Sept. 27, 1966 B. J. ALECK 3,274,813

GENERALIZED STRETCH FORMING

Original Filed March 28, 1962 3 Sheets-Sheet 1

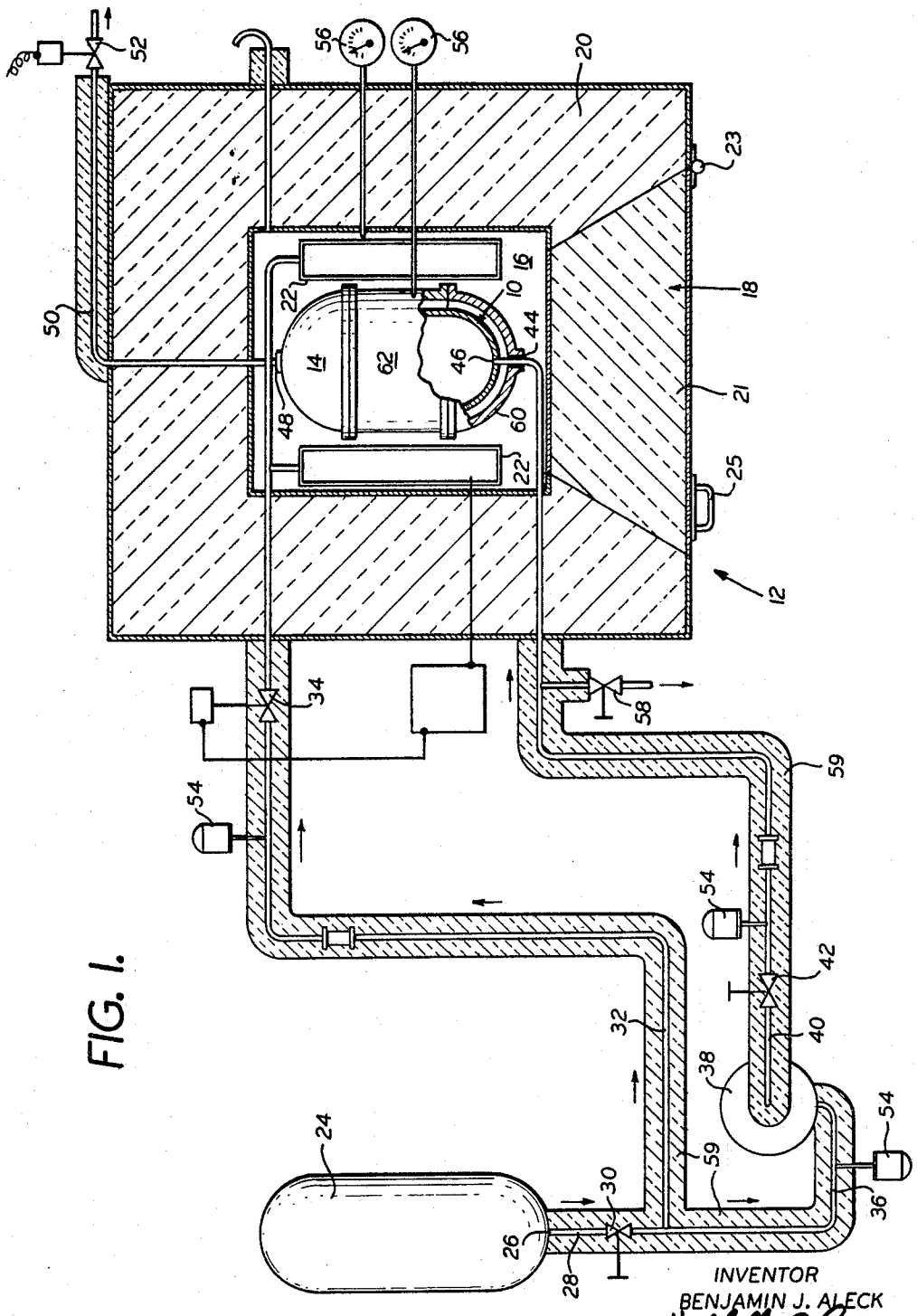


FIG. 1.

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Original Filed March 28, 1962 3 Sheets-Sheet 2

FIG. 2.

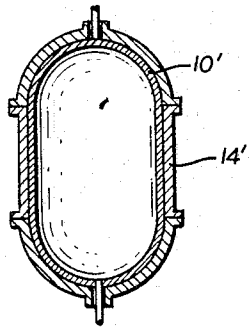


FIG. 3.

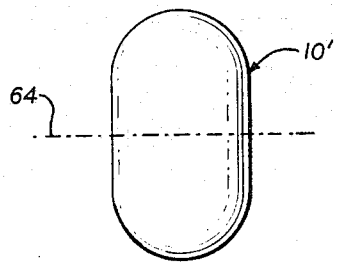


FIG. 4A.

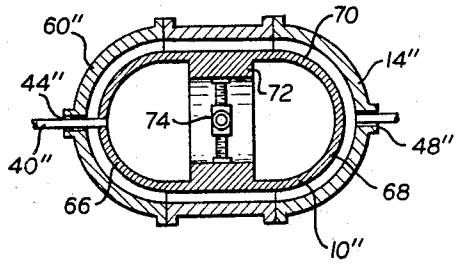


FIG. 4B.

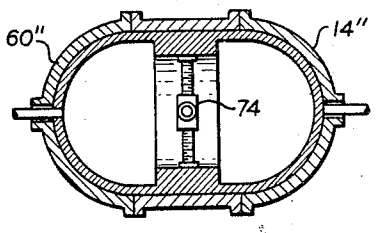


FIG. 4C.

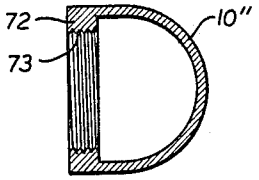


FIG. 5A.

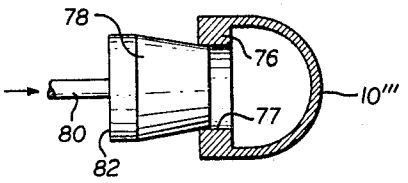


FIG. 5B.

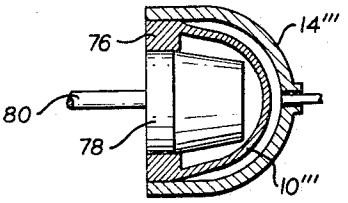
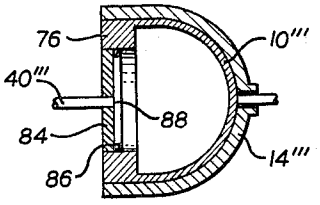
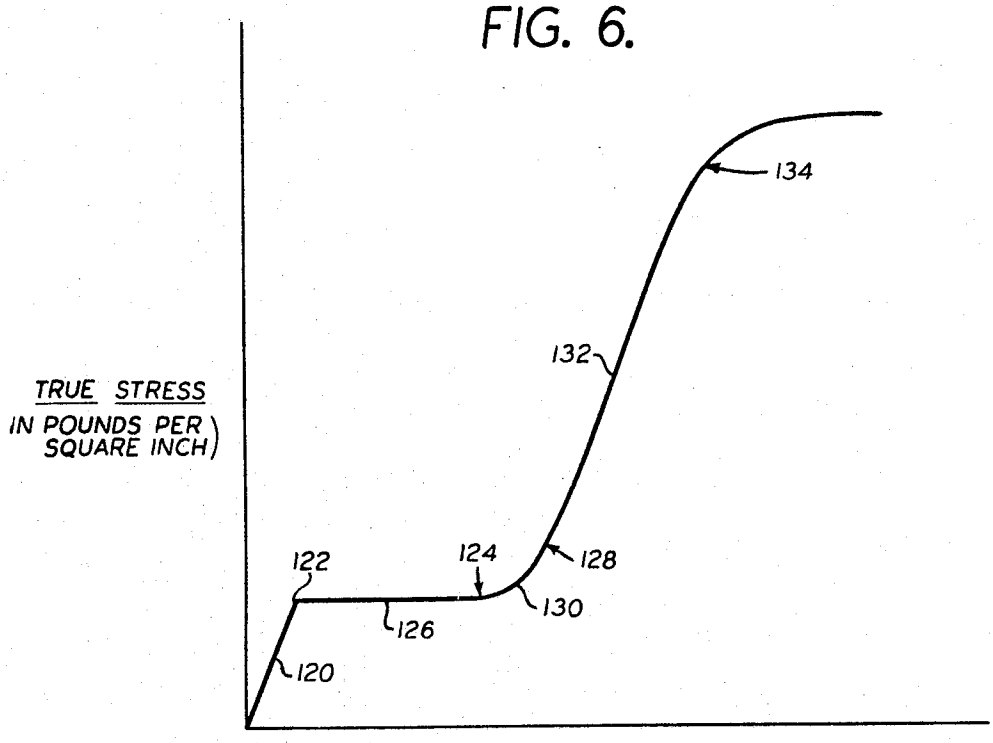


FIG. 5C.



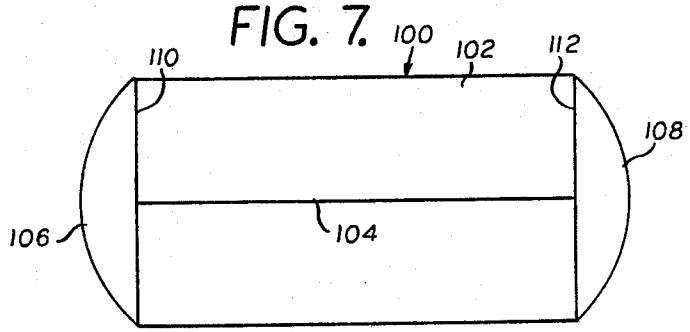
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FIG. 6.



$$\left[\log_e \varepsilon = \log_e \frac{\ell_f}{\ell_i} = \log_e \frac{A_o}{A_f}\right]$$

FIG. 7.



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GENERALIZED STRETCH FORMING

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Original application Mar. 28, 1962, Ser. No. 183,149, now Patent No. 3,197,851, dated Aug. 3, 1965. Divided and this application July 8, 1965, Ser. No. 470,367

2 Claims. (Cl. 72—62)

This invention relates to metallurgical processing and particularly to a metallurgical processing for forming high tensile strength pressure vessels. More particularly, the present invention relates to a novel step in metallurgical processing for forming high tensile strength pressure vessels from metallic materials and particularly from metallic materials having at least two distinct crystal structures, both of which can exist at room temperature. The present invention further relates to apparatus for performing the novel step in the metallurgical processing.

This application is a division of my earlier filed copending application Serial No. 183,149 (now U.S. Patent No. 3,197,851), filed by me on March 28, 1962, which application is in turn a continuation-in-part of my earlier filed now abandoned application Serial No. 834,439, filed by me on August 18, 1959, both of which applications are assigned to the assignee hereof.

There are many uses for high tensile strength pressure vessels and such uses are multiplying over the years. In a number of such uses, the weight of the pressure vessel is of great importance. For instance, if the pressure vessel is to be carried by a man such as, for example, portable oxy-acetylene tanks, it is desirable for the pressure vessels to be as light as possible and still meet the strength requirements.

One especially critical use for light-weight vessels is in the field of solid fuel rockets, where pressure vessels are employed to store the solid rocket fuel and to contain such fuel during ignition and combustion thereof. During such time, the vessel is subjected to extremely high pressures. In such applications it is obvious that failure of the vessel itself means failure of the rocket and, accordingly, considerable strength must be built into such pressure vessels. However, the weight of such pressure vessels is a vital factor in rocketry as the weight of the vessel itself will cut into the overall weight of the payload. Accordingly, it is most desirable to create a high strength pressure vessel of very light weight. Naturally, if the material from which the material is made has a very high tensile strength, its overall strength and resistance to pressure will increase for a given weight of material. Thus light weight vessels can be made if extremely high tensile strength material is available.

There are many metallurgical processes available today for strengthening steels and other metals suitable for pressure vessels and particularly for solid fuel rocket casings. For instance, cold rolled stainless steels are available and these materials have very high tensile strength after having been cold rolled. However, during the fabrication of vessels from such materials, it is generally necessary to weld the cold rolled stainless steel together to form the vessel. During the welding operation the metal in the zone of the welds, of course, is subjected to high heat which heat generally destroys the gain in strength achieved by the cold rolling. Accordingly, the final vessel, though made out of material that generally speaking has high tensile strength, will have distinct low

tensile strength zones in the vicinity of the welds which zones will limit the overall strength of the vessel.

When forming pressure vessels from materials that are difficult to weld, such as, for instance, titanium, it is often necessary to thicken the ends of the portions of the vessel blank which are to be butt welded to one another in order to get additional strength in the weld. The need for additional strength is due not only to the difficulty of effecting a good weld, but also due to the fact that the welding operation causes a loss in strength previously gained by earlier employed metallurgical processes. However, the technique of thickening the ends is extremely costly because in the present day art, the thickened ends of such vessels are formed by machining out material between the ends whereby to leave a flared or flanged end. This is an extremely expensive procedure due in part to the cost of machining and also due in part to the fact that the machining removes (and thus wastes) costly material, such as titanium.

The main object of the present invention is to provide a novel step in a metallurgical process for forming pressure vessels which step will produce an extremely high strength vessel for a given weight.

Still another object of the present invention is the provision of a metallurgical process for working pressure vessels whereby to convert the metallic material forming the pressure vessel into a high tensile strength material.

Still another object of the present invention is the provision of a metallurgical process for forming welded high tensile strength pressure vessels.

Yet a further object of the present invention is the provision of a metallurgical process for working pressure vessels made out of metallic materials having two distinct phases or crystal structures both of which can exist at room temperature.

The above and other objects, and characteristics of the present invention will be understood more fully from the following description taken in connection with the accompanying drawings.

In accordance with the present invention a pressure vessel blank is formed of metal, preferably by welding. Thereafter, the vessel blank is placed in a die of larger size than the blank itself. The vessel blank is then subjected to high internal pressure as by injecting or compressing a fluid therewithin, the pressure being sufficient to stretch the metal from which the vessel blank is made. The stretching of the vessel blank will also cause a stretching of the welds and area surrounding the welds whereby to result in an increase in strength of the entire vessel blank including the weld therein.

In some instances, the pressure can be applied to stretch only the weld areas whereby to raise the strength of the weld areas.

The stretch forming technique may be used in combination with various metallurgical processes such as a heat treatment or precipitation hardening to further increase the streength gain in the pressure vessel. For instance, in materials exhibiting a martensitic transformation, if the stretch forming is performed at certain temperatures, it can be employed to induce such martensitic transformation whereby to yield a very high tensile strength pressure vessel made in whole or part of martensitic material, including the weld areas.

In the drawings:

FIG. 1 is a diagrammatic view of an apparatus for processing pressure vessel blank at cryogenic temperatures;

FIG. 2 is a sectional view of a pressure vessel formed in accordance with the present invention disposed within a die;

FIG. 3 is a side elevational view of a pressure vessel which has been formed in the die shown in FIG. 2;

FIGS. 4A, 4B and 4C illustrate several steps in the method of forming an open ended pressure vessel having a threaded boss at the end thereof;

FIGS. 5A, 5B and 5C are views of various steps in forming an open ended pressure vessel using a modified form of the novel method disclosed herein;

FIG. 6 is a true stress vs. true strain graph of typical ductile metals; and

FIG. 7 is an elevational view of a cylindrical welded vessel blank.

Referring first to FIG. 7, a conventional pressure vessel blank **100** is illustrated therein. This blank may be formed of a metal and, as shown, is fabricated by taking a sheet of said material to form a central cylinder **102** by means of a longitudinally extending weld **104**. To enclose the vessel two vessel heads **106** and **108** are welded to the ends of the vessel blank **100** as by circumferential welds **110** and **112**, respectively. The vessel heads **106** and **108** may be planar but, preferably, are of convex configuration.

Assuming that the vessel **100** has been fabricated from a very high tensile strength material which was previously treated by some metal working process such as ausforming or cold rolling or the like, the overall strength of the vessel will still be far below that which would be theoretically possible from the tensile strength of the material prior to fabrication thereof. This sharp reduction in the strength of the vessel is due to the fact that when the material is welded as at the welds **104**, **110** and **112**, the benefits of the metallurgical process used to raise the tensile strength of the material prior to fabrication of the vessel blank **100** are generally all or at least partly lost because of the heat of welding. Thus, although most of the material will be extremely strong and of high tensile strength, the welds themselves and the zones immediately adjacent the welds will be sharply weakened whereby to provide zones of weakness which limit the overall strength of the vessel.

In accordance with the present invention the vessel blank **100** is subjected to internal pressure of sufficient magnitude to exceed the elastic limit of at least the weld areas in the material whereby to cause a stretching of the welds and areas adjacent the welds and, preferably, of the overall material itself. Such stretching, as will be described in greater detail hereinafter, can improve the mechanical properties of the welds and of the material, or can effect a change in the crystallographic structure of the welds or material or can be used in combination with known metallurgical process to treat the entire vessel blank after forming whereby to insure high tensile strength throughout the entire vessel including the welds. It will be obvious that upon the application of internal pressure, the areas of minimum tensile strength, that is the areas surrounding and including the welds, will yield first and will continue to yield without any exceeding of the elastic limit of the stronger material uneffected by the welding operation until the strength of the welds has come up to the strength of the overall material. If pressure is continued to be applied after this point then the entire vessel blank including the now strengthened weld areas will continue to stretch to give additional strength to the overall vessel.

FIG. 6 shows a true stress vs. true strain curve for a typical ductile work hardenable metal such as, for example, austenitic stainless steel. It will be noted that true stress is shown in pounds per square inch and true strain is shown in percent of deformation (diametral stretching). As is well known to those skilled in the art, true stress is equal to the tensile force on the material divided by the actual area of the material. True

stress is to be contrasted with nominal stress which is equal to the actual tensile force divided by the nominal or original area of the material. True strain is defined as the natural logarithm of unit deformation, i.e. $\log_e \epsilon$, which is equal to

$$\log_e \frac{\text{final length } (l)}{\text{initial length } (l_i)}$$

or

$$\log_e \frac{\text{original area } (A_o)}{\text{final area } (A_f)}$$

It will be seen that in the portion of the curve designated by the reference character **120** the curve rises almost vertically and substantially linearly. This portion of the curve represents purely elastic deformation and the metal observes Hooke's law. That is, if the stress is relieved anywhere within this portion of the curve the metal will elastically return to substantially its initial shape. However, once the elastic limit has been exceeded at the point **122**, the material tends to yield with small increase in true stress, this portion of the curve being observed to be substantially horizontal and running from the point **122** to the point shown by the arrow **124**. This approximately horizontal portion of the curve is designated by the reference character **126**. In this area of the curve there is considerable yielding of the material and Hooke's law is not followed. Between the point defined by the arrow **124** and the point defined by the arrow **128** the curve shows a concave upward characteristic and it is in this area where work of a substantial amount commences to be put into the material to sharply increase its tensile strength. This portion of the curve is designated by the reference numeral **130**. Beyond the concave upward portion **130**, the true stress vs. true strain curve commences to follow a sharp upwardly rising part which is substantially linear but slightly concave downward, which part of the curve is designated by the reference character **132**. As stress increases this part of the curve becomes more and more horizontal but never bends downwardly due to the fact that as soon as this tendency arises, the material breaks. Generally speaking, it is preferred to stress the material during stretching thereof into the portion of the curve part **132** between the arrows **128** and **134** wherein a substantial strength gain is achieved.

With continued reference to FIG. 6, it is presently necessary in order to achieve substantial strength gains to cause deformation beyond the arrow **124**. That is, it is necessary to stretch the vessel blank sufficiently to move at least into the concave upward portion **130** of the true stress vs. true strain curve. Most preferably, it is desirable to stretch the vessel beyond the concave upward portion of the curve and well into the concave downward portion **132** of the curve. For stainless steels and particularly for AISI No. 301 stainless steel, the point **124** is reached at about 5% unit deformation (i.e., $\epsilon=5\%$), and this is the minimum deformation above which any substantial tensile strength gain can be achieved. For 301 stainless steel it is desired to stretch the material in the vessel blank somewhere between the 10 and 18 percent unit deformation (i.e., $\epsilon=10\%$ to 18%). However, some improvement in mechanical properties of the vessel is achievable at deformations below point **124** (i.e., $\epsilon<5\%$) and, for certain applications this may be desirable.

A number of metals display what is known as a martensitic transformation. The martensitic transformation is a rearrangement of the crystallographic structure without any change in the chemical composition of the crystal structure. It is diffusionless. Moreover, such transformations in materials in which they occur are spontaneous at certain temperatures. For instance, as the temperature of the material is dropped, a temperature

point will be reached where a martensitic transformation will commence occurring spontaneously. This temperature is known as the M_s temperature. The martensitic transformation will progress further as the temperature of the material continues to be dropped until at a certain temperature, generally known as the M_f temperature, there will be maximum spontaneous martensitic transformation, that is as much martensite as can be formed will be formed. It has been found that the martensitic transformation can be started above the M_s temperature if the material is deformed, that is, if mechanical work is put into the material. However, there is a maximum temperature above which no martensitic transformation will occur even if deformation takes place. This temperature is known as the M_d temperature. Moreover, it has been found that at temperatures below the M_s temperature, the martensitic transformation can be made to progress further than it normally would spontaneously, provided the material is mechanically deformed at such a temperature.

In view of this knowledge and finding, I have discovered that with pressure vessels made of materials which exhibit a martensitic transformation, it is desirable to stretch the vessel blank at a temperature below the M_d temperature, and preferably, close to the M_s temperature and most preferably at or slightly below the M_s temperature. When the stretching of such vessel blanks is performed at such temperatures, the vessel blank will gain in strength not only due to the stretching of the material, but also due to the crystallographic transformation of the material to the generally stronger martensitic phase. While it is preferred to stretch form materials exhibiting the martensitic transformation at about the M_s temperature at which temperature the material will be relatively ductile to thereby enable the processor to substantially deform the vessel blank while forming martensite, substantial strength gains can be achieved at temperatures below the M_s temperature at which there is a substantial amount of martensite already present and even at or below the M_f temperature at which all the martensite formable has been formed.

The following table lists the M_s temperatures for a number of materials:

Material:	Approximate M_s temp. (° F.)
Titanium	1570
Aluminum-copper alloys (percent Al)—	
11.5	740
13.0	430
15.0	150
Steel—AISI No.—	
1034	740
1035	750
1050	610
1095	420
2340	520
3190	300
4130	690
4330	630
4330+.17% V	610
4340	550
Iron-nickel alloys (percent Ni)—	
9.5	975
14.5	660
19.0	410
23.75	250
28.0	45
29.3	−20
29.7	−45
30.7	−100
31.7	−175
32.4	−230
32.7	−290
33.0	−370

In addition to the materials listed in the chart, the austenitic stainless steels also exhibit a martensitic transformation and for these steels an equation exists to calculate the approximate M_s temperature. This equation is as follows:

$$M_s \text{ temp. } (^\circ \text{F.}) = 75\ (14.6 - \text{Cr}\%) + 110\ (8.9 - \text{Ni}\%) + 60\ (1.33 - \text{Mn}\%) + 50\ (.47 - \text{Si}\%) + 3{,}000\ (.068 - (\text{C}\% + \text{N}\%))$$

Utilizing the above formula, it has been found that with four stainless steels the following occurs: With a stainless steel having the following composition—

	Percent
Cr	16.8
Ni	6.1
Mn	1.33
Si	1.49
C	.027
N	.048
Fe	Balance

the calculated M_s temperature is 71 degrees F. The measured M_s temperature is 156° F. The following are other compositions of stainless steel with both measured and calculated M_s temperatures:

	Percent
Cr	17.30
Ni	7.56
Mn	1.33
Si	.49
C	.031
N	.05
Fe	Balance

A material having the above composition has an M_s temperature calculated by the above presented formula of −95° F. The M_s temperatures as measured by standard techniques is −60° F. For stainless steel having the following composition—

	Percent
Cr	16.7
Ni	10.2
Mn	1.42
Si	0.46
C	.023
N	.042
Fe	Balance

the calculated M_s temperature is −297° F. and the measured M_s temperature is about −320° F.

Another stainless steel has the following composition—

	Percent
Cr	11.7
Ni	14.8
Mn	1.25
Si	0.33
C	0.052
N	0.035
Fe	Balance

This material has a calculated M_s temperature of −479° F. (obviously impossible) and an actual measured M_s temperature of −452° F.

With all materials displaying a martensitic transformation, as already noted, the stretch forming preferably takes place at a temperature below the M_d temperature and more preferably at a temperature at or below the M_s temperature, whereby to effect a martensitic transformation at least due to deformation and, within the preferred temperature range, partially by deformation and partially by the spontaneous transformation due to temperature alone. In any of these events, assuming that the vessel blank to be stretched has been welded, it will be seen that the weld areas will also be stretched and the

martensitic transformation will take place therein as well as in the non-weld areas of the vessel whereby to greatly increase the overall strength of the pressure vessel, including the weld areas.

The step of stretch forming as described hereinbefore can also be employed in connection with other types of metallurgical treatments than those necessary to effect a martensitic transformation. For instance, with ferrous materials, conventional heat treatment techniques can be employed to effect a pearlitic transformation or a transformation to bainite, preferably a lower bainite, in conjunction with the stretch forming technique. For instance, if it is desired to stretch form a pressure vessel blank and form bainite, then the pressure vessel blank will be heated above the equilibrium temperature of the vessel blank material and then quenched to a temperature in the isothermal transformation temperature range of the material to form bainite, with the lower portion of the range being desired, then maintaining the temperature of the vessel substantially constant while stretching it. While data for the determining of isothermal temperatures of various ferrous materials necessary to form bainite are readily available from standard time-temperature transformation curves (T-T-T curves), as an example, and not by way of limitation, the following table of temperature ranges for typical materials is presented.

Material:	Isothermal transformation temperature range, ° F.
Nickel steel (19% Ni, 101° C.)	700 to 800
AISA 410 hardenable stainless steel	800 to 1300
AISA 4340 steel	600 to 1100
AISA 1080 steel	500 to 1100

During the isothermal period of the process, the material will transform into bainite. Moreover, if the temperature tends to be towards the bottom of the range presented, the bainite will be what is commonly known as lower bainite, which is a very strong tough material. Naturally, with respect to transformation to bainite, this is only applicable to ferrous materials.

From the foregoing, it will be seen that the stretch forming of pressure vessel blanks in combination with various metallurgical processes will give rise to very strong high tensile strength pressure vessels. Stretch forming is particularly useful with respect to welded vessels in view of the fact that the welds of the vessel are treated along with the rest of the material of the vessel after formation of the vessel blank whereby to give high strength throughout the vessel, which is not ordinarily achievable by conventional techniques in which the vessel material is treated prior to formation into a pressure vessel and the benefits of the treatment are lost in the vicinity of welds when welding is performed. The gain from stretch forming may be due to an improvement in grain structure of the vessel blanks throughout, or the increase in yield point due to working, or any of these in combination with gains coming from known metallurgical processes.

Various techniques may be employed in stretch forming pressure vessel blanks into high tensile strength vessels, and these will now be described in connection with the drawings and particularly in connection with FIGS. 1 through 5C thereof. Moreover, the method will be described in connection with a pressure vessel blank formed of stainless steel designated as AISI stainless steel Number 302 which has the following composition:

Carbon	.15% max.
Manganese	2% max.
Silicon	1%.
Chromium	17 to 19%.
Nickel	8–10%.
Phosphorous	.041% max.
Sulfur	.03% max.
Austenitic iron	Balance.

Certain of the stainless steels coming within the ranges of the AISI No. 302 stainless steel have an M_s temperature in the vicinity of —320° F. Accordingly, if it is desired during stretch forming to produce a martensitic transformation of such stainless steel, it will be necessary to stretch form the vessel blank preferably at the M_s temperature of —320° F. Of course, a certain amount of martensitic transformation can be achieved during stretch forming at higher temperatures up to the M_d temperature of the steel. However, it is preferred to work at or below the M_s temperature in order to maximize the amount of martensitic transformation.

To effect stretch forming at the M_s temperature of the 302 stainless steel, it is, of course, necessary to employ cooling apparatus in connection with the stretching apparatus, which apparatus is illustrated in FIG. 1 and is generally designated by the reference character **12**. The vessel blanks which are made of 302 stainless steel are generally designated by the reference character **10**.

The apparatus **12** includes a die **14** the internal surface of which is substantially identical to the final surface to be achieved for the finished pressure vessel to be formed from the vessel blank **10**. Die **14** is disposed within a cold chamber **16** of an insulating chest **18** having a relatively thick thermal insulating wall **20** surrounding the chamber **16**. Wall **20** is provided with a door or closure **21** to provide access to chamber **16**. Door **21** may be hinged as at **23** and have a handle **25**. Also disposed within chamber **16** are cooling coils or trays **22** here shown to be in the form of two flat coils although a helical coil may be employed. The cooling trays **22** may be formed by taking a piece of tubing and bending it to follow a tortuous path. The cooling trays **22** are employed to cool the die **14** to the desired working temperature which is preferably about —320° F. in order to produce a martensitic transformation. It should be understood that cooling of the die, although advantageous, is not absolutely necessary to working the present invention as the important factor is the cooling of the vessel blank which may be achieved without a pre-cooling of the die.

To achieve the very low temperatures of the order of —320° F., a coolant or refrigerant such as liquid nitrogen is preferably employed. As shown herein the liquid nitrogen coolant is contained in a tank **24** having an outlet **26** which is connected to a conduit **28** for conveying the liquid nitrogen out of the tank **24**. A valve **30** may be interposed in the conduit **28** to control the flow of the liquid nitrogen. As shown herein the liquid nitrogen is supplied to the cooling trays **22** by a branch pipe **32** having a control valve **34** interposed therein. The conduit **28** is provided with a second branch pipe **36** which goes to the intake of a pump **38** having an outlet **40** the flow through which is controlled by a valve **42**. The outlet pipe **40** extends through the insulating wall **20** of the cooling box **18** and into the chamber **16**. In the chamber **16** the pipe **40** passes through an opening **44** in the die **14** and is threadedly connected to the pressure vessel blank **10** at a threaded inlet **46** therein. The die **14** has an opening **48** at its other end to which is connected an outlet pipe **50** having a valve **52** interposed therewithin to control the flow of fluids therethrough. If desired, the pipes **32**, **36** and **40** may be provided with check valves **54** to limit the pressure therewithin. Furthermore, temperature measuring instruments **56** may be included to monitor the temperature of various parts such as the die, the trays and the chamber. Moreover, if desired, a bleed valve **58** may be included in communication with the pipe **40** to relieve the pressure in the pressure vessel **10** at the end of the pressure step as will be described hereinafter. To prevent the refrigerant from picking up heat, pipes or conduits **28**, **32**, **36** and **40** may be thermally insulated as by insulation **59**.

To form a pressure vessel in accordance with the present invention in apparatus **12**, the valve **30** is first closed and the pipes **32** and **40** are vented to remove liquid nitrogen from the latter two pipes. The door **21** in the

insulating wall **20** of cold chest **18** is opened and the die **14** is also opened. The die **14** may be opened by providing it with a removable section. As shown in FIG. 1, die **14** has one of its hemispherical sections **60** secured to the central cylindrical section **62** thereof by threaded securing elements (not shown) which may be removed to permit the detachment of the hemispherical section **60** from the remainder of the die **14**. Thereupon the pressure vessel blank **10** may be disposed within the interior of the die **14**. The method of forming the pressure vessel blank **10** will be described hereinafter in greater details. Suffice it to say at this time that the outer shape of pressure vessel blank **10** is of smaller size than the interior surface of the die **14**. With the pressure vessel blank **10** disposed within the die the pipe **40** may be connected to the inlet **46** and the removable hemispherical section **60** may be secured to the remainder of the die **14** to thus close the die. Thereafter, the door **21** may be closed.

After the completion of the insertion of the blank **10** in the die **14**, the valve **30** may be opened and the valve **34** may be opened to permit liquid nitrogen in the tank **24** to flow under its own pressure into the cooling trays **22** to thus lower the temperature of the die **14**. At the same time or shortly thereafter the pump **38** may be energized and the valve **42** may be opened to permit liquid nitrogen under a pressure of the order of 2000 to 2500 p.s.i. to be fed through the pipe **40** into the interior of the pressure vessel blank **10**. With the liquid nitrogen being supplied to the interior of the pressure vessel blank as well as to the cooling trays the temperature of the die and the pressure vessel blank **10** will rapidly drop to approximately the temperature of the liquid nitrogen, that is —320° F. Moreover, with the liquid nitrogen being supplied to the interior of the pressure vessel blank **10** at high pressure the liquid nitrogen will force the pressure vessel blank to be stretched outwardly to conform the outer surface thereof to the inner surface of the die **14**. This stretching may be of the order of 10% to 20% which is well beyond the elastic limit of the vessel blank material thereby resulting in a plastic deformation of the vessel blank. This degree of deformation at the working temperature of —320° F. will cause a substantial amount of transformation to the martensitic phase to produce a substantial gain in strength over and above that produced by work hardening. Accordingly, when the pressure on the inside of the pressure vessel blank **10** is relieved the pressure vessel blank will not return to its original shape but will, save for a slight elastic shrinkage, substantially conform to the shape of the interior of the die **14**.

Accordingly, after the application of the pressure on the interior of the vessel by introducing liquid nitrogen therein under pressure, the pressure may be relieved by shutting off the pump **38**, closing the valve **42** and opening the relief valve **48** which will vent the liquid nitrogen in the tank to atmosphere. At the same time the valve **30** may be closed to discontinue supplying liquid nitrogen to the cooling trays **22**. Thereafter, the door **21** in the wall **20** may be opened, the hemispherical section **60** of die **14** may be removed from the remainder of the die and the pressure vessel, now stretched fully to size, may be removed from the remainder of the die and thereafter the method may be repeated.

It will be understood that the pressure vessel, after being stretched to size, may be readily removed from the die as after the pressure is relieved from the interior of the vessel, the vessel will shrink slightly within the elastic range and thus pull away from the wall of the die.

The purpose of the vent **50** should be explained. As the die **14** is relatively well sealed, and as there is air between the outer surface of the pressure vessel blank and the inner surface of the die, when pressure is applied to the interior of the vessel blank **10** to cause a stretching thereof the air in the space between the blank and the die will be compressed. Unless this air is permitted to flow out between the space it will cause some malshaping of the final pressure vessel. Accordingly, the vent **50** is provided to permit the air to flow from the space between the vessel and the die to the atmosphere through the valve **52**.

The shape of the initial vessel blank **10** is of some importance in achieving a pressure vessel of the desired qualities. As shown in FIGS. 1 and 2 the vessel blank **10** has a uniform wall thickness and is made of two hemispherical end sections which are welded or otherwise connected to a cylindrical center section. While this particular shape will work satisfactorily for the formation of a closed ended high strength pressure vessel it can be demonstrated that hemispherical sections and cylindrical sections are stretched at different rates under uniform pressure. Specifically, the hemispherical sections cannot be stretched linearly as much as the cylindrical section for the same percent increase in area. Accordingly, in lieu of the shape of the blank **10** shown in fragmentary view in FIG. 1 a blank perhaps of the shape of a "dog bone" would be preferable in order to end up with a vessel having uniform strength throughout. Other shapes of vessel blanks may be calculated depending upon the desired shape of the end product.

While the method described hereinbefore is eminently suited to forming high tensile strength pressure vessels having closed ends and uniform wall thicknesses, it cannot be used readily as such to form an open ended vessel. If an attempt were made to form an open ended vessel by making a vessel blank similar in configuration to but smaller in size than the open ended vessel desired, when pressure is applied to the interior of the blank the open end would stretch and upon stretching would break any seal theretofore made to contain the pressure. With the seal broken, pressure would be lost and there would be relatively little stretching accomplished.

Accordingly, additional steps must be performed in order to manufacture an open ended high tensile strength vessel in accordance with the present invention. The simplest method of accomplishing this is to form a vessel blank having closed ends as has been described hereinbefore. The closed ended blank is then stretch formed in accordance with the aforedescribed method and the final vessel coming out of the die will be of a shape equivalent to the shape of two open ended vessels with their open ends joined together. Thereafter, the stretch formed vessel (which is really two connected open ended stretch formed vessels) may be cut along the line of connection of the two open ended vessels. After cutting, there will be two vessels of the desired shape. This is illustrated in FIG. 3 of the drawings, wherein a finished stretch formed closed ended vessel **10'** is shown. The dotted line **64** in FIG. 3 is the line of juncture of two identical open ended vessels. Accordingly, when the stretch formed vessel **10'** is cut along the line **64** two open ended vessels will be produced.

In lieu of simultaneously forming two open ended vessels as described in the preceding paragraph, a single open ended vessel can be so formed by fabricating a close ended vessel blank and stretching it as described above to the desired form except for the inclusion of the unwanted closed end. After stretching at sub-zero temperatures, the unwanted end can be removed as by cutting or otherwise to yield the desired open ended vessel.

Often times it is desirable to form a high tensile strength pressure vessel which has a thickened wall portion. When such a vessel is desired the method described in connection with FIG. 1 must be modified, as with a portion of the wall of the vessel blank thicker than the remainder of the wall there may not be uniform stretching when pressure is applied. To overcome this difficulty supplementary means for forcing out or stretching the thickened wall portion can be employed. Such a means may be, for instance, a multi-armed jack **74** as shown in FIGS. 4A and 4B. In lieu of the jack **74**, having a multiplicity of angularly related distendable arms, a plurality of an-

gularly related jacks may be employed. Referring now to FIGS. 4A and 4B the vessel blank **10''** is shown having two hemispherical end sections **66** and **68** of substantially uniform thickness and a central cylindrical section **70** having an inwardly directed flange **72**. If such a vessel blank were placed in a die **14''** and if pressure were applied to the interior of the vessel blank to stretch it to conform to the inner surface of the die **14''** the relatively thin walled sections of the vessel blank **10''** would stretch out to conform to the die. But, the thickened wall portion represented by the flange **72** would resist such deformation. Hence, the end product would not be of the desired shape.

To overcome this, while the vessel blank **10''** is being formed the multi-armed jack **74** is disposed within the blank in operative engagement with the flange **72**. After completion of the vessel blank **10''** the blank may be disposed within the die **14''** with the inlet for the pressure fluid connected to the pipe **40''**. The vessel blank may then be cooled either by cooling the die by such means as the cooling trays **22** or by introducing refrigerant into the interior of the vessel blank. After the cooling of the vessel blank to the temperature as hereinbefore described, the jack **74** is operated to distend its arms and thus stretch the thick portion of the wall i.e. flange **72**, of the vessel blank **10''**. Thereafter, pressure can be applied to the interior of the vessel blank to stretch the thin wall portions as hereinbefore described. In this way a pressure vessel having a portion of its wall of thicker dimension than the remainder can be formed.

If it is desired to form an open ended pressure vessel having a thick wall portion as shown in FIG. 4C then the finished vessel shown in FIG. 4B may, after removal from the die, be cut through its center section to yield two finished open ended pressure vessels as shown in FIG. 4C. Often, the internal flange is utilized in open ended vessels to provide a threaded connection. Accordingly, in FIG. 4C, the flange **72** is shown provided with a thread **73**.

It is possible to form a single open ended pressure vessel in accordance with the present invention. The open ended vessel may have a thickened wall portion or it may be provided with a uniform thickness throughout. The method of forming a single vessel will be substantially the same in either event. Such a method is illustrated in FIGS. 5A to 5C wherein a vessel blank **10'''** having a flange **76** is shown. The flange **76** is adjacent the open end **77** of the vessel. In forming an open ended pressure vessel from an open ended pressure vessel blank **10'''**, the vessel blank, after formation, is first placed in a die **14'''**, the interior of which is formed to the shape desired for the final pressure vessel. The vessel blank is then cooled, preferably by cooling the die although direct cooling may be employed. After cooling the open end **77** is stretched by mechanical means to cause it to assume the shape designed for it in the final stretched vessel. The remainder of the vessel blank **10'''** at this point remains unstretched. However, with the open end **77** now stretched to its final shape, a seal may be effected with the open end to subject the remainder of the vessel blank to stretching pressures, which seal will not be lost as the end **77** cannot stretch any further to break the seal. Accordingly, when pressure is applied, the remainder of the vessel blank will be stretched to cause it to conform to the shape of the die and thus form a finished open ended vessel.

Referring now particularly to FIGS. 5A, 5B and 5C a vessel blank **10'''** having an open end **77** is shown. As shown herein the vessel blank **10'''** has a flange **76** adjacent the open end although, as indicated hereinbefore, this method is applicable to open ended blanks having uniform wall thicknesses as well. The vessel blank **10'''** as described is placed in die **14'''** the internal surface of which conforms to the final shape of the vessel. The vessel blank **10'''** is then cooled. Preferably, although not necessarily, cooling is accomplished by cooling the die as by introducing refrigerant into cooling trays such as the cooling trays **22** as shown in FIG. 1. When the vessel blank has been cooled to the desired sub-zero temperature the open end **77** is stretched by mechanical means. Such a means may be a multi-armed jack like the jack **74** shown in FIGS. 4A and 4B. In lieu thereof a tapered mandril may be inserted into the open end **77** of the cooled vessel blank and a force applied to the shaft **80** connected to the mandril **78** to force the mandril inwardly of the blank and thus stretch out the open end **77**. With the outer wall of the open end of the vessel blank stretched to engage the die a seal may be effected as by a plate **84** and an O-ring **86**. Plate **84** is preferably provided with an inlet opening **88** to which the pipe **40'''** may be connected for conveying the pressure medium such as, for instance, liquid nitrogen from a pump to the interior of the vessel blank. After connection, the vessel blank may be stretched by introducing the pressure medium into the interior of the blank as hereinbefore described. After application of pressure to stretch the remainder of the vessel blank the pressure may be cut off and the stretched vessel may be removed from the die and it will be in the proper form and of extremely high tensile strength.

In connection with the modification described above with regard to FIGS. 5A to 5C, the mandril **78** may itself be employed to effect the seal of the open end. In such an event the mandril should be provided with an opening to permit the pressure medium, preferably the refrigerant under pressure, to be introduced into the interior of the vessel blank after stretching of the open end. Moreover, if a thickened wall portion is located at other than the open end, a suitable stretching means, such as multi-armed jack **74**, may be employed to stretch such thickened wall portion separately from the stretching of the open end of the vessel and the thin wall portion thereof.

While it is presently preferred to apply the internal pressure to the vessel blank by means of the refrigerant under pressure as has been described in detail hereinbefore, the present method can be worked by utilizing other means of applying pressure to the interior of the vessel blank. For instance, explosions within a vessel blank may be employed to supply the necessary pressure for stretching the vessel blank to conform to the interior of the wall of the die. However, the advantages of utilizing the refrigerant itself are great. By utilizing the refrigerant itself as the vehicle or means for applying pressure to the interior of the vessel blank a very rapid cooling and an assurance of a maintenance of the vessel blank at very low temperatures is achieved. As a matter of fact, if the refrigerant serves as the pressure vehicle, it may be possible to eliminate die cooling means such as trays **22** and still cool the vessel blank to the desired temperature. Accordingly, it may be possible to reduce the cost of the equipment for working the present invention. Moreover, there is no danger of any corrosive condensations as might possibly occur if other fluids are injected into the interior of the vessel blank under pressure to effect the stretching. Furthermore, it will be apparent that some fluids, such as, for instance, water, are inconvenient to use as they might freeze and thus prevent the application of the internal pressure. For these reasons the use of the refrigerant as the pressure means is the preferred embodiment.

In the example given above, both the weld area and the remainder of the vessel blank were stretched upon the application of pressure to the interior thereof. However, it will be understood that a vessel blank can be fabricated from very highly tensile strength metal, the method of fabrication of the blank being as by welding. However, upon the welding being employed to form the vessel blank, the benefits of the prior metallurgical processing for yielding the high strength material will be lost

in the weld areas due to annealing in such areas, whereby to render a vessel blank made generally of high tensile strength material but with weakened areas in and around the welds. With such a vessel, all that is necessary to do is to stretch the weld areas to increase their strength with no need for stretching the remainder of the material making the vessel blank. Naturally, in view of the fact that the welds and the area surrounding them are substantially weaker than the remainder of the vessel blank, the welds will stretch first whereby to give the result desired.

One of the advantages of stretching only weld areas is realized when extremely large vessel blanks are to be formed. Generally speaking, the cost of building dies to house huge pressure vessels as might be employed as solid fuel rocket casing for an intercontinental ballistic missle will be so great as to render the process not readily useable. Accordingly, when fabricating such a vessel blank by using stretch forming techniques, what can be done is that a plurality of individual sections can be formed of very high tensile strength material such as cryogenically rolled stainless steel. Each of the sections is essentially cylindrical. The sections can then be joined together as by welding whereby to weaken the material in the area of the welds but to render a very large vessel primarily made of extremely strong material. Thereafter, without the use of a die, pressure can be applied to the interior of the vessel so fabricated to stretch the weld areas and thereby gain strength in the weld areas. If it is desired to stretch the weld areas to effect a martensitic transformation of the material in the weld zones, then local temperature control in the area of the welds can be effected to bring the weld areas close to the M_s temperature of the material prior to stretching whereby to induce a substantial degree of martensitic transformation upon stretching the weld areas. Accordingly, if the material from which the vessel was made is an AISI 302 stainless steel, it will be necessary to cool the weld areas by liquid nitrogen or similar cryogenic material in order to bring the stainless steel in the weld areas down to its M_s temperature.

However, it will be seen that this type of stretching will not require a die and can be done out in the open with relatively simple equipment.

Furthermore, it is possible to have high tensile strength pressure vessels to which additional hardware must be secured after formation. Ofttimes it is necessary to secure the hardware by welding or other process employing great heat, which process will tend to anneal the vessel material in the area in connection with the additional hardware. Accordingly, in order to bring the vessel back up to strength after securing the hardware, it will be necessary only to stretch form the vessel blank in the area where hardware has been secured. Thus, when working on very large vessels, or it may be necessary only to isolate certain portions of them for stretching whereby to cut down the amout of work to be done, the size of equipment, and so forth.

While I have herein shown and described the preferred form of this invention and have suggested several modifications therein, other changes and modifications may be made therein within the scope of the appended claims without departing from the spirit and scope of this invention.

Having thus described my invention, what I desire to secure and claim by Letters Patent is:

1. Apparatus for forming high tensile strength pressure vessels, comprising a die adapted to receive a vessel blank and having at least a portion of the interior of the size and shape of said vessel, said die having two openings therein, a container, refrigerant in said container, a pump having an inlet and an outlet, a first conduit connecting said container of refrigerant to said pump inlet, a second conduit extending from said pump outlet through one of said openings in said die and adapted to be connected in communication with the interior of said vessel blank for supplying said refrigerant under pressure to the interior thereof to cool and stretch said vessel blank to substantially conform to the interior of said die, and third conduit means for venting the space between said die and said vessel blank.

2. Apparatus for forming high tensile strength pressure vessels as defined in claim 1, further comprising means in spaced relation to the outside of said die for cooling said die, and a fourth conduit for supplying said last mentioned cooling means with refrigerant from said container.

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