ELECTROMAGNETIC FORMING COIL


Int. Cl. B65D 26/14

U.S. Cl. 72—56

ABSTRACT OF THE DISCLOSURE

Magnetic pulse forming apparatus includes an electromagnetic forming coil with means for connection to a pulse-source of electrical energy, separable portions having an open and closed position, and a contactor for providing a plurality of parallel current paths of substantially equal inductance across non-interfering surfaces of the separable coil portions when in the closed position. Means are also provided to produce equal contact resistance at all contact points of the contactor so that, overall, a uniform current distribution is produced over the plurality of paths when the coil is pulsed.

The present invention relates generally to forming apparatus, and more particularly to apparatus for forming a workpiece by energy acquired from a varying magnetic field.

Various apparatus have heretofore been developed for forming materials by employing a varying magnetic field of high intensity. In such apparatus generally, an electric current pulse of high amperage and short duration is passed through a conductor, typically in the form of a coil, to thereby produce a pulsed magnetic field of high intensity in the proximity of the workpiece positioned in or adjacent the coil. The workpiece, which is typically of a conductive material or employed together with a conductive material, is positioned in the pulsed magnetic field and a current pulse is thereby induced in the workpiece. This current pulse then interacts with the varying magnetic field to produce a force acting on the workpiece. The resulting force, or magnetic pressure, is made sufficiently great to cause the desired deformation of the workpiece, the swaging of one piece to another, etc. Repeated pulses of current may be applied to the conductor or coil, thus causing a series of deforming impulses to be applied to the workpiece.

As indicated above, such apparatus for electromagnetic forming of a workpiece may typically employ a conductor in the form of a coil, generally termed a "work coil," "forming coil," or "shaper," which surrounds that part of the workpiece to be formed so that radially directed forces will be applied to the workpiece. For example, in the typical case of magnetic swaging, it is generally possible to insert an elongated uniform workpiece into the forming coil aperture or opening which defines the coil workspace. However, when using such a forming coil with certain shapes or sizes of workpieces, a problem may arise in that the workpiece cannot be inserted within the coil aperture, or the formed assembly cannot be withdrawn from the aperture. This problem may arise, for example, in connection with workpieces having a generally "dumbbell" shape, wherein the end portions may be flanged or otherwise dimensioned so as to be larger than the coil aperture, making it impossible to pass the workpiece therethrough. The coil aperture must be sufficiently small in the working area to provide sufficient pressure for an efficient forming operation. Further, other applications and workpiece configurations may also prevent the workpiece from being inserted axially into the forming coil, and examples of such configurations are those which are closed in themselves, such as a ring, or those which, for some other reason, cannot be threaded through the coil. Examples of this latter type are swaging applications on pipelines or electrical conductors which, by reason of their indefinite or long lengths, or their installations, cannot be threaded through a coil.

Electromagnetic work coils have heretofore been proposed that could be opened, at least on one point of their circumference, so as to be capable of gripping or extending around a workpiece. However, since the discharge current path has to be linked with the workpiece, such a coil structure necessarily requires that the current path be opened every time the workpiece is inserted or taken out of the coil aperture or workspace. Therefore, at least one electrical contact assembly need be provided on the coil capable of carrying the required high current pulses across the separable coil parts and the coil must be capable of being readily opened for insertion and removal of the workpiece. In such prior constructions, the contacts were disposed in the interface between the separable coil-halves, and in a particular prior construction the contacts were formed by mating cylindrical surfaces in the coil interface. However, with such structures the recoil or reaction of the forming coil to the magnetic pressure generated during a pulsing operation tends to push the coil-halves apart which thus tends to lessen the contact pressure. This tends to cause arcing, and in a relatively short time, the contacts may be pitted or otherwise degraded sufficiently to impair the operation of the coil, providing only a relatively short useful coil life. Such contact failure has generally been the principal limiting factor with respect to the useful life of such forming coils.

Additionally, in order to provide the necessary high magnetic pressure in the workspace while at the same time providing a minimum current density through the contacts, such prior proposed coil structures have generally required a relatively narrow width in the region of the workspace, i.e., in the working orifice or shaper portion of the coil, and a large width in the general region of the contacts to minimize the current density. For example, the cross-sectional width of the coil might diverge from the workspace to the contact area so that the width of the contact area would be at least four or more times as wide as the working area. Thus, if such a design were to be extended to higher powers, the contacting areas would have to be made wider and wider and, since the mass of the coil progresses roughly with the cube of the linear dimensions, this requirement would very rapidly lead to undesirably heavy coils for which there is considerable difficulty in obtaining a sound piece of metal by casting or forging.

Accordingly, it is an object of the present invention to provide an improved separable or openable electromagnetic forming coil.

It is another object of the invention to provide such a forming coil in which the recoil of the shaper does not significantly reduce the contact pressure maintaining the closed circuit path of the coil.

It is a further object of the invention to provide a contact system for an electromagnetic forming coil which produces a uniform current distribution at the contacts to minimize degradation thereof so that a substantially longer useful coil life is provided as compared to the aforementioned prior structures.

It is still a further object of the invention to provide a forming coil which requires an actuating or latching mechanism for the coil-halves which need provide only a relatively small force against recoil as compared to that required by such prior proposed designs where the latching mechanism was also required to maintain high contact pressure.

These and other objects of the present invention will...
become apparent by reference to the following description and accompanying drawings, in which:

FIG. 1 is a schematic elevational view of a forming coil assembly in accordance with one embodiment of the present invention;

FIG. 2 is a partial right side view of the coil assembly of FIG. 1;

FIG. 3 is a perspective view of one of the movable contactors of the assembly of FIG. 1;

FIG. 4 is an enlarged detail view, partially in section and partially in block, taken along line 4—4 in FIG. 1;

FIG. 5 is a sectional elevation of the system of the coil assembly illustrated in FIG. 1;

FIG. 6 is an enlarged diagrammatic representation of an alternative contact system to that shown in FIG. 5;

FIG. 7 is a partial sectional view taken along the line 7—7 in FIG. 6;

FIG. 8 is an elevation diagrammatically showing a modification of the contactor of FIG. 3;

FIG. 9 is a sectional view taken along line 9—9 in FIG. 8;

FIG. 10 is a plan view diagrammatically showing another modification of the contactor of FIG. 3;

FIG. 11 is a right end view of the contact arrangement illustrated in FIG. 10; and

FIG. 12 is a view, partially in elevation and partially schematic, showing an electromagnetic forming coil system in accordance with a further embodiment of the invention.

Referring now generally to FIG. 1, there is schematically shown an electromagnetic single turn forming coil 10 comprising a pair of separable conductive members, shapers, or dies 12 and 14 having an open position, illustrated in broken line, for insertion and removal of the workpiece 13, and a closed position, shown in solid line, for defining a workspace 16 containing the workpiece during the forming operation. The workpiece is shown for example as a shaft having a collar thereon to be swaged thereto. The conductive members 12 and 14 have opposing or interfacing pairs of surfaces 18—20 and 22—24 on opposite lateral sides of the workspace 16 which are disposed generally normal to the plane of motion of the dies to define, generally, the planes of separation thereof. A layer of insulation, or an insulating air gap, is provided between the respective pairs of interfacing surfaces on both sides of the workspace so that desirably no current flow is permitted through the interfacing surfaces from one shaper face to the other. However, current flow may be conducted between the dies 12 and 14 by contacting means, illustrated as movable bridging switches or contactors 26a, 26b, 26c and 26d (the latter two not being visible in FIG. 1 because of their location behind the coil). These contactors electrically interconnect both of the dies or coil-halves by direct contact with respect to stationary contact pairs 28a—28a′, 28b—28b′, 28c—28c′ and 28d—28d′ located, generally, in planes transverse to the interfacing surfaces of the dies on the lateral, mutually parallel, front and back external faces thereof. That is, each of the stationary contacts, represented by dotted lines in FIG. 1, is on an external face or surface which is in a plane parallel to the plane in which the coil-halves are operable. Consequently, the contacting and bridging arrangement between the dies is such as to provide a sliding, rather than a separating, action in the event of relative movement between the coil-halves, such as on recoil during a forming operation.

The stationary contact pairs 28a and 28a′, 28b and 28b′, etc., corresponding to each of the contactors 26a through 26d, are preferably tapered with respect to each other so that they are substantially closer to each other (and to their associated interfacing surface) at their furthest distance from the workpiece 16 and diverge away from each other (and from the interfacing surface) at distances closer to the workspace. With such a general configuration, as will be explained in detail hereinafter, a plurality of conductive paths may be provided by the contactors which bridge each of the interfacing portions of the dies in a manner providing substantially equal inductance as well as equal resistance in each path for uniform current flow through the contactors 26a through 26d, yielding an increased contact life and, consequently, a substantially long useful coil life.

A pulse current source, illustrated as a block 30 applies the required energy to the forming coil 10 by current conduction through the dies 12 and 14. In the embodiment of FIG. 1, the upper die 12 is movable and formed from a continuous contacting plate, while the lower die is stationary and formed from two discrete conductive plate sections 32 and 34 which are separated by an insulating layer 36 so that each section may be connected to an opposite pole of the source. The separable forming coil 10, which may be sometimes termed a "clam-shell" coil, is shown in dotted line as being openable vertically by means of the actuator 38, which may be in the form of any suitable mechanism, such as a hydraulic piston and cylinder arrangement, which lifts the upper die to the position designated as 12'. Alternatively, the forming coil may be opened in other manners, if desired, as will be later described in connection with the coil assembly of FIG. 12.

More particularly, the contacts 28a through 28a′ and 28b through 28b′ may be formed, for example, by silver strips brazed onto the planar surfaces of the dies. The contactors 26a through 26d comprise an individually adjustable contact assemblies which are urged against each pair or set of contact strips to electrically and mechanically bridge the interfacing surfaces of the dies, as shown in FIG. 2, with the applied forces being indicated by arrows 40 and 42. Consequently, with the dies 12 and 14 in their closed position and with the movable contact assemblies 26a through 26d in their engaged position, a complete single turn coil is formed which may be energized by the pulse current source 30 to produce a current flow through the coil as indicated by the arrows in FIG. 1. Each of the movable contact assemblies 26a through 26d preferably comprise a plurality of laminar contact blades 44, as shown in FIG. 3. These blades are retained in a holder or housing and supporting structure 46 by means of tab portions 48 (FIG. 4) on the inner ends of each contact blade which are then urged outwardly by a pressure element such as an elastomeric cushion 54 or the like disposed between the inner edges of the blades 44 and the back wall of the housing 46. The tabs 48 are thus normally urged against the inner surfaces of the holder flanges 56, but when the contactor is moved into engagement with the associated pair of contact strips 28—28′ by the application of forces 40 and 42 (FIG. 2), the applied force from the rod or shaft 58 is distributed by the rigid back wall of the holder 46 and the cushion 54 to thereby apply a uniform pressure to all of the contact blades 44. The contact blades 44 thus provide a multitude of parallel bridging paths across the contact strips at pairs of contact points on the forward edge of each blade. Because the engagement pressure is uniform, an equal contact resistance is produced at each contact point.

This arrangement is shown in greater detail in FIG. 4 for the contactor 26a, the other contactors having the same type of construction. The plurality of contact blades 44 are formed from relatively thin metal stock in an adjacent and laminar manner, and are each generally T-shaped, having an inner portion disposed within the cavity of the housing or holder 46 and an outer portion protruding therefrom. Each of the contact blades are movable relative to each other and to the holder 46, and each presents an outer edge which forms the contact points with the contact strips 28a and 28a′ fixed to the dies. The back wall portion of the holder 46 functions as a means for distributing the force applied thereto by an actuator 80 via the reciprocally movable rod or shaft 58. The distributed force is applied to the back edges of the inner portion of each of the contact blades 44 by the cush-
ion 54 interposed and confined between the back edges of the contact blades and the wall of the holder so that a substantially high force is applied to substantially all of the cushion area in the direction producing contact engagement. This causes a hydrostatic-like pressure to be applied on the plurality of contact blades, resulting in a uniform pressure being applied thereto so that an equal contact resistance will be produced at each of the contact points between the blades and the contact strips. Since each contact blade is independently movable with respect to the others, and since the pressure is everywhere substantially equal, equalization of contact resistance occurs generally regardless of the state of wear of the contacts. Each of the contactors may, for example, have a construction like those disclosed in copingending application Ser. No. 712,777, now Pat. No. 3,487,456, filed Mar. 13, 1968, of the same inventor, and assigned to the assignee hereof. A supporting structure 62 comprising suitable bearing means for a rotatable shaft 58 and associated parts rigidly holds this movable contact assembly in fixed relation to the forming coil. The supporting structure 62 may be attached by any suitable means to a supporting frame (not shown). Thus, with the contact assemblies disposed on the external surfaces of the dies, any recoil of the dies during the pulse forming period results in a sliding action of the contacts, while each contactor provides a multitude of alternate conductive bridging paths having equal contact resistance at each point of contact. The contact resistance at each point of contact between the contact blade and a contact strip is maintained uniform by the hydrostatic or quasi-hydrostatic force-producing element 54 in each of the contactors, and these elements may comprise the elastomeric cushion, previously mentioned, or a noncompressible fluid-filled flexible container or chamber. Various exemplary structures to produce such uniform contact pressure and an equalized contact resistance are disclosed in the aforementioned copending application; however, other types of structures may be employed in accordance with the principles of the present invention, but generally less advantageously. In the contactor illustrated in FIG. 4, the cushion 54 may be composed of a rectangularly solid elastomeric material such as rubber or rubber-like plastic which acts similarly to a fluid in producing a hydrostatic-like or quasi-hydrostatic pressure distribution when it, itself, is placed under a high pressure or compressive force. The elastomeric material should generally be as soft as possible to yield the best hydraulic properties. If desired, a multiple layer cushion structure may be employed wherein the layers vary in hardness with the harder layer disposed adjacent the blades to prevent extrusion upon compression by the holder which confines the cushion on its other five sides.

Now, in accordance with a further feature of the present invention to provide a uniform current distribution through the alternate parallel current paths of each contact arrangement, because of the inherent non-uniform current density in the coil, the contact arrangement is configured and arranged so as to provide substantially equal inductance and resistance over each of these parallel paths. Thus, with equal contact resistance at each contact point and with equal resistance and inductance over each current path, a substantially uniform current distribution is provided over the entire contact area of each contactor when the coil is pulsed to further increase the contact life and the useful life of the coil assembly.

More particularly, the inductance of the current paths through each of the contactors is equalized by varying the length of each successive current path a suitable amount for the particular winding geometry involved so as to compensate for the particular uneven current distribution in the forming coil. Referring again to FIG. 1, and as previously mentioned, the lower die 14 comprises the two conductive sections 32 and 34 which are electrically insulated from each other by the insulation 36, and each section is coupled to a respective pole or terminal of the source 30. The workspace 16 is defined generally in the central region of the forming coil by an aperture formed by the interior curved surface portions 82, 84 and 86, of each of the respective coil parts 12, 32 and 34. Thus, for example, the current path may be from the source 30, to the stationary part 32, through contactors 26a and 26c, movable die 12, contactors 26b and 26d, stationary die section 34 and back to the source 30. This is because of the high-frequency components of current produced by the pulse current source 30 when discharged through the forming coil 10, a non-uniform current distribution is produced therein. More specifically, the current may be considered as traveling essentially adjacent to and on opposite sides of the insulating 36, and in the area adjacent the coil aperture or workspace 16, opposite the workpiece placed therein, as indicated by the path of the arrows shown in FIG. 1. These are actually the high current density regions of the coil with the current density decreasing as a function of distance away from these regions during each current pulse. A fragmentary view of the forming coil is presented in FIG. 5 showing an enlarged and very diagrammatic representation of the contact blades of contactor 26a and the contact strips 28a and 28a' for facilitating an understanding of this aspect of the invention. The contact blades of contactor 26a are represented for simplicity by the parallel sequence of five spaced vertical conductor elements 44a through 44e which are representative of the edges of the contact blades 44 illustrated in FIG. 3, but actually assembled in an adjacent laminar manner. Since the current flow through the stationary die section 32 is concentrated near or adjacent to the insulation 36 and tends to flow adjacent the workspace aperture 16, the current is believed to take different and alternate paths, as indicated by the arrows, through each of the contact blades 44a through 44e to the movable die 12 in which the current continues to follow the path adjacent the workspace aperture 16. The conductor blades 44a through 44e make contact with portions of contact strips 28a and 28a', and the points of contact are thus made at positions 60 and 62, 64 and 66, 68 and 70, 72 and 74, and 76 and 78. The contact resistance at each contact point is made equal in the manner previously discussed. In addition, however, the contact strips 28a and 28a' (and their respective counterparts) are disposed so as to be diverging toward the coil aperture or workspace 16 so that the edges of the blades 44a, 44b, etc., between respective contact points 60 and 62, 64 and 66, etc., vary in effective electrical length to produce an equal inductance in each of the parallel paths. More particularly, in view of the current distribution of FIG. 5, the current can take alternate paths through the different contact blades. If the contact strips 28a and 28a' were parallel, i.e., at right angles to the blades, so that the contact points were at equal distances from the interfacing surfaces 22 and 24, the various current paths would be of substantially different lengths. Since the effective inductance of each path is generally proportional to its effective length and the reactance is generally proportional to its inductance, a very uneven current distribution may result through the contactors. Another important factor, although believed to be less significant than the inductance, is the varying resistance over each of the current paths due to their different lengths (i.e., the different distances the current must travel), even assuming equalized contact resistance. Consequently, in operation, the limit of current carrying ability for the blades of each workspace would likely be reached long before the limit for blades further away. However, by varying the spacings of the contact points in a diverging manner, the effective lengths of the current paths are increased as a function of distance toward the workspace, thus increasing the inductance and, to some extent, the resistance of each successive path to compensate for the different path lengths through the coil, therefore, it is generally advan-
tageous to bring the points 60 and 62, i.e., those furthest from the workspace, as close to the interface gap as possible so as to minimize the inductance of the furthest path. Thus the current paths closer to the workspace are brought up to the same value of inductance by bringing the successive pairs of points 64 and 66, 68 and 70, 72 and 74, and 76 and 78 successively wider apart. Although the drawing of FIG. 5 shows the strips 28a and 28a' (as well as their counterparts) as straight or nearly straight lines, this orientation will generally represent merely an approximation of the optimum shape or configuration. The particular shape, which may be a curve, to produce the desired or optimum variations in length of the bridging between contact points of each successive conductor blade may be established from a magnetic field plot for any particular coil geometry.

Referring now to FIGS. 6 and 7, there is shown an alternative form of stationary contact structure 100 and 102 associated respectively with each die or coil half 12 and 14. The contactor 26a is structured as previously described in connection with FIGS. 3 and 4. However, instead of employing contact strips such as 28a, 28a', etc., shallow depressions 104 and 106 are milled into the surface of each of the dies and the lengths of the current paths corresponding to each of the contactor blades is then accomplished by suitably shapes the edges 108 and 110 to provide the equalized inductance (and path resistance) previously described. The effective lengths of the current paths through the successive contactor blades thus correspond to the varying distance between the milled edges 108 and 110 across which the contact blades bridge one shaper to the other. The application of a substantially high force on the contactor 26a is represented by the arrow 112 in FIG. 7 in a manner similar to that of FIG. 2.

The same general results with respect to equalizing the path inductance and resistance may alternatively be achieved by varying the effective path lengths by particularly shaping the contactor blades rather than the stationary contact sets. Referring now to FIGS. 8 and 9, there is shown a modified form of the contact blades 44 of the contactor illustrated in FIG. 3. In the modified form, the contactor blades 44 are generally recessed with two raised projections or protruding portions on each blade arranged in such a manner as to form the desired contact. Provision for equalization of path inductance and resistance when mating with parallel contacts on the dies, i.e., contacts which are equally and uniformly spaced from the interface gaps of the coil. The spacing between the projecting portions 114 and 116, as shown in FIG. 9, on each successive blade is determined in the same manner as the geometry of the fixed contact strips previously described in connection with the embodiment of FIG. 1, the straight-line configurations illustrated in FIG. 8 being generally an approximation to the most optimum geometry which may generally be a curve. As before, the most optimum configuration may be determined by a magnetic field plot for any particular coil construction, and a straight-line approximation may be employed when balanced against other considerations such as cost and ease of manufacture.

Another manner of achieving the desired equalization of inductance and path resistance for uniform current distribution throughout the contact area is illustrated in FIGS. 10 and 11. As shown, the contact blades are similar to those of the contactor illustrated in FIG. 3 but have a channel or slot 120 of varying depth through the face of the contact blades so that the effective length normal to the plane of the coil 10 is varied to equalize the inductance of each current path through the contactor blades. This form of contactor may be employed with parallel stationary contacts of the same type as described in connection with the embodiment of FIGS. 8 and 9. As shown in FIG. 11, the contact blades 44' make contact with the stationary contact strips 28 and 28' on the dies 12 and 14 at the projecting edges 122 and 124, and each successive lamination or blade provides a generally U-shaped current path of successively varying length bridging the dies. As shown in FIG. 10, the added inductance for equalization is the greatest toward the right-hand side of the figure and is the least toward the left-hand side of the figure. Thus the workspace would be located to the right of the contact assembly as shown.

Other forms of contact arrangement may alternatively be employed in accordance with the principles of the invention, such as, for example, an arrangement utilizing a combination of the features of the embodiments of FIGS. 1, 6, 8 and 10.

Referring now to FIG. 12, there is shown an alternative embodiment of a coil assembly to that of FIG. 1 wherein corresponding parts are designated with primed reference numerals corresponding to those used in FIG. 1. As in the embodiment of FIG. 1, there is a movable die 12' and a stationary die 14', the latter of which is divided into two conductive sections 32' and 34' separated by insulation 36'. Each one of the conductive sections 32' and 34' is connected to one pole of the current source 30' which is merely illustrated as the housing containing a matching transformer for matching the impedance of the forming coil 10 to the output impedance of the pulse power supply, the power supply and matching transformer, per se, forming no part of the present invention. The dies are also mechanically mounted on the source housing 30', as shown. Each of the dies 12' and 14' contain pairs of contact strips of the type illustrated in FIGS. 1 and 2 and which diverge toward the workspace-defining aperture 16'. Four contactor assemblies like that disclosed in FIGS. 3 and 4 and previously described are utilized with the forming coil of FIG. 12, but only contactor 26b' is shown for clarity of illustration.

The movable shaper or coil-half 12' is hinged for pivotal movement about a pivot 200 and is operated by a pneumatic cylinder assembly 202 through a suitable linkage. The coil 10' is illustrated in FIG. 12 in its open position for insertion or removal of a workpiece (not shown). The pneumatic cylinder 202 operates the movable die 12' through a piston-rod 204 pivotally attached to one end of a bell crank 206 having its intermediate point pivotally connected to the upper die pivot hinge 200. The other end of the bell crank is fixedly attached to the upper surface portion of the die 12' by means of a resilient mount 208 for isolation of shocks during forming or cutting away from the cylinder and linkages. The lower end of the hydraulic cylinder assembly 202 is pivotally attached to a mounting lug at pivot 210, the mounting lug being rigidly attached to the housing 30'.

Hydraulic rams are provided as the actuators 80 (FIG. 4) associated with each of the four contactors, but only one is schematically illustrated as 80' in FIG. 12. A hydraulic control system 212, of any suitable type, is provided as illustrated in block form and is responsive to an input control signal, indicated by arrow 214, to operate a pneumatic cylinder circuit so that the proper sequence of operations will be performed in both opening and closing of the coil-halves. More particularly, the hydraulic rams for pressurizing the contactors may be operated by a pneumatic-hydraulic booster similar to the master cylinder of an automotive braking system which is tied into the pneumatic cylinder circuit for control by the system 212.

In operation, on actuation by the command signal on input 214, the pneumatic control circuit causes the pneumatic cylinder assembly 202 to move the upper die 12' to its closed position to perform a forming operation. Subsequently, in response to an appropriate signal from the pneumatic-hydraulic booster, each of the contactors is caused to move into their engaged contacting position and it continues to maintain a substantially high force on all of the contactors to provide minimum and equalized contact resistance across all of the contact points associated with
each contactor. After a forming operation has been completed, the sequence of operations is effected in reverse of that previously described so that the booster releases and withdraws each of the contactors from their engaged position and subsequently the pneumatic cylinder assembly 202 opens the coil-halves. Of course, any other system may be utilized to operate the coil assembly and the contact assemblies associated therewith, and other particular arrangements for opening the coil-halves may alternatively be employed.

In the construction illustrated in FIG. 12, side plates 216 are bolted on both sides of the stationary die 14 so as to bridge the two sections 32' and 34' of opposite polarity and these functions to increase the effective reluctance of the insulating slot or layers 36'. These side plates may contain a conductive metallic insert or are themselves made out of metal with suitable insulation to prevent shortening the coil. Although no insulation is shown covering the movable shaper and the stationary coil parts, such insulation may be provided if desired. Addition of any form of suitable cooling mechanism may be provided in conjunction with the coil, if desired.

As can now be seen, the embodiments of the invention herein described include contacts which are at generally right angles to the main direction of recoil during a pulsing operation so that they will, under the most severe conditions, experience at most only a sliding motion over their surfaces, rather than any tendency to separate which would lessen the contact pressure. The forces tending to repel the contact blades from such shapers is, due to the lower current density, of a considerably lower order of magnitude and will in the present designs be overcome by the force of the contact-actuating mechanisms described. Furthermore, since the shaper-actuating mechanism does not have to provide contact pressure, as would be the case where the contacts were located in the interfacing surfaces of the dies, it can be constructed to provide a relatively smaller force. Thus, the shaper-actuating mechanism will bring the coil-halves together while the mechanism which provides the contact clamping force is de-energized, and only after the coil-halves have been brought into operating relation will the contacts be pressurized into contacting engagement.

A further advantage of the present designs is that they permit the use of rolled or forged coil which is readily available; and in addition, the contacts can be made relatively small and are so located that they will, in general, not interfere with either the workpiece itself or the positioning mechanisms which may typically be utilized with such a forming coil.

Various modifications of the features and embodiments disclosed herein will be apparent to those skilled in the art; and as such, the scope of the invention should be defined only by the claims, and equivalents thereof.

Various features of the invention are set forth in the following claims.

What is claimed is:

1. Apparatus for electromagnetically forming a workpiece, comprising a pair of relatively separable conductive members having an open position for insertion and removal of the workpiece and a closed position defining a workspace for the forming operation, means for coupling said conductive members to a pulse-source of electrical energy to cause an electrical current to flow through said conductive members, said conductive members having a predictive movement of relative movement between said open and closed positions and respective insulator spaced interfacing surfaces generally transverse to said path of relative movement, said conductive members having respective contact surfaces adjacent said interfacing surfaces and disposed generally parallel to said path of movement of the conductive members, and contacting means electrically interconnecting both of said conductive members by contact therewith at said respective contact surfaces so as to bridge the interfacing surfaces when said conductive members are in said closed position.

2. The apparatus of claim 1 wherein said contacting means includes means for providing a plurality of conductive parallel bridging paths across said contact surfaces of said separable conductive members.

3. The apparatus of claim 2 wherein conductive members have a non-uniform current distribution there-through and said plurality of conductive bridging paths are so disposed as to provide substantially equal inductance over each parallel path.

4. The apparatus of claim 1 wherein said contacting means comprises a plurality of contacting elements adapted to engage said conductive surfaces to form parallel conductive paths at points between each element and each contact surface, and means for providing a geometry for each path in relation to said separable conductive members such as to provide a substantially equal inductance for the currents therethrough resulting from said pulse-source of electrical energy applied to said conductive members.

5. The apparatus of claim 4 wherein said contacting means further comprises force-distributing means adapted to receive a force applied thereto, and pressure means responsive to said force-distributing means for providing hydrostatic-like pressure on said plurality of contacting elements, applying an equal pressure to each contacting element so that equalization of contact resistance is produced at each contact point when said elements are in engagement with said contact surfaces.

6. The apparatus of claim 2 wherein said paths are defined from a respective point of contact on one conductive member to a corresponding point of contact on the other conductive member at each of said contact surfaces, and said apparatus further comprises means for providing successively longer path lengths as a function of distance along said plane of separation toward said workspace.

7. The apparatus of claim 6 wherein said last mentioned means includes said contact surfaces associated with each conductive member, said contact surfaces comprising raised conductive strips on opposite sides of said plane of separation of said conductive members and positioned to generally diverge toward said workspace.

8. The apparatus of claim 6 wherein said last mentioned means includes said contact surfaces associated with each conductive member, said contact surfaces comprising depressions on opposite sides of said plane of separation of said conductive members and having contactable edges generally diverging toward said workspace.

9. The apparatus of claim 6 wherein said last mentioned means includes said contacting means having each successive conductive bridging path of different length, successively increasing with distance toward said workspace.

10. The apparatus of claim 9 wherein said contacting means includes a multitude of laminar blades having contacting edges adapted for engagement with said contact surfaces, a channel disposed between the contacting edges of said blades, the depth of said channel increasing with distance toward said workspace for successively increasing the inductance through each of said blades so that the inductance in each of said current paths is equalized.

11. Apparatus for electromagnetically forming a workpiece, comprising a pair of separable conductive dies having an open position for insertion and removal of the workpiece and a closed position defining a workspace for the forming operation, means for coupling said conductive dies to a pulse-source of electrical energy to cause an electrical current to flow through said conductive dies, said conductive dies having a predictive movement of relative movement between said open and closed positions and respective insulator spaced interfacing surfaces generally transverse to said path of relative movement, said conductive dies having respective contact surfaces adjacent said interfacing surfaces and disposed generally parallel to said path of movement of the conductive dies, and contacting means electrically interconnecting both of said conductive dies by contact therewith at said respective contact surfaces so as to bridge the interfacing surfaces when said conductive dies are in said closed position.

12. The apparatus of claim 11 wherein said contacting means includes means for providing a plurality of conductive parallel bridging paths across said contact surfaces of said separable conductive dies.

13. The apparatus of claim 12 wherein conductive dies have a non-uniform current distribution there-through and said plurality of conductive bridging paths are so disposed as to provide substantially equal inductance over each parallel path.

14. The apparatus of claim 11 wherein said contacting means comprises a plurality of contacting elements adapted to engage said conductive surfaces to form parallel conductive paths at points between each element and each contact surface, and means for providing a geometry for each path in relation to said separable conductive members such as to provide a substantially equal inductance for the currents therethrough resulting from said pulse-source of electrical energy applied to said conductive dies.

15. The apparatus of claim 14 wherein said contacting means further comprises force-distributing means adapted to receive a force applied thereto, and pressure means responsive to said force-distributing means for providing hydrostatic-like pressure on said plurality of contacting elements, applying an equal pressure to each contacting element so that equalization of contact resistance is produced at each contact point when said elements are in engagement with said contact surfaces.

16. The apparatus of claim 12 wherein said paths are defined from a respective point of contact on one conductive die to a corresponding point of contact on the other conductive die at each of said contact surfaces, and said apparatus further comprises means for providing successively longer path lengths as a function of distance along said plane of separation toward said workspace.

17. The apparatus of claim 16 wherein said last mentioned means includes said contact surfaces associated with each conductive die, said contact surfaces comprising raised conductive strips on opposite sides of said plane of separation of said conductive dies and positioned to generally diverge toward said workspace.

18. The apparatus of claim 16 wherein said last mentioned means includes said contact surfaces associated with each conductive die, said contact surfaces comprising depressions on opposite sides of said plane of separation of said conductive dies and having contactable edges generally diverging toward said workspace.

19. The apparatus of claim 16 wherein said last mentioned means includes said contacting means having each successive conductive bridging path of different length, successively increasing with distance toward said workspace.
11. Connecting bridge across said region of separation on engagement with said contact surfaces when said dies are in said closed position, said contactor and said contact surfaces permitting any recoil movement generally parallel to the plane of movement of said conductive dies while maintaining said engagement during the forming of the workpiece.

12. The apparatus of claim 11 wherein said contactor comprises a multitude of laminar blades for bridging said contact surfaces to form a multitude of parallel paths thereacross, the length of each successive parallel path being such as to provide sufficiently varying inductances to compensate for the non-uniform current distribution through the dies so as to provide a uniform reactance through each current path in the dies.

13. The apparatus of claim 12 wherein said contactor comprises a hydrostatic-like pressure distributing means, and said apparatus includes force producing means for driving said contactor into engagement with said contact surfaces and for maintaining a force thereon sufficient to produce a uniform pressure at each contact point thereby providing equal contact resistances thereat.

14. The apparatus of claim 13 comprising a further force producing means coupled to one of said dies for moving same into said open and closed position, and control means coupled to both of the force producing means for sequentially moving said dies into said closed position for a forming operation, moving said contactor into contacting engagement, moving said contactor into disengagement after the forming operation, and then moving said dies into said open position.

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RICHARD J. HERBST, Primary Examiner
UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,610,007 Dated October 5, 1971
Inventor(s) Paul Wildi

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

In the heading to the printed specification, lines 4 and 5, "Gulf General Atomic Incorporated, San Diego, Calif." should read -- Gulf Oil Corporation, a corporation of Pennsylvania --.

Signed and sealed this 9th day of May 1972.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR. ROBERT GOTTSCHALK
Attesting Officer Commissioner of Patents