

June 9, 1964

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3,136,049

EXPLOSIVE METHOD AND APPARATUS FOR DEFORMING METAL

Filed July 27, 1959

4 Sheets-Sheet 1

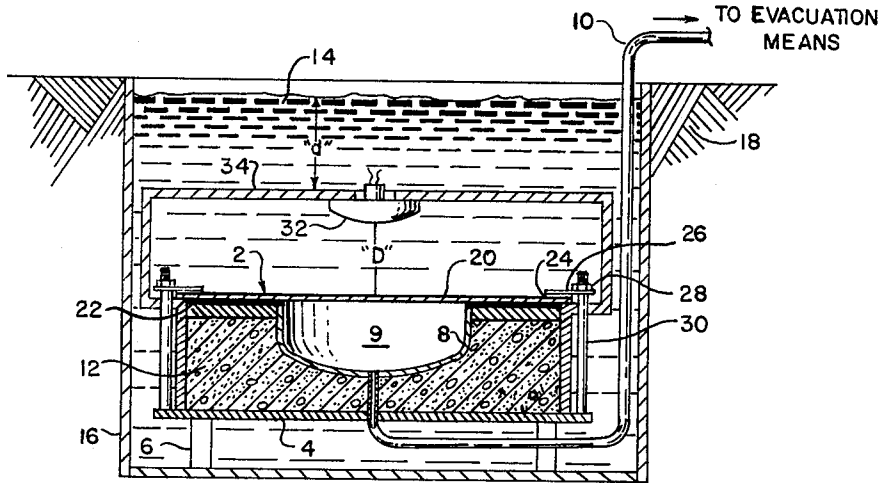


Fig. - 1



Fig. - 2a

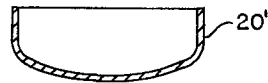


Fig. - 2b

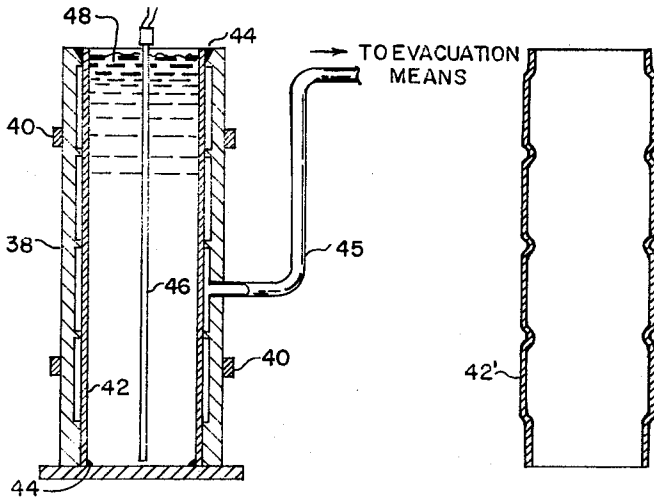


Fig. - 3

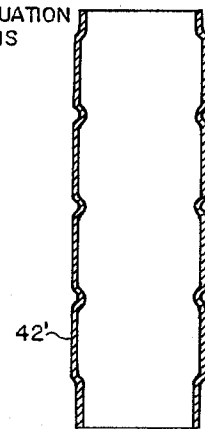


Fig. - 4

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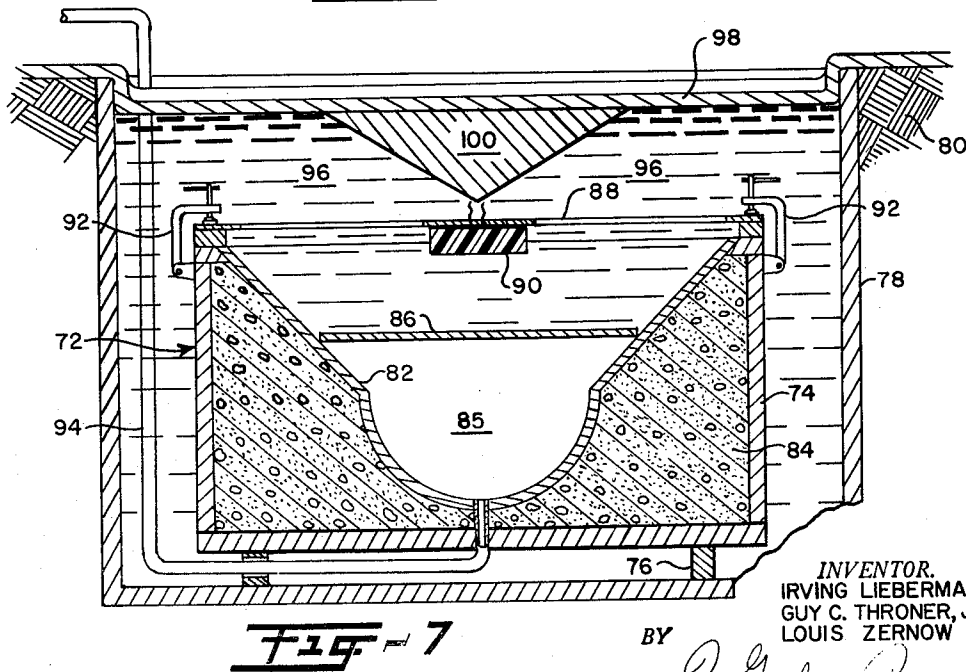
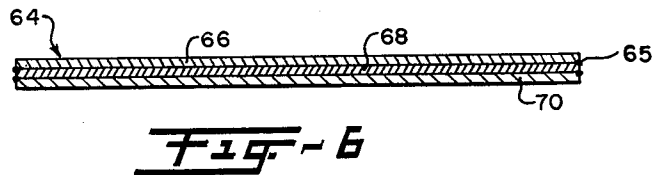
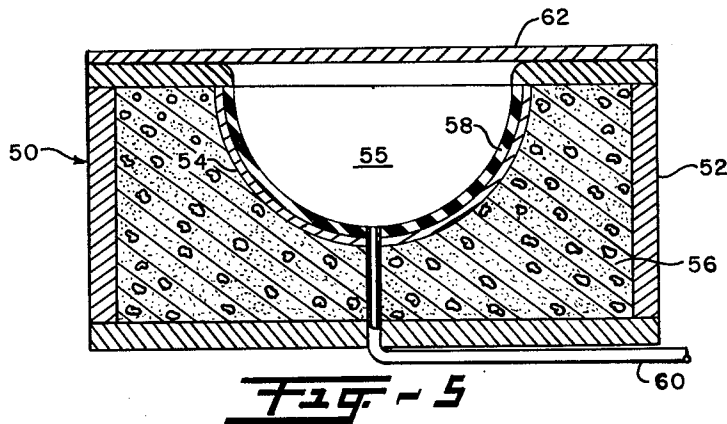
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4 Sheets-Sheet 2



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4 Sheets-Sheet 3

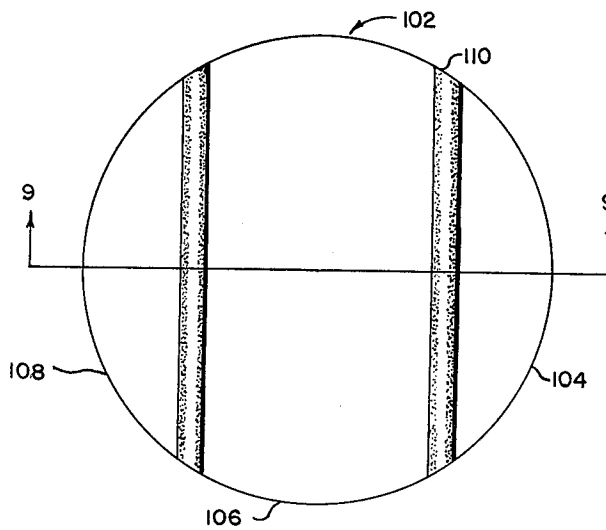


Fig - 8

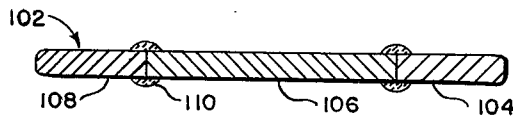


Fig - 9

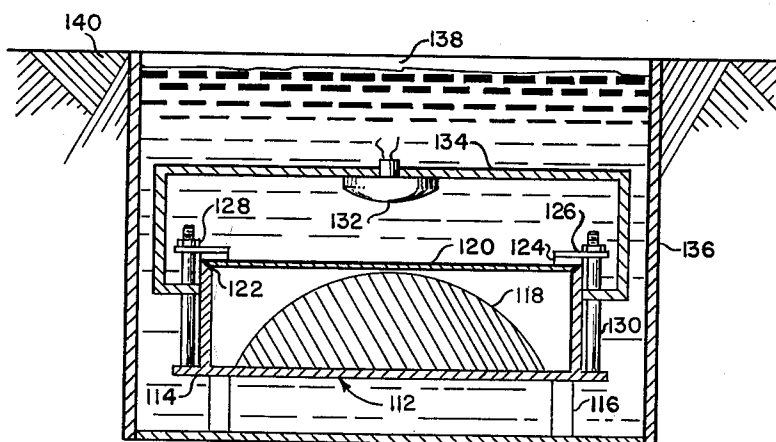


Fig - 10

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4 Sheets-Sheet 4

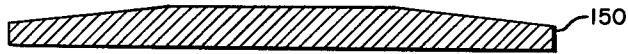


Fig. 11a

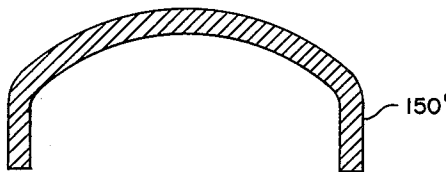


Fig. 11b

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3,136,049

EXPLOSIVE METHOD AND APPARATUS FOR DEFORMING METAL

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Filed July 27, 1959, Ser. No. 829,904

21 Claims. (Cl. 29—421)

This invention relates to the forming of metal parts generally, and to the forming of such parts by explosive forces specifically.

Although standard metal fabrication techniques such as machining, milling, or molding, are satisfactory for the fabrication of parts of conventional configuration, such means often cannot be advantageously employed where unusual shapes are required in the end product, or where the materials being used do not lend themselves to these operations. When expensive materials are used the fabrication of conventional parts may become prohibitively expensive, even when conventional techniques are employed. Limited quantity requirements or excessively large sizes may make tooling prohibitive or impractical.

It is therefore the principal object of the present invention to provide a novel method of and improved means for the forming of metal parts.

Another object of this invention is to provide a novel method of and improved means for explosive forming and trueing of cylindrical members, or other shapes which may be preformed to approximate the final desired shape.

Still another object of this invention is to provide a novel method of and improved means for progressive draw forming of metal parts.

And yet another object of this invention is to provide a novel method of and improved means for explosively forming metallic members without buckling and wrinkling.

In its principal aspect, the invention comprises a method and apparatus whereby metallic blanks to be fabricated in various shapes are placed over a mold and together with the mold submerged in fluid. An explosive charge is detonated in the fluid above the blank. The shock wave and other resultant reactions produced by the explosion causes the metal to conform to the shape of the die.

An optional feature of this invention is a die lined with resilient material, eliminating the metallic spring-back phenomena and permitting practice of the progressive draw process with a minimum number of dies. Another optional feature is the step of forming a composite sandwich unit, the center or top member of which is the blank to be formed, to prevent wrinkling and buckling of the blank during the explosive forming process. Still another optional feature of the present invention is the combination of steps of simultaneously forming a plurality of blanks arranged in laminate form, and then individually trueing each member of the laminate to its desired contour. And another optional feature of this invention is means for explosively holding down the edges of the blank to be formed in order to prevent buckling and wrinkling. And a further optional feature is a means for controlling the material thickness of domes and other shapes formed from blanks by the explosive forming process of this invention.

These and other objects and aspects, features and advantages of the invention will be apparent to those skilled in the art from the following more detailed description taken in conjunction with the appended drawings, wherein:

FIG. 1 is a sectional view of apparatus utilized to fabricate metal parts by explosive forming;

FIG. 2a shows in section a metal blank as used in this process, while FIG. 2b shows the same metal blank after explosive forming in the apparatus of FIG. 1;

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FIG. 3 shows in section apparatus for explosively forming and/or trueing a cylindrical member;

FIG. 4 depicts in section a cylindrical member obtained from the use of the apparatus of FIG. 3;

FIG. 5 is a sectional view of the unique forming die utilized to attenuate the spring-back phenomena of the metal blank and in the progressive draw process;

FIG. 6 is a sectional view of a composite sandwich configuration utilized to eliminate wrinkling and buckling in the explosive forming process;

FIG. 7 is a view illustrating a modification of the apparatus of FIG. 1 wherein the blank to be formed is explosively held down at its periphery to prevent wrinkling and buckling;

FIG. 8 is a plan view of a composite blank formed of smaller sections of like or dissimilar material which may be joined by welding prior to fabrication by the method of this invention;

FIG. 9 is a sectional view of the composite blank of FIG. 8 taken along sectional line 9—9;

FIG. 10 is a view in section of apparatus utilized in the practice of this invention which employs a male die; and,

FIG. 11a is a sectional view of a pre-tapered blank prior to forming by the explosive forming process of this invention, while FIG. 11b illustrates the same metal blank formed as a dome of uniform thickness.

With reference now to FIG. 1, the explosive forming apparatus 2 is shown as comprising a frame 4 mounted on supports 6. A mold or die 8 is arranged within the frame 4, the space between the die 8 and the frame 4 being filled with a solid non-resilient material 12 such as concrete, lead, etc. A vacuum line 10 located at any convenient location in the cavity 9, provides an exit from the die to an evacuation means, not shown. The blank to be fabricated 20, which is of a material such as steel, is arranged across the die 8 in a manner forming a cavity 9 sealed from fluids 14 with the assistance of a commercial sealant material 22. A hold-down ring 24 is placed over the blank 20 and held down by pressure bars 26, to which a given compression has been applied as determined by the force applied to the hold-down nuts 28. The hold-down nuts 28 tighten down on the hold-down rod 30 which is fastened to the frame 4. This method of hold-down is described merely to illustrate how the material may be held.

Other methods of hold-down may be applied. An explosive charge 32 adapted to be fired by conventional means, not shown, is suspended above the blank 20 on suspension member 334 which is attached to frame 4, a distance "D" which varies with the configuration, thickness, type and final desired form of the fabricated blank.

The cavity region 9 of the die 8 beneath the blank 20 is evacuated through the vacuum line 10. The explosive forming apparatus 2 is placed on the bottom of a tank 16 which is set in the ground 18 and the interior of the tank flooded with water or other fluid 14 which fills the tank 16. The explosive charge 32 is then fired. The distance "d" of the fluid level above the explosive charge 32 may be varied to obtain optimum confinement and maximum bubble pulse pressure exerted upon the blank 20 to be formed. A full discussion of the effects of the overburden of a submerged explosive will be found in Chapter 8, Motion of the Gas Sphere, "Underwater Explosions," by Robert H. Cole, Princeton University Press, Princeton, New Jersey, 1948. A high velocity shock wave is transmitted from the detonating charge 32 through the fluid 14 and in partially attenuated condition impacts the blank 20, forcing the blank 20 into the evacuated die cavity 9. Behind this shock wave pressure is the bubble pulse pressure obtained from the expansion of the gaseous products of the detonating explosives. This pressure continues to form the partially formed blank 20 into the mold cavity 9. The relative contributions of the shock wave and succeeding

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pressures which are generated are influenced by the type of explosive charge utilized, i.e., high shock pressures resulting from very high velocity explosives such as TNT, composition B and composition C-4 and reduced shock pressures with the lower velocity explosives such as dynamites. In accordance with the shape of the final desired product and influenced by the blank material, either the former or the latter type of explosive may be required. The blank material and final shape will also influence the required configuration of the explosive charge.

Various formulae have been devised setting forth the inter-relationship among the several parameters. These formulae may be used for guidance in obtaining optimum results inasmuch as the use of too great an amount of explosive may crack the mold or deform the blank, whereas use of too little may result in less than the desired blank deflection. Examples of formulae for the forming of domes by the practice of this invention are given below. If it is desired to form members of different configuration, suitable changes must of course be made in the formulae. In a preferred embodiment of this invention which utilized equipment as illustrated in FIG. 1, a half-inch strip of sealant 22 was applied to the lip of the mold to act as a vacuum seal between the blank which was set over the mold and the internal cavity of the mold. The blank was held down by means of a hold-down ring and eight evenly spaced hold-down retainers pressed against the ring around its circumference. A uniform torque of 100 foot-lbs. was applied to the hold-down nuts which produced the transverse force on the retainers. The cavity formed by the blank of the mold was evacuated to a pressure of approximately 4 to 5 inches of mercury absolute.

The explosive charge was suspended at standoff distances of 4, 6 and 9 inches above the geometrical center of the mold. The entire assembly was lowered into the water tank and the water level throughout the test was maintained at 110 inches above the blank. The blank material was mild steel, type AISI 1020, hot rolled, and the explosive utilized was liquid nitromethane sensitized with an amine such as diethyl amine, and sold by the Aerojet-General Corporation, 6352 North Irwindale Avenue, Azusa, California, under the trademark Aerex. It is described in detail in copending United States Patent Application Serial No. 605,747, filed July 18, 1945, and assigned to the same assignee as the present invention.

The depth of deflection of the blank is a function of the weight of the explosive charge, the standoff distance of the charge from the blank and the thickness of the blank. We have derived an empirical equation relating these variables to the forming of a type 1020 steel blank into a 24" diameter semi-elliptical dome as follows:

$$Z = .23 \frac{W^{.54}}{D^{.33}} \left(\frac{1}{t} \right)^{.67}$$

where

Z=deflection (inches)

W=weight of Aerex (grams)

D=standoff (inches)

t=blank thickness (inches)

Studies were also made to determine the volume of the dome formed as a function of blank thickness, standoff distance of the explosive charge and the weight of charge. For the explosive and blank material named the derived equation is:

$$V = 17.7 \frac{W^{.69}}{D^{.37}} \left(\frac{1}{t} \right)^{1.08}$$

where

V=volume of dome formed in cubic inches

W=weight of Aerex (grams)

D=standoff (inches)

t=blank thickness (inches)

We have also found that the extent and volume of the deflection of the said domes is related to the type of explosives used. For example, in making tests of 1/4-inch

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thick blank material as described, and an explosive stand-off of 4 inches the relation between the depth of deflection and the amount of explosives used may be expressed in the simplified equation:

$$Z = K_d W^{0.54}$$

where Z=deflection in inches, W is the weight of explosive in grams, and K_d is a constant related to the type of explosive. Constant K_d values are tabulated below for the various explosives used:

Explosive type:	K_d
Aerex -----	0.375
EL506A (PETN with plastic binder) -----	0.336
Composition C-4 -----	0.362
Gelatin, 60% strength -----	0.348
Gelamite, 60% strength -----	0.322
Lump coal "C," 60% strength -----	0.264

It was also found that, similarly, the volume of the formed semi-elliptical domes was a function of the weight of explosive and the type of explosive. The equation relating the volumes of the formed domes to the amount of explosive is expressed in the simplified equation:

$$V = K_v W^{0.703}$$

where V=the volume of the dome formed in cubic inches, W=the weight of explosive in grams, and K_v is a constant related to the type of explosive used. The constant values compared for the different explosives are tabulated below:

Explosive type:	K_v
Aerex -----	44.2
EL506A (PETN with plastic binder) -----	39.8
Composition C-4 -----	42.7
Gelatin, 60% strength -----	41.9
Gelamite, 60% strength -----	36.6
Lump coal "C," 60% strength -----	27.4

Similarly, when 3 1/2" diameter semi-elliptical domes were to be formed of 1/4-inch 4130 AISI steel, it was found that both the deflection and volume of the dome were related to the weight of explosive used. Utilizing an Aerex explosive charge suspended 4 inches above the blank in apparatus as described in connection with FIG. 1, the relation between the depth of deflection and the weight of explosive used may be expressed in the simplified equation:

$$Z = K_d W^{.712}$$

where Z is the deflection in inches, W is the weight of Aerex explosive in grams, and K_d is a constant related to the yield or tensile strength blank material used. Constant K_d values are tabulated below for 4130 steel blanks of various tensile strengths.

Tensile strength, p.s.i.:	K_d
70,000 -----	.121
125,000 -----	.0868
155,000 -----	.0755
175,000 -----	.0716

It was also found that the volume of the formed semi-elliptical domes was a function of the weight of Aerex explosive used. The equation relating the volume of the dome to the amount of the explosive used is expressed in the simplified equation:

$$V = K_v W^{.806}$$

where V is the volume of the dome formed in cubic inches, W is the weight of sensitized nitromethane in grams, and K_v is a constant related to the tensile strength of the type 4130 steel blank. The constant values compared for tensile strengths are tabulated below.

Tensile strength, p.s.i.	K_v
70,000 -----	21.5
125,000 -----	13.8
155,000 -----	12.15
175,000 -----	11.65

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Similar formulae for obtaining optimum results may be readily obtained empirically for other materials such as steels, titanium alloys, etc., for assistance in practice of the process described herein.

We have found that the use of a wet lubricant covering the interior of the die mold 8 resulted in an increase in the depth of deflection of the formed dome. The use of lubricants also eliminates the need for the vacuum seal of the blank to the die lip. For example, a water soluble lubricant was used because of the ease of removal from a formed dome and the die.

The theoretical explanation for the superior results obtained in forming blank materials to the contour of the mold by the practice of this process has not been definitely established. Such evidence as is available, however, indicates that as the shock wave from the explosion impacts the metal blank 20, the impact force energizes the molecules into violent motion, thereby exceeding the metal's yield strength and causing the metal to flow into the cavity 9 of the mold or die 8. It is preferable that this process take place while submerged in a fluid inasmuch as it is believed that the products of detonation form a gas bubble which aids in the forming process. The gas bubble initially expands outwardly against the surrounding fluid, simultaneously exerting a pressure against the blank to be formed. When the fluid pressure exceeds the outward pressure of the gas, the bubble is compressed inwardly, raising the pressure of the bubble until such time as it is sufficiently high to again expand outwardly against the surrounding fluid. A full discussion of the oscillation of submerged gas bubbles under these circumstances may be found in the book "Underwater Explosions," Cole, cited supra. It is believed that the oscillation of the bubble in the vicinity of the blank produces a hammering effect thereon which is of assistance in the forming process. It is to be understood, of course, that the invention is independent of any theory which may be advanced to account for the results obtained.

FIG. 2a is illustrative of the blank 20 before being subjected to the explosive forming process of this invention, whereas FIG. 2b shows a sectional view of the blank 20 of FIG. 2a after it has been fabricated in the apparatus of FIG. 1. Although the apparatus shown here is adapted to form dome-shaped parts, metal members of other configurations may be formed by changing the die and variation of other parameters involved in the process. Thus, the top view of the molds, blanks and formed members may be of any desired configuration such as circular, square, elliptical, etc.

FIG. 3 is illustrative of another application of explosive forming which will true the longitudinal dimensions of a cylinder. A split die 38 which may have any conceivable interior configuration, is retained as a unit by banding 40. The cylinder blank to be formed 42, and/or trued is placed into the split die 38 and sealed fluid-tight by vacuum sealant 44 as indicated. The air is evacuated in the cavity between the work piece 42 and the wall of the die 38 to 4-5 inches of mercury absolute through evacuation pipe 45. A string explosive charge 46, or a ball or other configuration of charge, dependent upon the nature of the required final product, is centered within the cylinder blank 42. Fluid 48, which may be water, oil or other liquid capable of transmitting shocks and pressures, fills the cavity of the cylinder blank 42 and the unit is submerged into a tank of water, as in FIG. 1. Upon initiation of the explosive 46, the shock wave and other pressures generated by the detonating explosive charge are transmitted through the fluid 48 and force the cylinder blank 42 to conform to the interior configuration of the die 38. The effectiveness of the truing is only limited by the close tolerances to which the cylindrical die 38 is initially fabricated. FIG. 4 illustrates the final product, a cylinder 42', which is obtained by use of this process in the apparatus of FIG. 3.

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FIG. 5 shows a special explosive forming apparatus 50 which may be used in a progressive draw process, (where multiple forming operations are performed in successive order), and also to minimize or eliminate spring-back phenomena encountered in explosive forming many of the newer type high strength metals such as nickel, chrome, and vanadium steels. When using standard forming methods on such high strength metals to achieve a 90° bend, a die must often be constructed with a 120° or even 150° radius of curvature in speculation that the metal will spring back to the desired radius. Often the metals will not repond as predicted, and the part must be scrapped. When using the die or mold 50 of FIG. 5 in the described explosive forming process, more reliable and predictable results are obtainable.

As shown in FIG. 5, the molding apparatus 50 comprises a frame 52 upon which is mounted a mold or die 54. A portion of the apparatus between the frame and the die is filled with a non-resilient material 56 such as concrete. A vacuum line 60 communicates with the cavity portion 55 of the die 54. A resilient liner 58, such as rubber, lines the interior of the mold cavity. The blank 62 is placed across the top of the mold 54. The evacuation line 60 leads to conventional evacuation means such as a vacuum pump, not shown. A vacuum sealant (not shown) is employed at appropriate portions of the apparatus together with necessary hold-down rings, nuts and rods and pressure bars as in FIG. 1. As previously explained, the apparatus is submerged in fluid to the desired depth and an explosive charge detonated above the blank to be formed. The exploding charge transmits a shock wave and other forces resulting from the detonation which will force the blank 62 into the mold 54. Provision of the resilient liner 58 will overcome the normal spring-back which materials exhibit on being formed in dies as described above. The liner 58 will permit the blank 62 to form beyond the required depth, and assisted by the compressed resilient liner, the spring-back may be controlled so that the final formed part, shown here to be a head or dome, will have the desired dimensions. Although the resilient liner 58 is here shown to be arranged to line the die cavity, in another embodiment, the liner may be arranged horizontally under the blank to be formed. Preferably, the liner is attached to the underside of the blank as by glueing.

In practicing the process of a progressive draw, multiple detonations are employed in a selected order. Intentionally, where progressive draw is desirable, a mold having the smallest dimensions is utilized for the preliminary shock. This is followed by using a larger mold, or molds, for subsequent steps in the operation to achieve the final configuration and dimensions. In the present invention, where a progressive draw is desired, the additional mold is eliminated by using the resilient liner 58 in the required thickness. The mold 50 with liner 58 will act as a preliminary mold for the initial shot, and the blank to be formed is again fired in the mold apparatus 50 without the liner 58 in the subsequent shot. In this manner an additional mold is eliminated.

In FIG. 6 is shown a means permitting the forming of materials in thicknesses and dimensions which would normally wrinkle and buckle during the forming process. In the explosive forming process as applied to heads and tank closures, when the ratio of blank thickness to blank diameter is too small for a specific set of conditions, buckling and wrinkling in the formed item will occur. Formulae enabling determination of stability of plates under stress may be found at Table XVI, page 315 of "Formulas for Stress and Strain," R. J. Roark, McGraw-Hill Book Co., New York, 1954. The apparatus of the present invention will permit forming materials which would normally fail by wrinkling and buckling brought on by stresses because of the unfavorable thickness to diameter ratio. This elimination of unfavorable forming conditions is accomplished by preparing a laminated or

sandwich blank which comprises a member to be formed 68 sandwiched between an upper and/or lower members 66, 70. The laminated blank 64, may be welded as at point 65 or otherwise bonded as with an epoxy resin, forming a unit, or utilized as assembled without material attachment. The complete lamination 64 will form one unit, and is subjected to the explosive forming operation described above. After the explosive charge is detonated, the individual blank 68 is separated from the other laminations 66, 70 providing the desired part without buckling or wrinkling. Where the laminations are all of a material and thickness required in the formed dome, the three units may be trued and thus provide three individual units fabricated by the one shot. Alternatively, a lamination of two blanks may be processed in the same manner. In each case the individual members may subsequently be trued to the desired final contour.

It has been found necessary in forming heads to hold down the peripheral circumference of the blank in the region of the knuckle and rim of the head. FIG. 7 illustrates a method for utilizing the explosive impulse from the initial explosive charge as a hold-down on the blank. In a structure similar to that shown in FIG. 1, the forming member 72 comprises a frame 74 mounted on a stand 76 within a tank 78 which is set into the ground 80. A mold or die 82 is set within the frame 74 and the space between the die 82 and the frame 74 is filled with a non-resilient material such as concrete 84. The blank 86 to be formed is laid over the die 82 and an explosive holding member 88 is laid across the top of the frame 74, being rigidly secured thereto by C-clamps 92. An explosive charge 90 adapted for firing by conventional means, not shown, is secured to the holding member 88 and suspended a predetermined height above the blank 86. An evacuation pipe 94 leads to an external evacuation means, not shown, from the cavity 85 formed between the die 82 and the blank 86. The entire apparatus 72 is submerged in the tank 78 which is filled with a fluid 96. A holding member 98 is arranged across the top of the tank, and suspended from the bottom side thereof is a massive reflector 100.

Arrangement of a fairly massive reflector 100 above the explosive charge 90 will cause a compressive reflection to replace a rarefaction wave. The shape of the reflector will determine the angle that the reflection will take and the point at which the force component acting as a hold-down is effected on the blank 86. By application of the force holding the blank down in the same manner as a mechanical hold-down means, the circumferential rim of the blank is retarded for a period sufficiently long while the center portion is being formed, to allow sufficient stretching of material in the blank to overcome the tendency for the material to buckle and wrinkle. It is possible to achieve hold-down on the circumference of the blank to be formed by redistributing the explosive charge and the resultant detonation forces so as to obtain a hold-down on the rim of the blank. By varying the thickness of the explosive charge in a radial direction the amplitude of the shock is controlled, and by varying the diameter of the charge, the time of the arrival of the hold-down shock may be controlled. The amount of impact of the generated shock may be determined by varying the geometry of the explosive shock front. The delay in initial motion of the blank due to inertia of the material and the relatively fast transmission of the reflected shock to the blank during forming will permit the reflected shock to act on the blank periphery prior to the blank being fully deformed.

By utilizing the method and apparatus of the present invention sheets can be fabricated which are larger in size than steel mills are capable of producing with present tooling means. As shown in FIGURES 8 and 9, large blanks may be made from smaller sheets welded together to form items which cannot be formed by conventional means because of resulting weld failure. The large blank 102 is formed of three smaller sections 104, 106, 108

joined together by welds 110. The resulting blank 102 may be larger than the present capabilities of mills or alternatively may be of conventional size but composed of smaller sections of dissimilar metals. By use of an explosive forming technique such a blank can be fabricated without weld failure. The rate at which forming takes place by our explosive technique is so fast that weld cracks commonly encountered in conventional techniques are eliminated.

FIGURE 10 delineates a modification of the present invention utilizing a male die in place of the female dies of FIGURES 1, 3, 5 and 7. The explosive forming apparatus 112 comprises a frame 114 mounted on supports 116. A male (convex) mold or die 118 is arranged within the frame 114, and the steel blank 120 which is to be fabricated is laid across the top of frame 114, a suitable vacuum sealant 122 being inserted between the frame 114 and the blank 120 to provide an air-tight seal. A hold-down rim 124 is placed over the blank 120 and held down by pressure seals 126 which are given a compressive force by the hold-down nuts 128 as they are tightened by the hold-down rod 130 which is fastened to the frame 114. Other methods of hold-down may be utilized.

An explosive charge 132, adapted to be fired by conventional means, not shown, is suspended above the blank 120 on suspension member 134 at the required distance. The entire structure is submerged in a tank 136 which is set in the ground 140 and the entire interior of the tank flooded with a suitable fluid 138, such as water, to the desired height above the explosive charge 132.

As previously explained in connection with other embodiments, detonation of the explosive charge 132 causes a high velocity shock wave to be transmitted through the fluid 138 to impact the blank 120, forcing it to conform with the contour of the male die 118. It is to be noted that the charge 132 is fabricated to form properly shaped shock waves which will deliver pressures to the periphery of the blanks 120. Techniques of fabricating an explosive charge incorporating a wave shaper are disclosed in U.S. patent application, Serial No. 817,240, assigned to the assignee of the present invention, filed June 1, 1959, and now Patent No. 3,034,393.

It has been found in the forming of blanks by the practice of this invention that the natural tendency of the blank is to thin at the apex and thicken as the flange region is approached. To achieve a uniform material thickness, the blank 150 is specially prepared prior to forming. As shown in FIG. 11a, this preparation comprises grinding or otherwise removing material from the blank surface to give an initial blank thickness which will be greater in the thinning areas and smaller in the thickening areas. The degree of thinning of the steel blank is dependent upon the blank material used, the condition of the metal, the type of hold-down employed, and other factors. FIG. 11a illustrates a taper introduced into the surface of the blank 150 to compensate for the thickening which would normally occur in the region tapered. Thus, with the thinning in the apex and thickening in the tapered region occurring as the result of the practice of this invention, the arrangement of a blank 150 as shown in FIG. 11a in the apparatus of FIGS. 1, 5, 7 or 10 will result in a dome 150' of uniform thickness, as shown in FIG. 11b.

While preferred embodiments of the material and apparatus of the present invention have been specifically disclosed and illustrated in the specification and accompanying drawings, it is to be understood that the described embodiments are not limitative of the invention since various modifications may be made therein by those skilled in the art without departing from the scope of the invention as defined by the appended claims.

We claim:

1. A method of fabricating a metal member comprising the steps of, arranging a metal member to be formed over a mold having a top surface which is indented in

part, securing said member to said mold to form a unitary structure, submerging said unitary structure in a fluid body, evacuating the region between said member and the top surface of the mold, arranging an explosive charge in said fluid body above said unitary structure and below the surface of said fluid body, and detonating said explosive charge, whereby the resulting explosion forms said member in conformity with the contour of said mold.

2. A method of fabricating a metal member as described in claim 1, and in addition, the step of adhering a layer of a resilient material to the bottom surface of said member prior to arranging said member over the top surface of said mold.

3. A method of fabricating a metal member as described in claim 1 wherein said metallic member comprises a laminate having two or more separable metallic members.

4. A method of fabricating a metal member as described in claim 1 wherein said member comprises two or more metal blanks in the same plane welded together at their abutting lateral edges.

5. A method of fabricating a metal member as described in claim 1 wherein said member comprises two or more blanks in the same plane of dissimilar metals welded together at their abutting lateral edges.

6. A method of fabricating metal members as described in claim 1 wherein said explosive charge is a shaped charge which is fabricated to deliver compressive forces to the periphery of said member upon detonation.

7. A method of fabricating a metal member as described in claim 1 wherein the indented portion of the top surface of said mold is faced with a layer of resilient material.

8. A method of fabricating a metal member as described in claim 7, and in addition, the step of detonating a second submerged explosive charge above said member secured to a second mold to form a unitary structure, the top surface of said second mold being similarly indented in part but made of nonresilient material.

9. A method of fabricating a metal member comprising the steps of arranging a metallic member comprising a laminate of two or more separable blanks over a mold having the contour to which it is desired to fabricate said blanks of said laminate member; securing said member to said mold to form a unitary structure, submerging said unitary structure in a fluid body, arranging a first explosive charge in said fluid body above said unitary structure and below the surface of said fluid body, detonating said first explosive charge to generally conform said laminate to the contour of said mold, separating the blanks comprising the laminate, and trueing individually each blank member of said laminate to the desired final contour.

10. A method of fabricating 24" diameter semi-elliptical domes from 1/4-inch thick type AISI 1020 steel comprising the steps of arranging a blank to be formed over a mold having a top surface which is semi-elliptical in part, firmly securing said blank to said mold to form a unitary structure, submerging said unitary structure in a fluid body, evacuating the region between said blank and the semi-elliptical portion of the surface of the mold, arranging an explosive charge in said fluid body at a distance of 4 inches above said unitary structure and below the surface of said fluid body, and detonating said explosive charge, said explosive being of a weight determined by the formula:

$$W = \left(\frac{Z_0}{K_d} \right)^{1.85}$$

where W is the weight of said explosive charge in grams, Z is the desired depth of deflection of said AISI 1020 steel blank in inches, and K_d is a constant related to the type of explosive comprising said explosive charge.

11. A method of fabricating 24" diameter semi-el-

liptical domes from 1/4-inch thick type AISI 1020 steel comprising the steps of arranging a blank to be formed over a mold having a top surface which is semi-elliptical in part, firmly securing said blank to said mold to form a unitary structure, submerging said unitary structure in a fluid body, evacuating the region between said blank and the semi-elliptical portion of the surface of the mold, arranging an explosive charge in said fluid body at a distance of 4 inches above said unitary structure and below the surface of said fluid body, and detonating said explosive charge, said explosive being of a weight determined by the formula:

$$W = \left(\frac{V}{K_v} \right)^{1.422}$$

where W is the weight of said explosive charge in grams, V is the desired volume of the dome formed in cubic inches, and K_v is a constant related to the type of explosive comprising said explosive charge.

12. A method of fabricating 24" diameter semi-elliptical domes from type AISI 1020 steel comprising the steps of arranging the blank to be formed over a mold having a top surface which is semi-elliptical in part, firmly securing said blank to said mold to form a unitary structure, submerging said unitary structure in a fluid body, evacuating the region between said blank and the semi-elliptical portion of the surface of the mold, arranging an explosive charge of sensitized nitromethane in said fluid body above said unitary structure and below the surface of said fluid body, and detonating said explosive charge, said blank having a resultant deflection being provided by the formula:

$$Z = .23 \frac{W^{.54}}{D^{.33}} \left(\frac{1}{t} \right)^{.67}$$

where Z is the deflection of said blank in inches, W is the weight of said sensitized nitromethane explosive charge in grams, D is the distance of said explosive charge above said blank in inches, and t is the thickness of said AISI 1020 steel blank in inches.

13. A method of fabricating 24" diameter semi-elliptical domes from type AISI 1020 steel comprising the steps of arranging the blank to be formed over a mold having a top surface which is semi-elliptical in part, firmly securing said blank to said mold to form a unitary structure, submerging said unitary structure in a fluid body, evacuating the region between said blank and the semi-elliptical portion of the surface of the mold, arranging an explosive charge of sensitized nitromethane in said fluid body above said unitary structure and below the surface of said fluid body, and detonating said explosive charge, said dome having a resultant volume provided by the formula:

$$V = 17.7 \frac{W^{.69}}{D^{.37}} \left(\frac{1}{t} \right)^{1.08}$$

where V is the volume of the semi-elliptical dome formed in cubic inches, W is the weight of said sensitized nitromethane explosive charge in grams, D is the distance of said explosive charge above said blank in inches, and t is the thickness of said AISI 1020 steel blank in inches.

14. A method of fabricating and trueing a metal cylinder comprising the steps of arranging a hollow metal cylinder within a hollow die having a contoured inner surface, centrally arranging an explosive charge within the interior of the cylinder, filling the cavity of the cylinder with a fluid, evacuating the regions between said cylinder and the contoured inner surface of said die, submerging said die, cylinder, and explosive together in a fluid body, and detonating said explosive charge, whereby the resulting explosion forces said cylinder outwardly to conform with the contour of said die.

15. A method of fabricating a metal member comprising the steps of arranging a metal member to be formed over a mold having a top surface which is indented in

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part, submerging said mold and member in a fluid body, evacuating the region between said member and the top surface of said mold, arranging an explosive charge in said fluid body above said member and below the surface of said fluid body, submerging a massive reflector in said fluid body to a position above said explosive charge, said reflector having a configuration whereby compressive forces released upon detonation of said charge are reflected from said reflector to the periphery of said member, and detonating said charge, whereby the resulting explosion forms said member in conformity with the contour of said mold.

16. A method of fabricating a metal member as defined in claim 15 in which the metal member is arranged within the indented portion of the mold.

17. A method of fabricating a metal member comprising the steps of arranging a metal member to be formed over a mold having a top surface which is indented in part, submerging said mold and member in a fluid body, evacuating the region between said member and the top surface of said mold, arranging an explosive charge in said fluid body above said member and below the surface of said fluid body, said explosive charge being a shaped charge fabricated to deliver compressive forces to the periphery of said member upon detonation, and detonating said charge, whereby the resulting explosion forms said member in conformity with the contour of said mold.

18. Apparatus for the explosive forming of a metal member submerged in a body of fluid comprising: a frame member, a contoured die member arranged across the top of said frame member, said die member being adapted to receive a metal member to be formed on the top surface thereof, means for permitting evacuation of the region between said metal member and said contoured die member, means for retaining an explosive charge above the metal member to be formed, and a massive reflector positioned above said explosive charge in a manner reflecting compressive forces from the detonation of said explosive charge to the periphery of said metal member.

19. Apparatus for explosively trueing a cylinder submerged in a fluid body comprising, a hollow die having the desired contours on the inner surface thereof, said die being adapted to receive a hollow metal cylinder, means for permitting evacuation of cavities formed when a cylinder is inserted within said die, and means for centrally positioning an explosive charge in the interior of said hollow cylinder.

20. A method of fabricating semi-elliptical domes having a diameter of 31½" from ¼-inch thick type AISI 4130 steel comprising the steps of arranging a blank to be formed over a mold having a top surface which is concave in part, firmly securing said blank to said mold to form a unitary structure, submerging said unitary structure in a fluid body, evacuating the region between said blank and the concave portion of the surface of the mold, arranging an explosive charge of sensitized nitromethane in said fluid body at a distance of 4 inches above said unitary structure and below the surface of said fluid body,

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and detonating said explosive charge, said blank having a resultant deflection being provided by the formula:

$$Z = K_d W^{.712}$$

where Z is the depth of deflection of said blank in inches, K_d is a constant related to the tensile strength of the blank material, and W is the weight of said sensitized nitromethane explosive charge in grams.

21. A method of fabricating semi-elliptical domes having a diameter of 31½" from ¼-inch thick type AISI 4130 steel comprising the steps of arranging a blank to be formed over a mold having a top surface which is concave in part, firmly securing said blank to said mold to form a unitary structure, submerging said unitary structure in a fluid body, evacuating the region between said blank and the concave portion of the surface of the mold, arranging an explosive charge of sensitized nitromethane in said fluid body at a distance of 4 inches above said unitary structure and below the surface of said fluid body, and detonating said explosive charge, said dome having a resultant volume provided by the formula:

$$V = K_d W^{.808}$$

where V is the volume of the semi-elliptical dome formed in cubic inches, K_d is a constant related to the tensile strength of the blank material, and W is the weight of said sensitized nitromethane explosive charge in grams.

References Cited in the file of this patent

UNITED STATES PATENTS

1,935,916	Ragsdale	Nov. 21, 1933
2,016,569	Zinser	Oct. 8, 1935
2,434,379	Wiesher et al.	Jan. 13, 1948
2,486,130	Dietrich et al.	Oct. 25, 1949
2,555,497	McCullough et al.	June 5, 1951
2,586,706	Parr	Feb. 19, 1952
2,686,488	Montgomery	Aug. 17, 1954
2,770,034	Lyon	Nov. 13, 1956
2,779,279	Maiwurm	Jan. 29, 1957
2,820,286	Andrus	Jan. 21, 1958
2,836,530	Rees	May 27, 1958
2,858,603	Herrmann	Nov. 4, 1958
2,935,038	Chatten	May 3, 1960
2,969,758	Howlett et al.	Jan. 31, 1961
2,983,242	Cole	May 9, 1961
3,065,720	Rardin	Nov. 27, 1962

FOREIGN PATENTS

657,727	Great Britain	Sept. 26, 1951
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OTHER REFERENCES

"Explosives," Materials in Design Engineering, vol. 49, No. 2, February 1959, pages 82-87, pub. by Reinhold Pub. Corp., 430 Park Ave., New York, N.Y. Copy available in Group 330.

"Explosives Form Space Age Shapes," Steel, August 25, 1958, pages 82-86. Copy available in Group 330.

"Explosive Forming," American Machinist, vol. 103, No. 12, June 15, 1959, pages 127-138. Copy available in Group 330.