



(11)

EP 3 202 925 A1

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:
09.08.2017 Bulletin 2017/32

(21) Application number: **16382042.6**

(22) Date of filing: **02.02.2016**

(51) Int Cl.:
C21D 9/08 (2006.01) **C21D 7/12** (2006.01)
B21B 21/00 (2006.01) **B21C 37/00** (2006.01)
B21B 1/00 (2006.01) **B21B 17/06** (2006.01)
B21B 19/00 (2006.01)

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
MA MD

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(54) **STAINLESS STEEL TUBES AND METHOD FOR PRODUCTION THEREOF**

(57) A method for producing a tube of a stainless steel alloy tube which comprises the steps of hot working a stainless steel casting into a pretubular shaped workpiece or into a cylindrical bar, trepanning the cylindrical bar or machining an inner diameter of the pretubular shaped workpiece to obtain a tubular workpiece, and cold working the workpiece. The hot working comprises one

of: rolling, forging, and a combination thereof. The cold working comprises flow forming or pilgering. The stainless steel tube produced with the method comprises an outer diameter greater than or equal to 152 mm, an average wall thickness greater than or equal to 2.8 mm and less than or equal to 70 mm, and a length greater than 5 m.

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Description

TECHNICAL FIELD

[0001] The present invention relates to the production of tubes made of stainless steel alloys, particularly austenitic-ferritic stainless steel alloys such as duplex and super-duplex stainless steel, and the method for production thereof.

STATE OF THE ART

[0002] Several techniques and processes exist in the field of the metallurgy to produce components made of a variety of metals and alloys. The selection of the metal or alloy used in these components depends on the application and conditions that the components will be exposed to.

[0003] A particular product prone to be exposed to severe conditions is a tube that, together with other tubes, forms a pipe for transferring substances like, for example, oil&gas extracted from the well. As such, these tubes must cope with high levels of pressures and stresses. These levels may even be higher when the tubes are underwater which may be the case in, for example, sub-sea equipment. In addition to the high pressure, there are many corrosive and erosive agents in the sea that corrode the tubes, thus affecting their structural integrity and that may lead to the failure of the tubes. Another example of an environment with similar extreme conditions are wells.

[0004] The tubes and pipes that are used or located in these adverse environments should feature, inter alia, high strength and high resistance to corrosion cracking and pitting. A set of metals which may feature these characteristics are stainless steel alloys, and more specifically, austenitic-ferritic stainless steel alloys.

[0005] But not only the tubes are prone to suffer failures, also the joints of the tubes are susceptible to failure. In this regard, welding the tubes one to another so as to form a pipe is a critical process: if the joints between the tubes are not properly welded, defects such as phase precipitation may occur and cause additional stresses to the tubes which, in turn, negatively affect the resistance to corrosion. Moreover, the process of welding tubes is particularly expensive.

[0006] A common method for producing tubes is hot extrusion. The length of tubes produced, however, is largely limited by the maximum power of the ram pressing the workpiece on the die and the size of the extrusion press is large. Thus the productivity of the machinery is low and their efficiency is reduced.

[0007] U.S. patent no. 8,479,549 B1 relates to a method of producing cold-worked centrifugal cast tubular products in which the tubular workpiece casted of a corrosion resistant alloy, has material from its inner diameter removed, and then a metal forming process reduces the walls of the tubular workpiece. When the metal forming

process is flowforming, the walls of the workpiece may be reduced with several passes because the workpiece is not able to process large reductions in one pass, hence the progressive reduction of walls may be provided with subsequent flowforming passes.

[0008] Therefore, it would be convenient to produce tubes which may be used in environments characterized by demanding conditions, and which are as long as possible in order to reduce the number of joints and, additionally, the costs of welding the tubes. It would also be convenient to make the method for producing these tubes as effective as possible in terms of productivity.

DESCRIPTION OF THE INVENTION

[0009] The tubes made of stainless steel and method for production thereof disclosed in the present invention intends to solve the shortcomings of the tubes and methods of the prior art.

[0010] A first aspect of the invention relates to a method for producing a tube of a stainless steel alloy. The method comprises the steps:

- (a) hot working a stainless steel casting into a pretubular shaped workpiece or into a cylindrical bar;
- (b) trepanning the cylindrical bar or machining the pretubular shaped workpiece to obtain a tubular workpiece; and
- (c) cold working the tubular workpiece.

[0011] A pretubular shaped workpiece is a tube or a workpiece with a tubular shape that is machined or conformed to obtain the final dimensions of the tube, whereas a cylindrical bar is a bar with a rounded cross-section that is, for example, circular or oval.

[0012] A hot working process plastically deforms a stainless steel casting into a pretubular shaped workpiece or cylindrical bar while changing the microstructure and, therefore, the properties of the casting.

[0013] The shape of the casting may resemble, for example, but not limited to, an ingot or a bar. The shape may feature regular or irregular geometries such as, for instance, rectangular prisms, hexagonal prisms, round prisms, cylinders, etc.

[0014] In order for the process to be effectively applied to the casting, the stainless steel casting is heated to a temperature preferably higher than its recrystallization temperature. The casting is then plastically deformed so that its mechanical properties are enhanced for the production of tubes characterized by an elongated shape and reduced (i.e. thin) walls.

[0015] The internal structure of the casting typically features variable cavities, sizes of grains and segregations in the stainless steel that appear during its casting. Thus, while it is casted, the different temperatures present throughout the material, together with the effect of the gravity, generate a heterogeneous internal structure in the form of said cavities, grains with different size

and shape, and macro-scale and/or micro-scale segregation of alloying elements.

[0016] The hot working process homogenizes the microstructure of the resulting workpiece or bar. Therefore, with hot working, the casting is compacted internally causing changes in the resulting microstructure. Particularly, the workpiece or bar may recrystallize, that is, a new inner structure of crystals may be formed, generating fine grains that improve the mechanical properties as the internal stresses disappear due to the deformation. A consequence of the hot working is that the workpiece or bar features a larger ductility and, at the end, higher cold reductions can be applied in a single step, thus leading to the production of longer tubes.

[0017] The effect of the hot working process on the microstructure may be estimated using a deformation ratio. The ratio is defined as the original cross-section of the casting or workpiece divided by its cross-section after hot working. Reaching a deformation ratio of about 3 or greater may be advantageous in that an increase in the toughness and tensile strength of the workpiece or bar, in the longitudinal direction, is achieved.

[0018] A drilling or trepanning process removes a part of the bar with a hole that, generally, goes through the whole bar. The part removed may substantially correspond to a central part of at least one face or side of the bar. In the case of the pretubular shaped workpiece, its inner diameter is machined.

[0019] After trepanning the bar or machining the inner diameter of the pretubular shaped workpiece, a tubular workpiece is obtained. A cold working process reduces the section or area of the tubular workpiece so as to lengthen the tube to be produced. The process, thus, redistributes the stainless steel: the part of the steel that is removed from the workpiece in the radial direction, generally corresponding to the walls of the produced tube, is added to the workpiece in the axial direction. The cross section is reduced thereby elongating the pipe or tube.

[0020] Since the workpiece or bar has been hot-worked, its rather fine internal structure provides better conditions -compared to the conditions of the casting prior to the hot working- for the cold working. Consequently, the degree of reduction may be greater than if no hot working is performed. The reduction is directly related to the attainable length of the tube.

[0021] In preferred embodiments of the invention, the method further comprises (d) quenching the workpiece or bar, and step (d) is performed after step (a).

[0022] Quenching the pretubular shaped workpiece or cylindrical bar with a liquid minimizes phase transformations, particularly on its surface. The liquid may reduce, for example, the formation of a vapor phase on the surface of the workpiece or bar that prevents it from being rapidly cooled. With a quenching process, the workpiece or bar may maintain the mechanical properties it features after a hot working or solution annealing process, for example. Quenching takes place after hot working. In some

embodiments, the workpiece or bar is quenched after being subject to hot working and a thermal treatment such as, for example, solution annealing.

5 [0023] In these preferred embodiments, quenching is performed with water at a temperature not higher than 50°C, and preferably not higher than 35°C.

10 [0024] The liquid used in the quenching step may be water at a temperature equal to or below than 50°C such that the workpiece or bar may be rapidly cooled. Preferably, the liquid is at a temperature even lower than this value, such as equal to or below than 35°C, and hence cooling the workpiece or bar takes less time, and thereby its mechanical properties suffer less changes.

15 [0025] In preferred embodiments of the invention, the method further comprises (e) casting the stainless steel casting. Further, in these embodiments, casting the stainless steel casting -step (e)- is performed prior to hot working the stainless steel casting into a workpiece or bar -step (a).

20 [0026] The casting that is hot-worked in some embodiments is casted by melting the stainless steel alloy and pouring it in a mold. The dimensions of the produced casting, both in terms of its length and section -or diameter-, determine the maximum dimensions of the tube that may be produced since the stainless steel in the casting will be redistributed so as to form the tube, even though a part of said alloy may be lost during the production of the tube, for instance, while trepanning, machining or cold working the workpiece. Thus, the amount of stainless steel alloy necessary for the casting varies in accordance with the dimensions of the tube to be produced.

25 [0027] In preferred embodiments of the invention, the stainless steel alloy is an austenitic-ferritic stainless steel alloy.

30 [0028] The austenitic-ferritic stainless steel, including duplex stainless steel and super-duplex stainless steel, features greater strength than austenitic stainless steel and ferritic stainless steel. Also, austenitic-ferritic stainless steel is more resistant to pitting and crevice corrosion and stress corrosion cracking than austenitic or ferritic stainless steels. This makes austenitic-ferritic stainless steel convenient for products which are to be placed in environments with adverse conditions, particularly in wells and underwater (e.g. in the deep sea), where the level of pressure and the amount of corrosive substances or agents is high.

35 [0029] However, the austenitic-ferritic stainless steel features low ductility and, hence, forming products with this alloy requires larger forces than for forming products made of austenitic or ferritic stainless steel.

40 [0030] It is important that, in step (c), the microstructure of the austenitic-ferritic stainless steel alloys is controlled, so that at the end of the process the appropriate percentages of austenite and ferrite phases are present in the tubular workpiece or tube, because the mechanical properties and resistance to corrosion is largely determined by these phases. The alloying elements are selected such that the alphasenous elements (which promote the

formation of ferrite) and gammagenous elements (which promote the formation of austenite) are balanced. Besides, a correct thermic treatment temperature and a quick cooling stabilize both phases and prevent the formation of unwanted third phases.

[0031] In this sense, the distance between the phases is also important for avoiding hydrogen induced stress cracking (HISC). In particular, it is convenient that the austenite spacing is, at most, 30 μm (i.e. microns or micrometers) having a presence of ferrite phase between 40% and 60% (the endpoints being included in the range of possible values).

[0032] In some of these preferred embodiments, the austenitic-ferritic stainless steel alloy is duplex stainless steel. In some other of these preferred embodiments, the austenitic-ferritic stainless steel alloy is super duplex stainless steel.

[0033] In preferred embodiments of the invention, hot working comprises one of: rolling, forging, and a combination thereof.

[0034] Rolling the stainless steel casting homogenizes its inner structure in terms of the grain size, porosity, cavities, among others. The rolling mills plastically deform the casting, which typically features grains that are larger in its interior than on its surface -the part in contact with the casting mold-. The rolled workpiece may feature many different shapes such as, for example, cylindrical, rectangular, sheet-like, among others. Continuous or reversible rolling mills known in the art may be used, for example, for plastically deforming a casting like, for instance, a bar or an ingot.

[0035] The stainless steel casting may also be forged during the hot working step, in which case the casting may be held -although not necessarily- with pliers, bars, or the like, and a hammer or a die delivers blows so as to deform it. Forging may be performed by a user (e.g. a blacksmith) or by a machine (e.g. free forging). It is also possible to use a rotary forge press to deform the casting.

[0036] It is convenient to perform the forging process progressively (i.e. sequential blows that each cause a small deformation) so that the deformations may crystallize without forming any cracks.

[0037] In some cases, rolling and forging may be both performed on a casting sequentially.

[0038] In some embodiments of the invention, the method further comprises (f) solution annealing the bar or workpiece, at a temperature between 1030°C and 1120°C (the endpoints being included in the range of possible values).

[0039] In order to reduce the hardness of the bar or workpiece and increase its ductility, the bar or workpiece may be subject to solution annealing. Moreover, solution annealing may reduce internal stresses of the workpiece or bar as well. The bar or workpiece is, thus, heated above its recrystallization temperature, maintained during some time at a temperature higher than said recrystallization temperature, and then it is rapidly cooled (e.g. quenching with water).

[0040] In some embodiments of the invention, step (f) is performed on the pretubular shaped workpiece or cylindrical bar, that is, the solution annealing step may be performed after hot working the casting and before trepanning the bar or machining the pretubular-shaped workpiece such that the increase in ductility achieved with the plastic deformation is further improved. In the embodiments in which the method comprises quenching the bar or workpiece after hot working, solution annealing may take advantage of the quenching -step (d).

[0041] In some embodiments, step (f) is performed on the tubular workpiece, that is, after trepanning and before cold working since with the increase in ductility, the wall reduction and lengthening of the tubular product during the cold working process may be enhanced and, thus, it is possible to apply a greater reduction in a single pass, and/or produce a longer workpiece or tube with the same applied forces, or a workpiece or tube with the same length than not having performed solution annealing but applying less force.

[0042] Since cold working may generate stresses within the tubular workpiece, the solution annealing step may be performed after cold working as well so that it removes, at least partially, these inner stresses.

[0043] In some cases, after a solution annealing process, the workpiece may be quenched with a liquid such as water.

[0044] In preferred embodiments of the invention, the method further comprises (g) heating the stainless steel casting to a temperature higher than 1000°C, and preferably higher than 1200°C. Further, in these embodiments, step (g) is performed prior to step (a).

[0045] The stainless steel casting is heated at a temperature higher than its recrystallization temperature, generally above 1000°C, so that it may be deformed, in the hot working step, at a high temperature. It is convenient to achieve a temperature of at least 1000°C because intermetallic phases (sigma delta or ferrite delta) may be formed in some stainless steel alloys (e.g. duplex stainless steel), in the temperature range between 600°C and 1000°C. These intermetallic phases may cause or generate cracks in the workpiece. Preferably, the temperature in the furnace is higher than or equal to 1200°C so as to perform a hot working process more efficiently and without the risk that the temperature of the casting -due to heat being transferred to the support (e.g. an anvil), the environment, etc.- goes below the recrystallization temperature and/or below 1000°C.

[0046] In preferred embodiments of the invention, cold working comprises one of: flow forming and cold pilgering.

[0047] In the embodiments in which cold working comprises flow forming, a flow forming machine which includes, inter alia, a mandrel and a plurality of rollers with, typically, three or four rollers, reduces the thickness of the walls of the workpiece and makes the workpiece longer. The tubular workpiece may be subject either to forward flow forming or reverse flow forming.

[0048] The tubular workpiece is attached to the mandrel by means of the hole, for instance formed with the trepanning or machining of step (b). When the workpiece is secured, the mandrel may move the workpiece in a movement direction of the rollers. The rollers apply forces to the workpiece in the axial, longitudinal and tangential directions. The compressive force in a radial direction reduces the wall thickness, which combined with the forces in the other two directions results in a lengthening of the workpiece or tube.

[0049] Flow forming may improve the grain structure of the tubular workpiece or tube making the inner structure more homogeneous throughout the whole workpiece, and which may enhance its mechanical properties.

[0050] In the embodiments in which cold working comprises pilgering, a pilger mill may reshape the workpiece into an elongated tube with thinner walls. The ring dies of the mill, which may be ring-shaped, compress the workpiece in a radial direction and, thus, reduce its outer diameter. The mandrel, which may secure the workpiece using a hole of the workpiece -for instance formed with the trepanning or machining of step (b)- moves and rotates the workpiece, and may also reshape the inner diameter of the workpiece or tube.

[0051] The mandrel feeds and rotates the workpiece successively while two ring dies deform the workpiece, thereby causing a reduction of both the outer diameter and the thickness of the walls. The workpiece is first rotated coarsely (i.e. large angle variations, for example, about 60°) so as to deform the section that is currently processed by the dies, and then rotated finely (i.e. small angle variations, for example, about 20°) to adjust the shape of the section such that it features a polished circular section, that is, a substantially rounded outer diameter.

[0052] Pilgering is a semi-continuous process that is particularly efficient in long run productions. The tubular workpiece may be fed, in a forward motion, at a rate between 2 and 50 mm/s (the endpoints being included in the range of possible values), whereas the feed rate or forward motion rate of the flow forming machine may be between 0.5 mm/s and 10 mm/s (the endpoints being included in the range of possible values). Even though the feed rate in the flow forming machine may be lower than in the pilgering one, a lower number of passes may be necessary to produce a tube with flow forming.

[0053] In some embodiments of the invention, flow forming or pilgering at least reduces the workpiece's wall thickness between 25% and 35% (the endpoints being included in the range of possible values).

[0054] In some embodiments of the invention, flow forming or pilgering at least reduces thickness of walls of the workpiece between 35% and 50% (the endpoints being included in the range of possible values).

[0055] In some embodiments of the invention, flow forming or pilgering at least reduces thickness of walls of the tubular workpiece between 50% and 75% (the endpoints being included in the range of possible values).

[0056] In some embodiments, the cold working comprises flow forming, and the flow forming at least reduces thickness of walls of the tubular workpiece by 70% in one pass.

[0057] Due to the mechanical properties achieved after some processes or steps of some embodiments of the invention, the workpiece may support a wall reduction between 65% and 70% (the endpoints being included in the range of possible values) in a single pass. With such reductions, the flow forming machine takes less time to process the workpiece and reduce the number of passes needed to achieve the desired thickness. This is even more significant considering that cold working progressively reduces the ductility of the workpiece after each pass or deformation produced and, hence, the forces necessary to further deform the workpiece increase.

[0058] Another aspect of the present invention relates to stainless steel tubes produced with the method described above with respect to the first aspect of the invention.

[0059] The tube comprises

- an outer diameter greater than or equal to 152 mm, preferably greater than or equal to 200 mm and preferably greater than or equal to 250mm;
- an average wall thickness greater than or equal to 2.8 mm, and less than or equal to 70 mm, preferably greater than or equal to 12 mm and preferably greater than 39 mm; and
- a length greater than 5 m, preferably greater than or equal to 10 m, and preferably greater than 12m.

[0060] The tube preferably comprises an austenitic-ferritic stainless steel alloy and more preferably one of a duplex stainless steel and a super-duplex stainless steel; In some preferred embodiments, the tubes comprise an austenite spacing less than 30 microns (micrometers).

[0061] Austenitic-ferritic stainless steel tubes featuring austenite spacings that are below 30 μm (microns) are particularly resistant to HISC.

[0062] In some preferred embodiments, the tubes comprise a ferrite content greater than or equal to 40%, and less than or equal to 60%.

BRIEF DESCRIPTION OF THE DRAWINGS

[0063] To complete the description and in order to provide for a better understanding of the invention, a set of drawings is provided. Said drawings form an integral part of the description and illustrate an embodiment of the invention, which should not be interpreted as restricting the scope of the invention, but just as an example of how the invention can be carried out. The drawings comprise the following figures:

Figures 1A to 1D are flowcharts of methods in accordance with some embodiments of the invention. Figure 2 is a representation of a flow forming ma-

chine, which may be used for cold working in some embodiments of the invention.

Figure 3 is another representation of a flow forming machine.

Figure 4 is a photograph of the microstructure of a tube produced with a method in accordance with an embodiment of the invention.

DESCRIPTION OF A WAY OF CARRYING OUT THE INVENTION

[0064] Figure 1A is a flowchart 100 depicting the steps carried on a method of an embodiment of the invention.

[0065] In step 101 of the method, a stainless steel casting is hot worked into a pretubular-shaped workpiece or cylindrical bar, namely, the casting is plastically deformed in an environment that has a temperature higher than the casting's recrystallization temperature so that its internal structure is altered. Generally, the casting has a microstructure including differently-sized grains, material segregations, and cavities that appear during its casting. Hot working, that is, plastically deforming the casting, reduces the aforementioned defects within the resulting workpiece or bar since a new crystalline structure may be formed. This structure may be characterized by a more homogeneous distribution of grains, and a lower presence of cavities and/or alloy segregations. Consequently, the amount of internal stresses is lower, which improves some mechanical properties of the workpiece or bar; the ductility, for instance, may increase due to the hot working of step 101.

[0066] Some non-limiting examples of hot working are forging, rolling and drawing.

[0067] When the casting is hot-worked into a cylindrical bar, the bar is trepanned in step 102. A drilling or cutting machine drills a hole into the cylindrical bar, preferably a through hole with circular cross section. In the embodiments in which hot working -step 101- produces a pretubular shaped workpiece, the workpiece is subject to a machining process of its inner diameter in step 103. After step 102 or step 103, a tubular workpiece is obtained.

[0068] In step 104, the tubular workpiece is subject to cold working: the workpiece is plastically deformed at a temperature below its recrystallization temperature. Particularly, in step 104 the walls of the workpiece are reduced and the length of the tube produced is increased.

[0069] Some non-limiting examples of cold working are pilgering and flow forming. In these cases, the mandrel of the flow forming or pilgering machine holds the workpiece by means of the hole formed in step 102 or machined in step 103 so that the tubular workpiece may be subject to the deformations produced by the machine.

[0070] Figure 1B is a flowchart 110 that depicts the steps of a method for producing a tube in accordance with another embodiment.

[0071] The flowchart 110 comprises steps 101, 102, 103 and 104 corresponding to hot working, trepanning, machining and cold working, respectively, as described

above with respect to flowchart 100.

[0072] The method of Figure 1B further comprises step 105: casting, by which a stainless steel alloy is melt and poured in a mold. The stainless steel is left to dry forming the casting, which may take the shape of, for example, an ingot or a bar. The volume of stainless steel in the casting may determine the maximum amount of steel which may be used for producing the tube since, generally, no steel is added afterwards, rather, some steel is removed during one or more of the successive steps 101-104 of the method.

[0073] Then, the casting is at least subject to hot working (step 101), trepanning (step 102) or machining of the inner diameter (step 103), and cold working (step 104).

[0074] The casting and/or workpiece subject to the methods described with respect to flowcharts 100, 110 comprise a stainless steel alloy, the stainless steel alloy being an austenitic-ferritic stainless steel alloy that is, preferably, duplex stainless steel or super-duplex stainless steel.

[0075] Figure 1C shows flowchart 120 corresponding to a method in accordance with another embodiment of the invention.

[0076] The embodiment comprises steps 101, 102, 103 and 104 corresponding to hot working, trepanning, machining and cold working, respectively, and further comprises quenching -step 106- which takes place after step 101, and before step 102 or step 103.

[0077] In step 106, the pretubular shaped workpiece or cylindrical bar is rapidly cooled so that the internal structure obtained in step 101 is largely maintained. Therefore, quenching reduces the amount of phase transformations that may occur throughout the workpiece or bar and, particularly, on its surface after hot working.

[0078] Figure 1D is a flowchart 130 in accordance with another embodiment of the invention.

[0079] First a stainless steel casting is casted -step 105-. With hot working -step 101-, the casting is deformed such that its microstructure changes and, consequently, its mechanical properties are altered as well. The resulting workpiece is quenched -step 105- so as to maintain the altered mechanical properties, and then trepanned -step 102- so as to form a hole inside or machined -step 103- so as to reshape the hole inside. The tubular workpiece obtained is then deformed in a cold working process by reducing the walls and increasing the length of the tube -step 104.

[0080] The tubes produced in some of these embodiments feature a length longer than 5 m. In some of these embodiments, the length of the tubes produced is longer than 10 m. And in some of these embodiments, the length of the tubes produced is longer than 12 m. These tubes may feature an outer diameter greater than or equal to 252 mm, preferably greater than or equal to 200 mm, and preferably greater than or equal to 250mm; they may also feature an average wall thickness greater than or equal to 2.8 mm, and less than or equal to 70 mm, and preferably greater than or equal to 12 mm and less than or

equal to 39 mm.

[0081] Figure 2 shows a flow forming machine 200. A workpiece 201 having a tubular geometry is placed on the mandrel 202 of the machine, and held in place with a jaw chuck 203. The jaw chuck 203 makes the workpiece 201 rotate in accordance with the rotary motion of the mandrel 202 -an engine (not illustrated) provides said rotary motion-. The machine 200 further comprises a carriage 204 in which a plurality of rollers 205a-205d are arranged in an equidistant configuration with a progressive 90° phase difference between the rollers 205a-205d.

[0082] Both the mandrel 202 and the plurality of rollers 205a-205d feature rotary movements during the operation of the machine 200 such that the workpiece 201, as it goes through the set of rollers 205a-205d, has its outer diameter reduced, which in turn causes a reduction of the thickness of its walls, and its length increased-along the Y axis illustrated in the figure.

[0083] In the flow forming machine 200, there are up to 10 degrees of freedom which are adjusted and controlled during the production of tubes: the rotation of the mandrel 202, the rotation of each of the four rollers 205a-205d, the position of each of the four rollers 205a-205d relative to the workpiece 201 or mandrel 202 -horizontal position adjustments of rollers 205b and 205d, and vertical position adjustments of rollers 205a and 205c-, and the distance of the portion of the mandrel between the jaw chuck 203 and the carriage 204.

[0084] In some embodiments, the flow forming machine comprises two, three, six or more rollers and, consequently, the machine may feature more or less degrees of freedom. In these other embodiments, the rollers may also arranged following constant phase differences with respect to an imaginary circumference along which the rollers are distributed; the constant phase differences correspond to 360° divided by the number of rollers in the carriage.

[0085] The carriage 204 moves towards the jaw chuck 203, and the rollers 205a-205d, which rotate in a direction contrary to the rotary movement of the mandrel 202 and the workpiece 201, provide forces in the axial, radial and tangential directions. Although the rollers apply a compressive force on the workpiece 201, the carriage 204 must cope with and resist the forces applied by the rollers 205a-205d. Thus these forces -mainly those in the axial and radial directions, since the tangential component is much smaller than the other two-determine the structural requirements of the carriage 204.

[0086] The rollers can be offset axially to each other which allows three different roll configurations, depending on the requirements of the process. An axial offset to zero-line allows faster forming feed rates. An axial offset that is four times different, one for each roller, allows higher accuracy and perfect surface qualities combined with high reduction rates. The middle way, a pair wise axial offset allows stronger flow forming operations which means higher reductions, because each forming roller of the pair works as a counter-bearing and takes the force

of the opposite roller. The result is a perfect run-out at high feed rates.

[0087] Figure 3 shows a flow forming machine 300 in a 2D view. Similarly to the machine 200 of Figure 2, the mandrel 302 holds the workpiece 301, and the jaw chuck 303 also holding the workpiece 301 makes the workpiece rotate in accordance with the rotating motion of the mandrel 302.

[0088] As the carriage 304 moves towards the jaw chuck 303, the rollers 305a, 305b apply a compressive force to the workpiece 301 and incrementally produce a tube longer and with thinner walls.

[0089] The existence of so many degrees of freedom in the flow forming machine -and, by extension, the corresponding process- makes its operation a complex task. To this end, a computer numerical control manages the whole process and operation such that the produced tubes feature, throughout their whole volume, the mechanical and microstructural properties sought in the lower number of passes possible. In this sense, the computer numerical control may adjust the parameters related to the aforementioned degrees of freedom so that the axial and radial forces of the rollers 305a, 305b plastically deform the inner part of the workpiece 201 so as to generate compressive forces within its structure.

[0090] It is of particular relevance to determine an appropriate ratio between the rate 311 at which the carriage 304 moves towards the jaw chuck 303 and the rotary speed 312 of the mandrel 302. If this ratio is too high, the rollers 305a, 305b may not properly deform the workpiece 301. Conversely, if the ratio is too small, the time it takes to process the workpiece 301 may be unnecessarily long.

[0091] It is also convenient to adjust the angle of attack 310 of the rollers 305a, 305b, that is, the relative angle between the rollers 305a, 305b and the workpiece 301 as it is being flow formed. The angle of attack 310 may range between 6° and 45° (the endpoints being included in the range of possible values). Too pronounced angles of attack may also result in irregular deformations of the workpiece 301.

[0092] Preferably, the end of the workpiece 301 that will be first in contact with the rollers 305a, 305b has the edges of its opening chamfered so that the rollers do not deform the workpiece irregularly, which could render the tube unusable since the mechanical properties of that part of the tube may differ from the rest of the tube.

[0093] The flow forming not only reshapes the workpiece, it also changes its microstructure: the resulting grains may be oriented and have a homogeneous fine size, both of which provide improved mechanical properties.

[0094] Figure 4 shows the microstructure of a tube produced with a method in accordance with an embodiment of the invention. The tube comprises an austenitic-ferritic stainless steel alloy with an austenite phase 401 and a ferrite phase 402. In some embodiments, the austenitic-ferritic stainless steel alloy is a duplex stainless steel. In

some other embodiments, the austenitic-ferritic stainless steel alloy is a super-duplex stainless steel.

[0095] In average, the spacing of the austenite phases 401 is about 30 microns or less, which is convenient for resisting HISC phenomena. Such spacing may be observed using the illustrated segment 403, which is equivalent to 30 μm .

[0096] In this text, the term "comprises" and its derivations (such as "comprising", etc.) should not be understood in an excluding sense, that is, these terms should not be interpreted as excluding the possibility that what is described and defined may include further elements, steps, etc.

[0097] The invention is obviously not limited to the specific embodiment(s) described herein, but also encompasses any variations that may be considered by any person skilled in the art (for example, as regards the choice of materials, dimensions, components, configuration, etc.), within the general scope of the invention as defined in the claims.

Claims

1. A method for producing a tube of a stainless steel alloy, the method comprising:

- (a) hot working a stainless steel casting into a pretubular shaped workpiece or into a cylindrical bar;
- (b) trepanning the cylindrical bar or machining the inner diameter of the pretubular shaped workpiece to obtain a tubular workpiece; and
- (c) cold working the tubular workpiece.

2. The method of any of the preceding claims, wherein:

- the method further comprises (d) quenching the pretubular shaped workpiece or cylindrical bar; and
- (d) is performed after (a).

3. The method of any of the preceding claims, wherein:

- the method further comprises (e) casting the stainless steel casting; and
- (e) is performed prior to (a).

4. The method of any of the preceding claims, wherein the stainless steel alloy is an austenitic-ferritic stainless steel alloy.

5. The method of claim 4, wherein the stainless steel alloy is duplex stainless steel or super-duplex stainless steel.

6. The method of any of the preceding claims, wherein the hot working comprises one of: rolling, forging,

and a combination thereof.

7. The method of any of the preceding claims, further comprising (f) solution annealing the pretubular shaped workpiece or cylindrical bar, at a temperature between 1030°C and 1120°C.

8. The method of any of claims 1-6, further comprising (f) solution annealing the tubular workpiece, and wherein (f) is performed in at least one of the following: after (b) and prior to (c), and after (c).

9. The method of any of the preceding claims, wherein:

- the method further comprises (g) heating the stainless steel casting to a temperature higher than 1000°C, and preferably higher than 1200°C; and
- (g) is performed prior to (a).

10. The method of any of claims 2-9, wherein quenching the pretubular shaped workpiece or cylindrical bar is performed with water at a temperature not higher than 50°C, and preferably not higher than 35°C.

11. The method of any of the preceding claims, wherein the cold working comprises one of: flow forming and pilgering.

12. The method of claim 11, wherein the cold working comprises flow forming, and the flow forming at least reduces thickness of walls of the workpiece by 70% in one pass.

13. A stainless steel tube produced with the method of any of claims 1-12, **characterized by:**

- an outer diameter greater than or equal to 152 mm;
- an average wall thickness greater than or equal to 2.8 mm, and less than or equal to 70 mm; and
- a length greater than 5 m.

14. The stainless steel tube of claim 13, wherein:

- the outer diameter is greater than or equal to 200 mm;
- the average wall thickness is greater than 12 mm; and
- the length is greater than 10 m.

15. The stainless steel tube of any of claims 12-14, wherein the tube comprises an austenitic-ferritic stainless steel alloy with:

- an average austenite spacing less than or equal to 30 microns; and
- a ferrite content greater than or equal to 40%,

and less than or equal to 60%.

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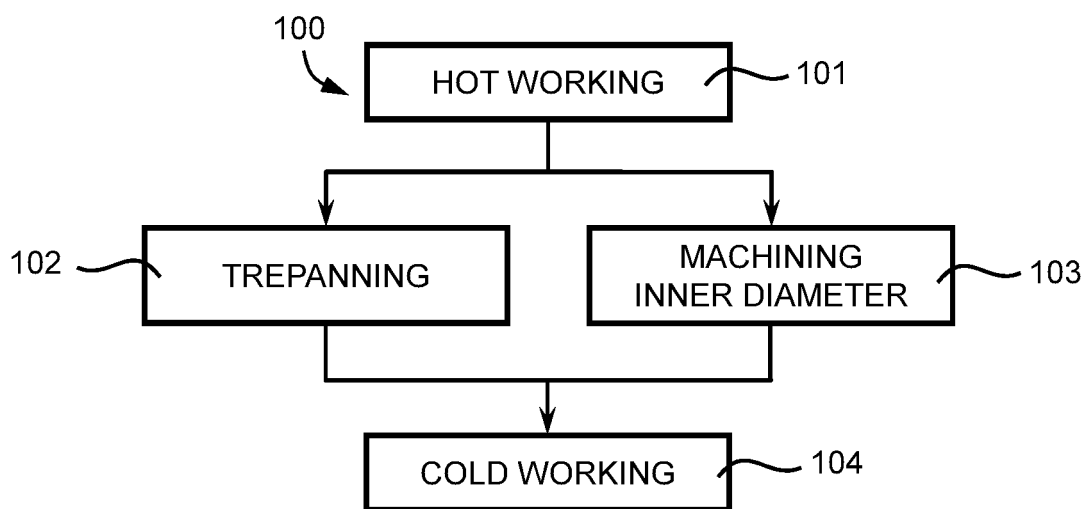


FIG. 1A

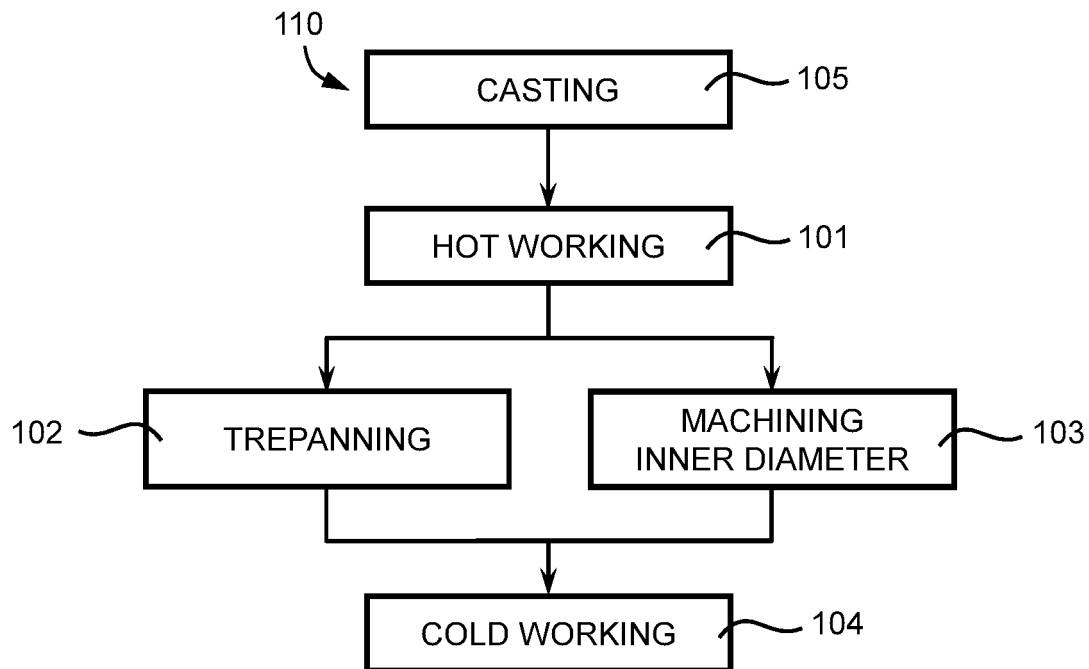


FIG. 1B

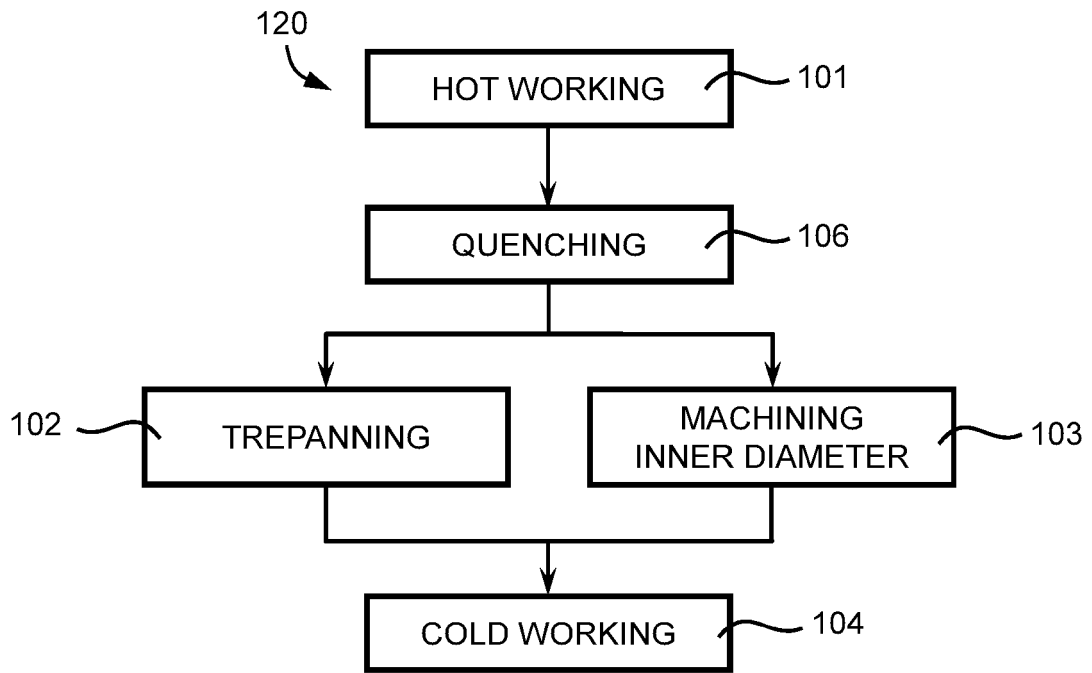


FIG. 1C

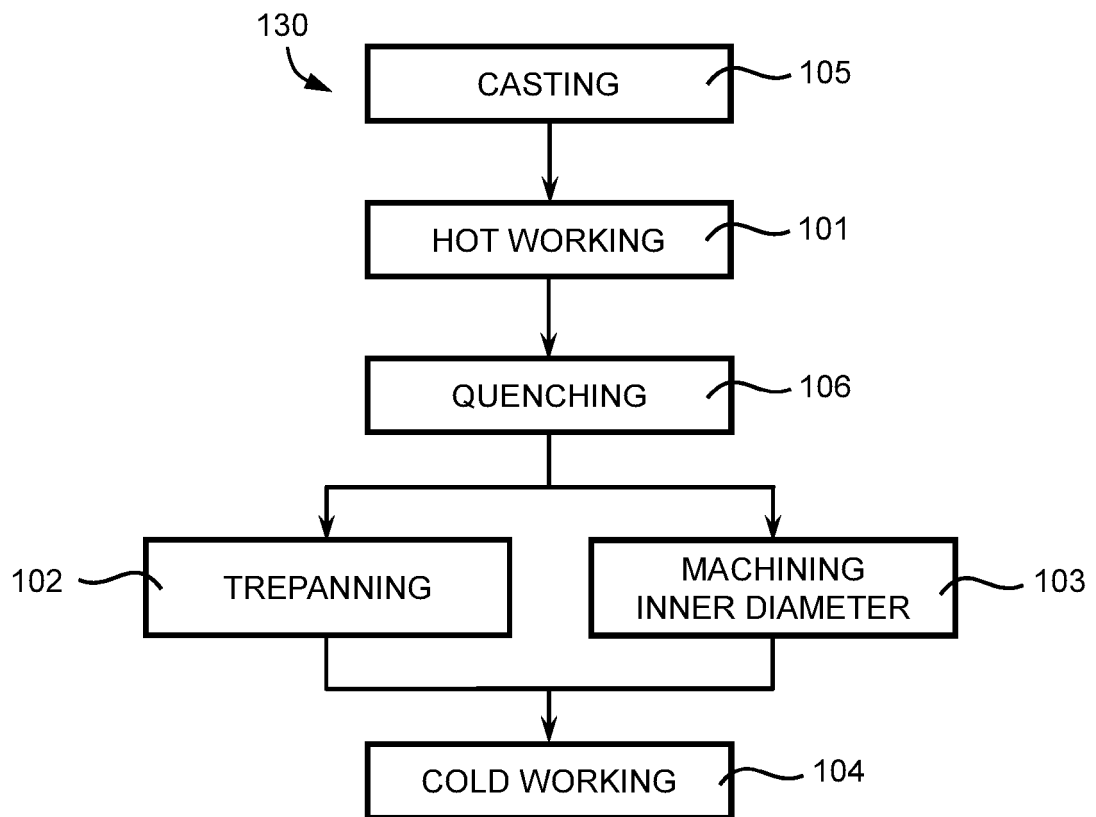


FIG. 1D

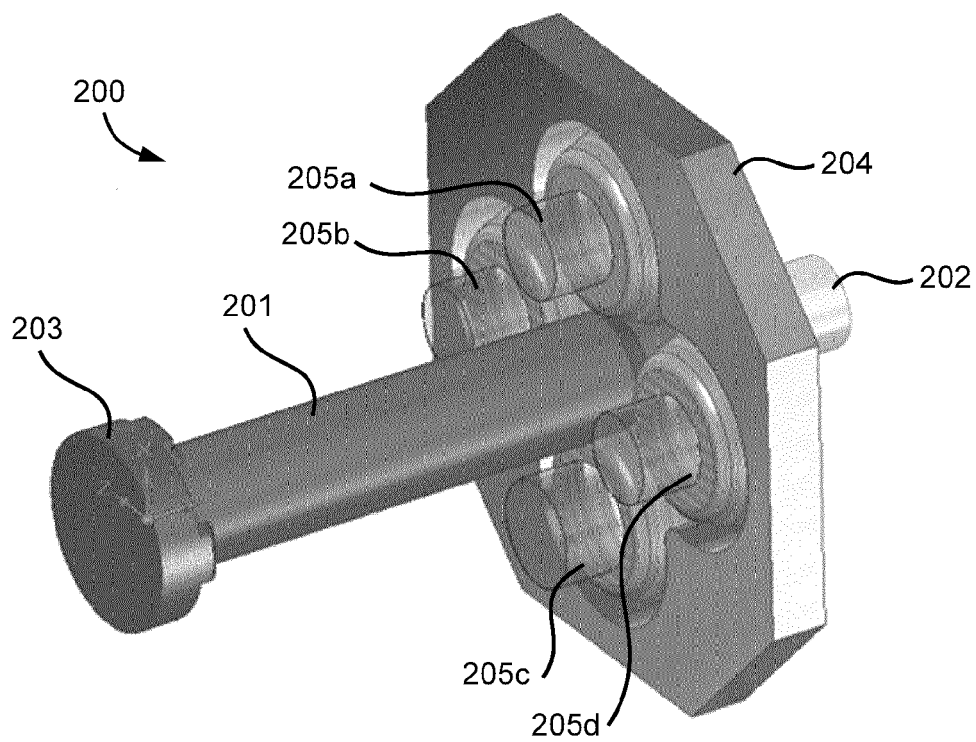


FIG. 2

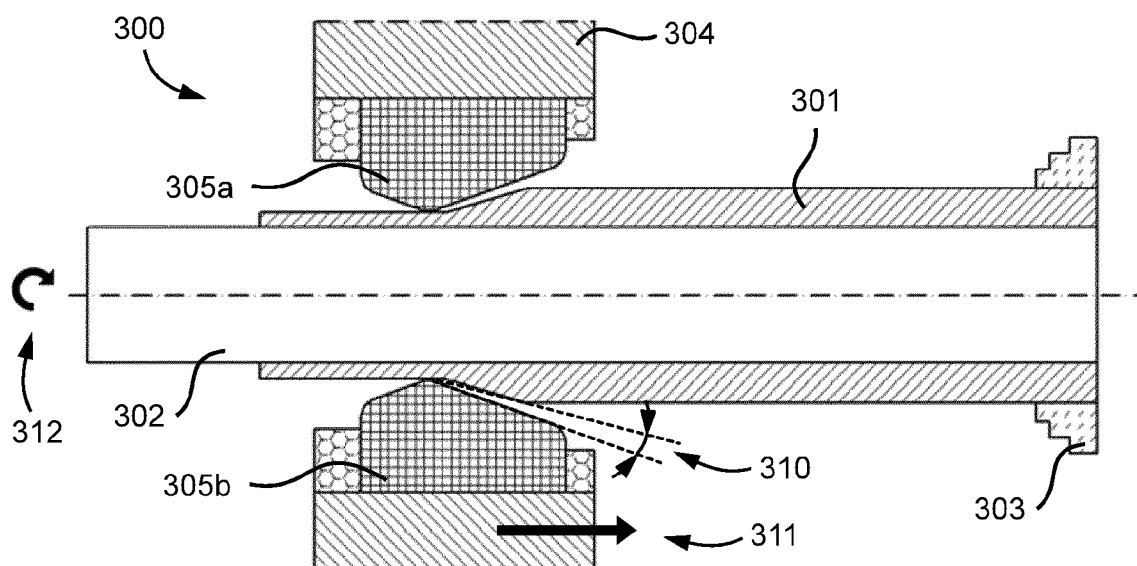


FIG. 3

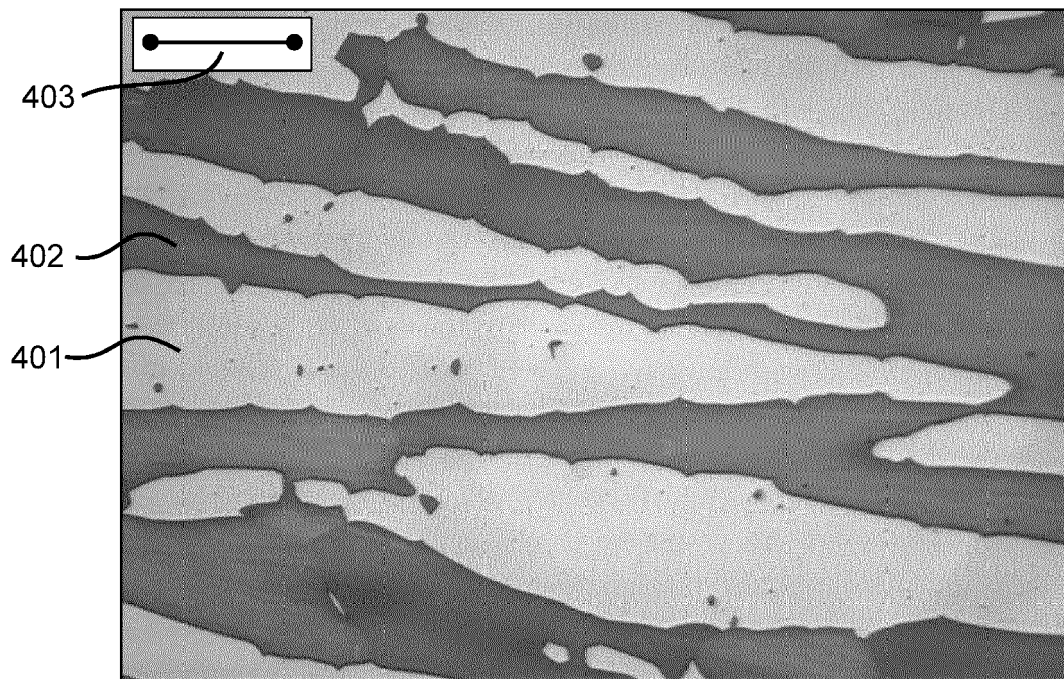


FIG. 4



EUROPEAN SEARCH REPORT

 Application Number
 EP 16 38 2042

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Place of search		Date of completion of the search	Examiner
Munich		4 July 2016	Badcock, Gordon
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5 This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
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