April 22, 1969 I BERMAN ET AL 3,439,405

METHOD OF VESSEL FABRICATION

Filed Nov. 25, 1966 Sheet 1 of 2

FIG 1

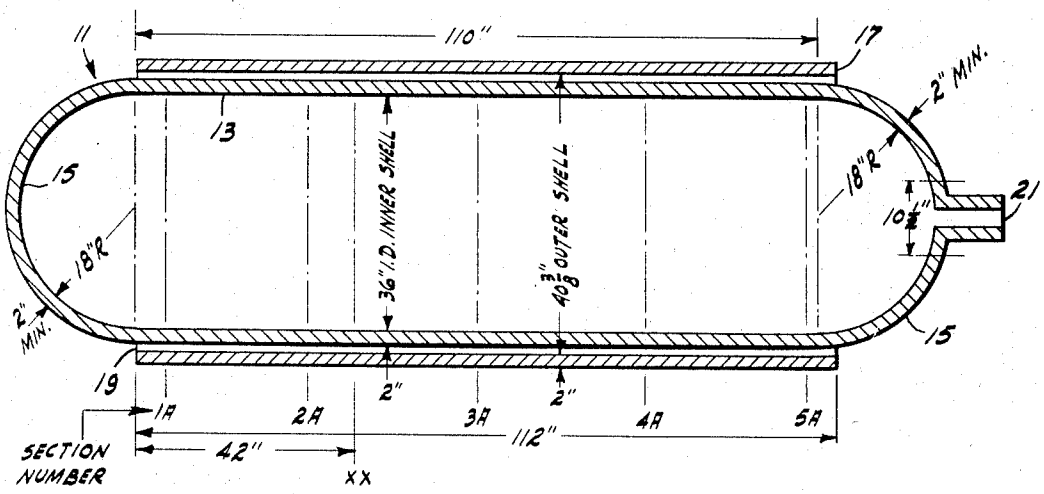
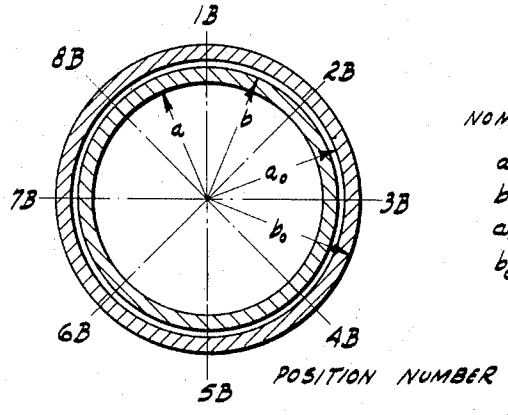


FIG 2



NOMINAL RADII

a = 18"

b = 20"

a_o = 20.188"

b_o = 22.188"

MEASURED INTER-LAYER CLEARANCE IN $\frac{1}{64}$" *

POSITION / SECTION	1B	2B	3B	4B	5B	6B	7B	8B
1A	14	14	13	26	18	12	7	14
2A	14	19	14	18	12	6	6	12
3A	16	17	8	18	17	18	6	8
4A	15	16	12	12	10	6	14	12
5A	15	20	14	11	4	7	15	16

* NOMINAL CLEARANCE = $\frac{3}{16}$"

FIG 3

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FIG. 4

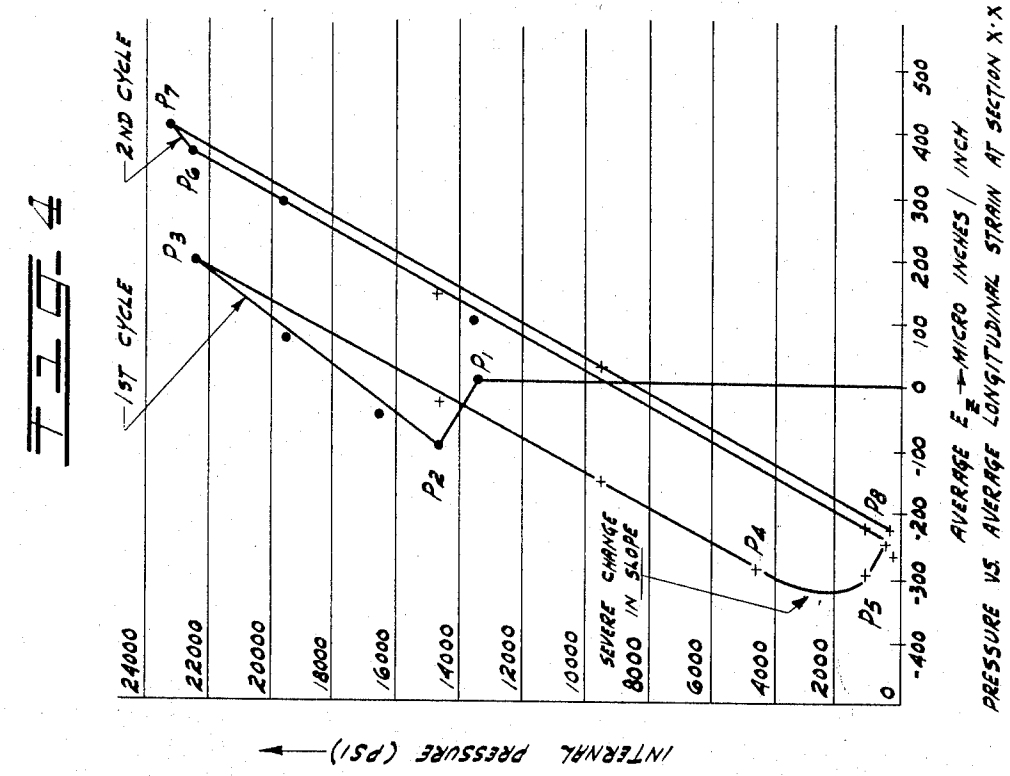
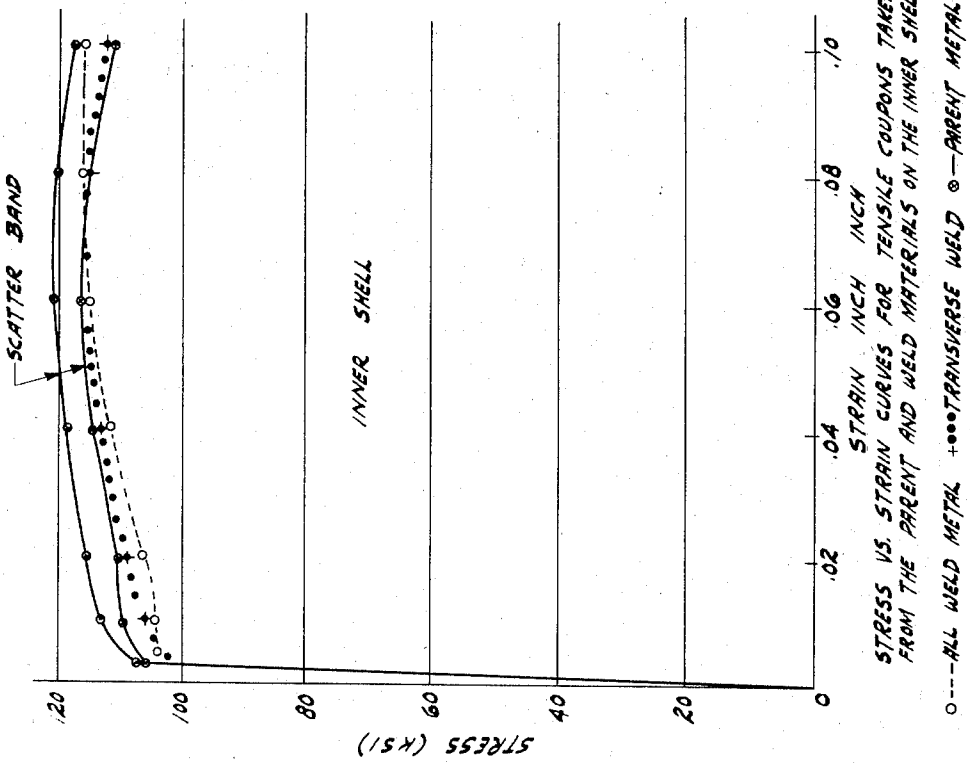

1ST CYCLE
2ND CYCLE
P1
P2
P3
P4
P5
P6
P7
P8
SEVERE CHANGE IN SLOPE
24000
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-400 -300 -200 -100 0 100 200 300 400 500
INTERNAL PRESSURE (PSI)
AVERAGE ϵ_z +-MICRO INCHES / INCH
PRESSURE VS AVERAGE LONGITUDINAL STRAIN AT SECTION X-X
• LOADING
+ UNLOADING

FIG. 5


SCATTER BAND
INNER SHELL
120
100
80
60
40
20
0
.02
.04
.06
.08
.10
STRESS (KSI)
STRAIN INCH / INCH
STRESS VS. STRAIN CURVES FOR TENSILE COUPONS TAKEN FROM THE PARENT AND WELD MATERIALS ON THE INNER SHELL
o---ALL WELD METAL +•••TRANSVERSE WELD ⊗—PARENT METAL

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3,439,405

METHOD OF VESSEL FABRICATION

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Int. Cl. B23p 11/02; B23q 17/00
U.S. Cl. 29—407 6 Claims

This invention relates to a method of manufacturing pressure vessels and the like, and in particular, to a method of manufacturing vessels from two layers of material.

As the pressure requirements of vessels increases, it is well recognized that the thickness of the wall material must also increase. However, as the thickness of the vessel material, in general a ferrous metal, increases in thickness, the problem of obtaining a uniform hardness of the material across its entire cross-section becomes increasingly difficult. As a result, the cost of the material becomes substantially more expensive and difficult to obtain.

In the past, the generally accepted practice in pressure vessel fabrication has been to use rolled forgings. Very worthwhile economic savings could be achieved if brake bending were used in place tof rolled forgings. With thinner sheets, brake bending could be utilized providing a suitable method of fabrication was available which could economically produce a multilayer vessel.

A generally accepted configuration for a pressure vessel is a cylinder with a hemispherical head at each end. Since the hemispherical heads must withstand approximately one-half the stress of the cylindrical portion of the vessel, the hemispherical heads can be one-half the thickness. For this reason, it is practical to construct an inner cylinder with two hemispherical heads all of which have substantially the same thickness. An outer cylinder is then formed and slid on the inner cylinder. A clearance between the inner cylinder and the outer cylinder is required to permit the inner cylinder to fit into the outer cylinder. Then the inner cylinder must be expanded into the outer one until there is virtually no freedom between the two cylinders. In order to achieve such an expansion, fabrication techniques are required by which the proper fabricating pressure can be accurately determined. Without the proper determination of such a pressure, pressure levels can be reached at which an instable fabrication occurs resulting in deformation and fractures. To further complicate the problem, the pressure for correct fabrication and the pressure for instable fabrication are very close together.

Of perhaps even greater importance is certainly that the two-layer vessel is properly fabricated. That is to say, it is essential that the two layers act as a monolayer at all pressures and that the method of fabrication include a control on whether or not fabrication is complete.

Therefore, it is an object of this invention to provide an improved method of fabricating two-layer vessels.

Another object is to provide a reliable and economical method of controlling the fabrication of a two-layer vessel.

Another object of this invention is to provide a method of fabricating a two-layer vessel which gives a positive indication of whether or not the two layers are acting as one layer at all pressures after tentative fabrication.

In accordance with this invention a hitherto unused indication, namely, longitudinal strain gages on the outside shell is shown to be a sensitive index to determine the adequacy of internal pressurization of fabrication. Longitudinal strain gages may also be used, either with or without circumferential gages, to indicate the onset of excessive plastic deformation. Longitudinal strain gages are attached to the outside surface of the outer cylindrical shell to observe the longitudinal strain behavior while the inner vessel is being expanded by any suitable method such as hydrostatically. A suitable internal pressure is selected so that the inner cylinder will become fully plastic and contact the outer cylinder without creating an instable condition. The internal pressure is then reduced. If the longitudinal strain gages show that axial sliding exists between the inner and outer cylinders, the inner pressure is again increased to a level above that initially applied so as to slightly increase the strain gage readings. Upon depressurization, the strain readings are again observed to assure that no axial sliding exists. Should any occur, further increased pressurization is applied until no axial slipping occurs.

This invention may be better understood from the following detailed description in conjunction with the accompanying drawings in which:

FIGURE 1 is a side elevation in cross section of a vessel prior to expansion of the inner cylinder into the outer cylinder;

FIGURE 2 is a cross-sectional view of FIG. 1;

FIGURE 3 is a chart of the irregularities between the inner cylinder and the outer cylinder in the sections of FIG. 1 and the positions of FIG. 2;

FIGURE 4 is a graphic illustration of the average measured relationship of internal pressure and strain at section x—x of FIG. 1 for two pressure cycles; and

FIGURE 5 is a graphic illustration of the stress-strain relationship for tensile coupons taken from the parent and weld materials of the inner shell.

Referring now to the drawings and particularly to FIG. 1, a vessel **11** is shown formed from an inner cylinder **13** with a hemispherical head **15** at each end. Surrounding the inner cylinder **13** is an outer cylinder **17** open at both ends. As was previously pointed out, a double thickness in the hemispherical heads **15** is not required since the hemispherical heads can withstand identical internal pressure with only approximately one-half the thickness of the cylindrical portion. An annular space **19** exists between the inner cylinder **13** and the outer cylinder **17**. Since these two cylinders **13**, **17** are formed by brake bending, irregularities exist in their shape. However, a nominal clearance of $\frac{3}{16}$ inch did exist between the two cylinders with variation in clearance ranging from $\frac{13}{32}$ of an inch to $\frac{1}{16}$ of an inch. The variations in clearance are caused by local changes of curvature as well as overall out-of-roundness. These noncircularities also vary axially. In addition, material property and plate thickness variations create stress nonuniformity. The end conditions are not considered because they are local and the heads would reinforce in operation as well as fabrication. In FIG. 3 is a chart of the actual measurements taken at sections **1A** through **5A** for positions **1B** through **8B** of FIG. 2.

It should be understood that the scope of this invention is not limited to either the specific configuration or the dimensions or both as herein described and as illustrated in the drawings. Similarly, the specific material and its properties are not limitations on the scope of this invention. The particular embodiment described is being used purely by way of example, as the explanations of the concepts involved and the advantages of this invention are best understood in the light of a specific numerical example.

The various dimensions of the particular vessel being utilized are shown in FIG. 1 and need not be repeated. The particular material selected is USS T–1 steel.

The chemical composition of this steel is as follows:

	C	Mn	Si	S	P	Cr	Ni	Cu	V	Mo	B
Outer cylinder	.17	.90	.28	.017	.011	.53	.79	.25	.07	.46	.003
Inner cylinder	.16	.84	.22	.021	.012	.53	.80	.25	.07	.46	.0025

In this specification the following symbols will be used:

a=Inner radius of the inner cylinder (inches)
a_o=Inner radius of the outer cylinder (inches)
b=Outer radius of the inner cylinder (inches)
b_o=Outer radius of the outer cylinder (inches)
c=Radial distance to the elastic-plastic boundary of a cylinder (inches)
E=Young's Modulus (p.s.i.)
p_i=Internal pressure (p.s.i.)
p_o=Interface pressure between the two cylinders (p.s.i.)
r=Radial distance of a cylinder (inches)
r_i=Inner radius of a cylinder (inches)
r_o=Outer radius of a cylinder (inches)
u=Radial displacement of a cylinder (inches)
Y=Yield strength of the material (p.s.i.)
ϵ_r=Radial strain (inches/inch)
ϵ_θ=Circumferential strain (inches/inch)
ϵ_z=Longitudinal (axial) strain (inches/inch)
ν=Poisson's ratio
σ_r=Radial stress (p.s.i.)
σ_θ=Circumferential stress (p.s.i.)
σ_z=Longitudinal (axial) stress (p.s.i.)

The first step in fabrication is the selection of a tentative pressure by means of calculation. In order to determine a tentative pressure, a yield point for the vessel material must be obtained. The use of the equations of perfect plasticity requires that the stress-strain curve sufficiently approximates such a material only to the strains reached. For the T-1 steel used, consider the point on the average tensile yield curve at which the total strain is equal to that necessary to close the nominal gap. In this case the ratio of the gap ($\frac{3}{16}$ inch) to the inner radius (18 inches) is 0.0104. The use of the gap to inner radius ratio as the total strain of the inner cylinder is arbitrary. The strain on the inner cylinder is a bit higher than this since it expands into the outer cylinder.

The tensile test stress-strain curves may be seen in FIG. 5 for the specimens from the parent metal and specimens transverse to the weld. If the total strain of 0.0104 is used in conjunction with the mean of the scatter band of the inner cylinder, the result is a yield stress of 112,300 p.s.i. for the inner cylinder. The tentative pressure for fabrication is only approximate and for simplicity, a yield strength of 112,300 p.s.i. will be used for both cylinders.

The inner cylinder becomes fully plastic and contacts the outer cylinder at which time both an inner and outer pressure acts on the inner cylinder. A relationship between the pressures and the geometric and material properties of the cylinder may be written as

$$p_i = p_o + Y_o \ln\left[\frac{a_o}{a+a_o-b}\right]$$

The value of p_o may be determined from consideration of the outer shell. Since the outer shell feels only the pressure on its outer surface and the criterion for fabrication pressure is assumed to be initial yielding of the outer cylinder, the result may be obtained from Tresca's yield criterion at the inner surface and written as

$$p_o = \frac{Y}{2}\left[1-\left(\frac{a_o}{b_o}\right)^2\right]$$

From these two equations, the value of p_i can be calculated using data as follows:

$E=30\times10^6$ p.s.i.
$\nu=0.3$
$a=18$ inches
$b=20$ inches
$a_o=20.188$ inches
$b_o=22.188$ inches

Using these values, p_i is equal to 21,400 p.s.i. This pressure should be on the low side of the true pressure because the plates are generally received thicker than nominal.

A comparison of the tentative pressure calculation wth the instability pressure p_u shows that the use of longitudinal strain gages as an aid in the determination of the fabrication pressure is important.

Strain gages can be located at numerous places about the vessel **11**. However, for purposes of simplicity of explanation, this explanation will only consider longitudinal strain gages located about the vessel **11** on line x—x of FIG. 1. Water was used as the pressurization medium and was introduced through the opening **21**.

For the purpose of pressure fabrication, the inner vessel was pressurized from zero to 22,400 p.s.i. in nine increments and the depressurization was accomplished in five steps back to 400 p.s.i. The vessel was subsequently pressurized to 23,100 p.s.i. in five steps and unloaded to zero in six steps. The pressurization to 22,400 p.s.i. and subsequent unloading is designated as Cycle 1. The reloading to 23,100 p.s.i. and its subsequent unloading to zero is designated as Cycle 2. In all cases, at pressures above 20,000 p.s.i., each pressure was held for at least fifteen minutes. The pressure was not changed until none of the strain gages showed any further increase of strain.

Initially as the pressure inside the inner cylinder **13** is increased, since there is no contact between the cylinders **13**, **17** there is no strain on the outer cylinder **17**. It was ascertained from analysis that because of the large gap **19** the inner cylinder **13** becomes fully plastic prior to its contact with the outer cylinder **17**. Since change in the longitudinal strain of the outer cylinder **17** is zero, the slope on the pressure versus longitudinal strain line from 0 to p_1 is infinite as seen in FIG. 4.

At internal pressure p_1 the inner cylinder which is fully plastic contacts the outer shell **17**. The outer shell **17** is radially expanded, but the pressure is not sufficient to prevent axial sliding between the two cylinders **13**, **17**. Thus, from internal pressure p_1 to p_2 the outer shell **17** indicates the behavior of an elastic open-ended cylinder subjected to a pressure p_o where p_o is the contact pressure.

At internal pressure p_2 the pressure contact between the two cylinders **13**, **17** is sufficient to prevent adidtional axial sliding. The sliding may not be totally prevented; but, for the purpose of the analysis it is assumed that the subsequent pressure force is resisted jointly by the two cylinders. **13**, **17** in proportion to their cross-sectional area. The pressure increase is continued until the pressure p_i reaches p_3, the tentative pressure.

Upon reduction of the internal pressure the inner shell **13** reverts to elastic behavior. The two cylinders **13**, **17** noticeably act as a four-inch thick walled monobloc cylinder with closed ends. As FIG. 4 readily shows, the slope of the curve in Cycle **1** from p_2 to p_3 is less steep than that of the descending pressure curve from p_3 to p_4. The difference in slope may be due to the fact that sliding may not be totally prevented on loading. On unloading the tendency to slide is reduce so there should be no sliding at the higher pressures during unloading. Another reason for the difference in slopes may be the local plasticity effects on loading.

When depressurization reached an internal pressure of p_4, axial sliding reoccurs. The outer cylinder again acts as an open end elastic cylinder with pressure p_o at its inner surface. The inner cylinder acts as a closed end elastic cylinder with a pressure p_i on the inside and p_o on the outside.

The axial sliding between the internal pressures p_4 and p_5 of the first cycle is an important feature of this invention. The pressurization for fabrication should be carried

out in at least two steps. The first step should be a pressurization to the tentative fabrication pressure such that reverse sliding to relieve the axial force between the cylinders occurs on depressurization. The second pressurization should not cause large overall strains of the outer cylinder.

The graphic effect of reverse sliding is a feature of longitudinal strain gages. This axial sliding cannot be noted if circumferential strain gages are used. This is because with circumferential strain results, the slopes for the monobloc cylinder behavior and for the reverse sliding are identical.

The large axial force between the two cylinders **13**, **17** caused by different elongations in loading and the friction force was largely dissipated in the reverse sliding. Therefore, on reloading for the second cycle the cylinder contact is sufficient to cause elastic monobloc action to the maximum pressure of previous pressuriaztion. This is shown in FIG. 4 between p_5 and p_6. At p_6 the strain is the same as at p_3, since the scale has shifted due to axial sliding.

Additional pressure is added to cause a slight increase in longitudinal strain as shown between p_6 and p_7. The longitudinal strain gages at this point in the fabrication serve to give an indication of adequate fabrication pressure as well as warn of plastic instability. With longitudinal gages, a severe change in strain indicates that deformation is taking place. For this reason, while the additional pressure increment is being applied in the second cycle, the longitudinal gages should be closely observed and the pressure released at any showing of a run away condition. It should be pointed out that with circumferential strain gages, a small amount of deformation may be noted at the elevated pressure of the second cycle on individual gages as well as on averages of the gage readings.

The depressurization shown as p_7 to p_8 takes place as a monobloc cylinder and since no reverse sliding is evident, fabrication can be considered complete. Where reverse sliding occurs, the general procedure of the second cycle would be repeated as a third cycle or until reverse sliding stops.

It is to be understood that the above-described methods and arrangements are simply illustrations of the application of the principles of the invention. Numerous other methods and arrangements may be readily devised by those skilled in the art which will embody the principles of this invention and follow within the spirit and scope thereof.

What is claimed:

1. A method of fabricating a two-layer pressure vessel:
- forming an inner shell, said inner shell being a complete enclosure with an opening therein;
- forming an outer shell about said inner shell, the inside of said outer shell being slightly larger than the outside of said inner shell;
- determining a tentative internal pressure level for application to the inside of the inner shell to expand both the inner shell and the outer shell;
- applying a fluid medium to the inside of the inner shell through the opening therein to increase gradually the pressure up to the selected tentative inner pressure, thereby expanding both the inner vessel and the outer vessel;
- removing the fluid medium to decrease the pressure within the inner vessel thereby contracting both the inner vessel and the outer vessel;
- observing the longitudinal strain on the ouside of the outer shell in relation to the decreasing pressure to determine if their ratio remains constant thereby determining presence of reverse sliding;
- reapplying the fluid medium to the inside of the inner shell through the opening therein to increase gradually the pressure up to the selected tentative inner pressure;
- further increasing the pressure a slight amount over the tentative inner pressure;
- removing again the fluid medium to decrease the pressure within the inner vessel thereby contracting both the inner vessel and the outer vessel; and
- observing again the longitudinal strain on the outside of the outer shell in relation to the decreasing pressure to determine if their ratio remains constant thereby determining the presence of reverse sliding.

2. A method according to claim **1** wherein said inner vessel is formed from a cylinder with a hemisphere at both ends.

3. A method according to claim **2** wherein said outer vessel is a cylinder open at both ends.

4. A method according to claim **3** wherein the cylinder of the inner vessel and the outer vessel are fabricated by brake bending.

5. A method of fabricating a two-layer pressure vessel:
- forming by brake bending an inner cylinder;
- forming two hemispherical heads;
- welding said two hemispherical heads to said inner cylinder to form an inner vessel, said inner vessel having an opening therein;
- forming by brake bending an outer cylinder, said outer cylinder being at least as long as said inner cylinder and having a nominal inner diameter slightly larger than the nominal outer diameter of said inner cylinder, said outer cylinder and said inner vessel having substantially the same thickness;
- sliding said outer cylinder over said inner vessel;
- placing longitudinal strain gages about the ouside of said outer cylinder at a location substantially remote from either end of said outer cylinder;
- determining a tentative internal pressure for application to the inside of the inner shell to expand both the inner shell and the outer shell;
- applying hydrostatic pressure to the inside of said inner vessel through the opening therein to increase gradually the internal pressure within the inner vessel up to the tentative internal pressure;
- observing the relationship between the longitudinal strain on the outside of the outer cylinder and the increasing internal pressure to avoid deformation;
- removing the hydrostatic pressure to decrease the pressure within the inner vessel thereby contracting both the inner vessel and the outer cylinder;
- observing the relationship between the longitudinal strain on the outside of the outer shell and the decreasing internal pressure to determine if the ratio remains constant thereby determining the presence of reverse bending;
- reapplying when reverse bending occurs a hydrostatic pressure to the inside of the inner vessel through the opening therein to increase gradually the internal pressure within the inner vessel up to the tentative internal pressure;
- observing again the relationship between the longitudinal strain on the outside of the outer cylinder and the increasing internal pressure to avoid deformation;
- further increasing the hydrostatic pressure a slight amount above the tentative internal pressure;
- observing the effect of the increase in internal pressure on the longitudinal strain to avoid any substantial increase in longitudinal strain;
- removing again the hydrostatic pressure to decrease the internal pressure within the inner vessel thereby contracting both the inner vessel and the outer cylinder;
- observing again the relationship between the longitudinal strain on the outside of the outer cylinder and the decreasing internal pressure to determine if the ratio remains constant thereby determining the presence of reverse bending.

6. A method according to claim 5 wherein the tentative internal pressure is determined by the relationship

$$p_i=\frac{Y}{2}\left[1-\left(\frac{a_o}{b_o}\right)^2\right]+Y\ \ln\left[\frac{a_o}{a+a_o-b}\right]$$

in which

p_i is the internal pressure within the inner vessel,
Y is the yield strength of the material,
a_o is the initial inner radius of the outer cylinder,
b_o is the initial outer radius of the outer cylinder,
a is the initial inner radius of the inner cylinder, and
b is the initial outer radius of the inner cylinder.

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CHARLIE T. MOON, *Primary Examiner.*

U.S. Cl. X.R.

29—421, 446; 220—3

U.S. DEPARTMENT OF COMMERCE

PATENT OFFICE

Washington, D.C. 20231

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,439,405 April 22, 1969

Irwin Berman et al.

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

Column 1, line 25, "tof" should read -- of --. Column 3, lines 56 to 58 "$p_i=p_o+Y_o \ln\left[\frac{a_o}{a+a_o-b}\right]$" should read -- $p_i=p_o+Y \ln\left[\frac{a_o}{a+a_o-b}\right]$ --. Column 4, line 51, "cylinders." should read -- cylinders --. Column 6, lines 52, 53 and 75, "bending", each occurrence, should read -- sliding --.

Signed and sealed this 14th day of April 1970.

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

WILLIAM E. SCHUYLER, JR
Commissioner of Patents