The present invention relates generally to forming methods and apparatus and more particularly to a method and apparatus for forming a workpiece utilizing a magnetic force. A conductive workpiece can be formed into a desired shape by using the energy acquired from an intense, varying magnetic field. Heretofore, an intense, varying magnetic field has been used to induce an electromotive force in the conductive workpiece. Energy is transferred to the workpiece due to the induced current and the magnetic field, resulting in the workpiece being shaped and deformed. While this forming method has proven to be of great utility in forming conductive workpieces, its applicability to less conductive workpieces has been limited.

An object of the present invention is to provide a method and apparatus for forming a workpiece in which an intense, varying magnetic field is used to furnish the energy necessary for forming. Another object of the invention is to provide a method and device for magnetically forming a workpiece, which may be of a relatively nonconductive material. Still another object is to provide a forming device, which is durable in use.

Additional objects and advantages of the present invention will become apparent from the following description and appended claims.

In the drawings:

FIGURE 1 is a schematic, sectional view of one embodiment of a forming device, this device being adapted to shape a flat plate;

FIGURE 2 is a schematic sectional view of another embodiment of a forming device similar to that shown in FIGURE 1, but being provided with means for increasing the forming pressure applied;

FIGURE 3 is a schematic sectional view of another embodiment of a forming device constructed in accordance with the present invention, this device being adapted to shape a tubular workpiece;

FIGURE 4 is a cross-sectional view taken generally along line 4-4 of FIGURE 3; and

FIGURE 5 is a schematic sectional view of another embodiment of a forming device similar to that in FIGURE 1;

FIGURE 6 is a schematic sectional view of another embodiment of a forming device, which is adapted for expanding the end of a boiler tube in a tube sheet;

FIGURE 7 is a schematic sectional view of another embodiment of a forming device, which is adapted for application of radial compressive forces to a workpiece; and

FIGURE 8 is a schematic cross sectional view of another embodiment of a forming device constructed in accordance with the present invention, this device being adapted to expand a tubular workpiece.

Briefly, a forming device in accordance with the present invention includes a deformable pressure transmitting medium for transferring a magnetic force imparted to a conductive body to a workpiece. Sufficient energy is transferred to the workpiece to form it as desired.

More specifically, in the device shown in FIGURE 1, an insulated, pancake type of coil 10, such as that described in U.S. Patent No. 2,976,907, is employed to create an intense, varying magnetic field. In this connection, the coil 10 is wound in a flat spiral and is suitably insulated. The coil 10 is connected through a suitable switch means, such as an ignitron 12, to a capacitor bank 14, which may be selectively charged in the conventional manner. A switch 15 is provided for selectively connecting the ignitron 16 of the ignitron 12 through a resistor 17 to the cathode 18 thereof, thereby firing the same.

A cylindrical body or driver plate 19 of lightweight and conductive material such as copper, aluminum, etc., is disposed on the coil 10. A deformable medium 20, which preferably is elastic and lightweight, such as rubber, is disposed on the driver plate 19. However, in certain applications a material such as paraffin may be used. In the preferred embodiment of this device, the medium 20 is not attached to the driver plate 19, thereby permitting convenient replacement of the medium 20.

When the ignitron 12 is fired, a high amplitude current pulse is passed through the coil 10 and an intense, varying magnetic field is established between the driver plate 19 and the coil 10. The driver plate 19 and the medium 20 therewith are thereby forced against a workpiece 22, positioned between the medium 20 and a die 24 having a predetermined pattern 26 on its face 28. The die 24 and the coil 10 are suitably supported in spaced relation by support 29. However, the die 24 is normally required to provide, if any, backing or support because its own inertia is insufficient to overcome the momentum of the combination of the workpiece 22, the medium 18 and the driver plate 19.

Preferably, sufficient spacing is provided between the medium 20 and the die 24 so that a substantial amount of inertia is built up by the pressure transmitting medium 20 and the workpiece 22 before the workpiece strikes the die 24.

The use of the deformable medium 20 allows the workpiece 22 to conform to the pattern 26 of the die 24 without any resultant deformation of the driver 19. Hence, the same driver is reusable in subsequent forming operations.

Another embodiment of a forming device is illustrated in FIGURE 2. This device increases the pressure that can be applied to a workpiece without the necessity of an increase in the magnetic field strength.

The requisite magnetic field in this embodiment is provided by a suitably supported pancake type coil 32, which may be similar to that employed in FIGURE 1. A similar circuit (not shown) to that employed in FIGURE 1 may be utilized to pass a pulse of current through the coil 32.

A lower face 34 of a body or driver, made of a conductive material such as copper, aluminum, etc., generally designated by the numeral 35 is disposed adjacent the coil 32. The illustrated driver includes a lower cylindrical portion 36, an intermediate frustum or conical portion 37 and an upper cylindrical portion 38, the portions all being integrally connected. Thus, the lower face 34 is larger in area than the upper face 39 of the driver 35.

The upper face 39 of the driver 35 is positioned so as to contact a cylindrical deformable medium 40 which preferably is of an elastic material such as rubber. The medium 40 is encompassed by a suitably supported ring or annular restraint 41.

A workpiece 42 is suitably disposed between the medium 49 and a suitably supported die 43, having a predetermined pattern 44 on its face 45.

When the coil 32 is pulsed, an intense, varying magnetic field is produced which intersects the lower face 34 of the driver 35. The upper face 39 of the driver 35 being smaller in area than its lower face 34 results in the same force being applied to a smaller area, consequently resulting in the upper face 39 of the driver 35 applying a greater
pressure to the medium 40 without any increase required in the magnetic field strength. The upper face 39 of the driver 35 causes the medium 40 to force the workpiece 42 against the die 43, thereby forming the workpiece 42.

It should be understood that the driver illustrated in FIGURE 2 may be composed of a relatively nonconductive material as long as its lower face, which is disposed adjacent to the coil is made of a conductive material.

The forming device shown in FIGURE 3 is particularly adaptable for use in compressively shaping a portion of a tubular workpiece. In this illustrated embodiment, an intense, varying magnetic field is produced by coupling a cylindrical coil assembly 46 to a capacitor bank (not shown). The cylindrical coil assembly 46 may be similar to that described in a pending application, Serial No. 243,010, filed December 7, 1962, now Patent No. 3,195,335.

The coil assembly 46 generally includes an insulated, helical coil or solenoid 47, formed of a conductive material such as copper, beryllium copper, etc. The source of pulsed current and the control circuit therefor are connected to the solenoid 47. The solenoid 47 may be cooled to limit the temperature rise caused by high current pulses flowing therein. A generally cylindrical, split, annular field shaping element 48 of conductive material is removably disposed concentrically within the solenoid 47.

A flexible body or driver 50 is disposed within the field shaper 48. The driver 50 comprises a corrugated tube 52 of flexible conductive material such as beryllium copper, aluminum, etc. For greater flexibility, the tube 52 is composed of several layers of material. A deformable medium 54, which is preferably of elastic material, such as rubber, is placed within the corrugated tube 52 and arranged concentrically therein. A cylindrical passage 56 is provided along the center line of the medium 54.

A tubular workpiece 58, which is to be formed, is placed within the passage 56. A suitably supported end restrainer 60, composed of a relatively heavy, rigid material, such as steel is placed at each of the respective ends of flexible tube 52, preferably in tight contact with the ends of the medium 54 therein, so as to preclude undesirable endwise flow of the medium 54.

When the solenoid 47 is pulsed, an intense magnetic field is produced. The field shaper 48 directs and shapes the magnetic field so that it intersects the exterior of the flexible tube 52, causing the tube to be abruptly compressed. This forces the medium 54 against the tubular workpiece 58, thereby compressing the same. A die or mandrel (not shown) may be disposed within the interior of the tubular workpiece 58, so that the workpiece may be shaped as desired.

As illustrated in FIGURE 4, the central hole of the shaper 48 is contoured so as to substantially conform to the corrugations of the corrugated tube 52. In this way, a substantially uniform force is applied to the driver 50.

If the depth of the corrugation 62 is short as compared with the length of the tube 52, the shaper need not be contoured.

As illustrated in FIGURE 8, wherein parts similar to those shown in FIGURE 4 are indicated with the same reference numeral and the subscript a, the flexible driver 50a is used in conjunction with a cylindrical expansion type of coil assembly 63 to expand the tubular workpiece 58a. The expansion coil assembly 63 is placed within the corrugated tube 52a and the deformable medium 54a is disposed around the entire exterior of the tube 52a. The corrugated tube 52a, surrounded by the flexible medium 54a and containing the cylindrical coil assembly 63 within, is inserted into the tubular workpiece 58a. When the coil is pulsed, the intense magnetic field generated intersects the interior of the flexible tube, forcing the tube into the medium, thereby expanding the tubular workpiece.

The device shown in FIGURE 5 employs a fluid medium 64 for transmitting pressure to a workpiece 66. An intense, varying magnetic field is produced by a suitably supported pancake type coil 67, which may be similar to that employed in FIGURE 1. A suitable circuit and switch means (not shown), which may be similar to that employed in FIGURE 1, may be coupled to the coil 67 in order to pass a pulse of current through the coil 67.

A container generally designated by the numeral 69 is suitably disposed above the coil 67. The lower restraining wall of the container 69 is composed of a conductive diaphragm 70. The side walls 71 of the container 69 are composed of a rigid material to withstand the flow of the fluid medium 64. The workpiece 66 is disposed directly above the medium 64. A suitably supported die 72 having a predetermined pattern 73 on its face 74 is disposed above the workpiece 66. In a preferred embodiment of the device, sufficient spacing is provided between the workpiece 66 and the die 72, so as to enable said workpiece 66 to acquire a substantial amount of momentum when moving toward contact with the die.

When the coil 67 is pulsed, an intense, varying magnetic field is produced, which intersects the conductive diaphragm 70, thereby flexing 72. The diaphragm 70 hurls the fluid medium 64 against the workpiece 66, which, in turn, strikes the die 72. The contact made between the workpiece 66 and the die 72 forms the workpiece 66, as desired. After contact with the workpiece, the fluid medium 64 falls back into the container so as to be available for further use.

In FIGURE 6, there is shown an embodiment of a forming device, which is of particular applicability for expanding the end of a boiler tube 78, in a tube sheet 80. However, the forming device may be employed for the expanding of tubes other than boiler tubes. A suitably supported flat, pancake type coil 82, which may be similar to that employed in FIGURE 1, is used to produce an intense, varying magnetic field. A suitable circuit and switch means (not shown), which may be similar to that employed in FIGURE 1, is coupled to the coil 82 in order to pass a pulse of current through the coil 82.

A conductive body or driver 84 which may be similar to that employed in FIGURE 2 is disposed adjacent the coil 82. The smaller end of the driver 84 is disposed partially within the interior of the boiler tube 78 and is flush against the sides thereof. A deformable medium 86, which preferably is of elastic material such as rubber, is disposed within the boiler tube 78 adjacent the driver 84 and in line with the tube sheet. A restraining rod 88 is inserted in the opposite end of the boiler tube and against the medium 86, thereby enabling the medium to be constrained within the boiler tube 78.

When the coil 82 is pulsed, an intense, varying magnetic field is produced, which intersects the conductive driver 84, forcing the driver 84 against the deformable medium 86, which is constrained at its opposite end by the restraining rod 88. The medium is thus subjected to a high pressure, which it transmits to the side walls of the boiler tube 78 in which it is confined. The side walls of the boiler tube 78 being subjected to this pressure are thereby forced to expand into the holes 89 of the tube sheet 80.

A forming device is shown in FIGURE 7, which is adapted for applying radial, compressive forces to a generally spherical workpiece 90. A flat, suitably supported pancake type coil 92, which may be similar to that employed in FIGURE 1, is used to produce an intense, varying magnetic field. A suitable circuit and switch means (not shown), which may be similar to that employed in FIGURE 1, is coupled to the coil 92 in order to pass a pulse of current through said coil 92.

A conductive body or driver 94 which may be similar to that shown in FIGURE 2, is disposed directly above the coil 92. The lower surface of the driver faces the coil 92, and the upper surface faces a pressure transmitting medium 96, which preferably is a liquid medium such as oil or a medium such as paraffin, disposed directly above
the driver. The spherical workpiece is disposed at or near the center of the medium 96. The medium is encompassed by a ring or annular restrainer 100 composed of a rigid material and by a stationary restraining rod 102 disposed at the top of the medium 96 so as to bring about substantially complete confinement of the medium 96.

When the coil 92 is pulsed, the intense, varying magnetic field produced intersects the conductive driver 94, forcing the driver against the medium 96. The medium 96 being completely restrained is thereby subjected to a substantial pressure. This pressure is transmitted by the medium 96, to the workpiece 90, thereby subjecting the workpiece 90 to a radial, compressive force.

From the foregoing, it should be obvious that the principle of using a deformable, pressure transmitting medium to transfer the force produced by a varying magnetic field, so as to form a relatively nonconductive workpiece, can be applied to other varieties of forming operations than those previously described.

Various features of the invention which are believed to be new are set forth in the attached claims.

What is claimed is:

1. A method of forming a workpiece comprising, disposing of a deformable, pressure transmitting medium between said workpiece and a conductive driver, and establishing an intense, varying magnetic field which intersects said driver, whereby said driver is forced against said medium, which in turn is forced against said workpiece.

2. A magnetic forming device, comprising a conductive body, an elastic medium interposed between said conductive body and a workpiece to be formed, said means for establishing an intense, varying magnetic field which intersects said body, whereby, when the field is established, the body is forced against the elastic medium with sufficient energy to drive said elastic medium against the workpiece, thereby forcing said workpiece against the die.

3. A magnetic forming device, comprising a body having a pair of opposite faces, one of said faces being conductive and larger than the other face, a deformable medium interposed between the smaller face of the body and one side of a workpiece to be formed, a die disposed adjacent to the other side of said workpiece, and means for producing an intense, varying magnetic field, which intersects the conductive face of the body, whereby the field is established, the smaller face of said body is forced against the elastic medium which, in turn, is forced against the workpiece, thereby forcing said workpiece against the die.

4. A magnetic forming device, comprising a corrugated tube of a flexible, conductive material, an elastic medium within said tube, said medium having a passage therein for receiving a workpiece to be formed, and restrainers at the ends of the tube for constraining said medium within the tube and means for establishing an intense, varying magnetic field, which intersects the exterior of the tube, whereby, when the field is established said tube is compressed, forcing the medium against the workpiece, thereby shaping said workpiece as desired.

5. A magnetic forming device, comprising a corrugated tube of a flexible, conductive material, an elastic medium having one face thereof adjacent one side of the tube and space on an opposite face thereof for receiving a workpiece to be formed, end restrainers for constraining endwise movement of said medium, and means for establishing an intense, varying magnetic field, which intersects the face of the tube opposite that adjacent to the medium, whereby, when the field is established, said tube is moved in the direction of the field, forcing the medium against the workpiece, thereby shaping said workpiece as desired.

6. A magnetic forming device, comprising a corrugated tube of a flexible, conductive material, a cylindrical field shaping element concentrically disposed about said tube, an elastic medium within said tube, said elastic medium having a passage therein for receiving a workpiece to be formed, end restrainers at the end of the tube for constraining said medium within the tube, and means for establishing an intense, varying magnetic field which is shaped and directed by said field shaping element to intersect the exterior of the tube, whereby, when the field is established, said tube is compressed, forcing the elastic medium against the workpiece, thereby shaping said workpiece as desired.

7. A magnetic forming device, comprising a container having one open wall, the lower wall of said container including a conductive diaphragm, a fluid medium in said container, a die disposed over said open wall, a workpiece interposed between said fluid medium and said die, and means for establishing an intense, varying magnetic field which intersects said conductive diaphragm, whereby, when the field is established, said conductive diaphragm is flexed, driving the fluid medium against the workpiece which, in turn, is forced against the die.

8. A magnetic forming device for expanding the end of a boiler tube in an encompassing tube sheet, comprising a conductive body, one end of which extends partially within the end of a boiler tube to be formed, a deformable medium disposed within said boiler tube, having one end thereof adjacent said body, and being in line with the tube sheet, a restraining rod disposed in contact with the opposite end of said deformable medium, and means for establishing an intense, varying magnetic field which intersects the conductive body, whereby, when the field is established, said conductive body is forced against the constrained, deformable medium, thereby compressing said medium such that said medium forces the walls of the boiler tube to expand into contact with the tube sheet.

9. A magnetic forming device comprising a body, having one face thereof composed of conductive material, a deformable medium disposed adjacent to an opposite face of said body, a stationary restraining body disposed adjacent to the opposite side of said deformable medium, a cavity within said deformable medium for receiving a workpiece to be formed, rigid side walls disposed adjacent to the opposite sides of said deformable medium, encompassing the unenclosed portions of said medium, and means for establishing an intense, varying magnetic field, which intersects the conductive face, whereby, when the field is established, said body is forced against the constrained medium, compressing said medium, thereby subjecting the workpiece, disposed within said medium, to compressive forces.

10. A magnetic forming device for expanding the end of a tube in an encompassing tube sheet, comprising a conductive body, one end of which extends partially within the end of a tube to be formed, a deformable medium disposed within said tube, having one end thereof adjacent said body, and being in line with the tube sheet, a restraining rod disposed in contact with the opposite end of said deformable medium, and means for establishing an intense, varying magnetic field which intersects the conductive body, whereby, when the field is established, said conductive body is forced against the constrained, deformable medium, thereby compressing said medium such that said medium forces the walls of the tube to expand into contact with the tube sheet.

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CHARLES W. LANHAM, Primary Examiner.
R. J. HERBST, Assistant Examiner.