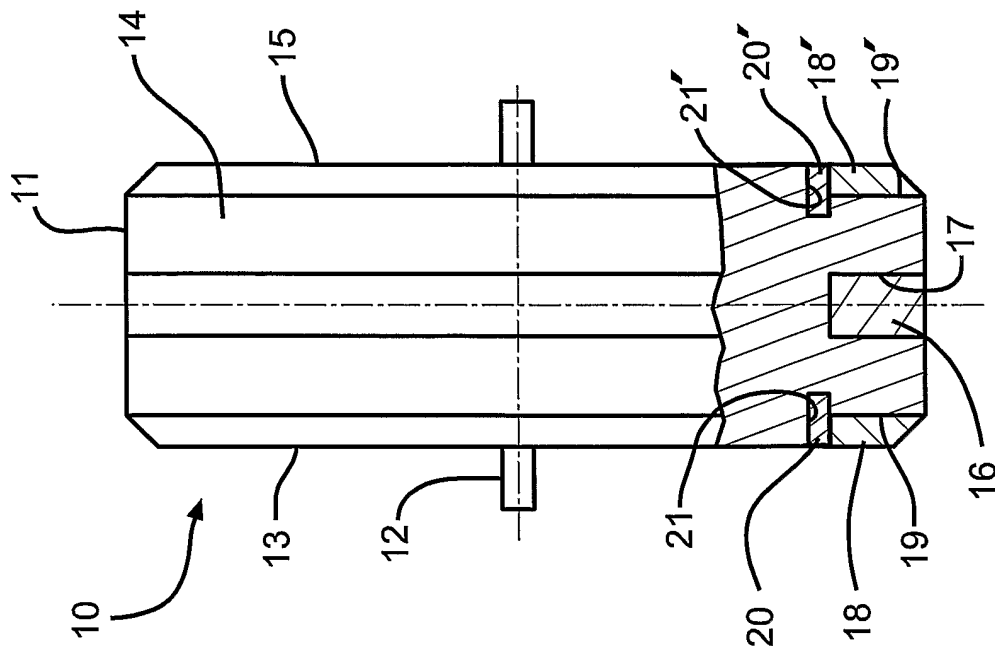


FIG. 29



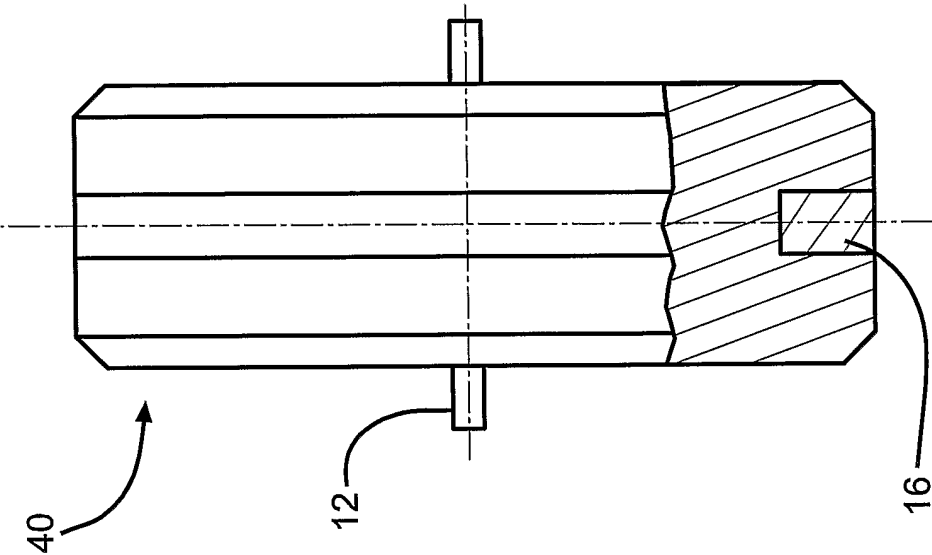


FIG. 33

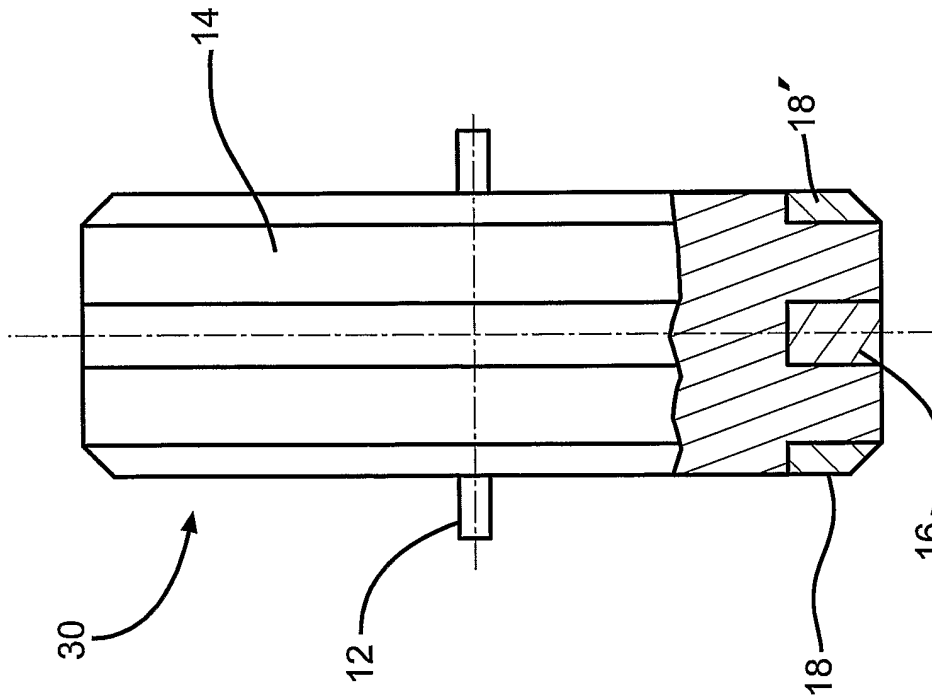


FIG. 32

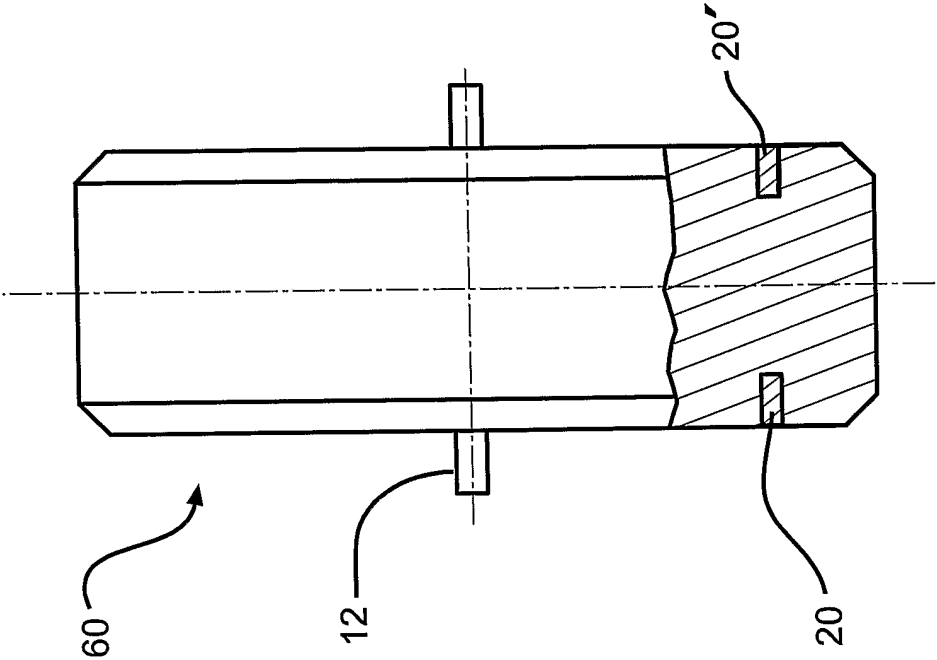


FIG. 35

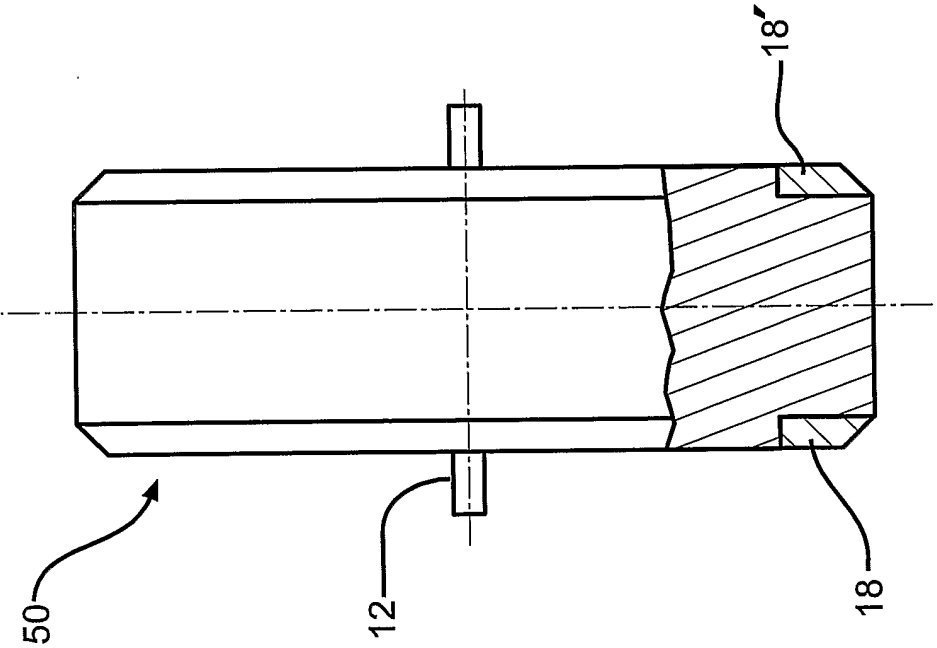


FIG. 34