July 30, 1968 K. F. SMITH 3,394,569

FORMING METHOD AND APPARATUS

Filed June 23, 1966

Fig. 1

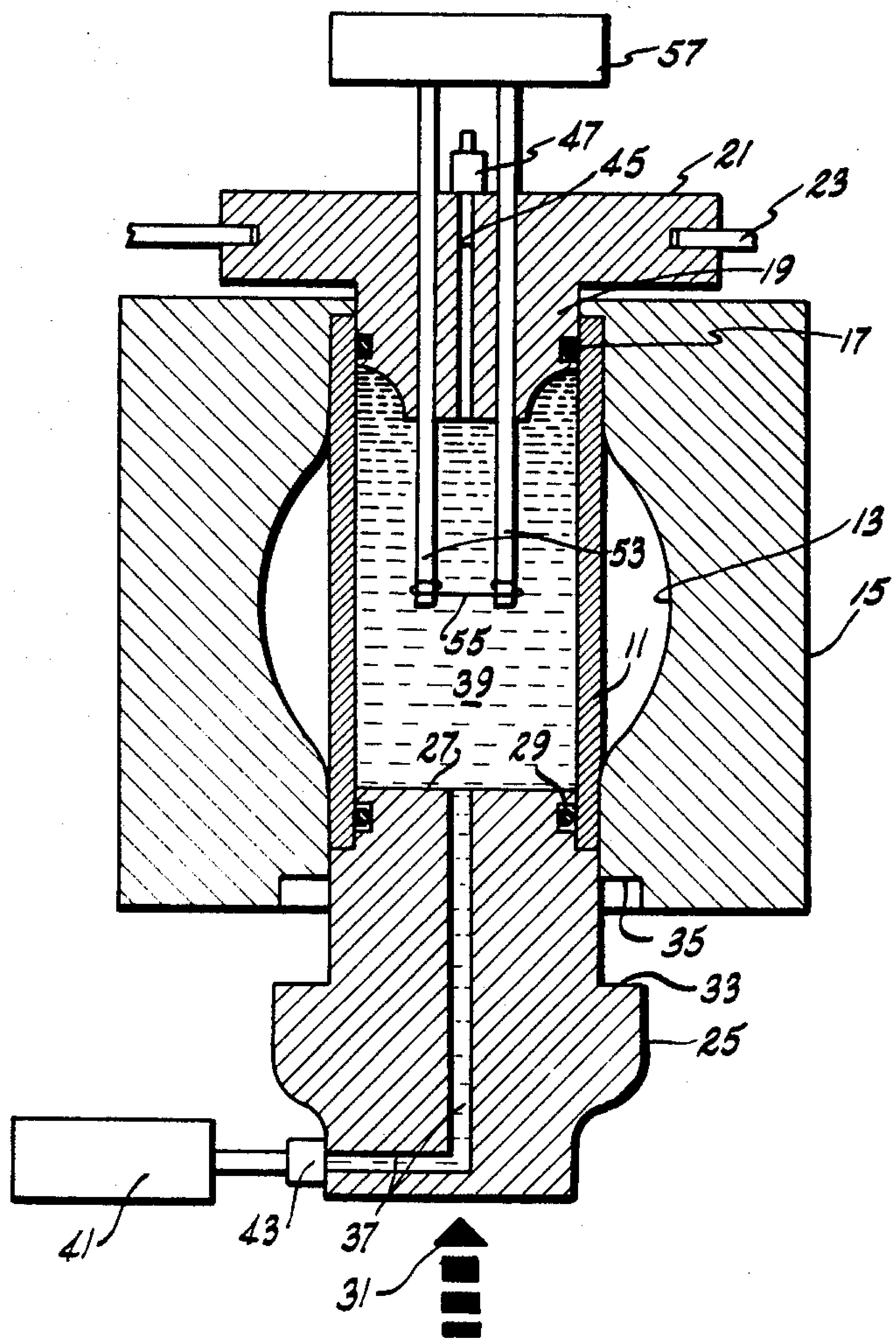


Fig. 2

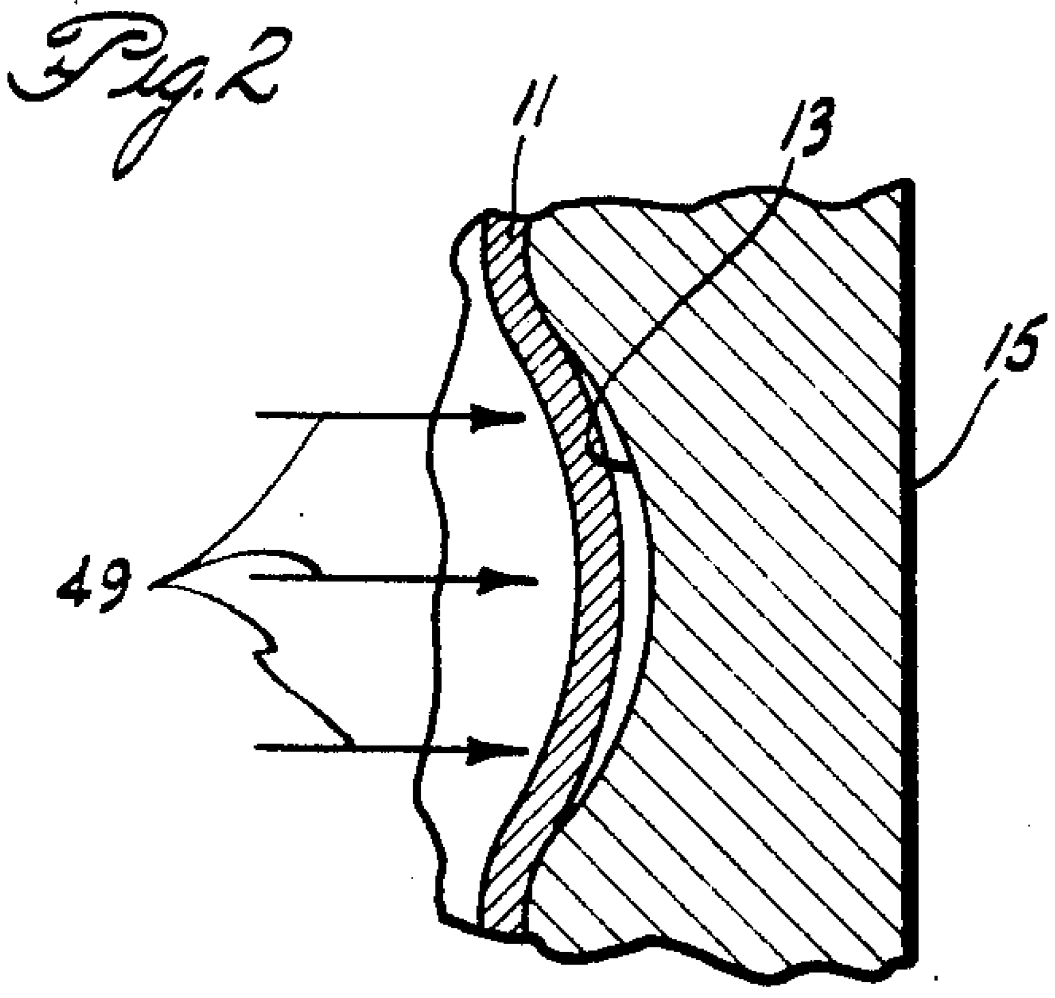
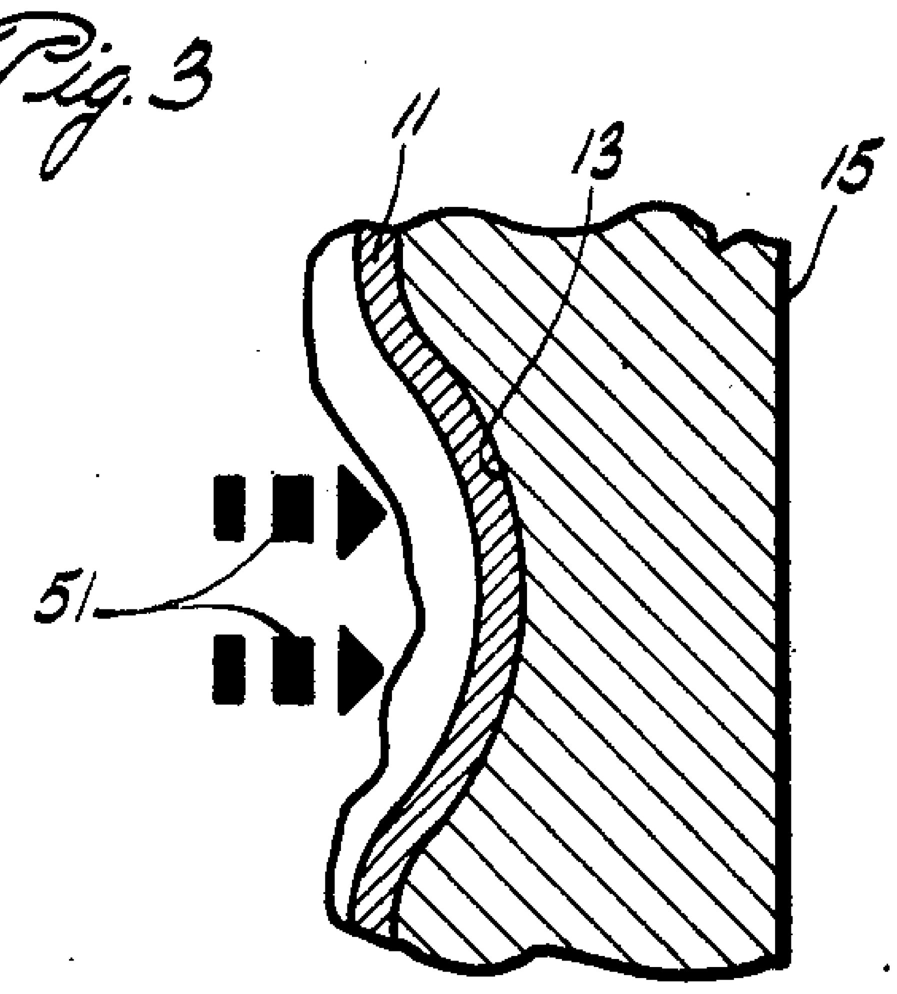


Fig. 3



Inventor
KENNETH FRANKLIN SMITH

By Anderson, Luedeka, Fitch, Even, & Tabin Attys.

United States Patent Office

3,394,569

Patented July 30, 1968

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3,394,569

FORMING METHOD AND APPARATUS

Kenneth Franklin Smith, Fort Worth, Tex., assignor to General Dynamics Corporation, New York, N.Y., a corporation of Delaware

Filed June 23, 1966, Ser. No. 560,003
5 Claims. (Cl. 72—56)

This invention relates to a forming method and apparatus and, more particularly, to a method and apparatus for forming workpieces which, because of their shape and/or material, do not readily lend themselves to forming by known techniques.

For some purposes, it is desirable to form workpieces of certain shapes, such as cylinders or cones, in a manner to produce a bulge or similar deformation intermediate the ends of the workpiece. One forming technique which has been used for producing such deformations is known as hydrostatic forming. In such forming, the cone or cylinder is filled with a hydraulic fluid and the pressure of the fluid is increased to a level sufficient to deform the workpiece outwardly into a surrounding die cavity. Simultaeously with the application of hydraulic pressure, the workpiece is column loaded (that is, subjected to substantial compressive forces) to force feed the material into the die cavity. Hydrostatic forming has also been utilized in forming workpieces of shapes other than cylinders or cones. For example, hydrostatic forming has been used to produce indentations in metallic plates.

Many materials are sensitive to relatively high strain rates and exhibit defects such as rupture or excessive thinning unless they are formed at relatively low strain rates. Hydrostatic forming is of advantage in the formation of such materials because the required low strain rates are easily obtained. Although successful in many applications, some difficulties have been encountered in connection with hydrostatic forming, particularly when the workpiece is of a material which tends to spring back. Such material frequently cannot be readily conformed to the surface of the die cavity when formed at the relatively slow strain rates usually associated with the hydrostatic forming process.

It is an object of this invention to provide an improved forming method and apparatus.

Another object of the invention is to provide a method and apparatus for forming workpieces which, because of their shape and/or material, do not readily lend themselves to forming by known techniques.

Still another object of the invention is to provide a hydrostatic forming method and apparatus wherein final shaping of the workpiece is readily accomplished.

Other objects and the various advantages of the invention will become apparent to those skilled in the art from the following description taken in connection with the accompanying drawing wherein:

FIGURE 1 is a vertical sectional view, partially in full section and partially schematic, of apparatus constructed in accordance with the invention for performing the method of the invention;

FIGURE 2 is a fragmentary view showing a portion of the apparatus of FIGURE 1, illustrating a step in the method of the invention; and

FIGURE 3 is a fragmentary view showing a portion df the apparatus of FIGURE 1, illustrating a further step in the method of the invention.

Briefly, in accordance with the invention, a workpiece is formed in a predetermined shape by a method which comprises first subjecting the workpiece to a hydraulic fluid pressure to thereby form the workpiece into an intermediate shape at a relatively slow strain rate. The workpiece is then finally shaped by producing an electrical spark in a hydraulic fluid to thereby form the workpiece at a relatively high strain rate.

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The method of the invention will be more clearly comprehended in connection with the description of the particular device illustrated in the drawings. It is to be understood, however, that the method of the invention is not limited to practice in connection with the specific apparatus shown. It is to be further understood that the particular apparatus shown is illustrative only of a preferred embodiment of the invention and that other embodiments, not illustrated, may be constructed in accordance with the invention.

Referring now particularly to the drawings, the illustrated workpiece **11** is in the form of a tube, but the invention is applicable to other shapes of workpieces as well (e.g., cones, plates, etc.). The material out of which the workpiece is comprised may be any of a variety of types, however, the invention has particular advantage in connection with materials, such as titanium, stainless steel, etc., which are sensitive to high strain rates and which have a tendency to spring back when formed at relatively slow strain rates. In forming workpieces of such material, it frequently becomes difficult to form the workpiece to the precise dimensions of a die.

The tubular workpiece **11** is supported adjacent a cavity **13** of an annular die **15**, the later surrounding the workpiece and being a split construction of conventional type. The upper portion of the workpiece is sealed, by means of an O-ring **17**, against the outer periphery of a circular projection **19** extending from an upper plug **21**. The upper plug **21** is secured firmly in position by means of a suitable clamping device, a portion of which is indicated at **23**.

At the opposite end of the workpiece **11** from the plug **21** is another plug **25**. The plug **25** has a circular projection **27** which extends partially into the tubular workpiece **11** and the workpiece is sealed to the projection **27** by means of an O-ring **29**. The plug **25** is axially movable upwardly in the direction of the arrow **31** to place a column loading force on the workpiece **11** for reasons which will be explained subsequently. An annular shoulder **33** surrounds the plug **25** and mates in an annular recess **35** in the die **15** to limit the upward axial travel of the plug **25**.

An L-shaped passage **37** is provided in the plug **25** for conducting hydraulic fluid **39** to the interior of the workpiece **11**. The hydraulic fluid passes through passage **37** from a hydraulic fluid source **41** through a check valve **43**. A bleeding passage **45** is provided in the upper plug **21** to permit air to escape from the interior of the workpiece through a check valve **47** when hydraulic fluid is pumped into the interior of the workpiece through the passage **37**.

In performing the initial forming operation on the workpiece **11**, the workpiece is clamped in place in the apparatus as shown in FIGURE 1. Hydraulic fluid is passed into the workpiece from the source **41** through the check valve **43** and the passage **37**, and force is applied to the lower plug **25** in the direction of the arrow **31** to provide a column or axial load on the workpiece **11**. Air inside the workpiece is expelled through the passage **45** and the check valve **47**. When the air has been displaced, the air outlet check valve **47** is closed and the source **41** continues to inject hydraulic fluid into the interior of the workpiece. Pressure is built up to a degree sufficient to deform the workpiece and strain it outwardly into the die cavity **13**. Simultaneously with the deforming of the workpiece, force is maintained on the lower plug **25** such that, in effect, the material of the workpiece is force fed into the die cavity.

As previously pointed out, hydrostatic pressure supplemented by column loading is an effective method of deforming a workpiece, particularly in connection with materials which are very sensitive to relatively high strain rates. The relatively low strain rates which are obtainable in hydrostatic forming usually prevent rupture or excessive thinning of many materials, which, when subjected to other forming operations, would incur such defects. Where the material being formed is of a type which exhibits a tendency to spring back, hydrostatic forming is unsatisfactory in obtaining final shaping of the workpiece to the die dimensions. Other forming processes utilizing higher strain rates ordinarily do not have this problem as acutely as in hydrostatic forming.

In accordance with the invention, the final shaping problem is overcome by accomplishing the final shaping step in a manner which utilizes the principles of electrohydraulic forming. In an electrohydraulic forming process, electric energy which is built up at a relatively slow rate in a condenser bank is suddenly discharged between a pair of electrodes which are immersed in a hydraulic fluid. This sudden discharge of electrical energy across an electrode gap produces a pressure pulse or sound wave which propagates radially from the line of action of the spark across the gap. The rate of propagation of the shock wave is relatively high, initially exceeding the velocity of sound in the particular medium, and the wave is accordingly of a correspondingly high energy content. The shock wave so produced is utilized to deform a workpiece, usually into a die. By regulating the charge built up on the condenser bank, the deforming force created can be precisely controlled. Thus, the amount of force can be varied such that only the amount of force sufficient to produce a particular desired shape will be applied to a workpiece.

Naturally, the latter type of forming involves a relatively high strain rate on the material. Many materials, when subjected to such high strain rates, would rupture or exhibit excessive thinning. In the present invention, however, the workpiece is formed in a manner such that substantially the entire amount of displacement into the die is produced by hydrostatic forming at relatively low strain rates. This result is illustrated in FIGURE 2 of the drawing wherein the force acting on the workpiece due to hydrostatic pressure is represented by the arrows **49**. To accomplish the final shaping of the workpiece in the die, a high energy electrical spark discharge is produced in the hydraulic fluid **39** occupying the interior of the workpiece **11**, thus driving the workpiece against the die cavity **13** as illustrated in FIGURE 3 of the drawing. The action of this force is represented by the arrows **51**. Although the strain rate in the final shaping operation is substantially higher than the strain rate in the initial forming step, the total amount of strain is so little in the final shaping step as to obviate any of the problems which might normally be encountered were a high strain rate to be applied over the entire displacement of the workpiece into the die.

In order to produce the spark, the circular projection **19** of the upper plug **21** has a pair of electrodes **53** passing therethrough and projecting into the interior of the workpiece **11**, terminating about halfway between the ends thereof. A thin wire **55**, such as a 40 to 60 mil diameter aluminum wire, is attached across the lower ends of the electrodes **53** to facilitate discharge between the electrodes. This technique is sometimes referred to as the "exploding wire" technique because the wire **55** is destroyed when the high voltage discharge occurs. Thus, a new piece of wire must be connected between the electrodes **53** for each forming operation, when using this technique. If desired, the electrodes **53** may be disposed closer together than shown to eliminate the need for a wire. This technique is sometimes referred to as the "spark" technique wherein the high voltage discharge jumps the gap between the lower ends of the electrodes.

The electrodes **53** are electrically connected to an energy storage bank **57**. The energy storage bank may comprise a plurality of capacitor banks (not shown) connected in parallel and connected to an external source of electrical power. The energy storage bank is controlled to build up a preselected level of electrical charge and to release this charge through the electrodes. By way of example, energy storage banks are known in the art which are capable of storing 48 kilojoules of electrical energy and can be fully charged in less than 10 seconds. Some or all of the capacitor banks in the energy storage bank may be charged at one time to vary the strength of the electrical discharge and thus regulate the force applied to the workpiece during the sizing step.

Once the forming operation is completed and the workpiece **11** is properly shaped in the die **15**, the workpiece is removed. In the illustrated apparatus, this is accomplished by draining the hydraulic fluid, releasing the clamping device **19**, opening the die **14** and then removing the plugs **17** and **21** from the respective ends of the workpiece. The process may then be repeated on another workpiece.

It may therefore be seen that the invention provides an improved forming method and apparatus for utilization in connection with workpieces which, because of their shape and/or material, do not readily lend themselves to forming by known techniques. Final shaping of the workpiece is readily accomplished by utilizing the principles of electrohydraulic forming, whereas the initial and major portion of the forming operation is accomplished by hydrostatic forming. The invention thereby combines the advantages of each of the two forming techniques to avoid difficulties frequently encountered with materials which are sensitive to relatively high strain rates but which have a tendency to spring back.

It should be understood that, while it is preferable to perform both forming steps in the same apparatus, the steps may be performed on separate apparatus. Also, the workpiece may be heated, either by induction or direct heating prior to or during either step. Also, the hydraulic fluid may be separated from the workpiece by a driver of rubber or similar flexible material.

Various other modifications and embodiments will be apparent to those skilled in the art from the foregoing discussion. Such other modifications and embodiments are intended to fall within the scope of the appended claims.

What is claimed is:

1. A method of forming a workpiece comprising subjecting the workpiece to a force developed by hydraulic fluid pressure to partially form the workpiece at a relatively slow strain rate, and subsequently subjecting the workpiece to a force produced by a spark in a hydraulic fluid to thereby conform the workpiece to the shape of a die at a relatively high strain rate.

2. A method in accordance with claim **1** wherein the workpiece is tubular and column loading is applied to the workpiece simultaneously with the application of fluid pressure thereto.

3. Apparatus for forming a workpiece including in combination, a die defining a die cavity, means for supporting the workpiece adjacent the die cavity, a hydraulic fluid in pressure communication with the workpiece, means for increasing the hydraulic fluid pressure to form the workpiece into an intermediate shape at a relatively slow strain rate and means for subsequently producing a spark in the hydraulic fluid to thereby force the workpiece against the surface of said die cavity at a relatively high strain rate.

4. Apparatus in accordance with claim **3** wherein the workpiece is tubular and wherein said die is of a configuration to surround the outer surface of the tubular workpiece.

5. Apparatus in accordance with claim **3** wherein means is provided for subjecting the workpiece to column loading while the hydraulic pressure is increased.

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CHARLES W. LANHAM, *Primary Examiner.*

K. C. DECKER, *Assistant Examiner.*

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,394,569 July 30, 1968

Kenneth Franklin Smith

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

In the heading to the printed specification, lines 3 and 4, "assignor to General Dynamics Corporation, New York, N. Y." should read -- assignor, by mesne assignments, to Gulf General Atomic Incorporated, San Diego, Calif. --. Column 1, line 64, "df" should read -- of --. Column 2, line 27, "later" should read -- latter --.

Signed and sealed this 30th day of December 1969.

(SEAL)

Attest:

Edward M. Fletcher, Jr.

Attesting Officer

WILLIAM E. SCHUYLER, JR.

Commissioner of Patents