United States Patent

Orr et al.

[15] **3,704,506**

[45] **Dec. 5, 1972**

[54] **ELECTROMAGNETIC HIGH ENERGY FORMING**

[72] Inventors: **La Vern G. Orr,** Auburn; **Nobuo Yutani,** Seattle, both of Wash.

[73] Assignee: **The Boeing Company,** Seattle, Wash.

[22] Filed: **Aug. 1, 1968**

[21] Appl. No.: **749,386**

[52] **U.S. Cl.**.....**29/243.54,** 29/421 M, 72/430, 72/56, 317/151

[51] **Int. Cl.**.....**B23p 11/00,** B21j 15/24, B21d 26/02

[58] **Field of Search**...72/56, 430; 29/421 M, 243.53, 29/243.54, 254; 317/151; 307/116; 83/575

[56] **References Cited**

UNITED STATES PATENTS

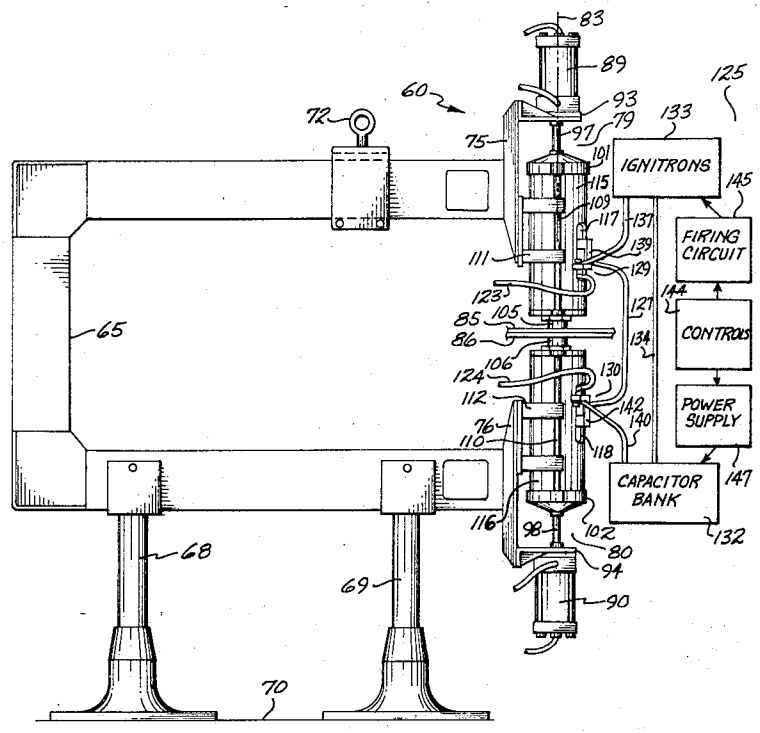
2,442,949	6/1948	Fischer	72/407 X
3,172,010	3/1965	Diebold	29/421 M UX
3,453,463	7/1969	Wildi	310/27
3,293,973	12/1966	Gerber et al.	83/575

Primary Examiner—Andrew R. Juhasz
Assistant Examiner—Leon Gilden
Attorney—Christensen and Sanborn

[57] **ABSTRACT**

Disclosed is an apparatus utilizing the forces exerted upon a conducting surface of a tool by a pulsed intense magnetic field to propel the tool against a workpiece. The conductor surface is initially positioned in a pulsed high flux density magnetic field. As the conductor is subjected to the suddenly rising magnetic field, electrical currents (so-called eddy currents) are produced by the passage of the field into the conductor surface developing an intense force repelling the tool away from the means generating the magnetic field. The working surface of the propelled tool imposes a high density force against the workpiece suitable for cutting or otherwise forming it. A specific application of such a tool for installing rivets is described in detail. The improved riveted structure produced by the electromagnetically propelled riveter is also disclosed.

31 Claims, 6 Drawing Figures



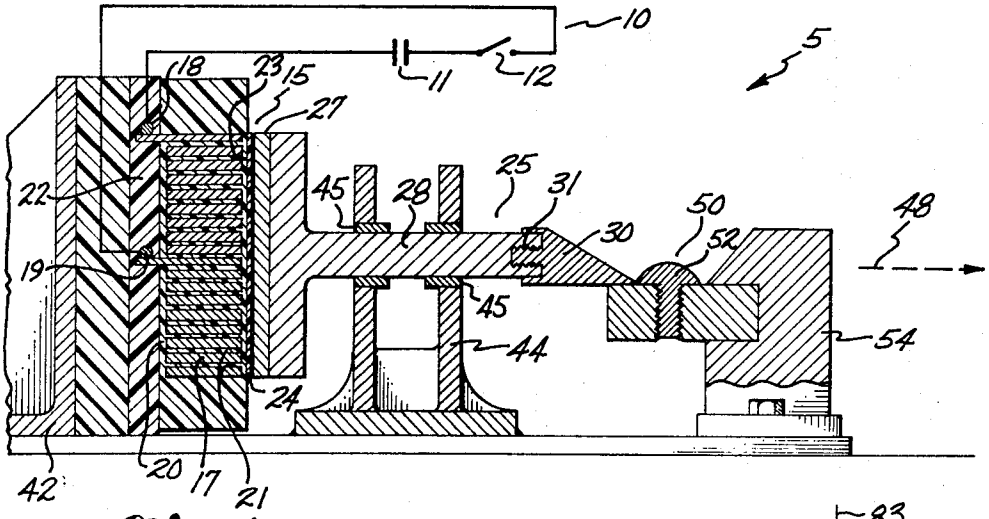
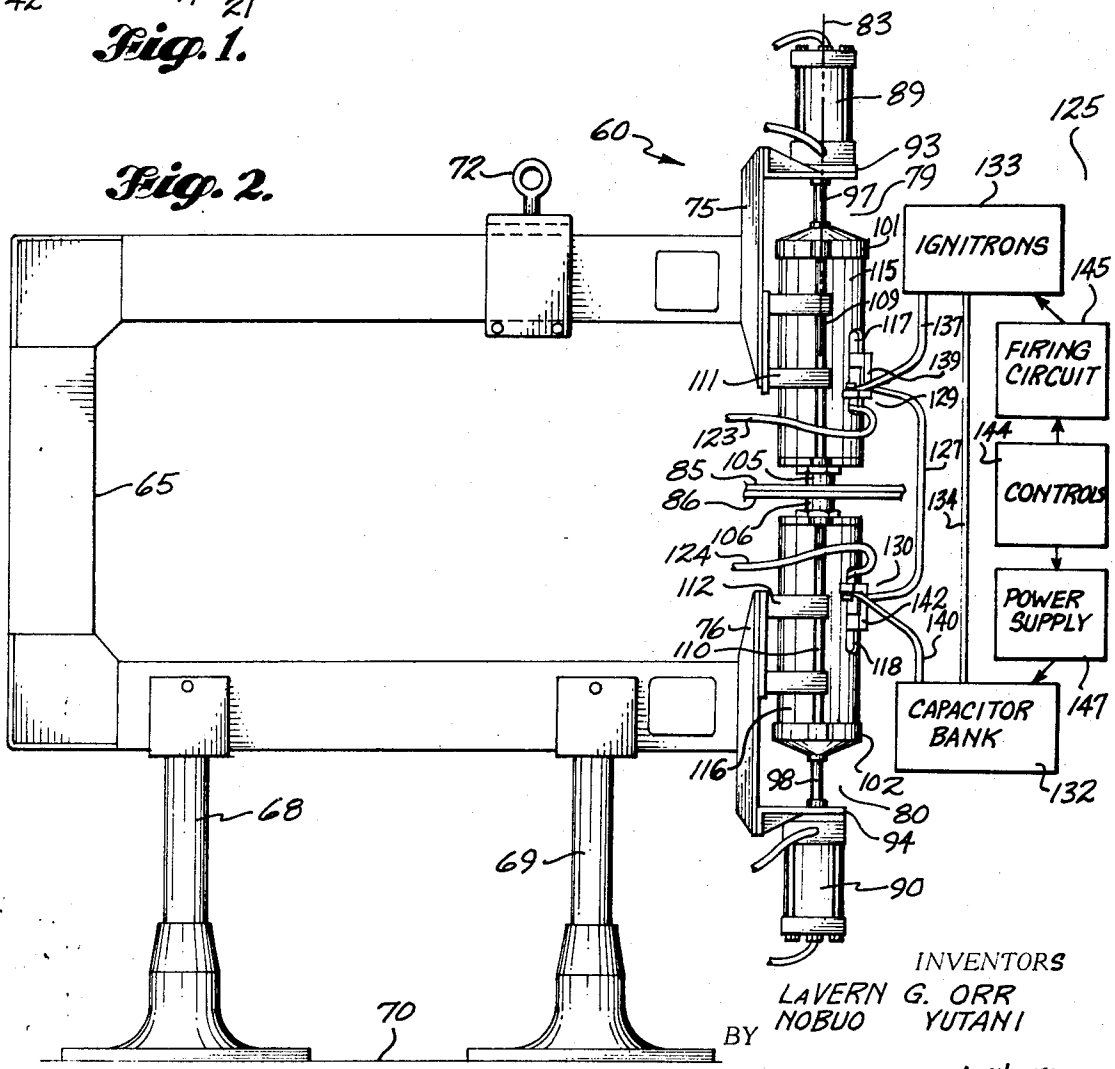


Fig. 1.

Fig. 2.



INVENTORS
LAVERN G. ORR
NOBUO YUTANI
BY
Christensen, Sanborn & Matthews
ATTORNEYS

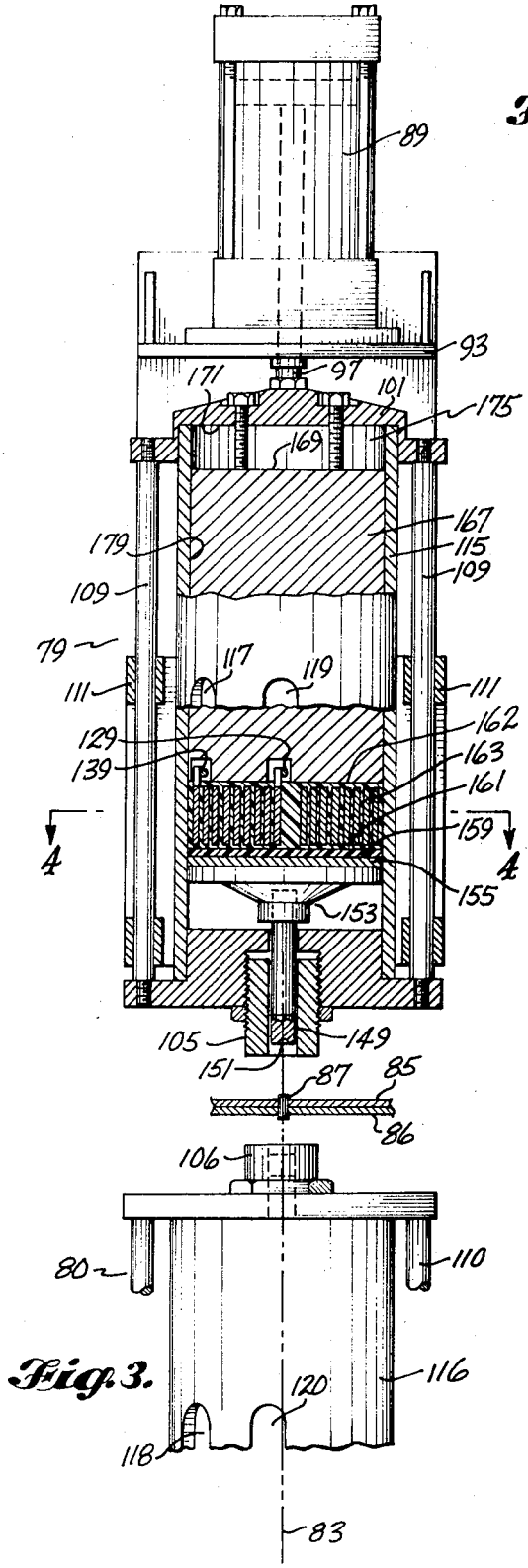


Fig. 3.

Fig. 4.

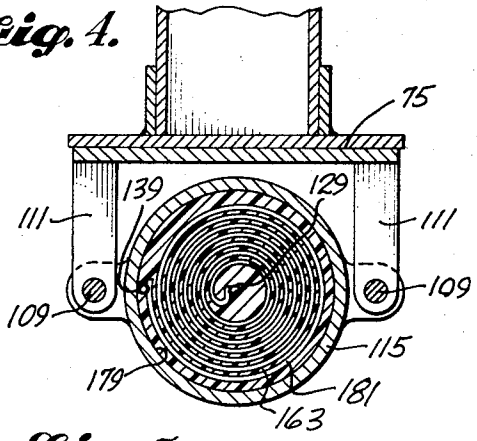


Fig. 5.

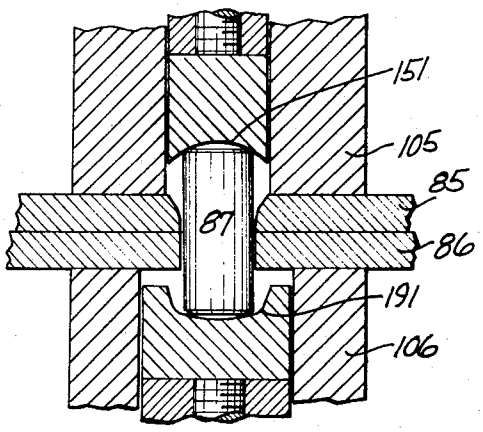
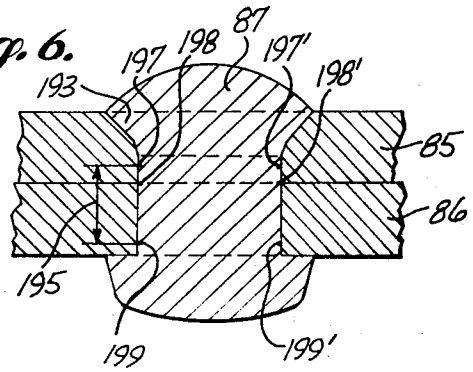


Fig. 6.



INVENTORS
LAVERN G. ORR
NOBUO YUTANI
BY
Christensen, Sanborn & Matthews
ATTORNEYS

ELECTROMAGNETIC HIGH ENERGY FORMING

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to apparatus for mechanically forming material and relates more particularly to electromagnetic apparatus which strikes the material with a high density force such as required to install rivets with a single impact.

2. Description of the Prior Art

Several techniques have been developed over the course of recent years for mechanically forming materials. In some techniques electrical energy is converted into a mechanical force which is used for blanking, shearing, forging, anchor setting, pressure welding, stamping, dimpling, hammering, punching, chipping, indenting, deforming and other similar operations in order that the material subjected to such an operation may be made more useful. In the patent to Michlein, U.S. Pat. No. 2,752,061, a mechanical force is used to cause cold plastic flow of the tubular portion of a rivet to properly install the rivet in place. As disclosed a solenoid is used to directly supply the power required in the production of the work stroke.

In the patent to Birdsall et al., U.S. Pat. No. 3,088,200, an electrical conductor material in tube form is mechanically forced into the shape of an internal mandrel due to the pressure of a magnetic field imposed upon the conductor material as a result of a suddenly rising magnetic field developed in a coil wrapped around the tube.

In the patent to Falcioni, U.S. Pat. No. 3,292,413, an aircraft rivet is installed by mechanical forces developed by an opposed pair of transducers vibrating at a frequency in excess of 20,000 cycles per second with the transducers placed in contact with opposite ends of the rivet.

In the patent to Golden et al., U.S. Pat. No. 3,345,843, the material is forced into a new die configured form as a result of the energy of a shock wave striking the material originally propagated by the sudden discharge of electric energy across an electrode gap in a liquid containing the material.

In each of these techniques electrical energy is transformed into a mechanical force useful in forming the workpiece involved. Each of these techniques, however, have certain inherent features which limit their usefulness. In the magnetic shaping process of Birdsall; et al., and in the electrohydraulic shaping process of Golden, et al., the working forces applied against the workpiece are more or less uniform and therefore not concentrated at any particular focus point against the workpiece. The ultrasonic vibrating forces of the Falcioni apparatus may be useful for installing rivets of relatively soft materials but the work hardening which results from repeated impacts on certain harder materials such as titanium often cause the rivets to crack and lose their strength.

While the solenoid rivet setting tool of the Michlein apparatus does serve the purpose of focusing the impacting force of the tool against the workpiece, the maximum force developed by a solenoid type device is limited by the saturation effects in its ferromagnetic material and is at most several hundred pounds. For example, in column three, line two of this patent, the force applied to install a small rivet was found to be in

excess of 1,600 pounds. Even if the cross section of a solenoid plunger were as small as 0.0001 square meters, the maximum force developed by such a plunger is about 1,800 pounds because of saturation.

While it is general practice to use a coil of conductive material to generate a magnetic field, the heat generated and the mechanical stresses induced in the coil by the pulse of electrical energy through the coil generally reduce the useful life or rate of operation of such coils. Production speeds of equipment using such coils are often limited by such useful life considerations.

It is therefore seen that previous techniques for converting electrical energy to a mechanical force for forming materials do not provide an effective system for focusing mechanical forces of sufficient magnitude against a selected portion of the workpiece in a short time. In addition, massive frameworks have been considered necessary before equipment would be thought suitable for a system for imposing and reacting from the magnitude of force necessary to install rivets having a three-eighths inch diameter or made of high strength material such as titanium. The squeeze type riveting machines capable of meeting the high installation force requirements anticipated for the supersonic transport are massive to the point of being larger than a house and very costly to the extent of several hundreds of thousands of dollars per machine.

Although it has been proposed that rivets be installed by one hammer hitting on one end of the rivet while another hammer is hitting on the other end of the rivet, the driving mechanism for such hammers have not produced the desired synchronous action. Use of mechanical, pneumatic, hydraulic, electrical or combination of these methods fail to provide synchronous action and in fact produce inconsistent and unreliable results because of system inertia or compressability effects.

In the field of riveting aircraft structures several problems are confronting the riveting equipment designer. Not only are these structures becoming larger and thereby requiring longer and larger rivets but also such structures are subjected to increased utilization requiring rivet installations of increased strength and sufficient fatigue life to ensure a profitable return on the purchaser's investment. Such joining of structures also require more force to install.

SUMMARY OF THE INVENTION AND OBJECTS

From the foregoing discussion of prior art techniques for material forming, it is clear that there is a need for a simply constructed, easily used apparatus for applying a high density mechanical force. It is therefore the principal object of this invention to provide a generally improved apparatus for converting electrical energy into a mechanical force of high density useful in forming materials.

It is another object of the instant invention to provide a material forming apparatus which is capable of exact control for repeatable work force outputs.

It is a further object of the instant invention to provide a high energy density material forming apparatus capable of producing a sufficient force in one blow against a workpiece to thereby avoid the degradation in the workpiece properties resulting from repeated blows

necessary in other systems to provide the same degree of forming results.

A still further object of the instant invention is to provide an apparatus for forming materials which applies the high energy force in a time measured by microseconds while at the same time includes a system for synchronizing the application of force by two or more such apparatus with great precision.

It is a related object of the instant invention to provide an improved coil structure useful in an apparatus for converting electrical energy to high density mechanical force including the provision of means for extending the useful life of the coil by minimizing the degradation due to system heat generation and by the provision of mechanical reinforcement for the coil.

A still further object of the instant invention is to provide an improved force application tool which is useful in applying a high density mechanical force to properly form a workpiece such as a rivet.

It is an additional object of the instant invention to provide structures which are joined by rivet installations having excellent strength and fatigue life.

It is also an object of the instant invention to provide a riveting apparatus which in addition to providing high density forces for rivet installations, also provides independent systems for part clamping and rivet-to-die preloading.

A still further object of the instant invention is to provide a generally improved riveting apparatus which because of it ability to apply such a high density rivet setting force in such a short time does not require a massive framework to ensure precise alignment of the tool.

Another object of the instant invention is to provide a recoil mechanism suitable for use in a high energy impact tool.

In accordance with the present invention, electrical energy is converted into a material forming mechanical force. The electrical energy is accumulated to provide hundreds and thousands of Joules at several thousand volts in a storage system such as a capacitor bank. Periodically through a discharging circuit an electrical current is passed through a flat wound coil to develop a rapidly rising, high density, magnetic field adjacent to the coil. The transducer or tool portion of the apparatus includes an electrical conductor surface placed adjacent to the flat wound coil within its magnetic field. Through the body of the tool a work application surface is connected to the conductor surface. As the electrical energy is discharged through the coil the rapidly rising magnetic field causes eddy currents to develop in the conductor surface producing a high energy repelling force between the coil and the conductor surface which propels the tool and its force application surface against the workpiece. If a double hammer system is used, exact synchronization between the propelled work application surfaces against the workpiece is possible through the use of a series connection between the two coils driving the two tools. The temperature of the coil can be controlled by injecting cool air or other suitable fluid against the surface of the coil and conductor plate. Since the impact of the tool against the workpiece is of a very short duration, it may be reacted by a suitable suspended mass recoil system, rather than as a static force through a massive riveter frame. For installing rivets, heading die shapes are used which restrict the expansion of the formed head yielding uniform radial expansion of the rivet and excellent joint strength and fatigue life.

These and other features and advantages of the invention will become more clearly apparent from the following detailed description thereof, which is to be read with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 is a diagrammatic view of the generalized embodiment of the invention with portions shown in cross-section for clarity;

FIG. 2 is a side elevation view illustrating an opposed hammer riveting embodiment of the instant invention;

FIG. 3 is an end elevation view of a portion of the opposed hammer embodiment of the invention with portions shown cut away or in section for clarity;

FIG. 4 is a section view of the invention as seen through lines 4-4 of FIG. 3;

FIG. 5 is a partial side section view in enlarged scale illustrating a rivet just prior to installation; and

FIG. 6 is a partial side section view showing the rivet of FIG. 5 as it is completely installed.

DESCRIPTION OF THE PREFERRED EMBODIMENTS:

With reference to FIG. 1 it is seen that the general embodiment 5 of the apparatus of the instant invention includes within its system an electrical energy source 10 to provide the necessary electric current for the magnetic field generator 15 for driving the transducer 25 with the resulting mechanical force applied in a first direction 48 against the workpiece 50. The electrical energy source 10 may include any suitable system for providing a high pulse of electrical current and, as shown, this is provided by capacitor bank 11 and a high current switch 12 connected in series with the magnetic field generator in the form of flat wound coil 17. Of course other cross-sectional shapes can be used for coil 17. As shown, coil 17 is formed by coiling a flat conductor ribbon such as copper to produce a number of turns having an outside terminal 18 and an inside terminal 19 at opposite ends of coil 17 for connection with energy source 10. Insulating material 21 is interspersed between the individual turns of the coil 17. One face 20 and the outside surface of coil 17 are supported by insulating casing 22 and the other face 23 of coil 17 is supported by a membrane 24 made of woven fiberglass or other similar strong insulating material.

When coil 17 is subjected to a high discharge of current from electrical energy source 10, there is a tendency for it to straighten out. This tendency is resisted by casing 22. The current also tends to cause coil 17 to unwind or spring in its axial direction. This movement is resisted by membrane 24 for the motion in a first direction 48 and by casing 22 for motion in the opposite direction. By utilizing a flat material for coil 17 in contrast to a circular conductor material, there is a greater frictional surface area presented along the first direction 48 for resisting the tendency for the coil to spring outwardly along its central axis. Insulation material 21 in the form of a potting compound such as adiprene or an epoxy system can be used along with

fiberglass tape or conventional transformer paper to insulate one turn of the coil from another.

Transducer **25** may be composed of any single or combination of force responsive and transmitting materials with sufficient rigidity and form to support a sheet of conducting material such as copper plate **27** at one end of body **28** of transducer **25**, with the surface of the sheet **27** generally parallel to face **23** of coil **17** adjacent to membrane **24**. In one such apparatus the surface of sheet **27** is initially 0.06 inches away from face **23** of coil **17**. At the other end of transducer body **28**, in the first direction **48** from the conductor sheet **27**, is positioned force application tool **30** which may be attached to body **28** by means of threads **31**. As shown, tool **30** is shaped as a chisel useful in cutting off the head of bolt **52** or otherwise forming workpiece **50**. Clamp **54** holds workpiece **50** and the whole assembly is supported by frame **40** which includes back stop member **42** in contact with the coil casing **22** and guide supports **44** having bearings **45** in guiding contact with transducer body **28**.

In operation, general embodiment **5** is initially positioned as shown in FIG. **1**. When a working stroke is desired, high current switch **12** is closed permitting electrical energy from capacitor bank **11** to be discharged through coil **17**. This high energy pulse of electrical current passing through coil **17** develops a rising magnetic field adjacent to coil **17**. Since conductor sheet **27** of transducer **25** is positioned within the effective magnetic field developed by coil **17**, a current is produced in sheet **27** that is proportional to the field intensity at its surface. The interaction of the field and such induced current produces a repelling pressure or force between coil **17** and transducer **25**. This instantaneous and tremendously intense repelling force between coil **17** and conductor sheet **27** imparts motion to transducer **25** along first direction **48**. This propelling force is of such high energy that tool **30** easily severs bolt head **52** away from its supporting workpiece **50**.

Although electrical energy source **10** may be charged to several thousand volts, the amount of power involved is not unreasonable since apparatus **5** may be "fired" every 10 seconds with normal household current and voltage feeding the electrical source to charge capacitor bank **11** between individual firings. This result is obtained because of the very short cycle time, as measured in microseconds, for the actual discharge of the energy through coil **17**.

By varying the form of the force application tool, it is possible to use the above described apparatus for a great number of material forming operations. Holes may be punched, dimples may be formed, edges may be cut, patterns may be imprinted, objects may be hammered, and sheets may be shaped, parts may be forged, anchors may be set, plates may be pressure welded, with all of these operation utilizing the extremely short pulse high density force provided by the apparatus of the instant invention.

For a better understanding of the basic principle and particular adaptability of such apparatus, a detailed description of its utilization in the forming of rivets is presented.

At the present time there are tremendous demands placed upon the developers of riveting equipment to meet the needs of the aircraft industry to rivet structures which must withstand higher loads and greater ranges of temperature. Greater service life is demanded of commercial airframes to provide a sound structure with greater fatigue life. Larger structures are being developed which require thicker sheets of material to be joined by riveting. This situation results in the requirement for both longer and larger diameter rivets of stronger materials which ultimately require a greater force to install and must provide greater reliability in any single installation. While referring to rivets herein we include all forms thereof since the apparatus involved is not materially different regardless of whether the rivet is in the form of a simple cylinder, a tapered plug, a cylinder with a manufactured head or of another configuration.

If the present trend of the state of the art in riveting equipment is followed, massive frameworks requiring railroad track support structures will be needed to produce the squeezing force necessary to install a large rivet made of titanium or other similar high strength material. It is clear, however, that the high initial cost in the form of a high capital investment for such equipment adds significantly to the cost of producing the products utilizing such rivets. It has been found that the use of repeated impacts of a lower force to form the rivet of some materials is unacceptable since such rivets become work hardened and have a tendency to crack due to the repeated impacts of the hammering system. In installations requiring fuel tight riveting and good fatigue life, repeated impact riveting is often unacceptable because the repeatability of net energy imparted to the rivet is difficult to obtain since the dynamic response of the workpiece affects the energy content per impact. In addition, the noise generated by the hammering type of riveting equipment adds materially to the fatigue of the employees involved in the riveting area.

To make more clear the significant forces involved in forming the larger stronger metal rivets, it is appropriate to start with a comparison between the 1,600 pounds required to form a rivet having a diameter of 0.140 inches as disclosed in the previously mentioned patent to Michlein, with the 32,000 pounds equivalent static force required for forming a stainless steel rivet of 0.250 inches in diameter.

To accomplish the previously related demanding rivet installation function the opposed synchronous rivet hammer apparatus **60** shown in FIGS. **2** to **4** has been developed. With reference to FIG. **2**, it is noted that opposed hammer riveter **60** is supported by a "C" shaped frame **65** mounted on pedestal legs **68** and **69** which are supported by the floor **70**. A convenient eyebolt **72** may be used with a suitable crane to move riveter assembly **60** from one work station to another within the manufacturing plant so that riveter **60** is readily adaptable to perform riveting on panels positioned in place in assembly tools or jigs. Support pads **75** and **76** are mounted on the open ends of the C frame **65** to provide alignment of the upper and lower rivet hammer units **79, 80** along the rivet axis **83**.

With continued reference to FIG. **2**, it is noted that sheets **85** and **86** can be clamped within frame **65** through the application of clamping pressure from upper and lower clamping fluid motors **89** and **90**.

These motors are attached to the pads 75 and 76 through support plates 93 and 94. Connecting rods 97, 98 project out from the motors 89 and 90 against the cap members 101, 102 of the hammer units 79 and 80. Clamping pads 105 and 106 actually engage the surfaces of sheets 85 and 86 and are spaced from cap members 101 and 102 by spacing rods 109 and 110 slidably supported within support guides 111 and 112 anchored to support pads 75 and 76. As pressurized fluid is supplied to clamping motors 89 and 90 in a conventional manner, clamping pressure is placed upon sheets 85 and 86.

Hammer units 79, 80 will be described in more detail with reference to FIGS. 3 and 4 but it should be noted the upper hammer coil housing 115 defines two longitudinal conduit slots 117 and 119 providing electrical connection to the hammer coil 163 by terminal connectors 129 and 139. Similarly lower coil housing 116 defines conduit slots 118 and 120 for terminal connectors 130 and 142. If required for coil temperature control, cooling medium can be applied to the coils through conduits 123 and 124 which may project through the slots 117, 119 and 118, 120. If desired each coil may be designed to permit the cooling medium to run through the body of the coil itself.

The electrical energy supply system 125 for opposed hammer units 79 and 80 is shown in FIG. 2 with the first point of interest being the use of a series connector 127 extending between terminal connector 129 of upper hammer unit 79 and corresponding terminal connector 130 of lower hammer unit 80. Capacitor bank 132 and the high current switch, shown as ignitrons 133, are connected in series through lead 134. Ignitrons 133 are connected through lead 137 to terminal connector 139 of upper hammer unit 79 and capacitor bank 132 is connected through lead 140 to the other terminal connector 142 of lower hammer unit 80. To provide the sequencing and timing function useful in controlling the amount of charge and the time of firing the charge through the hammer unit coils, suitable controls 144, firing circuit 145 and power supply unit 147 are connected to ignitrons 133 and capacitor bank 132, as shown in FIG. 2.

As shown in FIG. 3, rivet 87 extends along rivet axis 83 and projects through sheets 85 and 86. In line with rivet axis 83 and defined within clamp pad 105 is a tool channel 149 extending through the pad member 105. Positioned within and slidable along channel 149 is the heading die or working surface 151 of the transducer 153. An electrical conductor surface plate 155 is secured to transducer 153 in a firing position in intimate contact with the membrane member 159 which seals off the lower face or transducer face 161 of the flat wound coil 163. Positioned on the upper side and in nonconducting contact with flat wound coil 163 adjacent its recoil face 162 is recoil mass 167.

Surface 169, at the upper extreme end of recoil mass 167, serves to define, along with the inner side walls of housing 115 and the lower surface 171 of cap member 101, preload chamber 175. A suitable source of gas or fluid under pressure (not shown) is supplied to preload chamber 175 to initially insure intimate contact between membrane member 159 and conductor plate 155 and between working surface 151 and rivet 87. In the case of the lower hammer unit 80, the force of gravity pulls the recoil mass, coil and transducer downwardly away from contact with rivet 87, therefore, a similar pressurized preload chamber (not shown) is utilized to impose an upwardly directed force to prelaod rivet 87 as desired. In addition, an adjustable preset relief valve system (not shown) may be used in preload chamber 175 to permit the escape of the suspension gas or fluid during the recoil period when the recoil mass 167 is propelled toward the cap member 101, thereby reducing the size of preload chamber 175 and increasing the pressure on the suspension gas or fluid. To provide easy, non-wearing sliding of recoil mass 167, coil 163, and transducer 153 along the inside surface of housing 115, a coating of low friction insulating material 179, such as nylon or polytetrafluoroethylene, is used to coat the inside surface of housing 115. For safety and strength reasons, housing 115 is made of a fiberglass-epoxy laminate.

As shown in FIG. 4, coil 163 includes at one end interior terminal connector 129. Coil 163 is wrapped around a number of turns until it reaches its other end connected to terminal connector 139. Between each turn of the flat wound coil 163, insulating material 181 is packed in the form of a potting compound. Precoated electrical conductor material, such as varnish or insulating paper a few mils thick, individually or in combination with a potting compound, con comprise the insulation between turns of coil 163.

In the course of developing a suitable flat wound coil 163, various types of coil material separators and different numbers of turns were used. For example, one-sixteenth inch thick copper material has been used for the coils having a width of seven-sixteenths inch, with each coil separated from one another by a layer of transformer paper and a potting compound of an epoxy material. Initially a coil of 12 turns with a 3 inch outside diameter was used to drive a transducer having a 3 inch diameter conductor surface. Other coils having eighteen turns with a 5 inch outside diameter were used to drive a transducer having a 5 inch diameter conductor surface. As a number of turns increased the available force for propelling transducer 153 increased until at a certain point near forty turns the amount of discharge voltage required for the same deformation of the rivet began to increase. This occurred due to the interaction of the increased system inductance caused by the increased number of turns of the coil and with this the increase in duration of current pulse while its peak magnitude was reduced. It was also found that the propulsion force due to the rising field in between coil 163 and transducer 153 decreased as transducer 153 moves away from coil 163. For this reason a certain balance was obtained by noting the amount of voltage required for similar deformation of similar rivets with a variation in the number of turns in the coils used. A mere change of the conductor material for the conducting surface plate 155 from aluminum to copper decreased the system inductance of one system by 5 to 10 percent, thereby adding to the overall efficiency of this system without a decrease in the number of turns of the coil. The coil life was substantially increased by making more uniform the gap between adjacent coils, opening up the interior diameter of the coil and by using improved potting material 181.

Recent published statements concerning the advantages of reducing the conductor width for a flat wound coil indicated that there should be an increase power requirement of over fifty percent for doubling the width of the coil. In a comparison test, however, it was found that two pairs of coils, being the same in all respects except that one of the coils was reduced from ¾ inch width to ⅛ inch width, could each suitably install 0.250 inch diameter stainless steel rivets. It was noted that for the same rivet deformation, the coils with the ⅛ inch width wire required 4,060 Joules energy while those having a three quarter inch width wire required 4,500 Joules of energy. This is a power increase of only 11 percent for a 6 to 1 width increase ratio as compared to the noted published data, which was apparently based on calculations rather than actual observed testing. The importance of the wider strip of conductor, i.e., a conductor with a width to thickness ratio greater than 1 to 1, for the coil material is that it produces a significantly increased useful life for the coil by having a greater surface area for resisting the tendency of the coil to move along its central axis in response to the tremendous surge of electrical current through the coil.

Coil life has been also substantially increased by controlling the temperature of the coil through the use of a cooling gas such as CO_2 or normal plant air. Adequate cooling is obtained by directing a stream of such cooling medium through conduits **123** and **124** shown in FIG. **2** toward the region between membrane **159** and conducting surface **155** during the period that the coil system is recoiling after the electrical current is discharged through coil **163**.

In operation, opposed hammer riveter **60** is used to install rivet **87** after rivet **87** is placed in the rivet hole formed in sheets **85** and **86**. Through the action of clamping motors **89** and **90**, clamping pads **105** and **106** impose a clamping pressure on sheets **85** and **86** holding them together. A preloading of the rivet **87** is provided by increasing the pressure of a fluid or gas in preload chamber **175** causing heading die **151** to press against rivet **87** and a corresponding pressure is applied from the opposite lower hammering unit **80**. While clamping and preloading are not absolutely necessary for the proper operation of the unit, good results have been obtained by imposing a clamping pressure on the sheets **85**, **86** from zero to one thousand pound pounds and applying preload pressures on the riveter from zero to five hundred pounds.

Once the equipment is in this ready to fire condition, controls **144** permit the capacitor bank **132** to be discharged through the actuation of firing circuit **145** to operate ignitrons **133** so that the coils of hammer units **79** and **80** will simultaneously receive a high energy electrical current discharge. Such a discharge develops a rising magnetic field around the coil **163** and particularly in the vicinity of the conductor plate **155**. Since plate **155** is made of an electrical conductor, eddy currents are rapidly developed within the rising magnetic field developing a force repelling the magnetic force of coil **163**. This repelling force causes transducer **153** to be propelled toward the rivet **87** and this force is transmitted through heading die **151** causing the deformation and therefore the installation of rivet **87** within sheets **85** and **86**. An exactly opposite and simultaneous action occurs in the lower hammer unit **80** due to the series connection between the coils of the hammer unit **79** and **80** provided by series connector **127**. Thus there is no mechanical lag or system inertia which in any way causes a lack of synchronization between the opposed hammer blows applied with great force density against rivet **87**.

Because of the repulsion between transducer **153** and the coil **163**, there is a recoil force applied to coil **163** causing coil **163** and recoil mass **167** to move upwardly in an opposite direction from the movement of transducer **153**. Although the coil **163** could be held rigid as in embodiment **5** of FIG. **1**, the free suspension of coil **163** in housing **115** with a backup recoil mass **167** permits the use of a light frame for riveter **60**. A weight ratio between mass **167** and transducer **153** of over 10 to 1 will provide some propulsion useful for moving transducer **153** against rivet **87** with a better energy efficiency resulting at a weight ratio of about 25 to 1. The recoil force caused by the contact of the upper surface **169** of the recoil mass or the compressed preload medium against the fixed surface **171** of cap **101** is transmitted through the C frame **65**. This, of course, causes a temporary misalignment of upper hammer unit **79** as well as lower hammer unit **80** from rivet axis **83**. However, due to the time lag between the time that coil **163** starts its recoil motion and the time that the recoil force is applied to frame **65**, heading die **151** has completed its travel and consequent installation of rivet **87**. Thus, the temporary misalignment in the frame **65** has no affect in the accuracy of the setting of the rivet **87**.

In one installation similar to riveter **60**, the capacitor bank has a capacitance of 360 μfd with a voltage range between 0 to 10,000 volts. With this riveter, the order of magnitude of the impacting force between the rivet forming die surface and the rivet varies up to a static or slow rate equivalent of over 72,000 pounds. The duration of the die-rivet impact is measured in the range between 100 and 700 microseconds. This duration can be varied by altering electrical and mechanical constants of the system to something beyond this range.

Using a riveter installation similar to that shown in FIGS. **2** to **4** in one series of tests, three-sixteenths inch nominal diameter 6AL–4V titanium rivets were installed with their deformation equivalent to squeeze installations requiring 58 to 70 foot-pounds of energy. In this installation the coils had 27 turns each and the peak capacitor bank energy discharge was between 3,500 to 3,800 Joules at between 4,400 to 4,600 volts to produce a peak force of 16,000 to 20,000 pounds. It is therefore seen that the riveter of this invention provides a very high density energy impact on the rivet.

In another series of tests utilizing an electromagnetic riveter similar to that shown in FIGS. **2** to **4**, it was found that two specimen structures would not fail after 2,000,000 and 1,750,000 cycles at 60,000 psi stress, respectively, so that tests were stopped. Such results are considered outstanding when compared to the results of the previous standard squeeze riveting technique for similar structures which would be considered acceptable if no failure occurred after 300,000 cycles under the same test conditions. After sectioning these nonfailing rivet installations it was noted that the shank expansion for the cylindrical portion of the

rivets, which excludes the countersink portions, were surprisingly uniform along their length.

For a better understanding of the just mentioned test results, reference is directed to FIGS. **5** and **6**. As shown in FIG. **5** the two sheets of material to be joined, **85** and **86**, are aligned and clamped between the clamping pads **105** and **106**. A preload on rivet **87** is provided by engagement between the heading die surfaces **151** and **191** of the riveter **60**. FIG. **5** shows the relative position of the elements just prior to the discharge of electrical current through the riveter coils.

In FIG. **6** the condition of the same rivet **87** as it is installed in the plates **85, 86** is shown. The countersink portion **193** has been filled in by the rivet and the shaft of the rivet has become uniformly radially expanded to snugly and firmly fasten the sheets **85, 86** together. To appreciate the uniformity of shank expansion resulting from the use of the improved riveter of the instant invention, the cylindrical expansion of the shank between the boundaries **195** shown in the drawing have been measured to indicate that in this portion of the rivet there is a variation of less than one percent of the nominal diameter of the rivet between the most expanded portion of the rivet and the least expanded portion. Specifically for a rivet having a nominal diameter of 0.250 inches a measurement was taken between points **197** and **197'**, after installation, yielding a measurement of 0.273 inches. A second measurement between points **198** and **198'** at the interface between sheets **85** and **86** produced a measurement of 0.271 inches. A third measurement between points **199** and **199'**, at the other end of the cylindrical portion of the rivet, produced a measurement of 0.273 inches. The maximum variation (**0.273-0.271**) is 0.002 inches. One percent of the nominal diameter would have been 0.0025 inches. The average rivet radial expansion in a series of tests indicated a range between 3 to 10 percent of the rivet's nominal diameter all producing fuel-tight joints having extremely good fatigue life. For example, with a nominal rivet diameter of 0.250 an installed average diameter of 0.275 would be considered a 10 percent radial expansion. The measurements for uniformity of the rivet shank portion were taken with the distance between the surface of the plate **86** and the point **199** being approximately 10 percent of the shank height and the distance between the point **197** and the beginning of the rivet countersink portion **193** also being equal to about 10 percent of the shank height. Thus the span **195** is equal to approximately 80 percent of the shank cylindrical portion. Measurements closer to the countersink change or the surface of the sheet **86** are not considered reliable for the purposes of evaluating the uniformity of shank expansion.

We claim:

1. An apparatus for applying a mechanical force against a workpiece comprising:

first means for generating a first high intensity time varying magnetic field, said first generating means including a first coil having a plurality of turns;

first transducer means, including means defining a first electrically conductive surface positioned within said first field and means defining a first working surface, for converting the first repulsion force developed between said conductive surface and said generating means into a first mechanical force applied to said workpiece by said first working surface;

housing means including guiding surfaces for permitting said coil and transducer means to be slidably supported therealong; and

recoil mass means positioned in force transmitting relationship with the face of said coil remote from said transducer means, and including surfaces in sliding contact with said guiding surfaces;

said recoil mass means and said transducer means having a weight ratio greater than 10 to 1.

2. The apparatus of claim **1** wherein:

said recoil mass means and said transducer means have a weight ratio of 25 to 1.

3. The apparatus of claim **1** wherein:

said housing includes means for supporting a workpiece in line with the path of movement of said working surface.

4. The apparatus of claim **1** wherein:

said housing also includes means for arresting the movement of said recoil mass means as it moves away from said transducer.

5. The apparatus of claim **4** wherein:

said housing extends a recoil distance between said workpiece supporting means and the other end of said housing sufficient to permit said working surface to complete its travel in a first direction toward said workpiece before said recoil mass completes its travel in the opposite direction.

6. An apparatus for applying a mechanical force against a workpiece comprising:

first means for generating a first high intensity time varying magnetic field;

first transducer means, including means defining a first electrically conductive surface positioned within said first field and means defining a first working surface, for converting the first repulsion force developed between said conductive surface and said generating means into a first mechanical force applied to said workpiece by said first working surface;

second means for generating a second high intensity time varying magnetic field;

second transducer means, including means defining a second electrically conductive surface positioned within said second field and means defining a second working surface, for converting the second repulsion force developed between said second conductive surface and said second generating means into a second mechanical force applied to said workpiece by said second working surface in a direction generally opposite to the direction of said first mentioned mechanical force applied to said workpiece;

frame means including first and second support means;

said first support means including first positioning means for positioning said first field generating means and said first transducer means providing a first path for movement of said first working surface in a first direction;

said second support means including second positioning means for positioning said second field generating means and said second transducer means providing a second path for movement of

said second working surface in a second direction opposite to said first direction;

said first positioning means including first workpiece pad means and first clamping motor means operatively connected between said first support means and said first pad means for moving said pad means relative to said workpiece along said first and second directions;

said second positioning means including second workpiece pad means and second clamping motor means operatively connected between said second support means and said second pad means for moving said pad means relative to said workpiece along said first and second directions and for applying clamping pressure on opposite sides of said workpiece between said first and second pad means.

7. The apparatus of claim 6 including:

said first positioning means also including a first housing means having first guiding surfaces extending in said first and second directions;

said first field generating means including first electric coil means having an axis and external side walls generally parallel to said first guiding surfaces for guiding said first coil means therealong within said housing;

first recoil mass means positioned in force translating contact with the recoil surface of said first coil;

said first transducer means including side walls formed to slide along said first guiding surfaces with said first conductive surface positioned adjacent to the transducer surface of said coil opposite to said recoil surface.

8. The apparatus of claim 7 including:

said second positioning means also including a second housing means having second guiding surfaces extending along said first and second directions;

said second field generating means including second electric coil means having a second coil axis coincident with said first coil axis and external side walls generally parallel to said second guiding surfaces for guiding said first coil means therealong within said second housing;

second recoil mass means positioned in force translating contact with the recoil surface of said second coil;

said second transducer means including side walls formed to slide along said guiding surfaces with said second conductive surface positioned adjacent to the transducer surface of said second coil opposite to said recoil surface.

9. The apparatus of claim 7 wherein:

said recoil mass including another surface opposite to said surface contacting said coil;

said first housing including cap means closing off one end thereof and defining with said other surface of said recoil mass and said first guiding surfaces a preload chamber;

said preload chamber adapted to receive a pressure medium therein for urging said first recoil mass, said first coil means, and said first transducer in said first direction.

10. The apparatus of claim 1 including: means for cooling said magnetic field generating means.

11. The apparatus of claim 10 wherein:

said cooling means includes means for directing a cooling medium against and between said magnetic field generating means and said electrically conductive surface.

12. The apparatus of claim 1 wherein:

said first field generating means includes an electrical energy storage means in the form of a capacitor bank having a voltage capacity in the range between 0 to 10,000 volts.

13. An electromagnetic power tool apparatus for applying a high intensity impulse of mechanical work force to a workpiece external thereto comprising:

means for generating a rapidly rising magnetic field of high intensity, said generating means including a flat-wound electrically conductive coil having a plurality of turns and further including means for passing a high energy impulse of electrical current through said coil; and

transducer means having first and second substantially opposing sides and including means defining an electrically conductive surface at said first side, said surface being positioned immediately adjacent to a face of said coil and being electrically isolated from any source of applied electrical current, said transducer means further including a force application tool at said second side, said force application tool being propelled through a working stroke by the repulsion force developed between said conductive surface and said coil upon passing of said impulse of electrical current through said coil to thereby generate said magnetic field and induce eddy currents in said conductive surface, said force application tool being so exposed on said apparatus as to be workingly engageable at the beginning of said working stroke with a workpiece external to said apparatus.

14. The apparatus of claim 13 wherein:

said coil is formed of a ribbon of electrically conductive material having a width-to-thickness ratio greater than 1 to 1, said width extending in a first direction generally parallel to the axis of said coil.

15. An apparatus for applying a mechanical force against a workpiece comprising:

first means for generating a first high intensity time varying magnetic field, said first generating means including a first flat-wound electrically conductive coil having a plurality of turns;

first transducer means, including means defining a first electrically conductive surface positioned within said first field and means defining a first working surface, for converting the first repulsion force developed between said conductive surface and said coil into a first mechanical force applied to said workpiece by said first working surface;

housing means including guiding surfaces for permitting said coil and transducer means to be slidably supported therealong; and

recoil mass means positioned in force transmitting relationship with the face of said coil remote from said transducer means, and including surfaces in sliding contact with said guiding surfaces;

said recoil mass means and said transducer means having a weight ratio greater than 10 to 1.

16. The apparatus of claim 15 wherein:

said recoil mass means and said transducer means have a weight ratio of 25 to 1.

17. The apparatus of claim 15 wherein:

said housing includes means for supporting a workpiece in line with the path of movement of said working surface.

18. The apparatus of claim 15 wherein:

said housing also includes means for arresting the movement of said recoil mass means as it moves away from said transducer.

19. The apparatus of claim 18 wherein:

said housing extends a recoil distance between said workpiece supporting means and the other end of said housing sufficient to permit said working surface to complete its travel in a first direction toward said workpiece before said recoil mass completes its travel in the opposite direction.

20. An apparatus for applying a mechanical force against a workpiece comprising:

first means for generating a first high intensity time varying magnetic field, said first generating means including a first flat-wound electrically conductive coil having a plurality of turns;

first transducer means, including means defining a first electrically conductive surface positioned within said first field and means defining a first working surface, for converting the first repulsion force developed between said conductive surface and said coil into a first mechanical force applied to said workpiece by said first working surface;

second means for generating a second high intensity time varying magnetic field, said second generating means including a second flat-wound electrically conductive coil having a plurality of turns; and

second transducer means, including means defining a second electrically conductive surface positioned within said second field and means defining a second working surface, for converting the second repulsion force developed between said second conductive surface and said second coil into a second mechanical force applied to said workpiece by said second working surface in a direction generally opposite to the direction of said first mentioned mechanical force applied to said workpiece.

21. The apparatus of claim 20 wherein:

said first and second generating means include means for electrically connecting said first and second coils in series for simultaneously generating said first and second magnetic fields.

22. The apparatus of claim 20 including:

frame means including first and second support means;

said first support means including first positioning means for positioning said first coil and said first transducer means providing a first path for movement of said first working surface in a first direction;

said second support means including second positioning means for positioning said second coil and said second transducer means providing a second path for movement of said second working surface in a second direction opposite to said first direction.

23. The apparatus of claim 22 wherein:

said first positioning means including first workpiece pad means and first clamping motor means operatively connected between said first support means and said first pad means for moving said pad means relative to said workpiece along said first and second directions;

said second positioning means including second workpiece pad means and second clamping motor means operatively connected between said second support means and said second pad means for moving said pad means relative to said workpiece along said first and second directions and for applying clamping pressure on opposite sides of said workpiece between said first and second pad means.

24. The apparatus of claim 23 including:

first recoil mass means positioned in force translating contact with the recoil surface of said first coil;

said first positioning means also including a first housing means having first guiding surfaces extending in said first and second directions;

said first coil having external side walls generally parallel to said first guiding surfaces for guiding said first coil means therealong within said housing;

said first transducer means including side walls formed to slide along said first guiding surfaces with said first conductive surface positioned adjacent to the transducer surface of said first coil opposite to said recoil surface.

25. The apparatus of claim 24 including:

second recoil mass means positioned in force translating contact with the recoil surface of said second coil;

said second positioning means also including a second housing means having second guiding surfaces extending along said first and second directions;

said second coil having a second coil axis coincident with said first coil axis and external side walls generally parallel to said second guiding surfaces for guiding said first coil means therealong within said second housing;

said second transducer means including side walls formed to slide along said second guiding surfaces with said second conductive surface positioned adjacent to the transducer surface of said second coil opposite to said recoil surface.

26. The apparatus of claim 24 wherein:

said first recoil mass including another surface opposite to said surface contracting said first coil;

said first housing including cap means closing off one end thereof and defining with said other surface of said first recoil mass and said first guiding surfaces a preload chamber;

said preload chamber adapted to receive a pressure medium therein for urging said first recoil mass, said first coil means, and said first transducer in said first direction.

27. The apparatus of claim 13 wherein:

said first field generating means includes an electrical energy storage means in the form of a capacitor bank.

28. The apparatus of claim 27 wherein:

said capacitor bank has a voltage capacity in the range between 0 to 10,000 volts.

29. The apparatus of claim 13 wherein said force application tool is a rivet heading die.

30. The apparatus of claim 13 wherein said electrically conductive surface is substantially equal in size and shape to said face of said coil and is positioned symmetrically with respect to said face.

31. The apparatus of claim 13 wherein said force application tool is a rivet heading die.

* * * * *