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(54) **A METHOD OF MANUFACTURE OF VESSELS FOR PRESSURISED FLUIDS AND APPARATUS THEREOF**

VERFAHREN ZUR HERSTELLUNG VON GEFÄSSEN FÜR DRUCKFLUIDE UND VORRICHTUNG DAFÜR

PROCÉDÉ DE FABRICATION DE RÉCIPIENTS POUR FLUIDES SOUS PRESSION ET APPAREIL AFFÉRENT

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(56) References cited:
**EP-A2- 0 117 849 WO-A1-96/11759
BE-A5- 1 019 903 DE-B- 1 188 391
DE-U1-202006 019 115 GB-A- 745 863**

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Description

[0001] The present invention relates to a method of manufacture of vessels adapted to contain pressurised fluids, the manufacturing apparatus thereof and pressure vessels manufactured using this method. More particularly, the present invention concerns a backward extrusion method for the manufacture of metallic vessels capable of containing fluids under pressure, the extrusion apparatus thereof and pressure vessels manufactured according to that method. In particular, but not exclusively, the present invention relates to apparatus and a manufacturing method for closed-ended hoop wrap gas cylinders adapted to contain gases at pressures above atmospheric pressure and to the closed-ended hoop wrap gas cylinders produced by the method.

[0002] Currently pressure vessels are manufactured in aluminium, steel and composite materials. Type I pressure vessels are formed solely of metallic material such as steel or aluminium alloys. In contrast Type II pressure vessels comprise a metallic vessel (usually made of aluminium) which has a filamentous composite sleeve, formed for example of an epoxy resin, aramid and/or carbon fiber, surrounding the cylindrical side wall only of the vessel (referred to herein as hoop wrap). Type II pressure vessels are generally lighter in weight than Type I pressure vessels because the metallic vessel wall of a Type II pressure vessel can be thinner than a Type I pressure vessel without loss of performance. For both Type I and Type II pressure vessels, repeated dispensing and vessel re-filling of gas under pressure causes the vessel to flex and such flexing can encourage the propagation of cracks in the vessel wall.

[0003] For metallic and composite pressure vessels conventional manufacturing methods include hot and cold extrusion of a billet comprising a metallic material, usually an aluminium alloy for high pressure vessels. US3648351 provides an early example of backward extrusion of a closed-end hollow metallic vessel in which a slug or billet of a metallic material is forced to extrude up the sides of a ram the end of which bears down on the slug within a die cavity. WO96/11757 describes an improved manufacturing method using backward extrusion in which two materials mounted in the die cavity are extruded together.

[0004] In addition, autofrettage has been used to improve pressure vessel fatigue resistance. Autofrettage involves applying a pressure within the bore of the vessel sufficient to plastically deform the metal at the inner surface. The technique produces compressive residual stresses at or near the internal surface, and this enhances the fatigue resistance of the vessel subjected to cyclic internal pressure loading. WO96/11759, on which the preamble of the independent claims 1, 7 and 9 is based, describes the use of autofrettage in the manufacture of pressure vessels to cause regions of peak stress in the pressure vessel wall to move away from an internal or external wall surface.

[0005] The present invention seeks to provide a pressure vessel manufacturing method, manufacturing apparatus and pressure vessels manufactured using the method which improves the pressure vessel's resistance to fatigue.

[0006] The present invention also seeks to provide a pressure vessel manufacturing method, manufacturing apparatus and pressure vessels manufactured using the method which reduces the likelihood of premature failure.

[0007] The present invention further seeks to provide a cold extrusion manufacturing method and manufacturing apparatus particularly suited to manufacturing AA6XXX and AA7XXX series aluminium high pressure cylinders and cylinder liners.

[0008] Still further, the present invention seeks to provide closed-ended hoop wrap pressure vessels with improved performance in comparison to conventional closed-ended hoop wrap pressure vessels.

[0009] The present invention separately seeks to provide pressure vessels which meet the regulatory requirements of pressure vessel standards such as: EN12257 and/or ISO11119-1 and which have a compound curve internal surface.

[0010] The present invention therefore provides a method of forming a closed-ended pressure vessel, the method comprising: positioning a billet of an extrudable metal into a die, said billet having an axis and a forward surface; using a ram with a longitudinal axis of symmetry, an end face region and a substantially cylindrical side wall to cause the metal to extrude by driving the end face region of the ram into the forward surface of the billet along the axis of the billet so as to cause the metal to extrude into the space between the ram and the die and along the cylindrical side wall of the ram to form an extrudate; and removing the extrudate from the die and shaping the open end of the extrudate to form a shoulder and a neck, whereby the end face region of the ram has a surface profile comprising a central section, at least one intermediate ring and an outermost ring with intersecting but differing curvatures of radii: R , r , and R_c respectively, the central section, the at least one intermediate ring and the outermost ring connecting a central point where the end face intersects the longitudinal axis of the ram with the cylindrical side wall of the ram at an axial distance H from the central point, the axial distance H having a range $0.28ID$ to $0.5ID$, where ID is the cross-sectional diameter of the cylindrical side wall of the ram.

[0011] Preferably the axial distance H is in the range $0.3ID$ and $0.4ID$.

[0012] In a particularly preferred embodiment the axial distance H is substantially equal to $ID/3$.

[0013] The central section preferably has a radius of curvature R in the range $0.5ID$ and $1.2ID$.

[0014] More preferably the central section has a radius of curvature R substantially equal to $1.1ID$.

[0015] More preferably still the intermediate ring has a radius of curvature r in the range between $0.1ID$ and $0.5ID$.

[0016] The intermediate ring preferably has a radius of curvature r in the range $0.12ID$ and $0.13ID$.

[0017] In a further preferred embodiment the end face region of the ram may have a surface profile including at least two intermediate rings each with a different radius of surface curvature.

[0018] Preferably the outermost ring has a radius of curvature R_c in the range $ID/(3 \pm 2)$.

[0019] More preferably still the outermost ring has a radius of curvature R_c in the range $ID/(3 \pm 1)$.

[0020] The outermost ring preferably has a radius of curvature R_c substantially equal to $ID/2$.

[0021] The method may further comprise the step of subjecting the pressure vessel to autofrettage.

[0022] The billet may comprise a AA6XXX series aluminium alloy.

[0023] In a particularly preferred embodiment the billet comprises a AA7XXX series aluminium alloy.

[0024] In a second aspect the present invention provides extruding apparatus for use in the manufacture of a closed-ended pressure vessel, the extruding apparatus comprising a die for receiving a billet of an extrudable metal and a ram having a longitudinal axis of symmetry, an end face region and a substantially cylindrical side wall, the end face region of the ram having a surface profile comprising a central section, at least one intermediate ring and an outermost ring with intersecting but differing curvatures of radii: R , r , and R_c respectively, the central section, the at least one intermediate ring and the outermost ring connecting a central point where the end face intersects the longitudinal axis of the ram with the cylindrical side wall of the ram at an axial distance H from the central point, the axial distance H having a range $0.28ID$ to $0.5ID$, where ID is the cross-sectional diameter of the cylindrical side wall of the ram.

[0025] Preferably the axial distance H is in the range $0.3ID$ and $0.4ID$.

[0026] In a particularly preferred embodiment the axial distance H is substantially equal to $ID/3$.

[0027] The central section preferably has a radius of curvature R in the range $0.5ID$ and $1.2ID$.

[0028] More preferably the central section has a radius of curvature R substantially equal to $1.1ID$.

[0029] The intermediate ring preferably has a radius of curvature r in the range between $0.1ID$ and $0.5ID$.

[0030] More preferably the intermediate ring has a radius of curvature r in the range between $0.12ID$ and $0.13ID$.

[0031] In a further preferred embodiment the end face region of the ram may have a surface profile including at least two intermediate rings each with a different radius of surface curvature.

[0032] The outermost ring preferably has a radius of curvature R_c in the range $ID/(3 \pm 2)$.

[0033] More preferably the outermost ring has a radius of curvature R_c in the range $ID/(3 \pm 1)$.

[0034] More preferably still the outermost ring has a radius of curvature R_c substantially equal to $ID/2$.

[0035] In a third aspect the present invention provides a closed-ended pressure vessel formed of an extrudable metal, the pressure vessel comprising a closed-end section, a substantially cylindrical side wall with a cross sectional internal diameter ID , a shoulder and a neck and having a longitudinal axis of symmetry, the internal surface profile of the closed-end section comprising a central section, at least one intermediate ring and an outermost ring with intersecting but differing curvatures of radii: R , r , and R_c respectively, the central section, the at least intermediate ring and the outermost ring connecting a central point where

the closed-end section intersects the longitudinal axis with the cylindrical side wall at an axial distance H from the central point, the axial distance H having a range $0.28ID$ to $0.5ID$.

[0036] Preferably the axial distance H is in the range $0.3ID$ and $0.4ID$.

[0037] In a particularly preferred embodiment the axial distance H is substantially equal to $ID/3$.

[0038] The central section preferably has a radius of curvature R in the range $0.5ID$ and $1.2ID$.

[0039] More preferably the central section has a radius of curvature R substantially equal to $1.1ID$.

[0040] The intermediate ring preferably has a radius of curvature r in the range between $0.1ID$ and $0.5ID$.

[0041] More preferably the intermediate ring has a radius of curvature r in the range between $0.12ID$ and $0.13ID$.

[0042] In a further preferred embodiment, the internal surface profile of the closed-ended section may include at least two intermediate rings each with a different radius of surface curvature.

[0043] The outermost ring preferably has a radius of curvature R_c in the range $ID/(3 \pm 2)$.

[0044] More preferably the outermost ring has a radius of curvature R_c in the range $ID/(3 \pm 1)$.

[0045] In a particularly preferred embodiment the outermost ring has a radius of curvature R_c substantially equal to $ID/2$.

[0046] The closed-ended pressure vessel may comprise a AA6XXX series aluminium alloy.

[0047] In a particularly preferred embodiment the closed-ended pressure vessel comprising a AA7XXX series aluminium alloy.

[0048] In a further aspect the present invention provides a composite pressure vessel comprises a closed-ended pressure vessel as described above and a sleeve of a composite material.

[0049] The composite material may be selected from a carbon fibre composite, basalt fibre, aramid and/or fibre glass fibre.

[0050] The manufacturing method and manufacturing apparatus of the present invention enables closed-ended high pressure vessels to be manufactured using cold or warm extrusion which have an equivalent or improved lifetime in contrast to equivalent high pressure vessels manufactured using hot extrusion and which achieve equivalent performance even with lower pressure autofrettage.

[0051] An embodiment of the present invention will now be described by way of example only with reference to the

accompanying drawings, in which:

Fig. 1 illustrates schematically a series of stages in backward extrusion of a metallic billet to form a closed-ended pressure vessel;

Fig. 2 is perspective view through a cross section of the closed end of a pressure vessel according to the present invention;

Fig. 3 is a detailed cross-section of the closed end of the pressure vessel of Fig. 2;

Fig. 4 illustrates the relationship of the surface curvature radii of the closed end of the pressure vessel of Fig. 2;

Figs. 5a and 5b illustrate the first principal stresses and the Von Mises stresses using finite element analysis of the base of a conventional hoop wrap pressure vessel liner; and

Figs. 6a and 6b illustrate the first principal stresses and the Von Mises stresses using finite element analysis of the base of a hoop wrap pressure vessel liner in accordance with the present invention.

[0052] Although hot extrusion (in which the extrusion is typically performed above the recrystallization temperature) according to the present invention is possible, cold and/or warm extrusion (in which the extrusion is performed below the recrystallization temperature) is preferred being a lower cost procedure. Warm extrusion is typically performed with a starting billet temperature at 100-250°C whereas cold extrusion is typically performed with a starting billet temperature at below 100°C, preferably ambient temperature. However, the precise extrusion conditions are not material to this invention and conventional conditions for extrusion may be employed.

[0053] The method of manufacturing a closed-ended pressure vessel as shown in Fig. 1 involves the use of extrusion apparatus 1 in the backward extrusion of a metallic billet 2. In overview, the billet of metallic material 2, for example an aluminium alloy, is positioned at the bottom of a cavity 3 in a die 4 (also referred to as an extrusion sleeve). A ram 5, which is preferably cylindrical in cross-section and with substantially parallel side walls, is arranged for reciprocal movement along a common axis X of the ram 5, the die 4 and the billet 2. The ram 5 is inserted into the die cavity 3 so that the end face 6 of the ram 5 engages the surface of the billet 2 facing towards the opening of the die cavity 3. Continued reciprocal movement of the ram 5 towards the closed end of the die cavity 3 forces the end face region 6 of the ram into the metallic billet 2. This causes the metallic material of the billet 2 to extrude along the side walls surface of the ram 5. The speed with which the extrudate exits from the die cavity 3 is typically in the range 50-500 cm/min and lubrication (not shown) may also be provided at least where the end face 6 of the ram 5 contacts the billet 2 to reduce the extrusion pressure required. Reciprocal movement of the ram 5 is continued until the end face 6 of the ram reaches a predetermined distance away from the interior floor of the die cavity 3 generally corresponding to the desired thickness of the closed end of the resulting pressure vessel. Similarly, the radial separation of the side wall of the ram 5 from the cylindrical inner surface of the die 4 generally corresponds to the thickness of the cylindrical side wall of the pressure vessel. Thus, the internal profile of the closed end of the pressure vessel corresponds to the external profile of the ram 5.

[0054] Formation of the closed end of the pressure vessel results in an initial generally cup-shaped extrudate with a base, parallel side walls and an open top. The open top of the extrudate is then squared off and heated, typically induction heated to 300-450°C, prior to the formation of a neck using conventional swaging or spinning techniques. The resulting hollow body is solution heat treated; quenched, generally in cold water; and finally aged. Conventional finishing processes, such as autofrettage and shot peening, may also be performed to complete manufacture of the pressure vessel.

[0055] The extrusion method described above differs from conventional backward extrusion of a metallic billet by virtue of the use of novel and inventive extrusion apparatus 1. The features of the extrusion apparatus 1 are generally conventional in design with the exception of the external surface 10 of the end face of the ram 5, which is described in greater detail below. As mentioned earlier, the internal surface profile of the closed end of the pressure vessel corresponds to the profile of the external surface 10 of the ram 5 and so the external surface 10 of the ram 5 is described herein by reference to Figs. 2 to 4 which show in cross section the closed end of a pressure vessel manufactured using the die 4 and ram 5 of the extrusion apparatus 1.

[0056] In overview and with reference to Figs. 2 and 3 the pressure vessel has an external or outer diameter OD, which is substantially equal to the internal diameter of the cylindrical side wall of the extrusion sleeve or die 4, and an internal diameter ID which is substantially equal to the external cylindrical diameter of the external side wall of the ram 5. The difference a between the internal and external diameters corresponds to the thickness of the substantially cylindrical side wall 11 of the pressure vessel, i.e. $a = (OD-ID)/2$ which also substantially corresponds to the clearance or radial difference of the side walls of the ram 5 and the die 4.

[0057] Key features of the profile of the external surface 10 of the ram 5 include a central point 12 where the end of the ram 5 intersects its longitudinal axis of symmetry X, a central section 13 and at least two rings 14, 15 which connect the central point 12 to the substantially cylindrical side wall 11 of the ram 5. When viewed along the axis X, the central section 13 and the two rings 14 and 15 are all rotationally symmetric with respect to the axis X and concentric with respect to each other. In contrast the surface profiles of the central section 13 and the two rings 14 and 15 in the vertical cross-section of Figs. 3 and 4 can be clearly seen to have differing but intersecting surface curvatures. In each case,

the surface curvature of the central section 13, the intermediate ring 14 and the outermost ring 15 extends between their boundaries and has a radius of R , r , and R_c respectively.

[0058] The central point 12 lies at the centre of the central section 13. The surface profile of the central section 13 has a curvature of radius R between $0.5ID$ and $1.2ID$, more preferably between $0.8ID$ and $1.2ID$, and more preferably still $ID < R < 1.2ID$. The outer edge of the central section 13 joins or intersects the inner edge of the first knuckle section, referred to herein as an intermediate ring 14, which has a curvature of radius r between $0.1ID$ and $0.5ID$, more preferably between $0.1ID$ and $0.25ID$, and more preferably still $0.1ID < r < 0.15ID$. In turn, the outer edge of the intermediate ring 14 joins or intersects the inner edge of the second knuckle section referred to herein as the second or outermost ring 15 which has a curvature of radius $R_c = ID/(3 \pm 2)$, more preferably $R_c = ID/(3 \pm 1)$, more preferably still $0.4ID < R_c < 0.6ID$. Although the range of potential curvatures for the central section 13 and the two rings 14, 15 overlap each other, for any particular ram 5, the central section and the two rings defining the external surface 10 will each have a surface curvature that differs from the surface curvatures of the others and with the radius of the surface curvature of the intermediate ring 14 always smaller than the curvature of the central section 13 and the outermost ring 15.

[0059] With reference to Fig. 4, as the central section 13 is rotationally symmetric with respect to the axis X , the radius R of the central section's surface curvature is measured from a point (origin) a distance R along the axis X . Furthermore the intersection of the central section 13 with the intermediate ring 14, the intersection of the intermediate ring 14 with the outermost ring 15, and the intersection of the outermost ring 15 with the cylindrical side wall 11 are each blended to ensure no discontinuities in the surface profile of the end of the ram 5 that might be detrimental to the strength of the cylinder. This requires that at each intersection tangents to the curvatures of the surfaces either side of the junction (the tangents being orthogonal to the line of the junction) are substantially aligned and preferably common. In the case of the intersection of the outermost ring 15 with the cylindrical side wall 11, the tangent to the surface curvature of the outermost ring 15 (orthogonal to the line of the intersection) is substantially aligned with the surface of the cylindrical side wall 11.

[0060] A cross section taken through the ram 5 at the junction of the outermost ring 15 with the cylindrical side wall 11 intersects the axis X a distance H above the central point 12. The distance H is between $0.28ID$ and $0.5ID$, more preferably $0.3ID$ and $0.4ID$, more preferably still $H = ID/3$. As the tangent to the surface curvature of the outermost ring 15 is substantially aligned with the cylindrical wall 11 at the junction of the outermost ring 15 with the side wall 11, the radius R_c of the outermost ring's surface curvature is measured from a point (origin) that lies in a cross-sectional plane through the ram 5 at height H above the central point 12.

[0061] Thus to ensure that the curvature of the intermediate ring 14 is blended with both the central section 13 and the outermost ring 15, the radius r of the intermediate ring 14 is measured from a point (origin) corresponding to the intersection of R_c - r and R - r . Furthermore, the cross sectional diameter IDC of the center of the intermediate ring 14 is less than or equal to $OD - (3xa)$, where OD is the external cylindrical diameter of the pressure vessel (equal to the internal cylindrical diameter of the die 4) and a is the thickness of the pressure vessel wall (equal to the separation of the cylindrical side walls of the die 4 and the ram 5).

[0062] Although the figures illustrate a single intermediate ring 14, the internal surface profile of the pressure cylinder (and so also the external surface profile of the ram 5) may comprise more than one intermediate ring with each intermediate ring having its own radius of surface curvature and with each of the intermediate rings blending at its edges with the edges of adjacent rings i.e. the tangents to the surface curvature of each intermediate ring at the edges of the intermediate ring being substantially aligned with the tangents to the surface curvatures of adjacent rings. Furthermore, although the figures illustrate the surface curvature of the central section 13 to be defined by a single radius it is also envisaged that the central 13 may consist of an inner central section which is substantially flat and an outer central section, concentric to the inner central section, which has a surface curvature of radius R .

Example 1

[0063] A first set of exemplary dimensions for a die 4 and ram 5 of extrusion apparatus according to the present invention and the corresponding dimensions of the 5 litre AA7060 cylinder liner produced using the die and ram are set out below.

total height of cylinder = 465 mm
total weight of cylinder = 4.8 Kg

Ram and Die	5 litre AA7060 cylinder liner	(mm)
Internal diameter of die	OD	140

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(continued)

Ram and Die	5 litre AA7060 cylinder liner	(mm)
External diameter of ram	ID	129
Radial separation of die from cylindrical surface of ram	a	5.5
Axial height of contoured end of ram to cylindrical side wall	H	43
Innermost ring radius of contoured ram surface	R	146
Second ring radius of contoured ram surface	r	16
Outermost ring radius of contoured ram surface	Rc	64

Example 2

[0064] A second set of exemplary dimensions for a conventional 2 litre carbon fibre hoop wrap AA7060 alloy liner (and the corresponding dimensions of the die 4 and ram 5 of conventional extrusion apparatus) (**Shape A**) and similarly for a 2 litre carbon fibre hoop wrap AA7060 alloy liner (and its corresponding die and ram) (**Shape B**) in accordance with the present invention are set out below:

	Shape A (mm)	Shape B (mm)
OD	96.7	96.7
ID	88.5	88.5
a	4.1	4.1
H	22	29.5
R	105	101
r	11	11
Rc	44.4	44.4
a' (at H)	4.08	4.13

[0065] Comparative failure performance test results for pressure vessels manufactured under cold extrusion using the extrusion apparatus described in Example 2 and of 2 litre hoop wrap 7060 aluminium alloy liners (**Shape A**) manufactured using cold extrusion and a conventional backward extrusion die are set out below in Table 1.

Table 1

Shape A			Shape B	
Number of refill cycles to failure	Failure Site		Number of refill cycles to failure	Failure Site
11749	0	Sample 1	20226	2
10954	1	Sample 2	16255	2
12076	1	Sample 3	17918	2
9614	0	Sample 4	15190	3
9820	1	Sample 5	18680	2
		Sample 6	15681	2
Failure site 0 = leak, position unknown; Failure site 1 = rupture at cylinder bottom; Failure site 2 = leak in the cylinder body; and Failure site 3 = leak in the shoulder.				

[0066] The lifetime and failure characteristics of 5 litre hoop wrap 7060 aluminium alloy liners (**Shape B**) manufactured

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under cold extrusion using the apparatus described in Example 1 above were compared with the performance of 5 litre hoop wrap 7060 aluminium alloy liners (**Shape A**) also manufactured using cold extrusion but with a conventional backward extrusion die. The results in terms of lifetime (number of refill cycles to failure) and failure sites are set out below in Table 2.

Table 2

	Shape A	Shape B
No. of test cylinders	5	11
Minimum number of refill cycles to failure	10736	15343
Maximum number of cycles to failure	16513	20000
Average number of cycles to failure	14067	17754
Failure sites	1 x leak in cylinder body 2 x leak in lower part of cylinder body 1 x rupture in the cylinder bottom	10 x leak in the cylinder body 1 x test stopped with no leak

[0067] The results of Tables 1 and 2 clearly show a significant improvement in failure performance in comparison to equivalent conventional pressure vessels.

[0068] Twenty seven test pressure vessels having the dimensions set out in Example 1 were tested to failure. Five groups each of five pressure vessels were subjected to a pressure cycling test with each group of pressure vessels having had a different amount of autofrettage. The remaining two pressure vessels (having had no autofrettage) were subjected to a burst test. Each of the test pressure vessels was a 5 litre carbon fibre hoop wrap 7060 aluminium alloy pressure vessel manufactured in a cold backward extrusion process using a die 4 and ram 5 having the dimensions set out in Example 1. Details of the amount of autofrettage for each group of pressure vessels and the results of the tests are set out below in Table 3.

Table 3

Number of test samples	Autofrettage pressure	Value (BAR)	Internal shot peening	Results: average number of refill cycles to Failure
5	Without	0	YES	14084 (a)
5	Approved value	640	YES	18470 (a)
5	Approved value+10%	704	YES	24517 (a)
5	Approved value+20%	768	YES	26116 (b)
5	Approved value	640	NO	15856 (a)
2	Without	0	NO	Burst pressure=832 BAR Expansion volume=512cm ³
(a) represents failure in the cylinder body wall (b) represents failures at different parts of the cylinder.				

In the above tests two of the pressure vessels subjected to 110% autofrettage pressure and three of the pressure vessels subjected to 120% autofrettage pressure exhibited detachment of carbon fibres from the outer sleeve.

[0069] As discussed in WO96/11759 the effectiveness of autofrettage in improving fatigue performance is known to be dependent upon the design of the closed end of the pressure vessel. For example, pressure vessels with hemispherical closed ends do not exhibit significant improvements in fatigue performance when subjected to autofrettage. In contrast, pressure vessels with semi-ellipsoidal or torispherical dish shaped closed ends are known to deliver improved performance with autofrettage. Thus, autofrettage offers improved failure performance for pressure vessels having a closed end joined to a cylindrical side wall by a knuckle region. The autofrettage pressure is generally between 75% and 95% of the minimum burst pressure according to the relevant standard. Aluminium high pressure gas cylinders are usually designed so that the stress in the cylindrical side wall at service pressure does not exceed half the alloy yield stress,

and that the cylinder burst pressure is at least 2.5 times the operating pressure. Thus, in a AA7XXX series aluminium alloy cylinder having, for example, a yield stress of 450 MPa, the design should be such that wall stresses do not exceed 225 MPa.

[0070] The information in Tables 1 to 3 clearly show that hoop wrap pressure vessels manufactured according to the method and apparatus of the present invention also benefit from autofrettage and shot peening, offering a surprising improvement in failure performance in comparison to equivalent conventional pressure vessels. This enables pressure vessels according to the method and apparatus of the present invention to deliver at least equivalent and potentially improved failure performance at lower autofrettage pressures.

[0071] Finite element analysis (FEA) of a hoop wrap pressure vessel manufactured using the method and apparatus described above has revealed that the internal profile of the closed end of pressure vessels according to the present invention results in noticeably lower maximum stresses in comparison to pressure vessels with a conventional internal profile at the closed end.

[0072] With FEA the structure (in this case the closed end of the pressure vessel) is broken down into many small pieces (finite number of elements) of various types, sizes and shapes. The elements are assumed to have a simplified pattern of deformation (linear or quadratic etc.) and are connected at 'nodes' normally located at corners or edges of the elements. The elements are then assembled mathematically using basic rules of structural mechanics i.e. equilibrium of forces and continuity of displacements, resulting in a large system of simultaneous equations. By solving the system of simultaneous equations the deformed shape of the structure under load may be obtained and internal stresses and strains may be calculated from the deformed shape.

[0073] The finite element model (FEM) was based on a 7060 aluminium alloy liner and a carbon composite sleeve with ID=88.5 combined with 4 different sets of dimensions for the internal surface profile of the pressure vessel: Analysis 1, Analysis 2, Analysis 3 and Analysis 4. The FEA subjected each Analysis to the following loading steps: autofrettage pressure = 600 BAR; service pressure = 300 BAR; test pressure = 450 BAR and minimum design burst = 752 BAR to identify the first principal stress and the Von Mises stress at the test pressure of 450 BAR after autofrettage the results of which are set out in Table 4 below; Analysis 1 corresponds to a conventional pressure vessel adjusted to incorporate three concentric intersecting radii, whereas Analysis 4 corresponds to a pressure vessel manufactured using the method and apparatus described above, Analysis 4 being a particularly preferred embodiment. Analyses 2 and 3 were included purely for comparative purposes.

Table 4

	First Principal Stress (Mpa)	Von Mises Stress (Mpa)	H (mm)	R (mm)	r (mm)	Rc (mm)
Analysis 1	318	306	22	105	11	44.2
Analysis 2	323	308	22.125	77.36	8.85	88.5
Analysis 3	285	278	22.125	111.2	14.5	29.5
Analysis 4	241	235	29.5	100.5	11	44.25

[0074] Figs. 5a and 5b show the principal stresses and the Von Mises stresses for Analysis 1 and Figs. 6a and 6b show the principal stresses and the Von Mises stresses for Analysis 4. Figs. 5 and 6 show that the location of maximum stress in the knuckle region remains substantially the same for Analysis 1 and Analysis 4 (the same is also true for Analysis 2 and Analysis 3, not shown). Figs. 5 and 6 also show that for Type II pressure vessels manufactured using the method and apparatus described above, the maximum Von Mises stress remains at the inner surface of the pressure vessel even after autofrettage. However, the results in Table 4 clearly show that the absolute value of the first principal stress and the Von Mises stress are significantly lower for Analysis 4 than for any of the other Analyses. Also the FEA shows that the main factors contributing to the lowering of the maximum stress are the value of H and Rc.

[0075] The above method and apparatus are particularly suited, but not limited, to the cold extrusion manufacture of pressure vessels for AA6XXX and AA7XXX series of aluminium alloys (according to the Aluminum Association Inc. Register 2009) and to both Type I cylinders and Type II cylinder liners respectively which meet the fatigue requirements of hoop wrapped pressure vessel standards, for example, EN12257 and ISO11119-1 and corresponding standards in other regions of the world. Moreover, with the above method and apparatus Type II cylinders which at least match and often exceed the failure performance of equivalent conventional cylinders may be manufactured using autofrettage at lower pressures.

[0076] It is to be understood that the embodiments described above are only selected preferred exemplary embodiments. Changes may be made to the manufacturing method, manufacturing apparatus and to the pressure vessels produced by the method and apparatus described above without departing from the scope of the invention as claimed in the accompanying claims.

Claims

1. A method of forming a closed-ended pressure vessel, the method comprising:

positioning a billet (2) of an extrudable metal into a die (4), said billet (2) having an axis and a forward surface; using a ram (5) with a longitudinal axis of symmetry (x), an end face region (6) and a substantially cylindrical side wall (11) to cause the metal to extrude by driving the end face region (6) of the ram (5) into the forward surface of the billet along the axis of the billet so as to cause the metal to extrude into the space between the ram (5) and the die (4) and along the cylindrical side wall (11) of the ram to form an extrudate; and removing the extrudate from the die (4) and shaping the open end of the extrudate to form a shoulder and a neck, **characterised in that** the end face region (6) of the ram (5) has a surface profile (10) comprising a central section (13), at least one intermediate ring (14) and an outermost ring (15) with intersecting but differing surface curvatures of radii: R, r, and Rc respectively, the central section (13), the at least one intermediate ring (14) and the outermost ring (15) connecting a central point (12) where the end face region (6) intersects the longitudinal axis of the ram (5) with the cylindrical side wall (11) of the ram at an axial distance H from the central point (12), the axial distance H having a range 0.28ID to 0.5ID, where ID is the cross-sectional diameter of the cylindrical side wall (11) of the ram.

2. The method as claimed in claim 1, wherein the axial distance H is in the range 0.3ID and 0.4ID.

3. The method as claimed in any of the preceding claims, wherein the central section (13) has a radius of curvature R in the range 0.5ID and 1.2ID.

4. The method as claimed in any of the preceding claims, wherein the at least one intermediate ring (14) has a radius of curvature r in the range between 0.1ID and 0.5ID.

5. The method as claimed in any one of claims 1 to 4, wherein the end face region (6) of the ram (5) has a surface profile including at least two intermediate rings (14) each with a different radius of surface curvature.

6. The method as claimed in any one of claims 1 to 5, wherein the outermost ring (15) has a radius of curvature Rc substantially equal to ID/2.

7. Extruding apparatus (1) for use in the manufacture of a closed-ended pressure vessel, the extruding apparatus (1) comprising a die (4) for receiving a billet (2) of an extrudable metal and a ram (5) having a longitudinal axis of symmetry (x), an end face region (6) and a substantially cylindrical side wall (11), **characterized in that** the end face region (6) of the ram (5) has a surface profile (10) comprising a central section (13), at least one intermediate ring (14) and an outermost ring (15) with intersecting but differing surface curvatures of radii: R, r, and Rc respectively, the central section (13), the at least one intermediate ring (14) and the outermost ring (15) connecting a central point (12) where the end face intersects the longitudinal axis of the ram (5) with the cylindrical side wall (11) of the ram at an axial distance H from the central point (12), the axial distance H having a range 0.28ID to 0.5ID, where ID is the cross-sectional diameter of the cylindrical side wall (11) of the ram.

8. The extruding apparatus as claimed in claim 7, wherein the end face region (6) of the ram (5) has a surface profile (10) including at least two intermediate rings (14) each with a different radius of surface curvature.

9. A closed-ended pressure vessel formed of an extrudable metal, the pressure vessel comprising a closed-end section, a cylindrical side wall (11) with a cross sectional internal diameter ID, a shoulder and a neck and having a longitudinal axis of symmetry (x), **characterized in that** the internal surface profile of the closed-end section comprises a central section (13), at least one intermediate ring (14) and an outermost ring (15) with intersecting but differing curvatures of radii: R, r, and Rc respectively, the central section (13), the at least one intermediate ring (14) and the outermost ring (15) connecting a central point (12) where the closed-end section intersects the longitudinal axis (x) with the cylindrical side wall (11) at an axial distance H from the central point (12), the axial distance H having a range 0.28ID to 0.5ID.

10. The closed-ended pressure vessel as claimed in claim 9, wherein the axial distance H is in the range 0.3ID and 0.4ID.

11. The closed-ended pressure vessel as claimed in any one of claims 9 or 10, wherein the central section (13) has a radius of curvature R in the range 0.5ID and 1.2ID.

12. The closed-ended pressure vessel as claimed in any one of claims 9 to 11, wherein the intermediate ring (14) has a radius of curvature r in the range between $0.1ID$ and $0.5ID$.
13. The closed-ended pressure vessel as claimed in any one of claims 9 to 12, wherein the internal surface profile of the closed-ended section includes at least two intermediate rings (14) each with a different radius of surface curvature.
14. The closed-ended pressure vessel as claimed in any one of claims 9 to 13, wherein the outermost ring (15) has a radius of curvature R_c in the range $ID/(3 \pm 2)$.
15. The closed-ended pressure vessel as claimed in any one of claims 9 to 14, comprising a AA6XXX series aluminium alloy.
16. The closed-ended pressure vessel as claimed in any one of claims 9 to 14, comprising a AA7XXX series aluminium alloy.
17. A composite pressure vessel comprising a closed-ended pressure vessel as claimed in any one of claims 9 to 16 and a sleeve of a composite material.
18. A composite pressure vessel as claimed in claim 17, wherein the composite material includes one or more of a carbon fibre, basalt fibre, aramid fibre and glass fibre.

Patentansprüche

1. Verfahren zur Herstellung eines Druckbehälters mit geschlossenem Ende, wobei das Verfahren Folgendes aufweist:

Einsetzen eines Blocks (2) aus einem strangpressbaren Metall in ein Werkzeug (4), wobei der genannte Block (2) eine Achse und eine vordere Oberfläche hat;

Verwenden eines Stempels (5) mit einer Längs-Symmetrieachse (x), einer Endseitenregion (6) und einer im Wesentlichen zylindrischen Seitenwand (11), um das Verdrängen des Metalls durch Treiben der Endseitenregion (6) des Stempels (5) an der Achse des Blocks entlang in die vordere Oberfläche des Blocks zu verursachen, um zu verursachen, dass das Metall zum Bilden eines Extrudats in den Zwischenraum zwischen dem Stempel (5) und dem Werkzeug (4) und an der zylindrischen Seitenwand (11) des Stempels entlang verdrängt wird; und Entfernen des Extrudats aus dem Werkzeug (4) und Umformen des offenen Endes des Extrudats zu einer Schulter und einem Hals,

dadurch gekennzeichnet, dass die Endseitenregion (6) des Stempels (5) ein Oberflächenprofil (10) hat, das einen mittleren Abschnitt (13), wenigstens einen Zwischenring (14) und einen äußersten Ring (15) mit sich schneidenden aber unterschiedlichen Oberflächenkrümmungen der Radien R , r bzw. R_c aufweist, wobei der mittlere Abschnitt (13), der wenigstens einen Zwischenring (14) und der äußerste Ring (15) einen Mittelpunkt (12), an dem die Endseitenregion (6) die Längsachse des Stempels (5) schneidet, in einer axialen Entfernung H vom Mittelpunkt (12) mit der zylindrischen Seitenwand (11) des Stempels verbinden, wobei die axiale Entfernung H einen Bereich von $0,28ID$ bis $0,5ID$ hat, wobei ID der Querschnitts-Innendurchmesser der zylindrischen Seitenwand (11) des Stempels ist.

2. Verfahren nach Anspruch 1, wobei die axiale Entfernung H im Bereich von $0,3ID$ bis $0,4ID$ ist.
3. Verfahren nach einem der vorhergehenden Ansprüche, wobei der mittlere Abschnitt (13) einen Krümmungsradius R im Bereich von $0,5ID$ bis $1,2ID$ hat.
4. Verfahren nach einem der vorhergehenden Ansprüche, wobei der wenigstens eine Zwischenring (14) einen Krümmungsradius r im Bereich zwischen $0,1ID$ und $0,5ID$ hat.
5. Verfahren nach einem der Ansprüche 1 bis 4, wobei die Endseitenregion (6) des Stempels (5) ein Oberflächenprofil hat, das wenigstens zwei Zwischenringe (14), jeweils mit einem anderen Oberflächenkrümmungsradius, enthält.
6. Verfahren nach einem der Ansprüche 1 bis 5, wobei der äußerste Ring (15) einen Krümmungsradius R_c hat, der im Wesentlichen gleich $ID/2$ ist.

7. Strangpressvorrichtung (1) zur Verwendung bei der Herstellung eines Druckbehälters mit geschlossenem Ende, wobei die Strangpressvorrichtung (1) ein Werkzeug (4) zur Aufnahme eines Blocks (2) aus einem strangpressbaren Metall und einen Stempel (5) mit einer Längs-Symmetrieachse (x), einer Endseitenregion (6) und einer im Wesentlichen zylindrischen Seitenwand (11) aufweist, **dadurch gekennzeichnet, dass** die Endseitenregion (6) des Stempels (5) ein Oberflächenprofil (10) hat, das einen mittleren Abschnitt (13), wenigstens einen Zwischenring (14) und einen äußersten Ring (15) mit sich schneidenden, aber unterschiedlichen Oberflächenkrümmungen der Radien R, r bzw. Rc aufweist, wobei der mittlere Abschnitt (13), der wenigstens einen Zwischenring (14) und der äußerste Ring (15) einen Mittelpunkt (12), an dem die Endseitenfläche die Längsachse des Stempels (5) schneidet, in einer axialen Entfernung H vom Mittelpunkt (12) mit der zylindrischen Seitenwand (11) des Stempels (5) verbinden, wobei die axiale Entfernung H einen Bereich von 0,28ID bis 0,5ID hat, wobei ID der Querschnittsdurchmesser der zylindrischen Seitenwand (11) des Stempels ist.
8. Strangpressvorrichtung nach Anspruch 7, wobei die Endseitenregion (6) des Stempels (5) ein Oberflächenprofil (10) hat, das wenigstens zwei Zwischenringe (14), jeweils mit einem anderen Oberflächenkrümmungsradius, enthält.
9. Druckbehälter mit geschlossenem Ende, der aus einem extrudierbaren Metall hergestellt ist, wobei der Druckbehälter einen Abschnitt mit geschlossenem Ende, eine zylindrische Seitenwand (11) mit einem Querschnitts-Innendurchmesser ID, eine Schulter und einen Hals aufweist und eine Längs-Symmetrieachse (x) hat, **dadurch gekennzeichnet, dass** das Innenflächenprofil des Abschnitts mit geschlossenem Ende einen mittleren Abschnitt (13), wenigstens einen Zwischenring (14) und einen äußersten Ring (15) mit sich schneidenden, aber unterschiedlichen Oberflächenkrümmungen der Radien R, r bzw. Rc aufweist, wobei der mittlere Abschnitt (13), der wenigstens einen Zwischenring (14) und der äußerste Ring (15) einen Mittelpunkt (12), an dem der Abschnitt mit geschlossenem Ende die Längsachse (x) schneidet, in einer axialen Entfernung H vom Mittelpunkt (12) mit der zylindrischen Seitenwand (11) verbinden, wobei die axiale Entfernung H einen Bereich von 0,28ID bis 0,5ID hat.
10. Druckbehälter mit geschlossenem Ende nach Anspruch 9, wobei die axiale Entfernung H im Bereich von 0,3ID bis 0,4ID ist.
11. Druckbehälter mit geschlossenem Ende nach einem der Ansprüche 9 oder 10, wobei der mittlere Abschnitt (13) einen Krümmungsradius R im Bereich von 0,5ID bis 1,2ID hat.
12. Druckbehälter mit geschlossenem Ende nach einem der Ansprüche 9 bis 11, wobei der Zwischenring (14) einen Krümmungsradius r im Bereich zwischen 0,1ID und 0,5ID hat.
13. Druckbehälter mit geschlossenem Ende nach einem der Ansprüche 9 bis 12, wobei das Innenflächenprofil des Abschnitts mit geschlossenem Ende wenigstens zwei Zwischenringe (14), jeweils mit einem anderen Oberflächenkrümmungsradius, enthält.
14. Druckbehälter mit geschlossenem Ende nach einem der Ansprüche 9 bis 13, wobei der äußerste Ring (15) einen Krümmungsradius Rc im Bereich von $ID/(3 \pm 2)$ hat.
15. Druckbehälter mit geschlossenem Ende nach einem der Ansprüche 9 bis 14, der eine Aluminiumlegierung der Gruppe AA6xxx umfasst.
16. Druckbehälter mit geschlossenem Ende nach einem der Ansprüche 9 bis 14, der eine Aluminiumlegierung der Gruppe AA7xxx umfasst.
17. Zusammengesetzter Druckbehälter, der einen Druckbehälter mit geschlossenem Ende nach einem der Ansprüche 9 bis 16 und eine Hülle aus einem Verbundwerkstoff umfasst.
18. Zusammengesetzter Druckbehälter nach Anspruch 17, wobei der Verbundwerkstoff eine oder mehr der Folgenden umfasst: eine Kohlenstofffaser, eine Basaltfaser, eine Aramidfaser und eine Glasfaser.

Revendications

1. Procédé de façonnage d'un récipient sous pression à extrémité fermée, le procédé comprenant les étapes consistant à :

positionner une billette (2) de métal extrudable dans une filière (4), ladite billette (2) ayant un axe et une surface avant ;

utiliser un poussoir (5) ayant un axe de symétrie longitudinal (x), une zone de face frontale (6) et une paroi latérale essentiellement cylindrique (11), pour causer l'extrusion du métal en entraînant la zone de face frontale (6) du poussoir (5) dans la surface avant de la billette le long de l'axe de la billette, afin de causer l'extrusion du métal dans l'espace entre le poussoir (5) et la filière (4), et le long de la paroi latérale cylindrique (11) du poussoir, et de former ainsi un extrudat ; et

retirer l'extrudat de la filière (4) et façonner l'extrémité ouverte de l'extrudat afin de former un épaulement et un goulot,

caractérisé en ce que la zone de face frontale (6) du poussoir (5) présente un profil de surface (10) comprenant une section centrale (13), au moins un anneau intermédiaire (14) et un anneau extérieur (15) avec des courbures de surface différentes se recoupant de rayons R, r et Rc respectivement, la section centrale (13), l'au moins un anneau intermédiaire (14) et l'anneau extérieur (15) se connectant en un point central (12) où la zone de face frontale (6) recoupe l'axe longitudinal du poussoir (5) lorsque la paroi latérale cylindrique (11) du poussoir se trouve à une distance axiale H du point central (12), la distance axiale H étant dans une plage comprise entre $0,28ID$ et $0,5ID$, où ID est le diamètre transversal de la paroi latérale cylindrique (11) du poussoir.

2. Procédé selon la revendication 1, dans lequel la distance axiale H est dans la plage comprise entre $0,3ID$ et $0,4ID$.

3. Procédé selon l'une quelconque des revendications précédentes, dans lequel la section centrale (13) a un rayon de courbure R dans la plage comprise entre $0,5ID$ et $1,2ID$.

4. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'au moins un anneau intermédiaire (14) a un rayon de courbure r dans la plage comprise entre $0,1ID$ et $0,5ID$.

5. Procédé selon l'une quelconque des revendications 1 à 4, dans lequel la zone de face frontale (6) du poussoir (5) présente un profil de surface comprenant au moins deux anneaux intermédiaires (14) ayant chacun un rayon de courbure de surface différent.

6. Procédé selon l'une quelconque des revendications 1 à 5, dans lequel l'anneau extérieur (15) a un rayon de courbure Rc essentiellement égal à $ID/2$.

7. Appareil d'extrusion (1) à utiliser pour fabriquer un récipient sous pression à extrémité fermée, l'appareil d'extrusion (1) comprenant une filière (4) permettant d'accueillir une billette (2) de métal extrudable et un poussoir (5) ayant un axe de symétrie longitudinal (x), une zone de face frontale (6) et une paroi latérale essentiellement cylindrique (11), **caractérisé en ce que** la zone de face frontale (6) du poussoir (5) présente un profil de surface (10) comprenant une section centrale (13), au moins un anneau intermédiaire (14) et un anneau extérieur (15) avec des courbures de surface différentes se recoupant de rayons R, r et Rc respectivement, la section centrale (13), l'au moins un anneau intermédiaire (14) et l'anneau extérieur (15) se connectant en un point central (12) où la face frontale recoupe l'axe longitudinal du poussoir (5) lorsque la paroi latérale cylindrique (11) du poussoir (5) se trouve à une distance axiale H du point central (12), la distance axiale H est dans une plage comprise entre $0,28ID$ et $0,5ID$, où ID est le diamètre transversal de la paroi latérale cylindrique (11) du poussoir.

8. Appareil d'extrusion selon la revendication 7, dans lequel la zone de face frontale (6) du poussoir (5) présente un profil de surface (10) comprenant au moins deux anneaux intermédiaires (14) ayant chacun un rayon de courbure de surface différent.

9. Récipient sous pression à extrémité fermée façonné à partir d'un métal extrudable, le récipient sous pression comprenant une section d'extrémité fermée, une paroi latérale cylindrique (11) avec un diamètre interne transversal (ID), un épaulement et un goulot, et un axe de symétrie longitudinal (x), **caractérisé en ce que** le profil de surface interne de la section d'extrémité fermée comprend une section centrale (13), au moins un anneau intermédiaire (14) et un anneau extérieur (15) avec des courbures de surface différentes se recoupant de rayons R, r et Rc respectivement, la section centrale (13), l'au moins un anneau intermédiaire (14) et l'anneau extérieur (15) se connectant en un point central (12) où la section d'extrémité fermée recoupe l'axe longitudinal (x) lorsque la paroi latérale cylindrique (11) se trouve à une distance axiale H du point central (12), la distance axiale H étant dans une plage comprise entre $0,28ID$ et $0,5ID$.

10. Récipient sous pression à extrémité fermée selon la revendication 9, dans lequel la distance axiale H est dans la

plage comprise entre $0,3ID$ et $0,4ID$.

11. Récipient sous pression à extrémité fermée selon l'une quelconque des revendications 9 ou 10, dans lequel la section centrale (13) a un rayon de courbure R dans la plage comprise entre $0,5ID$ et $1,2ID$.

12. Récipient sous pression à extrémité fermée selon l'une quelconque des revendications 9 à 11, dans lequel l'anneau intermédiaire (14) a un rayon de courbure r dans la plage comprise entre $0,1ID$ et $0,5ID$.

13. Récipient sous pression à extrémité fermée selon l'une quelconque des revendications 9 à 12, dans lequel le profil de surface interne de la section d'extrémité fermée comprend au moins deux anneaux intermédiaires (14) ayant chacun un rayon de courbure de surface différent.

14. Récipient sous pression à extrémité fermée selon l'une quelconque des revendications 9 à 13, dans lequel l'anneau extérieur (15) a un rayon de courbure R_c dans la plage $ID/(3 \pm 2)$.

15. Récipient sous pression à extrémité fermée selon l'une quelconque des revendications 9 à 14, comprenant un alliage d'aluminium de série AA6XXX.

16. Récipient sous pression à extrémité fermée selon l'une quelconque des revendications 9 à 14, comprenant un alliage d'aluminium de série AA7XXX.

17. Récipient sous pression composite comprenant un récipient sous pression à extrémité fermée selon l'une quelconque des revendications 9 à 16, et un manchon en matériau composite.

18. Récipient sous pression composite selon la revendication 17, dans lequel le matériau composite comprend un ou plusieurs matériaux parmi une fibre de carbone, une fibre de basalte, une fibre aramide et une fibre de verre.

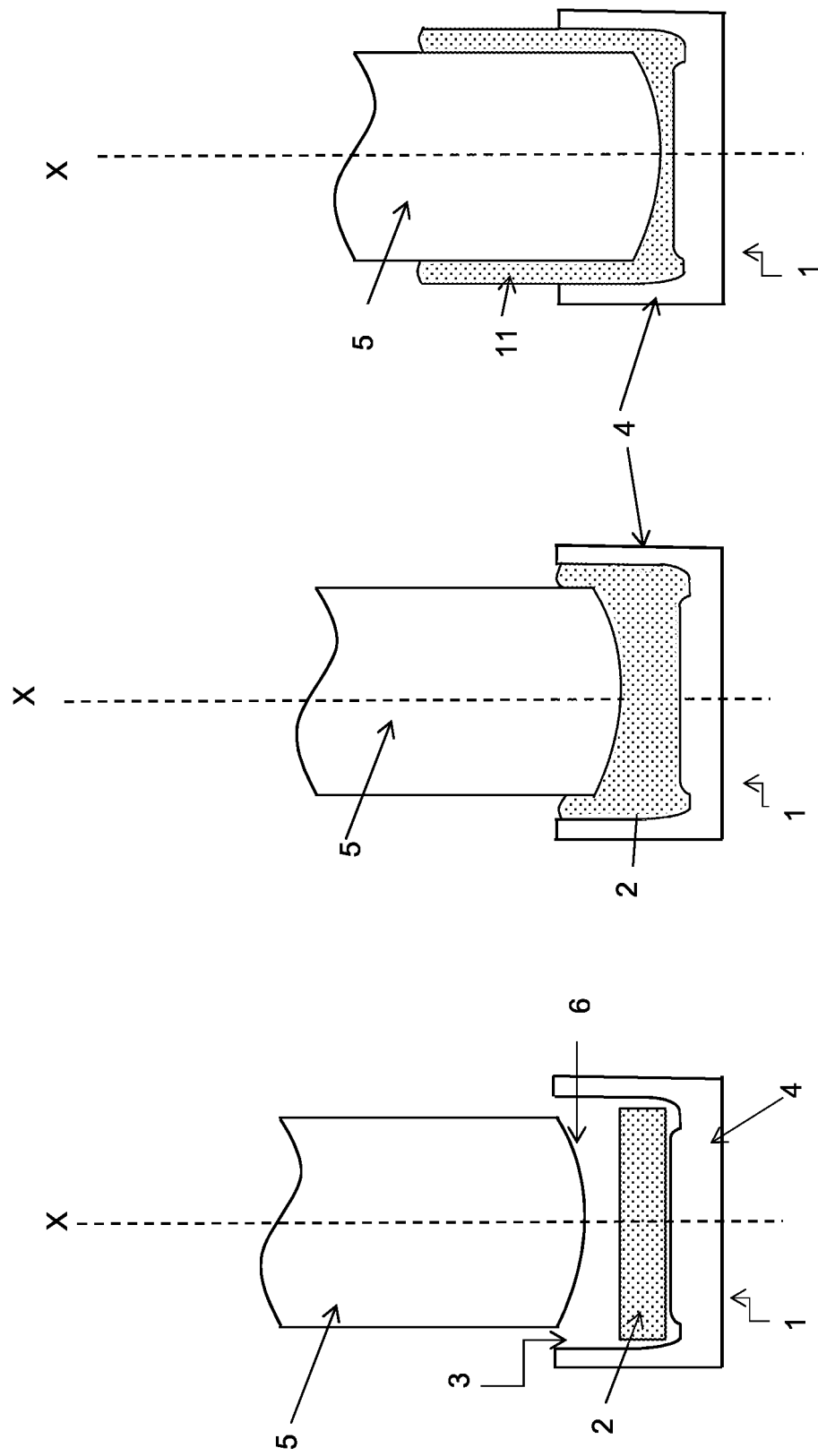


Fig. 1

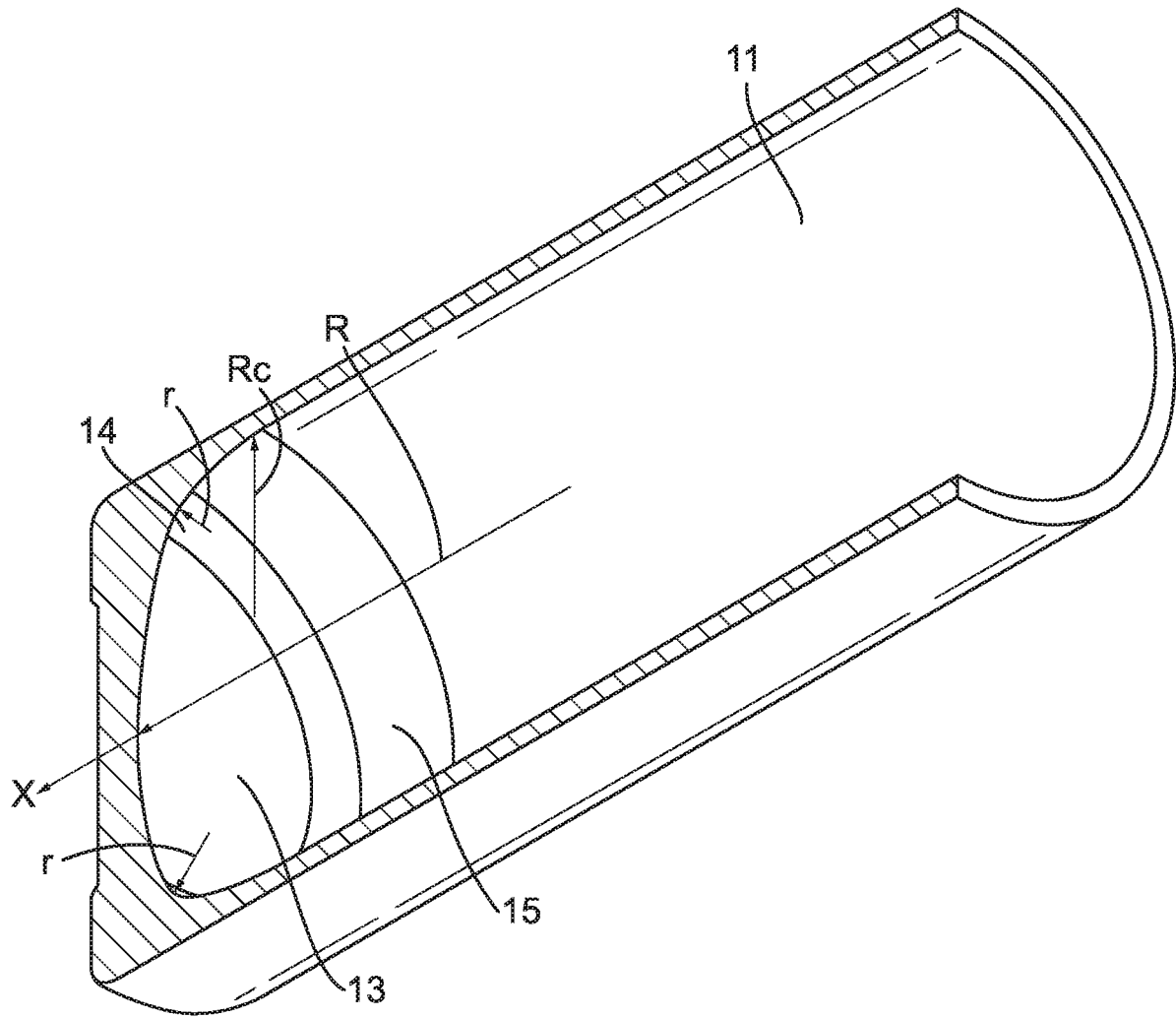


Fig. 2

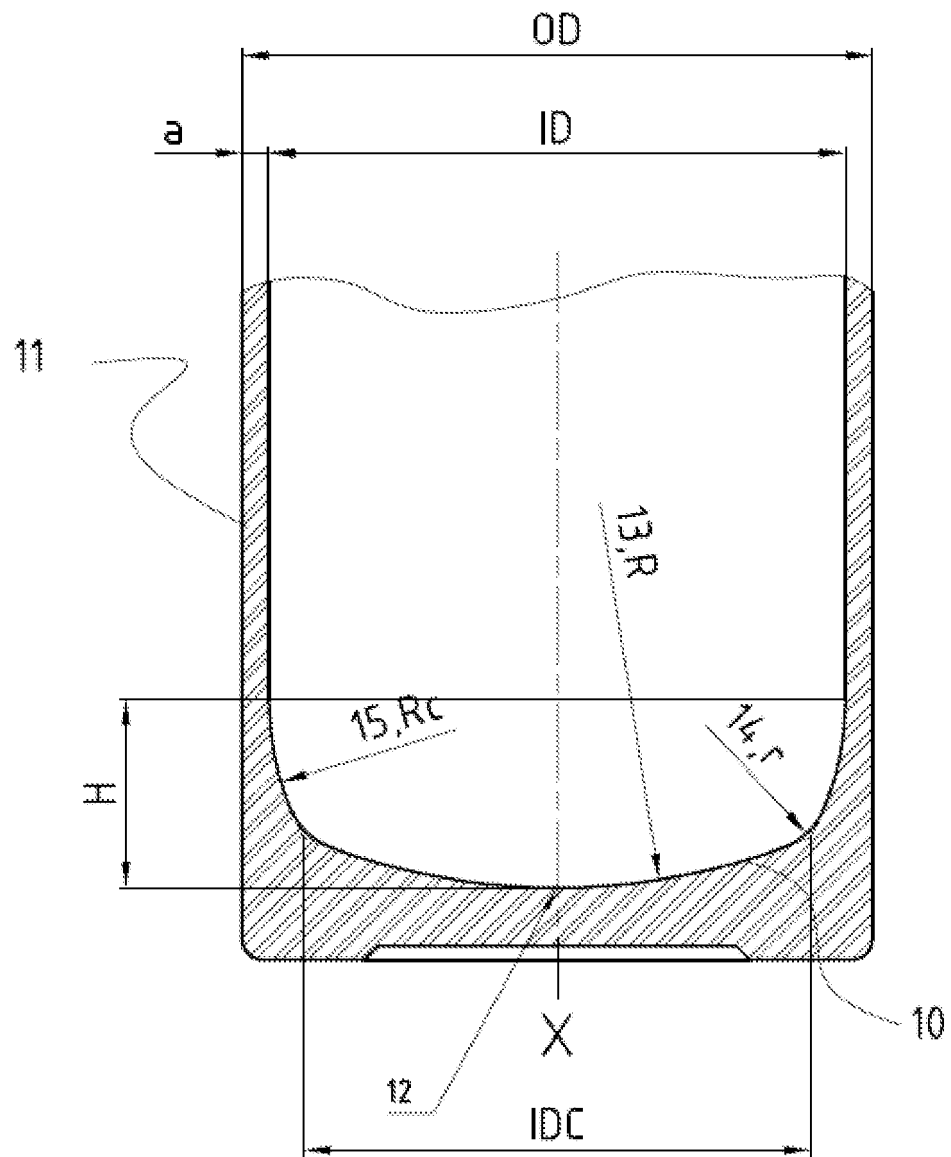


Fig 3

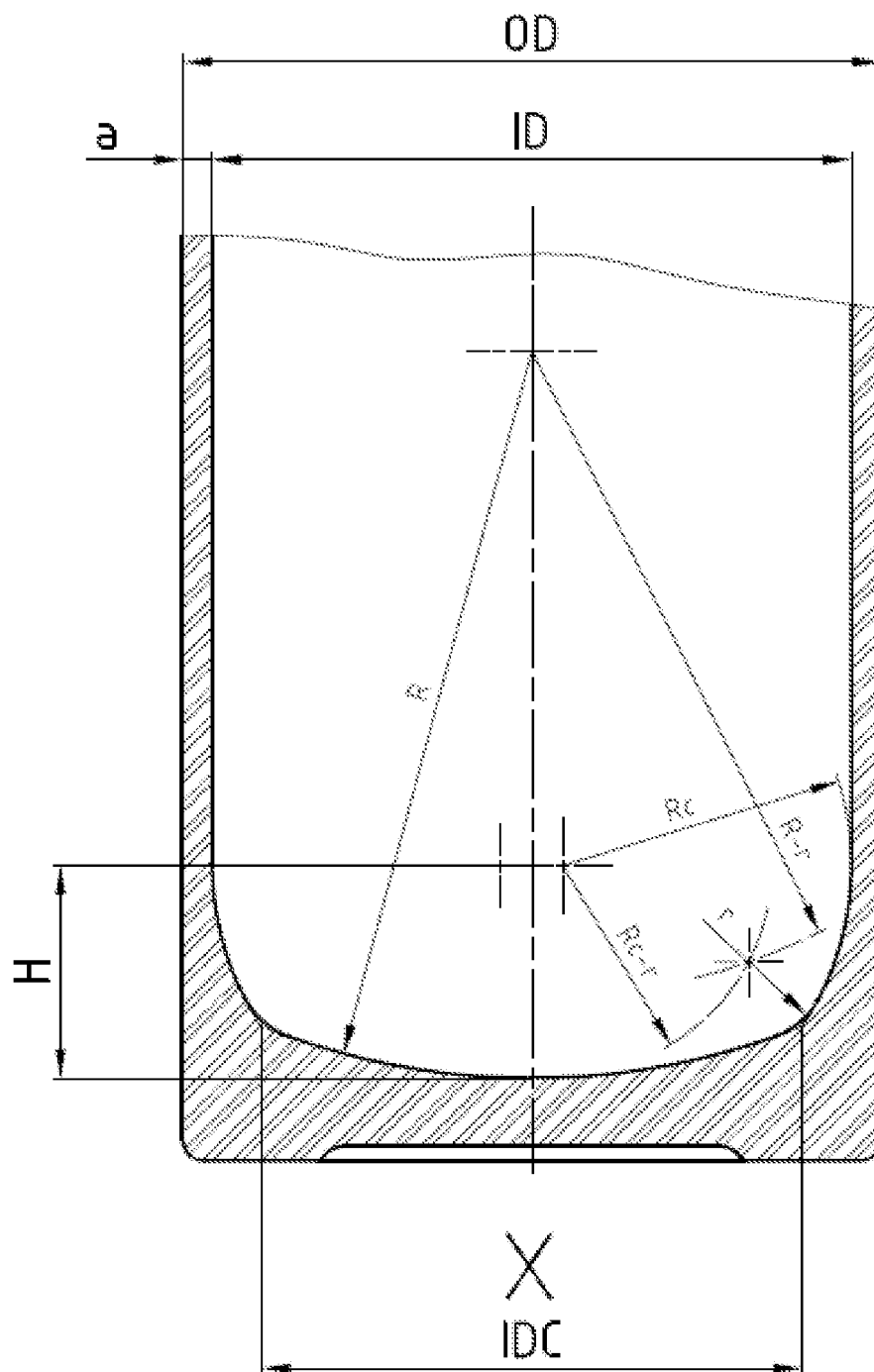


Fig 4

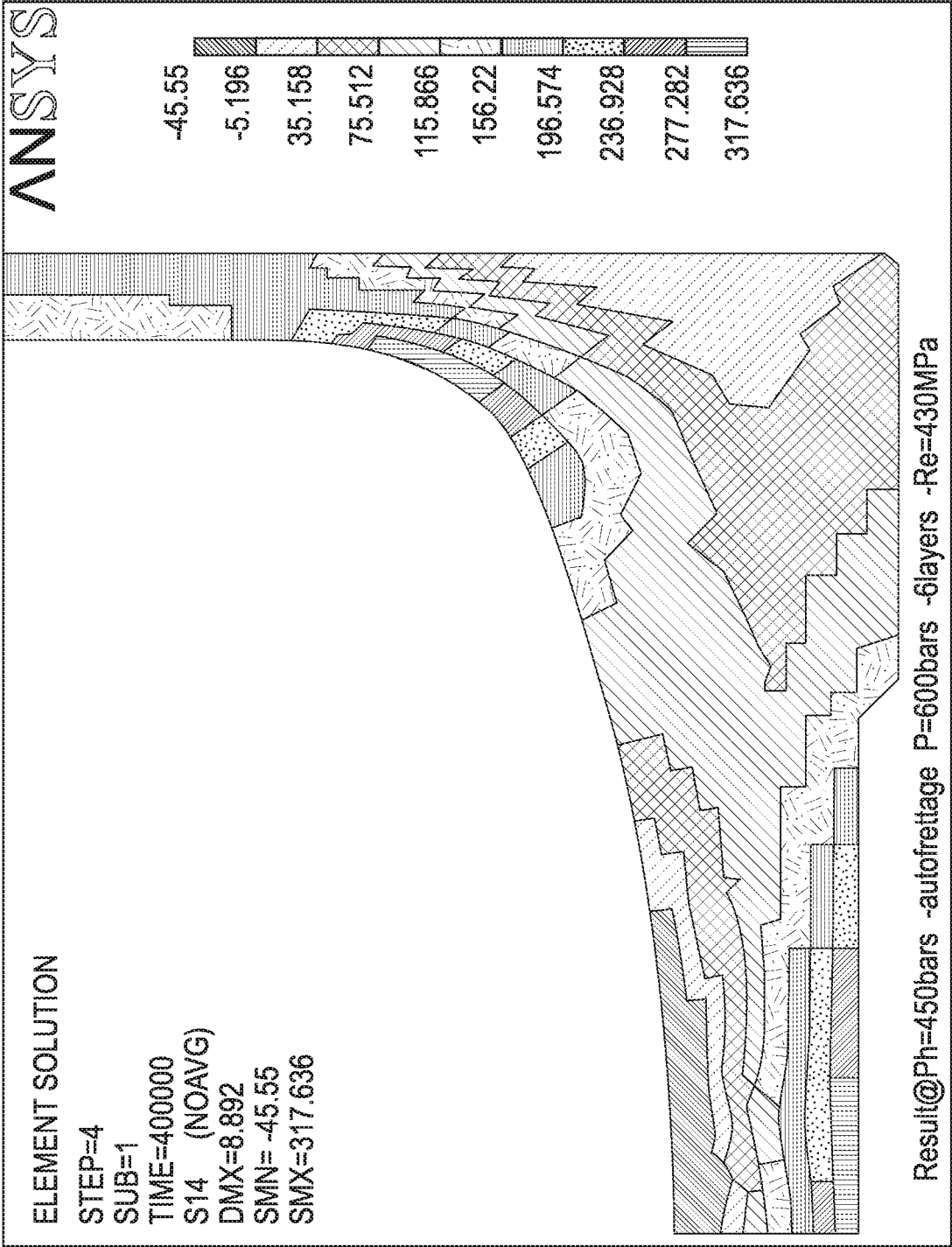


Fig. 5a

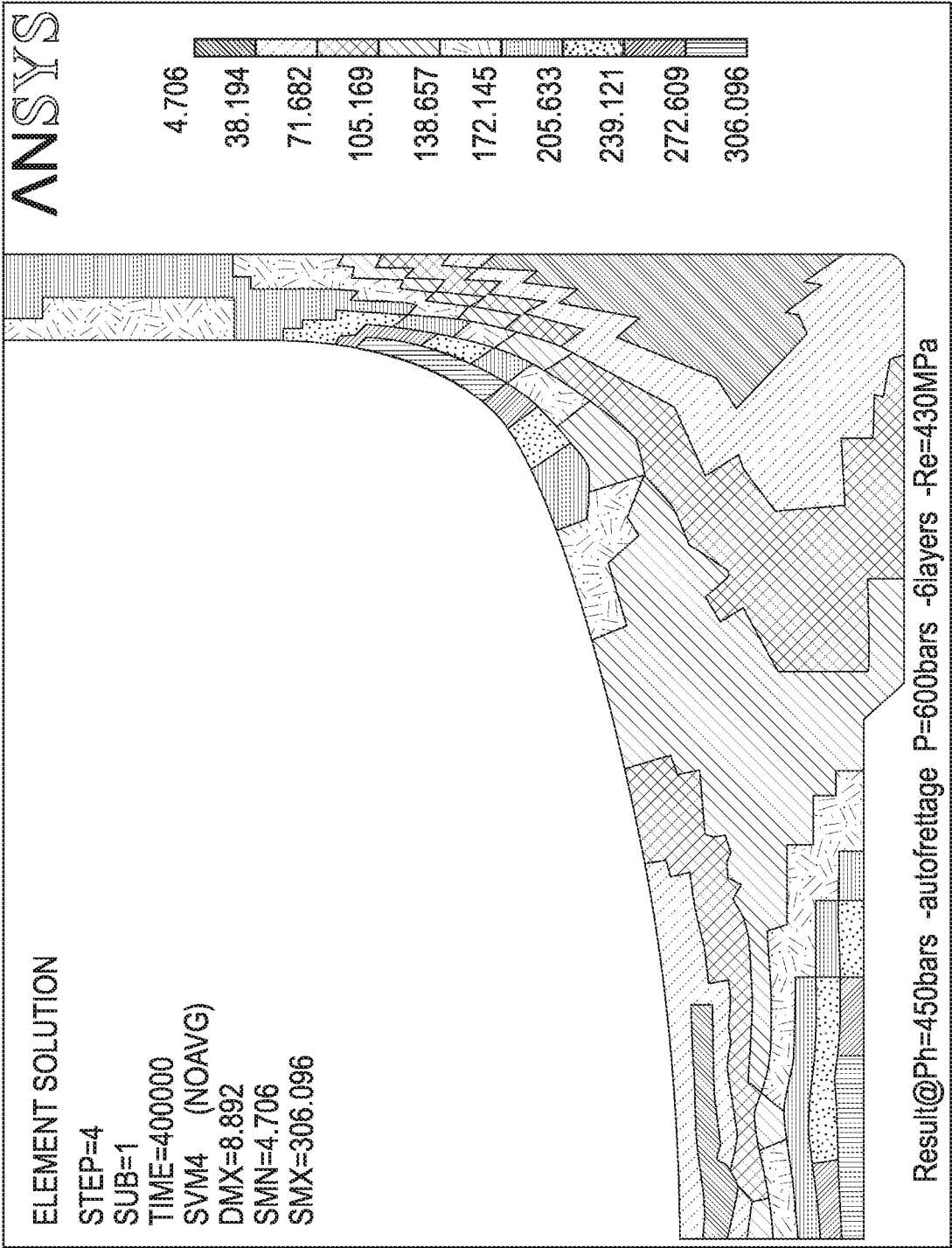


Fig. 5b

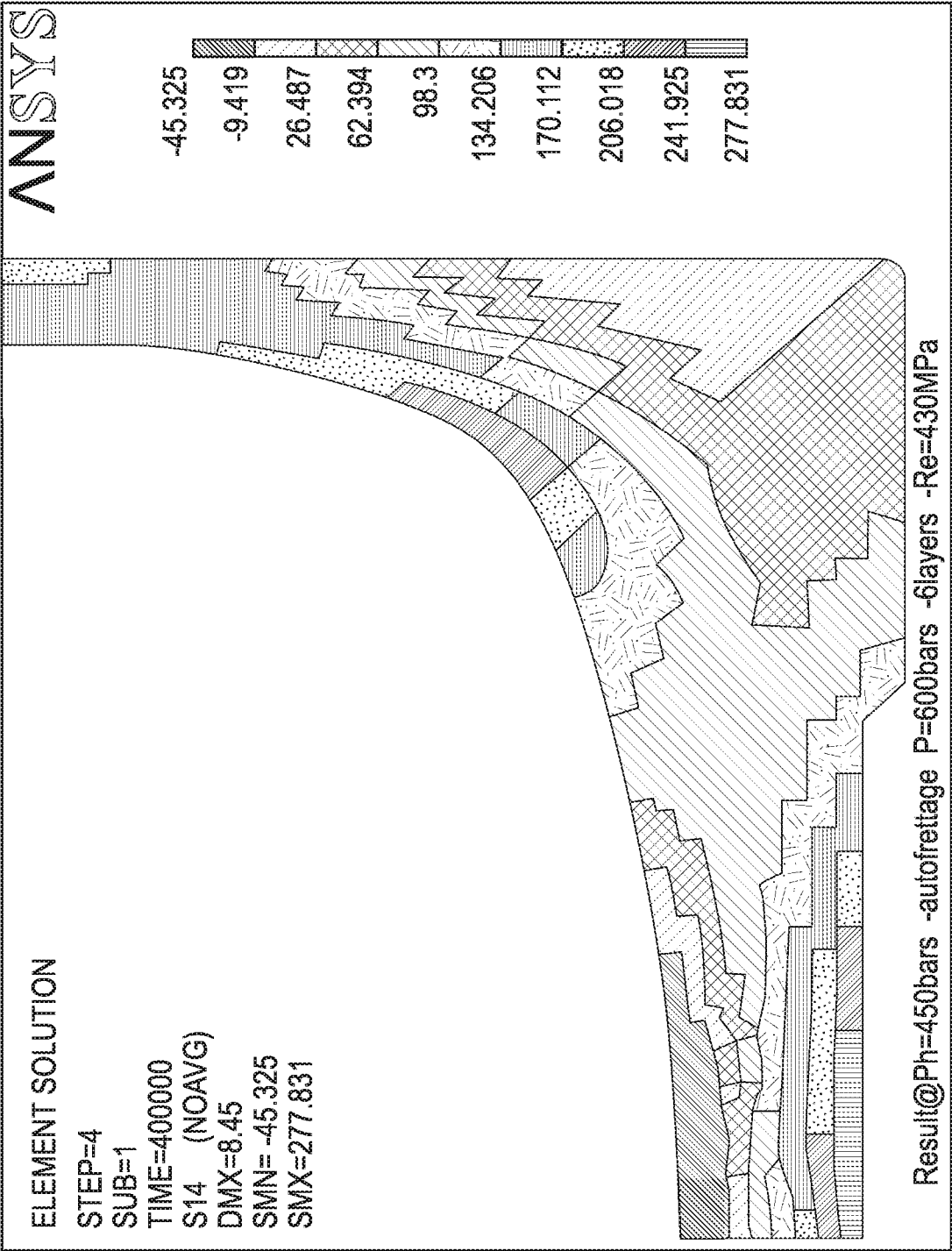


Fig. 6a

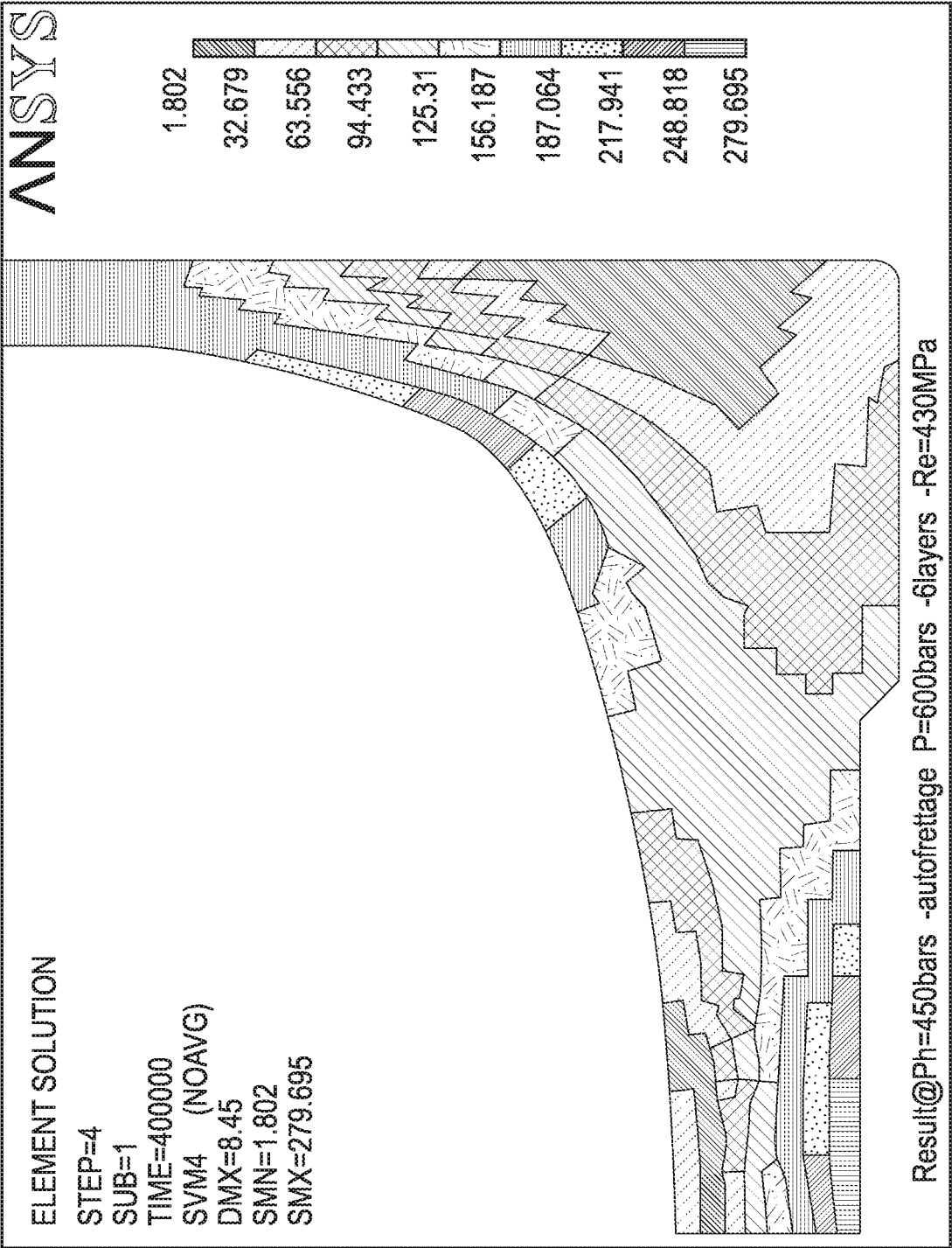


Fig. 6b

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 3648351 A [0003]
- WO 9611757 A [0003]
- WO 9611759 A [0004] [0069]