COLD-WORKING PROCESS FOR PRESSURE VESSEL

Filed July 13, 1956

Fig. 1

Fig. 2

Fig. 3

Fig. 4

YIELD POINT OF STEEL

UNWORKED STRUCTURE

COLD WORKED STRUCTURE

STRESS

STRAIN

INVENTOR.
ROBERT L. NOLAND

STRAIN

STRESS

ATTORNEYS
This invention relates to the strengthening of materials and has particular reference to the manufacture and cold-working of pressure vessels.

The well known methods of strengthening materials fall into two broad groupings, which are designated generally as heat treating operations and plastic working operations.

The heat treating operations, generally speaking, a quenching of the piece to be hardened from a high temperature to a lower temperature, the rate of cooling of the piece determining the amount of hardness. Where the piece is of substantial thickness, it is generally found that only surface hardening of the piece results, since the rate of cooling within the interior of the piece is appreciably less than the rate of cooling near the exterior of the piece. For this reason, among others, the usual heat treating operations are inadequate for hardening or strengthening relatively thick pieces of material.

Plastic working operations on materials, such as metals and their alloys, are divided into either hot-working or cold-working processes, depending upon the temperature at which the material is worked. The hot-working operations are performed at temperatures above the recrystallization temperature of the material, while cold-working operations are performed below the recrystallization temperature, generally fairly close to room temperature. However, aside from the temperature of working, the working operations themselves are quite similar.

In the usual mode of working ductile materials, such as steel, aluminum, and cooper, and certain plastics, such as polyvinyl chloride, the material is placed under tension and stressed beyond its elastic limit. The plastic deformation resulting as soon as the elastic limit is exceeded is accompanied by a hardening of the material. After the yield point of the material is reached, deformation increases much more rapidly with relatively small increases in load.

The yield point of the material is raised as the material is plastically deformed beyond its original yield point, a manifestation of the effects of plastic strain. The material continues to deform with increasing stress until the point of ultimate strength is reached, the load thereafter decreasing until the material fractures. Since, in normal design practices, it is necessary to design structures on the basis of their yield strength in order to avoid occurrence of permanent deformations during use, the purpose of plastic working operations is to raise the yield point as high as possible, that is, as close as possible to the rupture stress of the material.

In this connection, it is noted that in a typical stress-strain diagram for a ductile material such as steel, the yield point, ultimate strength, and point of fracture are all determined on the basis of the original cross-sectional area of the material. However, as work hardening proceeds, the elongation and the reduction in cross-sectional area of the material become appreciable, and the typical mode of calculation does not yield a true stress, but rather a stress below the actual amount, the extent of inaccuracy depending upon the extent of the reduction in area. If the actual unit stress is calculated, that is, that stress based on a reduced area, the material will have a higher ultimate strength and a higher point of fracture than is indicated by the usual stress-strain curves. It is the true stress values that are taken advantage of in closely controlled working processes, where the yield point of a particular material is sought to be raised to a practical maximum.

The optimum strength characteristics of a ductile material such as steel can be achieved by closely controlling the stretching operations so that there is no localized deformation or necking. By close control in these operations it is possible to work the material to a point where the yield point and ultimate strength are almost equal. The type of stress-strain curve for a particular material, obtained by following the above working procedures, is highly advantageous, inasmuch as it is possible to realize the maximum strength characteristics of the material in actual applications.

However, the great practical disadvantage of such working operations is that expensive and heavy equipment is necessary in order to accomplish any degree of work on the material. This is especially true where materials are cold-worked rather than hot-worked.

Cold-working the materials, as opposed to hot-working, is preferred for a number of reasons, among which are elimination of the necessity to correct thickness measurements for thermal contraction, avoidance of oxidation of the material, control of grain size, and better surface finish.

The major disadvantage in utilizing cold-working processes is that more power and heavier equipment are necessary because of the greater resistance to deformation of materials at lower temperatures. Particularly difficult to cold-work by the usual methods are open or closed-ended hollow chambers, such as cylinders, spheres, and various other shapes, of any appreciable diameter.

Accordingly, it is a major object of the present invention to provide a simplified and economical method of cold-working materials to attain high strength characteristics suitable for pressure vessels and conduits, such as high pressure tanks, pipe lines, and the like.

It is another object of the present invention to provide a method of cold-working materials which includes a simplified means of closely controlling the deformation of the material to be cold-worked as it exceeds its yield point.

It is a further object of the present invention to provide a simplified and economical method for cold-working hollow chambers which includes the step of stressing the material to be cold-worked beyond its yield point, the majority of the load added thereafter being transferred to a second material affixed to the first, thereby to closely control the plastic deformation of the first material.

It is still another object of the present invention to provide an improved pressure vessel by the cold-working methods described in the foregoing objects.

It is still another object of the present invention to make a pressure vessel having improved strength characteristics which includes a cold-worked material normally in a state of compression, in combination with a second dissimilar material normally maintained in a state of tension.

Other objects and advantages of my invention will become more readily understood by referring to the following detailed description, and to the accompanying drawings, in which:

FIGURE 1 is a perspective view of a hollow structure adapted to be cold-worked, according to the principles of the present invention, a segment of the wall thereof being shown in cross-section;

FIGURE 2 is a cross-section of an apparatus useful in connection with the cold-working of materials by the method of the present invention;

FIGURE 3 represents the stress-strain curve of the structure shown in FIGURE 1 before and after it has been cold-worked according to the principles of the present invention; and

FIGURE 4 represents the stress-strain curve of one of
the materials of the structure of FIGURE 1 after it has been cold-worked, according to the methods of the present invention.

In general, the method of cold-working materials comprises affixing to the material to be cold-worked, or ductile material, a second material having preferably a lower modulus of elasticity and a yield point above a certain minimum, the exact minimum calculable in a manner to be described, stressing the combined structure to the yield point of the material to be cold-worked, further stressing the structure beyond the yield point of the material to be cold-worked whereupon the extra stress applied is taken up by the second material, the deformation of the material being cold-worked being controlled and substantially determined by the rate of deformation of the second material, continuing to increase the stress of the structure until a point approximately equal to the rupture is obtained, and finally, relieving the stress.

The new stress-strain curve of the composite structure has a yield point just below the point of rupture of the cold-worked material. The stress-strain curve for the cold-worked material itself similarly has its yield point substantially above the normalized yield point of the material and is very near that of the point of rupture of the material.

The cold-worked material of the composite structure is permanently deformed by the stressing action it has undergone and results in a pre-stressing of the second material. The net result is that the composite structure is composed of a deformation-controlling material in tension, and a cold-worked material maintained in a state of compression. If the material in tension is very light-weight in comparison with the cold-worked material, then such a composite type of structure in a pressure vessel becomes especially advantageous whenever weight and high strength at all stress levels are critical factors, as, for example, in the fields of rocketry, guided missiles, and aircraft.

The cold-worked material may also be used alone, if desired; that is to say, after cold-working the ductile material according to the principles of the invention, the deformation-controlling material may be stripped off.

Referring now to FIGURE 1, a cylindrical hollow structure is shown, designated by the numeral 10, open at each end. The structure 10 has a wall 11 composed of two dissimilar materials, the material to be cold-worked having ductile properties, and comprising the inner member or shell 12, the outer member or shell 14 comprising a material having preferably a lower modulus of elasticity than the material to be cold-worked, and acting as the deformation-controlling material.

As a specific example, the inner member 12 of the structure 10 may be composed of a plain carbon steel, such as AISI-SAE 1050, having the following composition:

<table>
<thead>
<tr>
<th>Element</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur</td>
<td>0.050</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.18–0.23</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.50</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.40</td>
</tr>
</tbody>
</table>

or an alloy steel, such as AISI-SAE 4130, having the following composition:

<table>
<thead>
<tr>
<th>Element</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur</td>
<td>0.40</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.28–0.33</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.40–0.60</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.05</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.20–0.35</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.80–1.10</td>
</tr>
<tr>
<td>Other</td>
<td>0.15–0.25</td>
</tr>
</tbody>
</table>

It will, of course, be understood that the above are merely examples of steel materials that may be cold-worked according to the principles of the present invention, the invention not being limited to these steels particularly, or to steels as a group. A good example of the diverse applications to which the process may be put is that ductile plastics, such as polyvinyl chloride, are cold-worked in a manner similar to that described, the resulting product having greatly increased strength properties.

If a steel, such as AISI 4130, is to be cold-worked, the outer member 14 of the structure 10 may be composed of a material such as reinforced glass which has a substantially lower modulus of elasticity than does steel, steel has a modulus of elasticity approximately equal to 30×10⁶ p.s.i., as contrasted with glass which has a modulus of elasticity approximately equal to 6×10⁶ p.s.i.

The glass shell 14 is formed on the outside of the steel shell 12 in any suitable manner. Preferably, plastic or resin-impregnated glass filaments are wound about the steel shell 12 so as to withstand hoop tensile loads. The glass filaments may be wound helically or longitudinally, as well as in circular fashion, to withstand both longitudinal and hoop tensile stresses. The type of winding usually depends to a great extent upon the final use to be made of the vessel.

The resin in which the glass filaments are embedded acts as a reinforcing means, suitable resins for this purpose being those of the epoxy class, although, of course, there are numerous other suitable plastics.

The thickness of the glass member or shell 14 is determined upon the basis of the strength and other characteristics of the steel shell 12, as will be described in greater detail hereinafter.

The glass-metal structure 10 is placed in an oven maintained at a suitable temperature to cure the resin. The structure 10 is now ready for cold-working.

Referring now to FIGURE 2, a cold-working apparatus, designated by the numeral 20, comprises a steel base plug 22 having an outwardly extending concentric support member 24 integrally formed therewith. A resilient deformable cylindrical plug 26, made of a material such as rubber, and having substantially the same inner diameter as the shell 12, is mounted on the steel base 22 in any suitable manner, as by means of a rubber adhesive. The composite structure 10 is then placed about a rubber plug 26, being supported by a steel member 24. An upper steel plug 28, directly contacts the rubber plug 26 and is depressed by means of a variable load, designated by the thickened arrow.

As the load is applied to the steel plug 28, the rubber cylinder is compressed, its cross-sectional area increasing uniformly, thereby subjecting the structure 10 to a uniform internal hydrostatic pressure. The loading is increased until the structure 10 is stressed beyond the yield point of the inner steel member 12. If the structure 10 is to be completely enclosed, as for example, a spherical shell or usual oil or water hydrostatic pressures may be used to stress these structures past the yield point of the inner member. It is thus seen that only small openings are required in the enclosed structures for entrance and exit of the pressurizing fluid.

Before the yield point of the steel is exceeded, and if, for example, the structure 10 has steel and glass members of equal thickness, the steel shell 12 carries approximately 85% of the total load applied, and the glass shell 14, the remainder. The proportion of total load carried by each wall is readily determined by the relative moduli of elasticity of the steel and glass, the steel carrying that portion equal to the ratio of its modulus of elasticity to that of the combined moduli of elasticity. This relationship holds true until the yield point of the steel is reached. The yield point of a particular steel is 90,000 p.s.i., and a hydrostatic pressure of 108,000 p.s.i. is applied, the yield point of the steel, 90,000 p.s.i. is reached. The amount of stress exerted on the glass is, at this point, approximately 18,000 p.s.i.

As the hydrostatic pressure is further increased, for example, to 110,000 p.s.i., the yield point of the steel is exceeded; however, the usual resultant local deforma-
tion in the steel accompanying a stress beyond its yield point, is substantially prevented by the presence of the outer glass shell 14.

The glass shell 14 possesses uniform strength characteristics which positively and effectively prevent any local yielding or deformation of the steel, even though the stage of plastic deformation for the steel has been reached.

Further, the glass shell 14 takes up proportionally more of the load than before because less load is required for the deformation of the steel as it is stressed beyond its yield point. The rate of deformation of the steel shell 12 is retarded and controlled by the now lower rate of deformation of the glass shell 14, the rate of deformation of the glass shell following Hooke’s law until its yield point of 150,000 p.s.i. is reached. While the rate of deformation of the steel, above its yield point, affects, to a certain extent, the rate of deformation of the composite structure 10, the significant factor in determining the composite rate of deformation beyond the yield point of the steel is the rate of deformation of the glass shell 14.

Thus, it can be seen that by the relatively simple and inexpensive expedient of providing a deformation-controlling outer material, the inner steel shell 12 is positively and effectively prevented from localized deformation and yielding as it is being cold-worked.

Referring again to the above example, the total maximum load that can be applied to the structure 10 is determined only by the rupture point of the material to be cold-worked. This point is reached before the yield point of the glass shell is attained. This fact is determined by a consideration of the yield point of the glass and the stress upon it at that time when the yield point of the steel has been reached. The glass shell 14 has a yield point of 150,000 p.s.i. and carries only 18,000 p.s.i. when the yield point of the steel shell 12 is reached. Therefore, the glass shell could theoretically carry an additional 132,000 p.s.i. before yielding. However, the steel shell 12 plastically deforms so as to cause the true stress in the steel to be equal to the rupture stress, after the application of an additional load which is less than that required to attain the glass yield point. Therefore, it is seen that a maximum amount of cold-working may be accomplished by the above-described method, the result being that both the steel and the composite structure being nearly that of the true rupture stress of the steel.

The deformation-controlling outer material should preferably have, but need not have, a lower modulus of elasticity than the material to be cold-worked. Further, if the thickness of the outer material may have a smaller cross-sectional area than the inner material, but this is generally not preferable, since the stress increases as the area decreases for equal loads.

If the modulus of elasticity of the outer material is the same or higher than the material to be cold-worked, an equal or greater proportion of the load will be borne by the outer material, if the thicknesses are approximately equal. Thus, for equal elastic moduli and equal thicknesses of the materials, if a stress of 90,000 p.s.i. is the yield stress of the material to be cold-worked, at least 180,000 p.s.i. total load is required, 90,000 p.s.i. being carried by the outer material. This is to be contrasted with the principal steel-glass example, where 108,000 p.s.i. total load only was required to obtain the yield point of 90,000 p.s.i.

After a load of 180,000 p.s.i. has been exceeded in the instant example, and assuming the yield point of the outer material is somewhat above 90,000 p.s.i., the material may be controllably cold-worked in the same manner as described with reference to the glass-steel example. However, a greater total load for equal amounts of cold-working is required.

Thus, it can be seen that while it is advantageous and preferable to utilize a material of lower modulus of elasticity than the material to be cold-worked, it is not a prerequisite of the cold-working process.

Further, if the deformation-controlling material has a thickness less than that of the material to be cold-worked, for example, one-fourth, and has the same or higher modulus of elasticity, the outer material initially takes up at least approximately 20% of the total load applied, which again is comparable to the principal glass-steel example. If the yield point of the material is sufficiently high so that it can withstand the extra stress required for cold-working to the rupture stress of the inner ductile material, this structure would be suitable. It should be noted, however, that, as the area of the outer material is decreased, the stress thereon must increase, since the outer deformation-controlling material must carry the same fraction of the total load applied.

It should further be noted that the yield point of the outer material must have a certain minimum value depending upon the relative thicknesses of the materials to be used, their elastic moduli, the amount of cold-working desired, and other complex factors.

The proportion of total load carried by each material, before the yield point of the material to be cold-worked is attained, is determined according to the following formula:

\[
L_o = \frac{A_o E_o}{A_o E_o + A_d E_d} \quad (1)
\]

where \(L_o\) is the fraction of the total load carried by the material being cold-worked, \(A_o\) and \(A_d\) are the cross-sectional areas of the material to be cold-worked, and the deformation-controlling material, respectively, and \(E_o\) and \(E_d\) are the elastic moduli of the material being cold-worked, and the deformation-controlling material, respectively.

To obtain the stress in the deformation-controlling material when the yield point of the material cold-worked is reached, the following formula is used:

\[
P \frac{L_o}{A_d} = S_d\quad (3)
\]

where \(S_d\) is the stress in the deformation-controlling material, and \(P\) is the total weight load applied when the yield point of the material being cold-worked is reached.

Thus, \(S_d\) being equal to the minimum yield point required of the deformation-controlling material in order to commence the cold-working of the ductile material.

If the elastic moduli of the materials are changed with respect to each other, it is readily seen that the load carried by each will also be altered. As the loads, carried by each material, are changed, the minimum required yield point of the deformation-controlling material will also change and must be equal to the total stress carried by it when the yield stress for the material to be cold-worked is attained.

It should be understood, however, that the required minimum yield point of the deformation-controlling material is much more greatly affected and therefore determined by the amount of load taken up by it after the yield point of the steel is exceeded, rather than before the yield point of the steel is exceeded. The deformation-controlling material will carry much, if not substantially all, of the added extra load, since deformation of the steel will proceed with much less load than previ-
only required. The steel does take up some undetermined portion of the total load as the deformation proceeds, since it is being strengthened, and it is therefore difficult to ascertain the exact amount of load taken up by each of the materials. Therefore, it is difficult to ascertain the exact required yield strength of the deformation-controlling material for any particular amount of cold-working.

The minimum yield strength required for the cold-working is, therefore, if it is to be defined, definable in terms of the amount of load the deformation-controlling material carries when the yield point of the material to be deformed is reached. This determination depends upon the thicknesses of the material desired, which in turn depends upon weight and size considerations, and the determination also depends upon the elastic moduli of the materials in question. Mathematically, the minimum yield strength (S_y) is defined by Formula 4 above.

After the desired amount of work hardening has been accomplished, the load is released. The structure 10 is now suitable for use as a high pressure vessel in pipelines, rocket shells, missile shells and the like, either in its composite state or with the outer shell stripped off, as will be described hereinafter.

The stress-strain curve for the structure 10, as it is being cold-worked, is represented graphically in FIGURE 3. The strain on the structure 10 is proportional to the stress exerted thereon until the yield point of the steel shell 12 of the structure is attained. The slope of this line of proportionality is substantially equal to the addition of the elastic moduli of the particular steel and glass used.

Above the yield point, the structure 10 begins to deform more rapidly than in the elastic portion of the curve, conforming more closely to the slope of the line of proportionality of the glass shell 14. This is to be expected, since, above the yield point of the steel, the glass carries more of the increased load, and its rate of deformation is the controlling factor in determining the amount of deformation of the steel.

The stress is increased upon the structure 10 until the rupture point for the steel in the structure is nearly reached, the deformation of the structure being, at this point, a maximum.

As the load is released, the structure undergoes a certain amount of "spring back" but is permanently deformed due to the permanent plastic deformation of the steel.

The glass shell 14 may be stripped from the steel shell 12, if desired, but, in general, it is advantageous to retain the glass in place about the steel. If the glass shell 14 is retained in place, the permanent deformation produced in the steel causes the glass to be maintained in a state of tension. The glass shell 14 thereby exerts compressive forces on the steel and the steel is, in turn, maintained in a state of compression.

As internal hydrostatic pressure is applied to the structure, whether under actual working conditions or under test conditions, the stress-strain curve for the structure 10, after it has been cold-worked, will follow a straight line practically to the rupture point of the steel itself. Since the steel shell 12 in the structure 10 is initially under compression, the initial hoop tensile stress exerted upon the structure brings the total stress in the steel wall up to zero. The point of zero stress in the steel wall 12 is indicated at point A in FIGURE 3.

As the internal hydrostatic pressure is further increased, the tension in both steel and glass members increases linearly until the rupture point of the steel is nearly attained. This is designated as point B in FIGURE 3.

The glass shell 14 adds greatly to the strength characteristics of the pressure vessel 10. At low internal pressures, the glass shell takes up a portion of the load. At higher stress levels, that is, above point A in FIGURE 3, and practically up to the rupture point of the steel, the glass shell 14 also takes up a position of the load, as described previously. Thus, it can be seen that effective use is made of the glass shell 14 at all stress levels.

Since the glass wall is much lighter than the steel wall, having a density of approximately 0.065 pound per cubic inch, as compared with a density of approximately 0.283 for steel, it is readily seen that in combination with a steel inner wall, the composite vessel is highly advantageous for those high pressure uses where weight is a critical factor. Rocketry, missiles, and aircraft are some important examples of such fields of use.

Further, in a closed end vessel, the hoop tensile stresses are equal to twice the longitudinal stresses. By proper orientation of the glass filaments, the glass shell formed therefrom can be made to withstand a much greater hoop tensile load than longitudinal load. A preferred orientation to accomplish this purpose is both a circular and longitudinal winding of the glass filaments about the steel shell 12, that is, in order to avoid longitudinal failure of the vessel, prior to hoop failure, especially in the closed end vessel embodiment, it is preferable to form the outer glass shell 14 in a manner so as to have a plurality of longitudinal glass filaments, as well as circular windings.

Where the composite vessel 10 is to be used mainly as an internal pressure vessel, it is therefore highly advantageous to retain the glass shell 14 because of the added strength characteristics imparted thereby but with a relatively small increase in the total weight of the vessel.

After the steel has been cold-worked by the method previously described, the glass shell 14 may, in certain instances, be undesirable. The glass wall 14 may then be stripped off and the steel shell 12 used alone.

In order to facilitate the stripping off of the glass shell 14, it is usually necessary to coat the outer surface of the steel shell 12 with a wax or other mold releasing substance preparatory to the winding of the glass filaments.

The stress-strain curve of the steel shell 12, after being cold-worked, is shown in FIGURE 4. The point C designates the point of zero stress and the amount of permanent deformation, present in the steel. As the stress increases, the curve follows a straight line substantially parallel to the usual slope defined by Hooke's law. However, the proportionality continues beyond the normalized yield point of the steel, designated by D, and also continues linearly beyond the normalized ultimate strength designated by E. The linearity continues until point F is attained, point F being close to point G, the true rupture stress of the steel. Point F is the equivalent yield point obtained by following the principles of my invention.

It should be understood that the composite glass-steel structure 10 may be used, if desired, prior to the cold-working of the steel shell 12. In such instances, the vessel, upon being subjected to internal stress, would follow the initial portion of the curve in FIGURE 3, the vessel undergoing permanent deformation as the yield point of the steel is exceeded. However, it should be realized that optimum use of the glass-steel structure 10 is not made until after plastic deformation has been accomplished, as previously described.

Further, it is generally advantageous to eliminate the possibility of permanent deformation of the vessel 10 during use. For these reasons, the vessel is usually subjected to a hydrotest procedure such as the one previously described.

From the foregoing, it is seen that a method of cold-working ductile materials has been described which utilizes a simple and relatively inexpensive method of producing work hardened pressure vessels having a much higher yield point than that originally possessed by the normalized vessel. The structures that are cold-worked are not restricted to any specific shape. For example, hollow enclosed shapes, such as spherical or conical enclosed...
chambers, are similarly cold-worked according to the principles of the present invention.

Attention is directed particularly to the cooperative relationship between the outer material of the vessel and the inner wall comprising the material to be cold-worked, whereby the deformation of the material to be cold-worked is closely controlled as the stress on the material exceeds its normalized yield point.

Attention is also directed to the fact that the invention is not limited to the cold-working of steels, or metals in general, but has much wider applicability inasmuch as any ductile material can be cold-worked according to the principles of the present invention to make a high strength structure, a specific example of such wider applicability being the cold-working of ductile plastics.

Attention is further directed to the resulting cold-worked product having a composite wall comprising two layers of material, one of the layers in the wall being in a state of tension, and the other being in a state of compression. The pressure vessel so produced is advantageous, especially where great internal pressures and a necessity for light weight, are encountered, inasmuch as one of the materials be made of relatively low density material and still contribute to the over-all strength characteristics of the vessel.

It is to be understood that while a preferred embodiment of the invention has been described and illustrated, the invention is not limited to such an embodiment, but rather is limited only by the appended claims.

I claim:

1. A method of cold-working a hollow chamber composed of a metal material which comprises: affixing a second material comprising predominately glass to said metal material which is to be cold-worked to form a composite structure, said metal material having a substantially higher modulus of elasticity than that of said second material; stressing the structure beyond the yield strength of the metal material, the second material being of sufficient thickness to carry a major portion of the load added without rupture, after the yield point of the metal material has been exceeded, and preventing localized deformation as the metal material is stressed past its yield point; and relieving the stress on the structure.

2. A method of cold-working a hollow chamber composed of a steel material which comprises: affixing a second material comprising predominately glass to said steel material which is to be cold-worked, to form a composite structure, said steel material having a substantially higher modulus of elasticity than that of said second material; stressing the structure to a point past the yield point of the steel material but below its rupture point, the second material carrying some of the stress below the yield point of the steel material, and being of sufficient thickness to carry a major portion of load added without rupture, as the yield point of the steel material is exceeded thereby preventing localized deformation of the steel material during the cold-working stage; and relieving the stress on the structure.

3. A method of cold-working a hollow chamber composed of ductile metal which comprises: affixing a second material comprising predominately glass to said ductile metal, said second material having a substantially higher modulus of elasticity than the second material, to form a composite structure; stressing the structure to the yield point of the ductile metal whereby the ductile metal carries that portion of the total load which is substantially equal to

\[
\frac{(A_d)(E_d)}{A_dE_d + A_sE_d}
\]

where

\(A_d, A_s\) are the cross-sectional areas of the ductile metal and the second material respectively, and

\(E_d, E_s\) are the elastic moduli of the ductile metal and the second material respectively
having the steel in compression and the glass wall in tension and having a composite yield point near the rupture point of the steel.

<table>
<thead>
<tr>
<th>References Cited in the file of this patent</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>UNITED STATES PATENTS</td>
<td>5</td>
</tr>
<tr>
<td>2,337,247        Kepler                      Dec. 21, 1943</td>
<td></td>
</tr>
<tr>
<td>2,366,141        Alderfer                     Dec. 26, 1944</td>
<td></td>
</tr>
<tr>
<td>2,373,038        Lindsay                      Apr. 3, 1945</td>
<td></td>
</tr>
<tr>
<td>2,685,979        Zeek et al.                  Aug. 10, 1954</td>
<td></td>
</tr>
<tr>
<td>2,742,873        Moore                        Apr. 24, 1956</td>
<td></td>
</tr>
<tr>
<td>2,744,043        Ramberg                      May 1, 1956</td>
<td></td>
</tr>
<tr>
<td>2,809,762        Cardona                      Oct. 15, 1957</td>
<td></td>
</tr>
<tr>
<td>2,849,878        Adams                        Sept. 2, 1958</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FOREIGN PATENTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>671,609        Great Britain                May 7, 1952</td>
<td></td>
</tr>
</tbody>
</table>