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METHOD OF MAKING PRESSURE VESSELS
AND THE LIKE

Gwynne Raymond, Oklahoma City, Okla., Merl
D. Creech, Chicago, Ill., and Ralph L. Feagles,
Oklahoma City, Okla.,

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3 Claims. (Cl. 29—148.2)

This invention relates to a method of manu-
facturing pressure vessels and the like, particu-
larly those capable of withstandling extremely
high working pressures and temperatures, and is
a continuation in part of our pending application,
Serial No. 244,076, filed December 5, 1938, now

As disclosed in the above noted application
industry of today requires vessels which are
adapted to contain safely high pressures and tem-
peratures. In fact, many pressure processes re-
duire the use of vessels in such size that the walls
must be as much as six to eight inches in thick-
ness. Manufacture of such vessels is difficult
and an extremely expensive procedure. It is
impractical to roll plates of this thickness be-
cause shaping thereof produces uneven stresses
between the inner and outer portions of the
vessel wall. The inner portions of the vessel wall
are placed in compression and the outer portions
in such extreme tension that the metal fractures
because it is stretched to the point of failure.
Forging and heat treatment must, therefore, be
resorted to in forming metal sheets of the re-
quired thickness. The metal also becomes so
greatly distorted or deformed in the manufac-
turing procedure that the internal stresses seri-
ously weaken the vessel, and it is difficult to
calculate safe working pressures that they may
withstand.

To solve these problems, attempts have been
made to form vessels by winding layer upon layer
of sheet metal to build up walls of necessary
thickness and then to form the layers in as
nearly a homogeneous mass as possible by heat-
ing and forging. However, the result is inaccu-
rate and unsafe vessels are produced. Attempts
have also been made to reinforce tubular articles
such as pipe by wrapping the exterior with wire,
the coils being wound in side to side contact in
a plurality of layers, but such articles will not
withstand longitudinal bursting pressures and it
is impossible to apply the desired tension in each
wind for the reason that the wire would be
stretched beyond its elastic limit, and if a wire
of a size necessary to withstand the desired ten-
sion is used, internal stresses are produced in
the wire similar to those produced when forming
a vessel of thick metal plate, and, owing to the
numerous number of windings which would be
required, the vessel would be far more inaccurate
and entirely impractical especially due to the
fact that the windings will not reinforce the
vessel in an axial direction.

It is, therefore, the principal purpose of the
present invention to provide a method of form-
ing high pressure vessels wherein the internal
stresses of the wall structure are controlled so
that the stress is substantially uniform through-
out the thickness thereof and may be relied upon
to contain safely the working pressure for which
the vessel is designed.

Other objects of the invention are to provide
a method of forming a laminated vessel having
a high strength weight ratio for safely containing
a given pressure; to provide a method of vessel
construction by which the vessel may be accur-
ately tested for leaks; and to provide a method
of forming laminated vessels wherein the lami-
nations are securely anchored to the heads of
the vessel and each layer takes its part of the
working stresses transversely of the lamination
and longitudinally of the axis of the vessel.

In accomplishing these and other objects of
the invention, as hereinafter pointed out, we
have provided an improved method of procedure
as illustrated in the accompanying drawings,
wherein:

Fig. 1 is a longitudinal section through a ves-
sel constructed in accordance with the present
method.

Fig. 2 is a cross-section through the vessel on
the line 2—2 of Fig. 1.

Fig. 3 is a similar section on the line 3—3 of
Fig. 1 to better illustrate attachment of a fitting
to the wall thereof.

Fig. 4 is a perspective view of the inner shell
or foundation of a vessel having the heads welded
thereto and showing the method of testing for
leaks, particularly the welds securing the heads
to the shell.

Fig. 5 is a detail perspective view illustrating
method of winding a continuous metal ribbon
on the tested shell whereby any predetermined
degree of tension may be produced in the respec-
tive layers according to the working pressure
with which the tank is to be subjected.

Fig. 6 is a fragmentary section of the wall of
the tank in the course of construction, particu-
larly illustrating the method of winding the lami-
nations.

Fig. 7 is a detail perspective view of a joint used
in forming a ribbon of sufficient length to provide
the required number of windings.

Fig. 8 is a detail fragmentary section of a mod-
ified form of vessel.

Referring more in detail to the drawings:

In carrying out our invention, we have dis-
covered that when pressure is applied within the
interior of a thick wall vessel tending to enlarge
the diameter thereof, the outer diameter is not increased perceptibly. This is accounted for in the fact that the inner portion of the wall is compressed and the outer portion of the wall is placed in tension with the result that the internal stresses seriously weaken the vessel and it is not capable of resisting the working pressures for which the thickness was designed. We have also discovered that this action takes place in a laminated wall, as heretofore used, with the result that the stresses imparted in the various layers cannot adequately perform their part in which high internal pressures.

We have, therefore, found it essential to make use of stresses in ribbon layers by varying the tension imparted thereto during wrapping so that the tension is controlled and varied according to the stresses which the respective layers must withstand to form a vessel of maximum strength for a given number of laminations and wall thickness. When the cylindrical wall of a vessel is formed merely by winding one convolution upon another and the heads welded thereto, it is difficult to prevent leaks, and when a leak does occur the pressure creeps out between the laminations so that its origin cannot be determined from the outside of the vessel. To overcome this difficulty, we have adopted the principle of an automobile tire wherein an inner tube prevents leaks and the outer casing gives the required strength. We therefore make up an inner shell 1 by rolling a sheet of metal of a desired thickness to withstand testing pressures, taking in consideration the inner diameter of the tank, the metal being sufficiently thin to permit ready fabrication thereof in cylindrical form and weld to the ends thereof heads 2 and 3 which are preferably formed of solid metal and of desired thickness to withstand the internal working pressure of the completed vessel.

In the illustrated instance, the heads 2 and 3 are substantially hemispherical in form and have their inner circumference substantially corresponding to the inner circumference of the shell and the outer circumference corresponding to the outer diameter of the finished vessel. The abutting faces 4 therefore project circumferentially of the outer surface of the shell and are tapered from the plane of the centers of curvature to facilitate welding, as later described. The heads 2 and 3 are placed concentrically with the axis of the shell 1 and are welded thereto as indicated at 5 and 6. If the shell is to be provided with a fitting 7, the fitting should be of proper thickness to withstand the internal pressures of the finished vessel.

In the illustrated instance the fitting 7 is in the form of a ring having a central opening 8 registering with a corresponding opening 9 in the shell. The outer periphery of the fitting may be rounded on suitable curves, as at 10, and the terminal thereof flattened, as at 11, to secure temporarily a closure plate 12. The face of the fitting screws into the shell counterclockwise, as at 13, to receive welding 14 by which the fitting is attached to the shell. The portion of the fitting encircling the weld is preferably tapered, as at 15, to form an annular space to receive a welded metal 16 supplementing the inner weld 14.

The plate 12 is secured over the opening 8 by bolts 17 extending therethrough and secured in threaded sockets in the flattened face of the fitting. The plate 12 engages a T fitting 18, one terminal of which is connected by a nipple 19 and the other with a central opening in the plate, and the other connections are respectively provided with a supply line 20 and a pressure gauge 21 whereby testing medium, such as a liquid, is admitted to the tank under a pressure registered by the gauge 21 to test the shell or foundation of the vessel against pressures for which the thickness was designed. After testing, the plate 12 is removed and suitable trunnions 22 and 23 are temporarily welded or otherwise attached to the heads 2 and 3 in the axis thereof, as shown in Fig. 5, whereby the shell is rotatably supported in bearings 24 and 25 which are suitably secured in the heads 22 and 27. One of the trunnions, for example 22, is of sufficient length to be connected with any suitable power for effecting rotation of the shell. A metal ribbon is then prepared having a width corresponding to the spacing between the heads of the vessel and of sufficient length to provide the necessary number of convolutions to produce a vessel of predetermined wall thickness. One end of the ribbon is preferably skived and welded to the shell of the tank by a transverse weld as shown in Fig. 5. The ribbon is then placed in a gripping device such as clamping bars 28 and 29, having angle-shaped inner surfaces 30 and 31 cooperating with wedge plates 32 and 33 directly engaging the upper and lower surfaces of the ribbon. The wedge plates are drawn into clamping engagement with the ribbon by draw-bolts 34 and 35 inserted through the ends of the clamping bars 28—29. The thicker portions of the wedges are arranged so that when pulling pressure is applied to the bars in a direction away from the welded end of the ribbon, this pressure acts to enhance gripping action of the wedges to prevent slippage between the bars and ribbon. The ends of the bars are suitably connected with hydraulic cylinders 36—37 through rods 38—39 whereby variable tensions are applied in the ribbon through control of the fluid pressure medium used in the respective cylinders as the ribbon is being wound on the shell. The pressures indicated by the gauges 40 and 41 which are connected with the respective cylinders relate to the tension being maintained on the ribbon. While the tension is maintained on the ribbon, the shell or foundation is being rotated to wrap the ribbon therearound.

In the tank illustrated it is necessary to cut an opening 42 in each convolution so that the fitting will pass therethrough, permitting the convolutions to engage each other closely, whereby frictional contact of one convolution or layer upon the other prevents unwinding thereof and therefore maintains the imparted tension. If desired, the ribbon may be provided with welding apertures 43 whereby one convolution is welded to the other as indicated at 44. A sufficient number of convolutions is wound on the shell so that the peripheral face of the final convolution or layer registers with the circumferential edges of the heads. During readjustment of the bars 28 and 29, when the heads 22 and 27 have come to the limit of their stroke, tension may be maintained on the ribbon by a similar mechanism, adjustable weights, or the like. When the winding is complete the free edge of the ribbon is preferably skived, as indicated at 45, and welded to the underlying convolution by welding 46.

In order to provide a welding space between the convolutions and the heads, the side edges of the ribbon are so shaped that when wound on the shell they will lie on an angle corresponding to
the angle of the head faces 4 to form a welding space in which a welding material is deposited as indicated at 47 and 48. Welding material is also filled in around the fitting as indicated at 49.

In tanks requiring longer ribbons than the length of sheets obtainable, they may be formed of a series of sheets preferably having ends cut on a bias, as shown at 55 in Fig. 7, whereby the joint extends spirally relatively to the shell and the gripping action of the upper and lower sheets supplements the strength of the weld. In extremely long tanks, two or more ribbons of substantial width may be wound on the shell and welded together in the manner above described.

In order to avoid skiving or feathering of the inner edge of the shell, or that edge attached to the shell 1, the edges of the shell, when secured together, may be offset as indicated at 51, Fig. 8. The edge 52 of the ribbon may be abutted against the offset and welded as shown.

In order to give a better understanding of the variable or differential tension applied to the respective convolutions to produce a vessel of maximum strength, the operations of constructing a vessel of specific size are now to be described. Assuming that the vessel has a \( \frac{3}{4}'' \) shell rolled to a \( 7'' \) radius for producing a vessel of \( 14'' \) inside diameter, and assuming that a ribbon of \( \frac{3}{4}'' \) thickness and of substantial width, for example the full width between the heads of the shell, is to be wound in eight convolutions about the shell to produce an outside dimension of \( 8\frac{3}{4}'' \) radius or \( 17\frac{3}{4}'' \) in diameter, the steps are carried out as follows:

For calculations, a working pressure within the tank may be assumed to be 3,000 pounds per square inch. The A. S. M. E. Code gives the following stress in the above mentioned vessel:

\[
\text{Stress} = \frac{p}{r^2} \left( \frac{r_1}{r_1 - r_2} \right)^{0.5}.
\]

Substituting in the above formula we get stress at inner radius where \( r = r_1 \)

\[
S = \frac{0.760 \times 15.75 \times 3000}{2 	imes 1.75} = 15,500 \text{ lbs. per sq. in.}
\]

The stress in the above vessel using the more exact equation derived and applicable to shells relatively thick compared to the diameter (“Strength of Materials” case, Longmans, Chap. XXVIII)

Where

\[
r_1 = \text{inner radius of vessel}
\]

\[
r_2 = \text{outer radius of vessel}
\]

\[
p = \text{internal pressure}
\]

\[
s = \text{stress caused by this pressure}
\]

\[
S = \frac{pr_1^2}{r_1^2 - r_2^2}
\]

Substituting in the above formula we get stress at inner radius where \( r = r_1 \)

\[
S = \frac{3000 \times 15.75 \times 76.5}{(76.5 - 49)} = 13,680 \text{ lbs./in.}^2
\]

Stress at outer radius where \( r = r_2 \)

\[
S = \frac{3000 \times 15.75 \times 76.5}{(76.5 - 54.9)} = 10,700 \text{ lbs./in.}^2
\]

From the foregoing calculations it is seen that the stress is not distributed uniformly throughout the thickness of the shell but is greatest at the inner surface. The difference between the inner and outer fiber stress will become more and more as the thickness of the shell is increased with respect to the diameter. By varying the tension in the laminations, any desired stress distribution may be obtained. Thus by suitably decreasing the tension as the convolutions are wound, unequal distribution stresses are overcome and the ultimate stresses throughout the thickness of the wall are made substantially uniform.

In constructing the above mentioned vessel, the shell 1 is formed by rolling a \( \frac{3}{4}'' \) metal plate to \( 14'' \) inside diameter, welding the seam and applying the heads 2 and 3, after which the vessel is tested for leaks. The trunnions 22 and 23 are temporarily connected with the heads and mounted in the bearings 24 and 25, and the internal ribbon of \( \frac{3}{4}'' \) plate and of sufficient length to form eight convolutions or windings about the tank is prepared with or without the openings 43. If a ribbon of sufficient length is not available, plates may be welded together, as shown in Fig. 7, to provide the desired length. One end of the ribbon is then preferably skived and attached to the shell along a tangent parallel with the axis of the trunnions and in a position so that the side edges of the ribbon will cooperate with the faces 4 of the heads to form the welding grooves. The clamping bars 28 and 29 are attached at a suitable point on the ribbon relatively to the stroke of the rods 38 and 39 and fluid is admitted to the cylinders to apply tension in that portion of the ribbon between the bars and shell.

The desired tensions to be imparted in the ribbon so as to produce substantially uniform ultimate tensions in all the convolutions may be calculated as set out in the following table:

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension (lbs.)</td>
<td>448</td>
<td>396</td>
<td>356</td>
<td>324</td>
<td>297</td>
<td>274</td>
<td>252</td>
</tr>
</tbody>
</table>

The headings in the above table designate the thickness of the shell and the convolutions wound therearound. The figures in column one designate compression forces on the inner shell which vary from \(-598\) pounds with the first convolution to \(-2194\) pounds after the sixth or final convolution has been applied. The first figures in the columns designate tension in pounds per square inch of width maintained in the ribbon as the convolutions are formed. The subsequent figures in these columns define the tension maintained in the convolution with each wind. For example, after the second convolution has been wound over the first, maintaining a tension of \(510\) pounds per inch of width in the second convolution, the tension of the first convolution has been reduced from \(598\) to \(515\) pounds. After the third convolution has been formed the tension in the first convolution has been reduced to \(448\) pounds and tension in the second convolution has been reduced to \(446\) pounds. It will be noted that each reduction in winding tension averages about \(20\%\) less than the previous reduction. Thus the tensions of the convolutions after the final one has been applied are the figures in the bottom of the columns. It will be noted that these figures are, for practical purposes, of similar relative magnitude. For example, the tension in the first convolution is now \(246\) and \(284\), and the tension in the outermost convolution \(275\) pounds.

It will be noted that the final figures vary to the extent of three pounds but this slight variation is infinitesimal and may be, for practical purposes, termed uniform in amount, and can, with decimal calculations, be made exactly uniform.
The important requirement is that the tension applied during the winding of the outer convolutions is reduced from the tensions employed in winding the first convolution so that the windings respectively are subjected to substantially uniform stresses throughout the wall thickness of the vessel, thereby avoiding the uneven stresses which occur when forming vessels of solid plate metal of substantial thickness.

Continuing with the construction of the vessel in accordance with the above table, the pressure in the cylinders 36 and 37 will be adjusted so that as the shell is rotated to wrap the first wind or convolution the tension applied is 508 pounds on the gauges, which produces a compression force of 508 pounds in the shell. If the perforations 42 are provided in the ribbon, the wound convolution may be welded to the shell through, and if the shell is provided with a fitting 7 a suitable opening 42 is provided in the ribbon to pass the fitting. Upon completion of the first convolution the pressure in the cylinders is adjusted relative to rotation of the shell for reducing the tension imparted in the ribbon to 510 pounds as designated in the third column, the convolution being affixed in the same manner as the first convolution. After wrapping the second convolution the tension in the shell is 1,022 pounds and in the first convolution 512 pounds. The succeeding convolutions are wound in like manner, reducing the tension for each succeeding convolution to 446, 395, 353, 324, 296 and 275 respectively, as shown in columns four, five, six, seven, eight and nine of the table. After the final wind, the free end of the ribbon is welded along the edge thereof to the preceding convolution.

Attention is directed to the fact that if the perforations 43 are omitted, the frictional contact of one convolution on the other will prevent slipping and maintain the desired tensions. This frictional contact may be supplemented by welding the edges of the ribbon, or the edges may be finally welded by filling in the welding spaces at the heads of the vessel. During winding of the ribbon it may be necessary to disconnect and reengage the clamping bars, however, tension is maintained on the ribbon during this operation as previously pointed out. After completing the application of the ribbon, the trunnions are removed from the bearings 24 and 25, after which they are removed from the heads 2 and 3 to complete the construction of the vessel.

The stresses due to the tensions applied in accordance with the above table and to the internal pressure will be as set out in the following table:

<table>
<thead>
<tr>
<th>Radius</th>
<th>Initial stress</th>
<th>Stress due to pressure</th>
<th>Total stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.900</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
<tr>
<td>7.750</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
<tr>
<td>7.500</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
<tr>
<td>7.250</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
<tr>
<td>7.000</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
<tr>
<td>6.960</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
<tr>
<td>6.750</td>
<td>-2.925</td>
<td>13.683</td>
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<td>6.250</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
<tr>
<td>6.000</td>
<td>-2.925</td>
<td>13.683</td>
<td>10.758</td>
</tr>
</tbody>
</table>

As mentioned, the above table designates stresses in the first column designates the radius of the respective convolutions. The second column designates the initial stress on the respective convolution due to the winding tension, and the third column designates stress when internal pressure is applied in the tank. The final column denotes the total stress. The figures in column two are obtained by dividing the tensions in the last line of the first table by various convolutions. Column three is calculated by applying the above equation, and figures in the last column are obtained by adding algebraically the figures in columns two and three.

It is to be understood that the above calculations for a specific tank only illustrative of the variable stresses imparted during winding of the convolutions and these stresses may be varied therefrom to provide a tank suitable for any given purpose. However, the tension imparted during winding the convolutions is reduced in value from the inner to the outer convolutions and preferably so that the ultimate tensions in the respective convolutions are uniform or substantially uniform.

From the foregoing it is apparent that we have provided a method of producing a laminated vessel wherein the convolutions are maintained under a predetermined initial stress calculated to give maximum strength and to withstand safely the working pressures for which the tank is designed.

What we claim and desire to secure by Letters Patent is:

1. The method of forming the wall of a vessel capable of withstanding high internal pressure including, winding a metal sheet of substantial width in continuous successive convolutions one directly upon another with the face surface of one convolution in frictional contact with the next preceding convolution and with the edges of the sheet in substantial registry, applying tension in said sheet substantially uniformly throughout the width of the sheet at the time of winding said convolutions, selectively and progressively reducing the winding tension in each convolution, each reduction in winding tension being on an average of about 20% less than the previous reduction in winding tension so that the ultimate tensions and stresses in all the convolutions are substantially uniform, and welding at least the final convolution to the preceding convolution.

2. The method of making laminated tubular walled vessels capable of withstanding high internal pressure including, forming a tubular shell, winding a metal sheet of substantial width in continuous successive convolutions about the shell one directly upon and continuous with the other with the face surface of one convolution in frictional contact with the next preceding convolution and with side edges of the sheet in substantial registry, applying tension in said sheet uniformly across the width of said sheet at the time of winding said convolutions, selectively and progressively reducing the winding tension in each convolution, each reduction in winding tension being on an average of about 20% less than the previous reduction in winding tension so that the ultimate tensions and stresses in all convolutions are substantially uniform, and welding each successive convolution to the previous convolution progressively with the winding.

3. The method of forming the wall of a vessel capable of withstanding high internal pressure including, winding a sheet of substantial width in continuous successive convolutions one directly upon another with the face surface of one convolution in frictional contact with the next preceding convolution and with the edges of the sheet in substantial registry, applying tension in
said sheet substantially uniformly parallel with the axis of the winding at the time of winding said convolutions, selectively reducing the winding tension in said sheet after the winding of each convolution in an amount to produce an ultimate tension in each of the previous convolutions substantially that of the tension in effect in said sheet at the time of winding the final convolution whereby the ultimate tensions in all of the convolutions are substantially all similar in magnitude and so that the stresses in the wall of the completed vessel are substantially uniform throughout the thickness thereof, and securing at least the final convolution to the preceding convolution.

GWYNNE RAYMOND,
MERLE D. CREECH,
RALPH L. FEAGLES,