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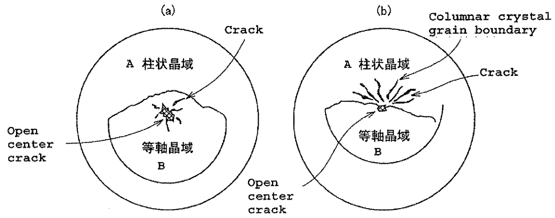
(54) **PROCESS FOR PRODUCING SEAMLESS PIPE**

(57) A process for producing a seamless pipe **characterized by** including a continuous casting step in which a round billet material having a carbon content of not more than 0.1% by mass and having an outside diameter exceeding 300 mm is cast so that the whole of a central circular region, in terms of cross section, which has a diameter of at least 60 mm may be constituted of an equiaxed crystal structure. Further, in the process for seamless-pipe production, the round billet obtained from the billet material as cast produced in the above continuous casting step may be pierced/rolled with a piercing/rolling machine under conditions in which the ratio of the number of billet rotations to the billet outer diameter draft is set in the suitable range according to the ratio of the gorge portion diameter to the inlet diameter at the inclined rolls, thereby giving a seamless pipe reduced in the incidence of inner surface flaws. Furthermore, as a piercing plug, a suitably configured plug, having a substantially round column-shaped front rolling section with a spherical tip face, may be used, so that Mannesmann fracture and circumferential shear strains are significantly inhibited and no billet onset-engagement failure occurs at all. This process for seamless-pipe production makes it possible to produce a seamless pipe much more improved in inner surface quality with exceedingly high productivity.

FIG. 6



A: Columnar crystal region
B: Equiaxed crystal region

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Description

TECHNICAL FIELD

[0001] The present invention relates to a process for producing a seamless pipe. More particularly, it relates to a process for producing a seamless pipe, comprising: a continuous round billet casting step in which axial center cracks, being very likely to be developed in an axial portion of billet and being deemed to be one of the causes of inner surface flaws of end products, can be reduced; and a piercing/rolling step in which the round billet casted in the above casting step is pierced and rolled to give a seamless pipe reduced in the incidence of inner surface flaws while preventing the occurrence of hollow shell inner surface flaws and averting any mis-rolling.

BACKGROUND ART

[0002] In the process for producing a seamless pipe from a continuously cast material by the Mannesmann process or the like without any rolling or forging step in between, axial center cracks, which are defects characteristic of ferrite solidification, tend to appear in the axial central portion of the continuously cast billet. Therefore, when such a crack-carrying cast material as such is used as a billet for pipe production, the cracks may promote the occurrence of internal surface flaws in the piercing/rolling step and the flaws may often become defects fatal to the product pipes.

[0003] For reducing internal defects in the continuously cast material, a secondary cooling technique has been disclosed which utilizes the thermal shrinkage on the occasion of cast cooling to improve the axial central portion quality of a continuously cast material.

Thus, Japanese Patent Application Publication No. 07-001096 discloses a method of reducing the center porosity occurring in the axial central portion of a cast material which comprises: starting surface cooling with a water volume density of 25-100 L/ (min·m^2) at the time that a solid phase fraction in the axial central portion of material reaches 0.1 to 0.3; and continuing the cooling with the above water volume density until the solid phase fraction in the axial central portion of the material reaches 0.8 or a higher level. The solid phase fraction, so referred to herein, means the fraction of solid phase in a solid-liquid coexisting phase. This prior art document fails to definitely show the mechanisms of development of the axial center cracks or the conditions for reducing the axial center cracks.

[0004] Further, methods of improving the cast inner quality by controlling the cast cooling through controlling the specific cooling water amount are disclosed in Japanese Patent Application Publication No. 08-332556 and Japanese Patent Application Publication No. 2001-62550.

[0005] The method disclosed in Japanese Patent Application Publication No. 08-332556 is a method capable of reducing the extent of center porosity in the axial central portion of a material to prevent axial center cracks. In steel grades in which the ferrite phase is formed as the primary crystal phase during solidification, however, axial center cracks sometimes occur. According to the method disclosed in Japanese Patent Application Publication No. 2001-62550, the rate of surface shrinkage can be made higher than the rate of material axial central portion shrinkage and the extent of center porosity or center segregation occurring in the axial central portion of a material can be reduced. However, like the method disclosed in Japanese Patent Application Publication No. 08-332556, this method sometimes allows the occurrence of axial center cracks in steel grades in which the ferrite phase is formed as the primary crystal phase during solidification. Therefore, in these respects, there is room for improvement in both the methods disclosed in the above-cited publications.

[0006] Japanese Patent Application Publication No. 2003-117643 discloses a method of reducing the extents of macro-segregation, semi-macro-segregation and center cavity, among others, by cooling the material surface by secondary cooling in the final stage of solidification and thereby utilizing the shrinkage of the solidified shell forming the material surface layer. However, in steel grades in which the ferrite phase is formed as the primary crystal phase during solidification, axial center cracks may sometimes occur; further improvement is therefore required.

[0007] Further, the present inventors have proposed, in Japanese Patent Application Publication No. 2004-330252, a method of continuously casting a round cast material having a C content of 0.1% by mass or less or a round material having a Cr content of 1% by mass or more and a C content of 0.15% or less which method comprises carrying out secondary cooling from just after the departure of the cast material from the mold and thereafter continuing final solidification stage secondary cooling from the point of time of arrival of the cast material surface temperature in the range of 950-1100˚C until complete solidification of the axial central portion of material. In the case of large diameter cast materials, however, the thermal resistance of the solidified shell is great and, therefore, the cooling effect can hardly spread to the axial central portion; thus, those cooling methods cannot produce satisfactory improving effects with respect of cracks.

[0008] On the other hand, the pipe production process using the Mannesmann plug mill system, which is a typical process for producing a seamless pipe, produces a hollow shell by feeding a solid billet heated to a predetermined temperature to a piercer for piercing and rolling of the axial central portion thereof. Then, the hollow shell is subjected to a elongation-rolling step using a mandrel mill and, after reheating or directly, to a diameter-determining rolling step using a stretch reducer or sizer mill and further to a trimming step to give a seamless pipe as an end product.

[0009] In the piercing/rolling step in which the billet is rolled along the pass line, a pair of barrel-shaped or cone-shaped inclined rolls whose roll axis lines are tilted relative to the pass line are disposed as opposed to each other. Further, a plug held on a mandrel disposed on the pass line is positioned between these inclined rolls.
Cone-shaped inclined rolls are also sometimes used as piercer rolls.

[0010] Fig. 1 is a schematic representation of the arrangement of cone-shaped inclined rolls used in the piercing/rolling step. Fig. 2 is a schematic representation of the arrangement of one of the cone-shaped inclined rolls as seen in the direction of the arrows A-A given in Fig. 1.
Each of the inclined rolls 1 has a gorge part 1a in between having a roll diameter of Dg, an inlet surface 1b having the shape of a substantially truncated cone reducing in diameter toward the end of inlet side, and an outlet surface 1c having the shape of a substantially truncated cone increasing in diameter toward the end of outlet side, thus, as a whole, having a cone-like shape.

[0011] These inclined rolls 1 are disposed in an axially symmetric manner such that the roll axis lines respectively form a cross angle γ with respect to the pass line X-X. Further, as shown in Fig. 2, one of the inclined rolls 1 is disposed to form a feed angle β with respect to the pass line X-X. On the other hand, the other roll 1 not shown in Fig.2 is also arranged across the pass line X-X in a manner tilted in the opposite direction to form a feed angle β with respect to the pass line X-X.

[0012] The inclined rolls 1 are directly connected with respective drive units 4. Thus, each inclined roll 1 can be rotated on its axis while securing the cross angle γ and feed angle β and causes the billet 3 to rotate.
The plug 2, as a whole, has a bullet-like shape and the rear end portion thereof is supported by the front end portion of a mandrel bar M, and the rear end portion of the mandrel bar M is connected to a thrust blocking mechanism (not shown).

[0013] The billet 3 fed to the piercer configured in the above manner is rolled by the inclined rolls 1 and plug 2 while passing through space between the inclined rolls and is rotated, and gives a hollow shell.

[0014] The mechanisms of the generation of hollow shell inner surface flaws in this piercing/rolling step are now described. The billet is compressed by a pair of inclined rolls while rotating during the period from onset-engagement onto the inclined rolls to reaching the plug tip. On this occasion, the billet axial central portion is rendered fragile and becomes easy to be pierced by virtue of the so-called "rotary forging effect". When the influence of this rotational forging effect is excessive, voids are formed in the axial central portion. In extreme cases, the axial central portion is destroyed and radial crack flaws are generated. Even when the billet before piercing/rolling is free of internal cracks in the axial central portion, the axial central portion voids and axial center crack flaws caused by such "rotational forging effect" as mentioned above may cause hollow shell inner surface flaws after piercing/rolling.

[0015] Further, in the case of a continuously cast round material readily susceptible to center segregation and center porosity or of a stainless steel having a 5% or more Cr content and susceptible to δ ferrite formation and, further, in the case of nonferrous material having poor workability, such as copper or a copper alloy, because of residual cast micro structures, the piercing/rolling of such materials results in promoting the development of hollow shell inner surface flaws.

[0016] Meanwhile, various methods have so far been proposed for preventing the development of hollow shell inner surface flaws in the piercing/rolling step. Thus, in Japanese Patent Application Publication No. 03-013222, Japanese Patent Application Publication No. 61-003605 and Japanese Patent Application Publication No. 2000-140911, for instance, methods are disclosed of optimizing the geometric positioning conditions for the billet, plug and inclined rolls, for example the billet outside diameter reduction rate and inclined roll opening.

[0017] However, the method disclosed in Japanese Patent Application Publication No. 03-13222 attaches great importance to the onset-engagement characteristic rather than to the prevention of the development of inner surface flaws in the top portion of a billet. The method disclosed in Japanese Patent Application Publication No. 61-3605 can indeed prevent the development of inner surface flaws in the rolled material but may possibly cause a failure in rolling(hereinafter also referred to as "mis-rolling") due to billet onset-engagement failure. Further, like the method disclosed in Japanese Patent Application Publication No. 03-013222, the method disclosed in Japanese Patent Application Publication No. 2000-140911 cannot prevent the development of inner surface flaws in the top portion of the billet to a satisfactory extent.

DISCLOSURE OF INVENTION

[0018] The present invention has been made aiming primarily at preventing the development of inner surface flaws in the continuous round billet casting step and piercing/rolling step in the seamless pipe production process, and an object thereof is to provide a process for producing a seamless pipe which comprises: a continuous round billet casting step capable of markedly reducing the incidence of axial center cracks which should result in inner surface flaws for products; and a piercing/rolling step capable of effectively preventing both the occurrence of mis-rolling and the development of hollow shell inner surface flaws in piercing/rolling the round cast billet, thus enabling high-quality products with a fewer incidence of inner surface flaws to be produced.

[0019] The present inventors made investigations in search of a process for producing a seamless pipe in which hollow shells reduced in incidence of inner surface flaws can be produced with high productivity and obtained the following findings (a) to (f). Based on these findings, they have completed the present invention.

[0020] (a) The ferrite phase is lower in strength as compared with the austenite phase, and billets having a C content of 0.1% by mass (hereinafter, "% by mass" is referred to as "%" for short) or less are susceptible to axial center cracks due to ferrite phase solidification. Billets having such a C content as mentioned above become more susceptible to the axial center cracks with the increase in diameter thereof and, when the billet diameter is in excess of 300 mm, not only the forced cooling effect of secondary cooling on the billet surface decreases but also the forced cooling rather causes the axial center cracks to extend and spread. Therefore, it is appropriate to carry out slow cooling, including radiation cooling from the billet surface.

[0021] (b) In the case of large-diameter billets, the incidence of axial center cracks can be reduced by the slow cooling of the billet surface and, in addition, increasing the equiaxed crystal content in the axial central portion when the axial central portion solid phase fraction is within the range of above 0 to 1.0 at the final stage of solidification. In the case of billets having a diameter exceeding 300 mm, the development of axial center cracks can be limited to a circular region with a radius of 15 mm from the billet center, in terms of billet cross section, by allowing the whole of a central circular region of at least 60 mm in diameter to be constituted of an equiaxed crystal structure.

[0022] (c) When a round billet cast by the method mentioned above under (b), without going through a blooming/ rolling step or the like for round-billet making, is subjected to piercing/rolling, the development of hollow shell inner surface flaws can be inhibited.

[0023] (d) When the ratio of "roll diameter Dg (cf. Fig. 5) at inclined roll gorge portion" to "roll diameter D1 (cf. Fig. 5) at roll inlet", namely where the roll-billet contacting starts (hereinafter also referred to as "inlet roll diameter"), i.e. the ratio Dg/D1, is low, inner surface flaws highly likely develop, whatever the ratio of "the number N of billet rotations from its onset-engagement onto the inclined rolls to reaching the plug tip" to "the billet outside diameter draft(reduction rate) Df", namely the ratio N/Df, takes. When the above-mentioned roll diameter ratio (Dg/D1) is high, the development of inner surface flaws can be inhibited but, when the above-mentioned ratio (N/Df) of "the number N of billet rotations" to "the billet outside diameter draft (Df)" is small, the incidence of mis-rolling increases.

Furthermore, when the ratio of the above-mentioned inlet roll diameter D1 to the billet outside diameter Bd, namely the ratio D1/Bd, is less than 2.5, the billet onset-engagement condition becomes unstable and mis-rolling tends to occur frequently.

[0024] (e) When a piercing/rolling plug having such a shape as shown in Fig. 4 is used, by configuring such that, among the various dimensions, (i)the outside diameter d of the front rolling section is not more than 35% of the billet outside diameter Bd, (ii)the sum (L1 + L2) of an axial length of a front spherical face portion and an axial length of a round column portion is not less than 50% of d and (iii) Length L3 in an axial direction of the contour formed by a circular arc with a radius of curvature R satisfies the requirement that the value of the parameter "(d/2Bd)/(R/L3)" be not more than 0.046, no onset-engagement failure occurs, the Mannesmann fracture and circumferential shear strains are restrained and the development of hollow shell inner surface flaws can be prevented, even if the billet outside diameter draft Df is lowered.

[0025] However, when the value of d is less than 12% of Bd, the front rolling section is readily melted down and the plug life is shortened. Further, when the length (L1 + L2) is longer than 3 times the diameter d, the front rolling section is readily deformed and, in addition, the whole plug length becomes excessively long.

Further, when the plug shape is such that R and L3 give a parameter value "(d/2Bd)/(R/L3)" less than 0.020, the development of circumferential shear strains cannot be restrained to a satisfactory extent.

The "billet outside diameter draft Df" (hereinafter also referred to as "plug tip draft Df"), so referred to herein, means the billet outside diameter draft at the plug tip position, as mentioned later herein, and is the value represented by {(Bd - Rpg)/Bd} x 100, where Rpg is the inclined roll gap at the plug tip position.

[0026] (f) When the high-temperature strength of the plug front rolling section is secured, by configuring such that, among the various dimensions of the plug having a shape shown in Fig. 4, the outside diameter d of the front rolling section is not more than 12% of the billet outside diameter Bd, the axial length (L1 + L2) is not less than 50% of d and the radius of curvature R and L3 satisfy the requirement that the value of the parameter "(d/2Bd)/(R/L3)" be not greater than 0.046, no billet onset-engagement failure occurs even if the billet outside diameter draft Df is reduced.

[0027] On the other hand, when the diameter d is less than 6% of Bd, the front rolling section is readily melted down because of its small heat capacity, in the same manner as described above under (e), even if an attempt is made to strengthen that portion. Furthermore, when (L1 + L2) is more than 3 times the diameter d, the front rolling section becomes readily deformable and, in addition, the whole plug length becomes excessively long.

Further, when the mandrel is shaped such that R and L3 give a parameter value, "(d/2Bd)/(R/L3)", less than 0.020, the development of circumferential shear strains cannot be restrained to a satisfactory extent.

[0028] The present invention has been completed based on the findings mentioned above, and the essential features thereof are found in a process for seamless pipe production which comprises a continuous casting step as defined below under (1), a round billet as defined below under (2) and a piercing/rolling step as defined below under any of (3)-(7).

[0029] (1) A process for seamless pipe production, characterized by including a continuous casting step in which a round billet having a carbon content of not more than 0.1% by mass and having a billet cross-sectional diameter exceeding 300 mm is cast so that the whole of a central circular region, in terms of the billet cross section, which has a diameter of at least 60 mm may be constituted of an equiaxed crystal structure, while carrying out slow cooling of the round billet surface at a cooling rate of not more than 10°C/minute during the period in which the axial central portion solid phase fraction is above 0 and increases up to 1.0 (hereinafter also referred to as "first aspect of the invention").

[0030] (2) The round billet as cast by the continuous casting step defined above under (1), characterized in that the axial center cracks found in the axial central portion of the billet is limited to a circular region with a radius of 15 mm or less from the billet center in terms of the billet cross section (hereinafter also referred to as "second aspect of the invention").

[0031] (3) A process for seamless pipe production, characterized by including a piercing/rolling step in which the round billet as defined above under (2) is pierced/rolled, without billet rolling in between (hereinafter also referred to as "third aspect of the invention").

[0032] (4) A process for seamless pipe production, characterized by including a piercing/rolling step in which the round billet as defined above under (2) is caused to revolve and move through a unit comprising: a pair or cone-shaped inclined rolls disposed as opposed to each other along the pass line; and a plug disposed in a space between the inclined rolls along the pass line, wherein the ratio of "roll diameter Dg (mm) at inclined roll gorge portion" to "roll diameter D1 (mm) where roll-billet contacting stars at the inclined roll inlet", namely the ratio Dg/D1, and the ratio of "the number N of billet rotations from billet onset-engagement to reaching plug tip" to "the billet outside diameter draft Df (%)", namely the ratio N/Df, satisfy the relation represented by any of the formulas (1) to (3) given below and, further, the ratio of the above-defined D1 to the billet outside diameter Bd (mm), namely the ratio D1/Bd, satisfies the relation represented by the formula (4) given below (hereinafter also referred to as "fourth aspect of the invention"):

when $Dg/D1 < 1.1$,

$$23 \leq N/(Df/100) \leq 40 \quad (1);$$

when $1.1 \leq Dg/D1 < 1.5$,

$$20 \leq N/(Df/100) \leq 44 \quad (2);$$

when $1.5 \leq Dg/D1 \leq 1.8$,

$$20 \leq N/(Df/100) \leq 48 \quad (3);$$

$$D1/Bd \geq 2.5 \quad (4);$$

wherein, the distance Ld (mm) from billet onset-engagement to plug tip position along the pass line, the feed angle β (°) of the inclined rolls and the inclined roll gap Rpg (mm) at the plug tip position satisfy the following formulas (5) and (6):

$$N = 2Ld/(\pi \cdot Bd \cdot \tan\beta) \quad (5);$$

$$Df = \{(Bd - Rpg)/Bd\} \times 100 \quad (6).$$

[0033] (5) A process for seamless pipe production, characterized by including a piercing/rolling step in which the solid round billet having an outside diameter Bd (mm) as defined above under (2) is pierced/rolled by an inclined roll type piercing/rolling machine using a plug consisting of: a front rolling section having a round column-like shape, an outside diameter d (mm) of which is constant over its length in an axial direction or is increasing toward the rear end in an axial direction, and which has a length L2 (mm) in an axial direction and has the front face spherically formed with a curvature of radius r (mm) and an axial length L1 (mm); a work section abutting the rear end of the front rolling section, which is formed of a curvature of a circular arc with a radius R (mm) and an axial length L3 (mm) so as to increase in outside diameter toward the rear end in an axial direction; and a reeling section abutting the rear end of the work section, which has a tapered round column-like shape with an included taper angle 2θ (˚) and axial length L4 (mm) so as to increase in outside diameter toward the maximum outside diameter D (mm) at the rear end in an axial direction, wherein the plug outside diameter d, the curvature radius R, axial lengths L1, L2 and L3 and the solid round billet outside diameter Bd satisfy all the relations represented by the formulas (7) to (9) given below (hereinafter also referred to as "fifth aspect of the invention"):

$$0.12 \leq d/Bd \leq 0.35 \qquad (7);$$

$$0.020 \leq (d/2Bd)/(R/L3) \leq 0.046 \qquad (8);$$

$$0.5d \leq L1 + L2 \leq 3d \qquad (9).$$

[0034] (6) A process for seamless pipe production, characterized by including a piercing/rolling step in which the solid round billet having an outside diameter Bd (mm) as defined above under (2) is pierced/rolled by an inclined roll type piercing/rolling machine using a plug consisting of: a front rolling section with a round column-like shape, having a constant outside diameter d (mm) over its length in an axial direction or increasing toward the rear end in an axial direction, which has a length L2 (mm) in an axial direction and has a front face spherically formed with a curvature of radius r (mm) and an axial length L1 (mm); a work section abutting the rear end of the front rolling section, which is formed of a curvature of a circular arc with a radius R (mm) and an axial length L3 (mm) so as to increase in outside diameter toward the rear end in an axial direction; and a reeling section abutting the rear end of the work section, which has a tapered round column-like shape with an included taper angle 2θ (˚) and an axial direction length L4 (mm) so as to increase in outside diameter toward the maximum outside diameter D (mm) at the rear end in an axial direction, wherein at least the front rolling section of the plug has a tensile strength of not less than 50 MPa at 1100˚C, and wherein the plug outside diameter d, curvature radius R, axial lengths L1, L2 and L3 and the solid round billet outside diameter Bd satisfy all the relations represented by the formulas (8) to (10) given below (hereinafter also referred to as "sixth aspect of the invention"):

$$0.06 \leq d/Bd \leq 0.12 \qquad (10);$$

$$0.020 \leq (d/2Bd)/(R/L3) \leq 0.046 \qquad (8);$$

$$0.5d \leq L1 + L2 \leq 3d \qquad (9).$$

[0035] (7) The process for seamless pipe production as set forth above under (6), characterized in that the front rolling section of the plug is replaceable (hereinafter also referred to as "seventh aspect of the invention").

[0036] The "axial central portion solid phase fraction", so referred to herein, is a solid phase fraction relative to the sum of solid phase and liquid phase in the axial central portion of the billet.

The term "slow cooling" refers to cooling at a slow cooling rate, including radiation cooling from the billet surface, among others, and means cooling the billet surface at a cooling rate of not more than 10˚C/minute.

The phrase "round column-like shape increasing in diameter toward the rear end in an axial direction and having an axial length L2 (mm)" means a round column-like shape which is increasing in diameter d toward the rear end in an axial direction with preferably a taper angle (the half of taper included angle) of 4˚ or less and has an axial length L2 (mm).

BRIEF DESCRIPTION OF THE DRAWINGS

[0037]

Fig. 1 is a schematic representation of the arrangement of cone-shaped inclined rolls used in piercing/rolling.
Fig. 2 is a schematic representation of the arrangement of one of the cone-shaped inclined rolls as seen in the direction of the arrows A-A given in Fig. 1.
Fig. 3 is a representation showing one example of a plug having a simple bullet-like shape.
Fig. 4 is a representation of a plug shape to be used in the practice of the present invention in the mode B thereof.
Fig. 5 is a schematic representation of the condition under which a billet is pierced/rolled by means of a pair of inclined rolls disposed as opposed to each other along the pass line and a plug disposed in a space between the rolls.
Fig. 6 is a schematic representation of the solidified macrostructure and axial center cracks in a billet cross section; Fig. 6 (a) illustrates the case where the billet axial central portion in which axial center cracks develop is filled with equiaxed crystals, and Fig. 6 (b) shows the case where that the billet axial central portion is not filled with equiaxed crystals.
Fig. 7 is a schematic representation, in longitudinal cross section, of a continuous casting apparatus to be used in the continuous casting step in the practice of the present invention.
Fig. 8 is a representation illustrating a plug lead and a billet outside diameter draft at the plug tip position in billet piercing/rolling.

BEST MODES FOR CARRYING OUT THE INVENTION

1. Modes of practice of the first to third aspects of the present invention

1-1. Best modes for carrying out the first to third aspects of the present invention

[0038] As described hereinabove, the process for seamless pipe production according to the present invention is a process for seamless pipe production, characterized by including a continuous casting step in which a round billet having a carbon content of not more than 0.1% by mass and having a billet cross-sectional diameter exceeding 300 mm is cast so that the whole of a central circular region having a diameter of at least 60 mm , in terms of billet cross section, is constituted of an equiaxed crystal structure, while carrying out slow cooling of the round billet surface at a cooling rate of not more than 10˚C/minute during the period in which an axial central portion solid phase fraction is above 0 and increases up to 1.0. In addition, the process for seamless pipe production is characterized by including a piercing/rolling step for a round billet as produced in the above continuous casting step, without billet rolling in between. In the following, the process of the present invention is described in more detail.

1-1-1. Relation between solidified billet macrostructure and inner surface flaws

[0039] As a result of detailed observations of billets and hollow shells, it was found that there is a close relation between the development of axial center cracks in the billet and the distribution of equiaxed crystals in the axial central portion thereof and, further, there is an important relation between the solidified macrostructure and associated axial center cracks in the billet and the incidence of inner surface flaws after piercing/rolling.
[0040] Fig. 6 is a schematic representation of the solidified macrostructure and axial center cracks in a billet cross section; Fig. 6 (a) illustrates the case where the billet axial central portion in which axial center cracks develop is filled with equiaxed crystals, and Fig. 6 (b) shows the case where that axial central portion is not filled with equiaxed crystals.
[0041] In the case of Fig. 6 (a) (hereinafter also referred to as "case (a)" for short), the axial center crack opening is large but the range of occurrence of axial center cracks away from the billet center is narrow. On the other hand, in the case of Fig. 6 (b) (hereinafter also referred to as "case (b)" for short), the axial center crack opening is small but axial center cracks occur in a wide range away from the billet center. In this case, axial center cracks are found as being formed along columnar crystal grain boundaries and look like fairly fine as being hair-cracks.
[0042] The differences between the above-mentioned case (a) and case (b) in solidified macrostructure and axial center cracks result presumably from the following reasons. Thus, when the billet axial central portion comes to the final solidification state, tensile stress attributable to thermal stress in a circumferential direction is generated. The tensile stress gets to maximum in a billet center which has the maximum temperature difference from the billet periphery and, when this tensile stress exceeds the strength of material, radial cracks, namely axial center cracks, develop in the billet axial central portion.
[0043] When the circumferential direction stresses mentioned above develop in the billet axial central portion, the stresses are readily dispersed in the case where the billet axial central portion is filled with an equiaxed crystal structure,

namely fine crystal grains. On the contrary, when the billet axial central portion has a columnar crystal structure, which is composed of large crystal grains, the stresses are readily concentrated at the faces of crystal grain boundaries; thus, even relatively weak stresses cause cracks.

[0044] The thermal stress increases as the solidification progresses to the billet axial central portion. In a columnar crystal region, however, a relatively weak stress causes fine cracks and the cracks extend to the axial central portion while releasing the stress, so that no widely open cracks are formed in the axial central portion. On the other hand, in an equiaxed crystal region, weak stresses induced at a portion surrounding the axial central region do not cause cracks and, therefore, thermal-stress-induced strain energy is not released but is accumulated with the lapse of time. As a result, when the thermal stress becomes maximum in the axial central portion, this stress comes up to greatly exceed the strength of the material and cracks develop. In this case, the accumulated energy is released all at once to give large open cracks.

[0045] It was found that, in the case of a billet large in cross-sectional diameter, forced cooling of the billet surface by spraying, for instance, cannot exert its cooling effect toward the inside of billet but recovery heat after the end of cooling causes large tensile strains within the billet, leading to the formation of much widely open center cracks.

[0046] Further, it was found that the piercing/rolling of round billets differing in inside solidified macrostructure and mode of axial center cracks, as mentioned above, results in different conditions of development of hollow shell inner surface flaws. That is, the incidence of hollow shell inner surface flaws is markedly reduced when the billet axial central portion is filled with equiaxed crystals, as in case (a), as compared with the case where the billet axial central portion is not filled with equiaxed crystals, as in case (b).

[0047] This indicates that, in the round billet piercing/rolling step, inner surface flaws are readily caused when the range of axial center cracks is wide stretched from the billet axial central portion, as in case (b), even if cracks are minute. This finding obtained by the present inventors is a novel finding quite different from any of the prior art findings.

1-1-2. Reasons for limitations of parameter range and preferred ranges in the first to third aspects of the invention

[0048] In the following, the reasons why the present invention is limited to the scope mentioned above are described, together with preferred scopes of the present invention.

1) C content in cast billet

[0049] It is well known that C is an austenite-stabilizing element and the C content governs the ferrite-austenite quantity ratio to a great extent. Generally, the ferrite phase is lower in strength than the austenite phase, and an examination made by the present inventors revealed that cast billets having a C content of 0.1% or less readily allow the development of such ferrite-phase-induced axial center cracks as mentioned above.

For the above reason, the present invention is based on the premise that the intended effects should be exhibited even when a cast billet is made using a molten steel having a C content of 0.1% or less which should readily cause axial center cracks.

2) Cast billet size and cooling method

[0050] It was found that, as the cast billet diameter increases, the development of axial center cracks tends to increase and, when the cast billet diameter exceeds 300 mm, not only the effect of secondary cooling consisting in forcedly cooling the cast billet surface decreases but extension of axial center cracks is rather caused. Therefore, in the case of large-diameter cast billets, it is necessary to avoid, as much as possible, such forced cooling as secondary cooling in the final stage of solidification and carry out slow cooling at a surface cooling rate of 10˚C/minute or less, including radiation cooling from the billet surface.

The cooling rate in the slow cooling is preferably adjusted to 8˚C/minute or less. So long as no heating or heat retention treatment is carried out, it is practical to employ a cooling rate of at least about 4˚C/minute under conditions allowing radiation cooling.

3) Timing of slow cooling and range for equiaxed crystal formation

[0051] The incidence of axial center cracks in cast billets can be reduced by slowly cooling the cast billet surface at the final stage of solidification, namely during the period when the cast billet axial central portion solid phase fraction is above 0 and increases up to 1.0, and simultaneously allowing the equiaxed crystal region in the cast billet cross-sectional central portion to expand. The above-mentioned slow cooling is preferably carried out in the cast billet surface temperature range of 1050-850˚C.

[0052] In the case of cast billets having a cross-sectional diameter exceeding 300 mm, the development of axial center cracks can be restricted to a circular region with a radius not more than 15 mm from the center of the cross section when a circular region with a diameter of at least 60 mm in the cross-sectional central portion is wholly constituted of an equiaxed crystal structure. Therefore, in the continuous casting step according to the present invention, the circular region with a diameter of at least 60 mm in the cross-sectional axial central portion of the cast billet should be wholly constituted of an equiaxed crystal structure and, at the same time, the cast billet surface should be cooled slowly during the period in which the axial central portion solid phase fraction is above 0 and increases up to 1.0. More preferably, the slow cooling is carried out within the range in which the axial central portion solid phase fraction is not less than 0.3 and not more than 0.8.

[0053] It was also found that the extent of the equiaxed crystal region can be controlled by adjusting the site and intensity of electromagnetic stirring and the casting temperature, among others. In particular, the casting temperature is important; the molten steel temperature in a tundish is preferably as low as possible, and the temperature difference AT (temperature of relevant steel - liquidus temperature of the steel) is preferably not more than 70˚C. However, when ΔT is excessively small, such problems as nozzle clogging and skinning, namely solidification of the molten steel skin in the mold; therefore, the value thereof is preferably not less than 20˚C.

As a result of various tests, it was further revealed that even when the above cast billet is reheated and is subjected to piercing/rolling in as-is condition without going through a blooming/rolling step or the like, the hollow shell obtained shows almost no development of inner surface flaws.

[0054] As for the preferred conditions in piercing/rolling the thus-obtained round cast billet by the Mannesmann plug mill technique in accordance with the third aspect of the invention, the roll feed angle β is within the range of 6-16˚ and the cast billet outside diameter draft is within the range of 3-7%.

1-2. Examples in relation to the first to third aspects of the invention

[0055] For confirming the effects of the present invention, the following continuous casting tests were carried out and, at the same time, piercing/rolling tests were performed using the round cast billets obtained, and the results were evaluated.

(Testing method)

[0056] Fig. 7 is a schematic representation, in longitudinal cross section, of a continuous casting apparatus for embodying the continuous casting step according to the present invention. A curved type continuous casting machine for casting round billets was used as the continuous casting apparatus. A molten steel 23 poured from a tundish 211 into a mold 22 via an immersed nozzle 21 is cooled by a top zone secondary cooling device 27 disposed just below the mold 22 and, while being supported by support rolls 28 and forming a solidified shell 25, pulled out by a pair of pinch rollers 29 to form a round cast billet 26. After being cooled by the top zone secondary cooling device, the cast billet 26 with the formed solidified shell 25 is further cooled by a final solidification stage secondary cooling device 210 for complete solidification.

[0057] Here, the top zone secondary cooling device 27 functions to cool the cast billet 26 in the region where the thickness of the solidified shell 25 is thin to thereby promote solidification thereof and prevent bulging-induced deformations thereof. The top zone secondary cooling device 27 comprises a 2-meter-long air mist sprayer line disposed just below the mold 22; the air-water ratio was about 50 (NL/minute air/(L/minute water)). The water density can be adjusted arbitrarily within the range up to a maximum of 500 L/(min·m^2).

[0058] The final solidification stage secondary cooling device 210 comprises a combination of five blocks each having a length of 1.2 m and is disposed at a distance of 30-36 m away from a meniscus 24. Air mist sprayers were also employed in this secondary cooling device, and the air/water ratio was constantly about 30 (NL/minute air/ (L/minute water)), irrespective of water quantity. The water quantity can be adjusted to an arbitrary value within the range up to a maximum of 100 L/ (min·m^2) as expressed in terms of water quantity density.

The axial central portion solid phase fraction in the cast billet 26 and the temperature distribution in the solidified shell 25 were determined by unsteady heat transfer calculations.

[0059] By comparing the calculation outcome with the results of the cast billet surface temperature measurement and riveting test, it was confirmed in advance that the above calculation outcome has high estimation accuracy. Therefore, the solidification state of each cast billet under each set of casting conditions can be represented precisely by this calculation technique.

Further, for stably securing an equiaxed crystal structure in each cast billet, a mold-internal electromagnetic stirring device 212 was disposed at a position of about 200 mm below the meniscus. The electromagnetic stirring device is operated at a frequency of 4 Hz, a maximum current of 600 A and a maximum magnetic flux density of 0.6 T (tesla). By varying the value of the current to be passed through the coil in the electromagnetic stirring device 212, it is possible to vary the magnetic flux density and, accordingly, the intensity of stirring. In this casting test, the rotation frequency of magnetic field was within the range of 3-6 Hz.

[0060] Further detailed test conditions are described. The molten steels used in the casting test contained the following elements: C: 0.05-0.07%, Si: 0.05-0.3%, Mn: 1.2-1.5%, P: 0.080-0.015% and S: 0.001-0.006%.
The test conditions were as shown in Table 1.

[0061] [Table 1]

Table 1

Test No.	Cast billet diameter (mm)	Casting speed (m/min)	Extent of molten steel superheating (˚C)	Electric current in electromagnetic stirring (A)	Water quantity density (L/min/m²)		Cooling rate*1 (˚C /min)	equiaxed crystal region diameter (mm)	axial center crack length*2 (mm)	Number of product pipe inner surface flaws*3 (flaws/pipe)
					Top zone	Final solidification stage				
A1	310	0.9	45	600	200	0	4.4	85	22	0
A2	310	1.0	40	600	200	0	4.5	88	21	0
A3	310	1.1	30	400	200	0	4.7	64	25	0.1
A4	310	1.1	28	400	200	15	9.3	66	26	0.1
A5	360	0.7	38	600	170	0	4.5	83	22	0
A6	360	0.7	35	600	170	0	4.4	85	20	0
A7	360	0.8	31	400	170	0	4.6	63	23	0
A8	360	0.8	28	400	170	10	8.5	67	24	0
A9	310	0.9	75	500	200	0	4.3	*55	88	22.1
A10	310	1.0	65	500	200	0	4.4	*57	87	20.0
A11	310	1.1	30	200	200	0	4.6	*48	60	15.3
A12	310	1.1	27	200	200	15	9.5	*49	63	16.7
A13	360	0.7	78	500	170	0	4.2	*42	82	19.0
A14	360	0.7	70	500	170	0	4.3	*44	79	19.1
A15	360	0.8	29	150	170	0	4.4	*30	61	16.4
A16	360	0.8	30	150	170	10	8.4	*15	67	17.4
A17	310	0.9	43	600	200	50	*25.2	83	45	10.3
A18	310	1.0	45	600	200	80	*45.6	88	56	12.5
A19	360	0.7	38	600	170	40	*25.3	85	48	11.8

(continued)

Test No.	Cast billet diameter (mm)	Casting speed (m/min)	Extent of molten steel superheating (˚C)	Electric current in electromagnetic stirring (A)	Water quantity density (L/min/m^2)		Cooling rate*1 (˚C /min)	equiaxed crystal region diameter (mm)	axial center crack length*2 (mm)	Number of product pipe inner surface flaws*3 (flaws/pipe)
					Top zone	Final solidification stage				
A20	360	0.7	35	600	170	70	*43.5	82	52	11.9

Notes:
* This symbol indicates that the value is outside the range defined herein (first aspect of the invention).
*1: Maximum value of the surface cooling rate during the period in which the billet axial central portion solid phase fraction was above zero and increased up to 1.0.
*2: Maximum diameter of the region in which axial center cracks were found among all cross-section samples observed.
*3: Average number of inner surface flaws per pipe as determined by inspection of 10 billet samples.

[0062] In the above table, the cooling rate represents a maximum billet surface cooling rate (˚C/min) within the period in which the billet axial central portion solid phase fraction was above 0 and increased up to 1.0.
The cast billet diameter was 310 mm or 360 mm. The extent of filling with equiaxed crystals in the cross-sectional axial central portion (the diameter of the circle that approximates the region of formation of equiaxed crystals) was varied by changing the molten steel temperature and electromagnetic stirring conditions on the occasion of casting. The liquidus temperature of the steel was 1520˚C, and the value (molten steel temperature - liquidus temperature) was regarded as the extent of superheating (˚C) of the molten steel in the tundish.
[0063] The ranges of the cast billet surface temperature and cast billet axial central portion solid phase fraction in the final solidification stage secondary cooling region were adjusted by varying the casting speed and secondary cooling conditions in the top zone. Portions corresponding to steady casting rate regions were excised from the round cast billets (round billets) and subjected to cast billet interior characterization and piercing/rolling testing.
[0064] For cast billet interior characterization, a 2-meter-long billet specimen was taken from each cast billet, and 10 cross-section sample plates were taken from portions pitched at an equal distance in a longitudinal direction and, after mirror polishing, subjected to acid etching for inspection of axial center cracks and of the extent of equiaxed crystal formation. The extent of filling with equiaxed crystals was evaluated in terms of equiaxed crystal region diameter by determining the diameter (mm) of the circle approximating the region where the solidified structure was wholly occupied by an equiaxed crystal structure.
[0065] Ten lengths of billet samples each being 6 m long for piercing/rolling testing were cut out for each set of casting conditions. These piercing/rolling test billet samples were heated to 1200˚C in a heating furnace and then pierced/rolled by a piercing/rolling machine (inclined roll type piercing/rolling machine) under the following conditions: roll feed angle β: 8-16˚, and billet outside diameter draft: 3-7%. Hollow shells with an outside diameter of 330 mm were produced from round billets with a diameter of 310 mm, and hollow shells with an outside diameter of 370 mm from round billets with a diameter of 360 mm. The thus-obtained hollow shells were examined for inner surface flaws by ultrasonic flaw detection test.
[0066] The equiaxed crystal region diameters, the axial center crack lengths and the number of inner surface flaws were as collectively shown in Table 1. Here, each axial center crack length in entry is indicated by the maximum diameter (mm) of the axial center crack occurrence region among all cross-section sample plates under observation, and each number of inner surface flaws shown indicates the average number of flaws (flaws per billet) determined based on the total number of inner surface flaws examined for 10 billet samples.

(Test results)

[0067] In Test Nos. A1 to A8, the requirements established in accordance with the first aspect of the present invention in the mode A thereof were all satisfied whereas, in Test Nos. A9 to A20 (Comparative Examples), at least one of the requirements defined in Claim 1 was not satisfied.
[0068] In each of Test Nos. A1 to A8, the equiaxed crystal region in the cast billet cross sectional axial central portion had a diameter of 60 mm or wider and the axial center crack lengths were at most 30 mm as a result of the slow rate of cooling, namely below 10˚C/minute, in the final solidification stage secondary cooling; the cast billet characteristics were thus good.
The hollow shells obtained by piercing/rolling of the round billets which was cast in these casting tests showed a low incidence of inner surface flaws, namely 0.1 (flaw/round billet) or lower.
[0069] On the contrary, in Test Nos. A9-A16, the extent of superheating of the molten steel in the tundish and the intensity of electromagnetic stirring were varied in contrast to Test Nos. A1 to A8. As a result, the equiaxed crystal region diameter in the cast billet cross sectional axial central portion was smaller than 60 mm, failing to satisfy the relevant requirement defined in the first aspect of the invention. A large number of axial center cracks developed in each cast billet along grain boundaries of columnar crystals distributed around equiaxed crystals, and the mode of axial center cracks was as shown in Fig. 1 (b). The axial center crack lengths were much longer as compared with the examples of the present invention, namely Test Nos. A1 to A8.
[0070] Further, the hollow shells obtained by piercing/rolling these round billets showed a very high number of inner surface flaws, namely a value exceeding 15 (flaws/billet).
[0071] In Test Nos. A17 to A20, the intensity of electromagnetic stirring was especially increased, and the cast billet surface was slowly cooled at a rate exceeding 25˚C/minute by forced spray cooling using the final solidification stage secondary cooling device within the range in which the cast billet axial central portion solid phase fraction was above 0 and increased up to 1.0. As a result, the condition of filling with equiaxed crystals in the billet cross sectional axial central portion was improved and the mode of axial center cracks became as shown in Fig. 1 (a) but, as a result of forced cooling, axial center cracks extended.
Furthermore, the numbers of inner surface flaws in the hollow shells obtained by piercing/rolling these round billets, although smaller as compared with the numbers in Test Nos. A9 to A16, were higher when compared with the numbers

in Test Nos. A1 to A8, namely the examples according to the present invention.

2. Modes for carrying out the fourth aspect of the invention

2-1. Best modes for carrying out the fourth aspect of the invention

[0072] As described hereinabove, the fourth aspect of the invention is directed to a process for seamless pipe production, characterized by including a piercing/rolling step in which a round billet according to the second aspect of the invention is rotated and moved through a unit comprising a pair or cone-shaped inclined rolls disposed as opposed to each other along the pass line and a plug disposed in a space between the inclined rolls along the pass line, wherein the ratio of "roll diameter Dg (mm) at the inclined roll gorge portion" to "roll diameter D1 (mm) where roll-billet contacting starts at the inclined roll inlet", namely the ratio Dg/D1, and the ratio of "the number N of billet rotations from billet onset-engagement to plug tip" to "the billet outside diameter draft Df (%)", namely the ratio N/Df, satisfy the relation represented by one of the formulas (1) to (3) given hereinabove and, further, the ratio of the above-defined D1 to the billet outside diameter Bd (mm), namely the ratio D1/Bd, satisfies the relation represented by the formula (4) given hereinabove. In the following, the present invention in this aspect is described in more detail.

2-1-1. Interrelationships among main factors exerting influences on piercing/rolling

[0073] As a result of investigations made in search of a method of satisfying all the requirements with respect to the prevention of mis-rolling events, the prevention of inner surface flaws due to lowering of the temperature of the hollow shell top portion and the prevention of inner surface flaws due to excessive rotary forging effects over the whole length inclusive of the top portion, it was found that the ratio of the inlet roll diameter where the billet starts contacting with the inclined rolls to the roll diameter at the gorge portion of the inclined rolls, and the ratio of the number of billet rotations from billet onset-engagement to plug tip position to the billet outside diameter draft are very important factors.

[0074] Fig. 5 is a schematic representation of the condition under which a round billet is pierced/rolled by means of a pair of inclined rolls disposed as opposed to each other along the pass line and a plug disposed in a space between the rolls. In the figure, the inclined rolls 1 are disposed at a feed angle β of zero. The gorge portion 1a of each cone-shaped inclined roll 1 is located at the position in which an inlet surface 1b intersects with an outlet surface 1c of the inclined roll 1, where the space between the pair of the inclined rolls 1 and 1 is minimal. The roll gorge portion 1a has a roll diameter of Dg (mm). The inlet surface 1b of the inclined roll 1 may also have a sectional shape consisted of two or more slopes or a curved sectional shape.

[0075] Further, in the geometric two-dimensional plane shown in Fig. 5, the inclined roll diameter at the point A where the billet 3 starts contacting with the inclined roll inlet surface 1b is designated as inlet roll diameter D1 (mm). The distance parallel to the pass line X-X (distance along the pass line) from the same point A to the tip position of the plug 2 is designated as Ld (mm). The inclined roll gap at this plug tip position is designated as Rpg (mm), and the angle between the pass line X-X and the inclined roll inlet surface 1b is designated as $\theta 1$.

[0076] Then, when the outside diameter of the billet 3 is designated as Bd (mm) and the inclining angle of the feed rolls as β (°), the number N of billet rotations from onset-engagement to arrival at the plug tip and the billet outside diameter draft Df can be respectively represented by the formulas (5) and (6) given hereinabove.
Then, the present inventors prepared billets having an outside diameter of 70 mm or 60 mm, keeping the axial central portion therein, using cast billets made by continuous casting from 0.2% C steel material and subjected them to piercing/rolling under the conditions shown in Table 2, and examined the incidence of onset-engagement failure and other mis-rolling events and the occurrence or nonoccurrence of inner surface flaws.

[0077] Further, they carried out piercing/rolling tests while varying the billet outside diameter draft Df at the plug tip position and the number N of billet rotations from billet onset-engagement to the plug tip position, respectively calculated from the formulas mentioned above, as well as the roll shape. The relationships between the ratio of the roll diameter Dg at the roll gorge portion to the roll diameter D1 where roll-billet contacting starts, namely the ratio Dg/D1 (hereinafter also referred to as "roll diameter ratio Dg/D1" for short) and the ratio of the number N of billet rotations from billet onset-engagement to arrival at the plug tip and the billet outside diameter draft Df at the plug tip position, namely the ratio N/Df (hereinafter also referred to as "ratio N/Of between the number N of billet rotations and the billet outside diameter draft Df" for short) and, further, the ratio of the roll diameter D1 where the billet starts contacting with the roll at the inclined roll inlet (hereinafter also referred to as "inlet roll diameter D1" for short) and the billet outside diameter Bd, namely the ratio D1/Bd, are shown in Table 3.

[0078] [Table 2]

Table 2

Billet outside diameter: Bd(mm)	70, 60
Roll gorge diameter: Dg(mm)	280~410
Roll feed angle: β(˚)	6~16
Roll cross angle: γ(˚)	5~30
Dg/D1	1.05~1.9
N/Df	15~50
D1/Bd	1.9~5.1
Hollow shell outside diameter (mm) Hollow shell wall thickness (mm)	72, 62 8~10

[0079] [Table 3]

Table 3

Dg/D1		1.05	1.1	1.3	1.5	1.8	1.9
D1/Bd		5.1	4.5	4.0	3.0	2.5	1.9
N/Df	15	△	△	▲	▲	▲	×
	18	●	●	△	△	△	▲
	20	●	○	○	○	○	○
	23	○	○	○	○	○	○
	30	○	○	○	○	○	○
	35	○	○	○	○	○	○
	40	○	○	○	○	○	○
	44	●	○	○	○	○	○
	48	●	●	●	○	○	○
	50	●	●	●	●	●	○

[0080] As for the evaluation results shown in Table 3, the symbol o (circle) indicates that no inner surface flaws developed all over the length of the hollow shell and no mis-rolling occurred. The symbol ● indicates that inner surface flaws developed on the hollow shell. The symbol × indicates that mis-rolling occurred for more than 3 billets among 20 billets that were subjected to piercing/rolling. The symbol ▲ indicates that 2 or 3 billets were mis-rolled among 20 billets that were subjected to piercing/rolling, and the symbol △ indicates that one out of 20 billets that were subjected to piercing/rolling was mis-rolled.

[0081] The results shown in Table 3 revealed the following facts, making it possible to confirm the effects of the invention. Thus, in the range of low roll diameter ratio Dg/D1, inner surface flaws readily develop, whether the ratio N/Df between the number N of billet rotations and the billet outside diameter draft Df is low or high. In the range of high roll diameter ratio Dg/D1, the development of inner surface flaws can be inhibited but, when the ratio N/Df between the number N of billet rotations and the billet outside diameter draft Df is low, the rate of incidence of mis-rolling increases. Further, in the range of low ratio D1/Bd between the inlet roll diameter D1 and the billet outside diameter Bd , for example, the ratio is lower than 2.5, the billet onset-engagement condition becomes unstable, leading to frequent mis-rolling events.

[0082] The fourth aspect of the invention has been completed based on the above-mentioned findings and, as mentioned above, is directed to a process for seamless pipe production which comprises using the round billet according to the second aspect of the invention and includes a piercing/rolling step in which one of the relations represented by the formulas (1)-(3) is satisfied and, further, the requirement represented by the formula (4) is satisfied.

2-1-2. Reasons for preferred range limitation in the fourth aspect of the invention

[0083] The process for seamless pipe production according to the fourth aspect of the invention includes a piercing/rolling step in which one of the requirements represented by the formulas (1)-(3) given hereinabove is satisfied according to the range of the roll diameter ratio Dg/D1 so that the development of inner surface flaws may be inhibited all over the length of hollow shell, inclusive of the top portion. Generally, high roll diameter ratio Dg/D1 values are effective in inhibiting the development of inner surface flaws; however, the upper limit thereto is determined from the equipment restraints.

[0084] For example, when the roll diameter Dg at the roll gorge portion is increased, the equipment scale is to be enlarged and the equipment cost increases. When, on the other hand, the inlet roll diameter D1 at the inclined roll is reduced, such equipment problems as decreased bearing strengths on the inlet side of rolling arise and, at the same time, the ratio D1/Bd between the inlet roll diameter D1 and the billet outside diameter Bd decreases as the roll diameter ratio Dg/D1 increases and, as a result, the incidence of mis-rolling events tends to increase, as shown in Table 3 given above. Therefore, there is an upper limit to the roll diameter ratio Dg/D1 and, herein, the upper limit is set to 1.8.

[0085] In piercing/rolling by commercial mills, the operation is carried out employing a billet outside diameter draft Df in the range of 4-8% as an appropriate range. Therefore, in adapting the ratio N/Df between the number of billet rotations N on the occasion of onset-engagement and the billet outside diameter draft Df to one of the formulas (1)-(3) given hereinabove, it is preferred that the requirement as the outside diameter draft Df being 4-8% be further satisfied.

[0086] Further, the process for seamless pipe production according to the fourth aspect of the invention is characterized by including a piercing/rolling step in which the ratio D1/Bd between the inlet roll diameter D1 and the billet outside diameter Bd satisfies the relation represented by the formula (4) given below so that billet onset-engagement failure and other mis-rolling events may be inhibited. When the D1/Bd value is below the lower limit value, slipping, among others, occurs on the occasion of billet onset-engagement and an unstable onset-engagement condition is created. While no upper limit to D1/Bd is prescribed herein, the ratio is restricted from the equipment viewpoint; it is preferred that the ratio be not more than 6.5.

$$B1/Bd \geq 2.5 \qquad (4)$$

[0087] The process for seamless pipe production according to the fourth aspect of the invention is oriented to the use of cone-shaped inclined rolls. The reason why barrel-shaped inclined rolls are not used is that not only there arise differences in quality and efficiency but also the roll diameter ratio Dg/D1 in the case of barrel-shaped inclined rolls is limited to 1.03 or less and, for technical reasons as well, it is difficult to apply them to the production method according to the fourth aspect of the invention.

[0088] The production method according to the fourth aspect of the invention can produce remarkable effects not only upon continuously cast materials the billets made of which are readily susceptible to center segregation or center porosity formation but also upon stainless steel materials containing at least 5% of Cr and readily allowing δ ferrite formation, and further in the field of nonferrous materials, upon copper, copper alloys and the like that are poor in workability due to residual cast structures.

2-2. Examples in relation to the fourth aspect of the invention

[0089] For confirming the effects of the fourth aspect of the invention, hollow shells were produced by piercing/rolling, and the results thereof were examined.

[0090] Using a piercing/rolling machine having the configuration shown in Fig. 1 and Fig. 2 and using the round billets obtained in Test No. A1 according to the first aspect of the invention and the round billets obtained in Test No. A5, piercing/rolling tests were carried out under the conditions shown in Table 4. The steel composition comprised: C: 0.05-0.07%, Si: 0.05-0.3%, Mn: 1.2-1.5% and the round billets had an outside diameter of 310 mm or 360 mm.

[0091] [Table 4]

Table 4

Billet outside diameter: Bd(mm)	310, 360
Roll gorge diameter: Dg(mm)	1300~1450
Roll feed angle: β(°)	6~16
Hollow shell outside diameter (mm)	330, 370
Piercing ratio	1.6~3.5

[0092] The results of the hollow shell production by piercing/rolling are shown in Table 5. The symbol ◎ (double circle) in the column "Inner surface flaw development" indicates that the number of inner surface flaws per one meter length of hollow shell was at most 1, the symbol ○ (circle) indicates that at most three inner surface flaws developed per one meter length of hollow shell, and the symbol × indicates that more than 3 inner surface flaws developed per one meter length of hollow shell. The incidence (%) of mis-rolling events is indicated in terms of the percentage of the number of billets mis-rolled to the total number (20) of billets that were subjected to piercing/rolling under the respective roll setting and rolling conditions.

[0093] [Table 5]

Table 5

Test No.	Roll setting and rolling conditions									Test results	
	Bd (mm)	Ld (mm)	Roll diameter ratio			Formulas (1)-(3)			Formula (4)	Inner surface flaw development	Incidence of mis-rolling events (%)
			D1 (mm)	Dg (mm)	Dg/D1	N	Df (%)	N/ (Df/l00)	D1/Bd		
B1	310	178	1126	1450	1.29	1.3	6	21.7	3.63	◎	0
B2	310	178	1076	1400	1.30	2.6	6	43.3	3.47	◎	0
B3	310	118	1285	1400	1.09	1.4	6	23.3	4.15	◎	0
B4	360	234	925	1350	1.58	2.0	5	39.0	2.57	◎	0
B5	360	138	1135	1350	1.19	1.4	4	35.0	3.15	◎	0
B6	360	310	1254	1400	1.12	2.3	4	*57.5	4.05	×	0
B7	310	310	1080	1400	1.30	2.8	6	*46.7	3.48	×	0
B8	310	360	887	1300	1.47	1.9	5	38.0	*2.46	○	7
B9	310	360	854	1350	1.58	2.0	5	40.0	*2.37	○	20
(Note): The symbol * indicates that the ratio is outside the range prescribed in accordance with the fourth aspect of the invention.											

[0094] According to the results shown in Table 5, one of the requirements represented by the formulas (1)-(3) was satisfied according to the value of the roll diameter ratio Dg/D1 and, at the same time, the requirement of the formula (4) was also satisfied in Test Nos. B1-B5 and, therefore, no mis-rolling events occurred and the development of inner surface flaws could be completely inhibited all over the length of hollow shell.

[0095] On the other hand, in Test Nos. B6-B9, the requirement of one of the formulas (1)-(3) given above or the requirement of the formula (4) given above could not be satisfied and, as a result, hollow shell inner surface flaws developed or onset-engagement failure occurred.

3. Modes for carrying out the fifth to seventh aspects of the invention

3-1. Best modes for carrying out the fifth to seventh aspect of the invention

[0096] As described hereinabove, the fifth aspect of the invention is directed to a process for seamless pipe production which includes a piercing/rolling step in which a solid round billet having an outside diameter Bd as defined in the second aspect of the invention is pierced/rolled by an inclined roll type piercing/rolling machine using a plug consisting of: a front rolling section with a round column-like shape, having a constant outside diameter d over its axial length or increasing in outside diameter toward the rear end in an axial direction, which has an axial length L2 and the front face spherically formed with a curvature of radius r and an axial length L1; a work section abutting the rear end of the front rolling section, which is formed of a curvature of a circular arc with a radius R and an axial length L3 so as to increase in outside diameter thereof toward the rear end in an axial direction; and a reeling section abutting the rear end of the work section, which has a tapered round column-like shape so as to increase in outside diameter toward the maximum outside diameter D at the rear end in an axial direction and to have an axial length L4, wherein the plug outside diameter d, curvature radius R, axial lengths L1, L2 and L3 and the solid round billet outside diameter Bd satisfy all the relations represented by the formulas (7) to (9) given hereinabove.

[0097] When a plug comprised of the above front rolling section that has a tensile strength of 50 MPa or more at 1100˚C is used in the process for seamless pipe production just mentioned above, the requirement of the formula (10) given hereinabove should be satisfied instead of the requirement of the formula (7). In the following, the fifth to seventh aspects of the invention are described in further detail.

[0098] Fig. 8 is a representation illustrating the plug lead and the billet outside diameter draft at the plug tip in piercing/rolling of round billets. In describing the invention, the plug lead PL is the axial distance from the roll gorge 1a contact position in each cone-shaped inclined roll 1 to the plug 2 tip position. The "RO" in the same figure indicates the shortest distance between the inclined rolls 1, 1 at the position of the gorge 1a.

[0099] When, in Fig. 8, the setting is made so that the plug lead PL be small, the value defined by the formula (6) given above increases accordingly and, therefore, "the case where a short plug lead is selected" is synonymous with "the case where an increased billet outside diameter draft is selected", as mentioned above.

[0100] The present inventors have described that the conditions specified hereinabove under (e) and (f) should preferably be satisfied so that the effects of the present invention may be produced; it is more preferred, however, that the conditions mentioned below be further satisfied.

[0101] In the above-mentioned fifth and sixth aspects of the invention, it is not always necessary that the cylindrical portion, belonging to the front rolling section and having a diameter of d and an axial length of L2, remain constant in diameter over its length; taking into consideration the possibility of repeated re-machining and heat treatment for reuse, such section may have a tapered column-like shape the outside diameter d of which is increasing from the tip toward the rear end in an axial direction with a taper angle (half of the included taper angle) of 4° or less.

[0102] Further, the reeling section is a section disposed for the purpose of rendering wall thickness of pipe constant and no positive wall thickness processing is performed in this section. Therefore, it is preferred that the angle of the reeling section be substantially equal to the roll outlet-side face angle.

It is the plug front rolling section that is required to have a high-temperature strength as prescribed herein. To that end, it is effective that the material to be used for the plug front rolling section be separated and different from a base material to be used for the work section and reeling section.

[0103] Generally, a 0.5% Cr-1.5% Ni-3.0% W-containing steel is preferably used as the plug base material. A high strength steel containing W and Mo, a Nb-10% W-2.5% Zr type Nb alloy, or a Mo-0.5% Ti-0.08% Zr type Mo alloy is preferably used as the material for the front rolling section, since these can satisfy the high-temperature strength requirement to full extent. In this case, the base material preferably has a scale thickness within the range of 200 μm to 1000 μm from the viewpoints of the scale adhesion tightness and plug life.

[0104] Further, a material derived from the base material by forming a thick scale layer thereon can also be used as material for the front rolling section. Coating of the material surface by thick scale layer is effective in securing heat resistance and inhibiting meltdown wastage and, at the same time, a thick scale layer exerts a favorable effect on the lubricity in piercing/rolling.

3-2. Examples in relation to the fifth to seventh aspects of the invention

(Example 1)

[0105] In Example 1, the round cast billets produced in Test No. 1 in accordance with the first aspect of the invention were machined to prepare billets ready for pipe-making where the axial central portion is kept therein and having an outside diameter of 70 mm, and the billets were pierced/rolled to confirm the effects of the process for seamless pipe production according to the fifth aspect of the invention. Two types of plugs were prepared: a two-zone type plug shaped as shown in Fig. 3 and a plug shaped as shown in Fig. 4. Dimensions of these plugs were as shown in Table 6. Plug No. C8 was a two-zone type plug. The material of all the plugs was a 0.5% Cr-1.5% Mo-3.0% W type alloy steel.

[0106] [Table 6]

Table 6

Plug No.	Dimensions of Plug									d/Bd	$\frac{(d/2Bd)}{(R/L3)}$	$\frac{(L1+L2)}{d}$
	D	d	L1	L2	L3	L4	θ	r	R			
C1	60.0	14.4	3.6	6.9	68.0	45.0	4.0	9.0	206.8	0.21	0.034	0.73
C2	60.0	14.4	3.6	6.9	73.0	40.0	4.0	9.0	240.1	0.21	0.031	0.73
C3	60.0	15.0	7.5	5.0	66.0	45.0	4.0	7.5	195.3	0.21	0.036	0.83
C4	60.0	18.0	9.0	3.5	66.0	45.0	4.0	9.0	218.7	0.26	0.039	0.69
C5	60.0	26.0	13.0	3.5	62.0	45.0	4.0	13.0	283.3	*0.37	0.041	0.63
C6	60.0	18.0	9.0	3.5	51.0	60.0	4.0	9.0	128.5	0.26	*0.051	0.69
C7	60.0	10.0	5.0	28.0	45.5	45.0	4.0	5.0	80.1	0.14	0.041	*3.30
C8	60.0	-	5.6	-	72.9	45.0	4.0	9.0	262.0	-	-	-

(Note) : D, d, L1-L4, r and R are given in mm, and θ is given in degrees (°). The symbol * indicates that the parameter is outside the range prescribed in accordance with the fifth aspect of the invention.

[0107] Prepared as the inclined rolls (main rolls) of the piercing/rolling machine were cone type rolls each having a gorge portion outside diameter of 410 mm and, in a state of setting at a feed angle β of 0˚ and a cross angle γ to be mentioned later herein, showing 3.5˚ both in inlet-side face angle between the inlet-side face of the inclined roll and a straight line parallel to the pass line X-X and in outlet-side face angle between the outlet-side face of the inclined roll and a straight line parallel to the pass line X-X. The inlet-side diameter and outlet-side diameter of the inclined rolls were varied according to the cross angle γ (5˚, 10˚, 15˚) to be mentioned later herein.

[0108] The plug and inclined rolls mentioned above were mounted on a piercing/rolling machine, as shown in Fig. 5, and billets each of 70 mm in diameter were prepared from the round cast billet materials produced in the continuous casting step according to the first aspect of the invention, wherein the axial central portion of the round cast billet material is kept therein, the length of billet is 700 mm and a steel composition comprises C: 0.05-0.07%, Si: 0.05-0.3% and Mn: 1.2-1.5%. And then, billets were heated to 1250˚C and subjected to piercing/rolling tests to produce hollow shells having an outside diameter of 75 mm, a wall thickness of 6 mm and a length of 2100 mm.

[0109] In the piercing/rolling tests, the feed angle β of the main rolls was always set to 10˚, and the cross angle γ of the cone type inclined rolls was varied to 5˚, 10˚ or 15˚. The billet outside diameter draft Df at the plug tip was varied to five stages: 3%, 4%, 5%, 6% and 7%. Shown in Table 7 are the data concerning the shortest distance RO between the inclined rolls, the plug lead PL, and the gap Rpg between the inclined rolls at the plug tip position, as set on those occasions. The test results obtained then are shown in Table 8.

[0110] [Table 7]

Table 7

Billet outside diameter draft at plug tip position (%)														
3%			4%			5%			6%			7%		
RO	PL	Rpg	RO	PL	Rpg	RO	PL	Rpg	RO	PL	Rpg	RO	PL	Rpg
61.5	50.5	67.9	61.1	48.0	67.2	60.8	45.0	66.5	60.4	42.5	65.8	60.1	40.0	65.1
(Note): RO, PL and Rpg are given in mm.														

[0111] [Table 8]

Table 8

Cross ang le γ(˚)		5					10					15				
Df(%)		3	4	5	6	7	3	4	5	6	7	3	4	5	6	7
Plug No.	C1	◎	○	○	○	×	◎	◎	○	○	○	◎	◎	◎	○	○
	C2	◎	◎	○	○	×	◎	◎	○	○	○	◎	◎	◎	◎	○
	C3	◎	◎	○	○	×	◎	◎	◎	○	○	◎	◎	◎	◎	○
	C4	◎	○	○	○	×	◎	◎	○	○	○	◎	◎	◎	○	○
	*C5	W	W	W	M×	M×	W	W	W	M○	M×	W	W	W	M○	M×
	*C6	W	W	M○	M×	×	W	W	M○	M○	×	W	W	M○	M○	×
	*C7	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
	*C8	W	M○	×	×	×	W	M○	○	×	×	W	M◎	○	×	×

(Notes) :
The symbol ◎ indicates that no inner surface flaws developed.
The symbol ○ indicates that at most five trivial inner surface flaws developed.
The symbol × indicates that a large number, exceeding 5, of inner surface flaws developed.
The symbol M indicates that rolling was possible although there was some tendency toward insufficient billet onset-engagement.
The symbol W indicates that billet onset-engagement failure occurred, rendering further rolling impossible.
The symbol P indicates that the plug tip was damaged by meltdown wastage.
The symbol * indicates that the parameter was outside the range prescribed in the fifth aspect of the invention.

[0112] In those cases where the plugs Nos. C1 to C4 satisfying the conditions defined in the fifth aspect of the invention were used, no onset-engagement failure occurred at all even when the billet outside diameter draft Df at the plug tip position was lowered to 3%, and good-quality hollow shells showing no inner surface flaws or only a very small number of flaws were obtained.
On the contrary, in the cases where the plugs Nos. C5 and C6 and the 2-zone type plug No. C8, which failed to satisfy the conditions defined in the fifth aspect of the invention, were used, onset-engagement failures occurred in all cases when the billet outside diameter draft Df was 3%. When the plug No. C7 failing to meet the conditions defined in the fifth aspect of the invention was used, the plug tip position was damaged by meltdown wastage.
[0113] When the plugs satisfying the conditions defined in the fifth aspect of the invention were used and the inclined roll cross angle γ in the piercing/rolling machine was 5˚, the maximum value of the billet outside diameter draft Df at which no inner surface flaws developed at all was 3% and, by increasing the cross angle, it was possible to increase the upper limit of the billet outside diameter draft Df at which no inner surface flaws developed at all.
On the contrary, when the plugs failing to satisfy the conditions defined in the fifth aspect of the invention were used, the development of inner surface flaws could not be inhibited completely.

(Example 2)

[0114] In Example 2, the effects of the process for seamless pipe production according to the fifth to seventh aspects of the invention were verified by subjecting the billets obtained from round cast billet materials produced by the continuous casting method according to the first aspect of the invention to piercing/rolling tests using a piercing/rolling machine in actual use.
Round billets obtained from cast billet materials produced in Test No. A1 according to the first aspect of the invention and having an outside diameter of 310 mm, a length of 5600 mm and a steel composition of C: 0.05-0.07%, Si: 0.05-0.3% and Mn: 1.2-1.5% were heated to 1250˚C and then subjected to piercing/rolling tests to produce hollow shells having an outside diameter of 325 mm, a wall thickness of 48 mm and a length or 10000 mm.
[0115] Three kinds of plugs shaped as shown in Fig. 4 and a 2-zone plug as shown in Fig. 3 were prepared as the plugs to be used. Dimensions of these plugs were as shown in Table 9.
[0116] [Table 9]

Table 9

Plug No.	Dimensions of Plug									d/Bd	$\frac{(d/2Bd)}{(R/L3)}$	$\frac{(L1+L2)}{d}$
	D	d	L1	L2	L3	L4	θ	r	R			
C9	207.0	60.0	12.2	42.8	205.0	100.0	4.5	43.0	588.6	0.19	0.034	0.92
C10	207.0	-	17.0	-	243.0	100.0	4.5	35.0	604.3	-	-	-
C11	207.0	36.0	9.0	49.0	202.0	100.0	4.5	20.1	454.8	0.12	0.026	1.61
C12	207.0	34.0	17.0	34.0	209.0	100.0	4.5	17.0	476.7	0.11	0.024	1.50

(Note): D, d, L1-L4, r and R are given in mm, and θ is given in degrees (˚).

[0117] The data concerning the shortest distance RO between the inclined rolls, the plug lead PL, and the gap Rpg between the inclined rolls at the plug tip position, as set are shown in Table 10 and Table 11.

[0118] [Table 10]

Table 10

Billet outside diameter draft at plug tip position (%)														
2.0%			2.5%			3.0%			4.0%			5.0%		
RO	PL	Rpg	RO	PL	Rpg	RO	PL	Rpg	RO	PL	Rpg	RO	PL	Rpg
280.0	213.0	303.8	279.2	207.0	302.3	278.3	202.0	300.7	276.6	190.0	297.6	274.8	178.0	294.5
(Note): RO, PL and Rpg are given in mm.														

[0119] [Table 11]

Table 11

Billet outside diameter draft at plug tip position (%)					
6.0%			7.0%		
RO	PL	Rpg	RO	PL	Rpg
273.1	167.0	291.4	271.3	155.0	288.3
(Note): RO, PL and Rpg are given in mm.					

[0120] The inclined rolls in the piercing/rolling machine used in the tests had a gorge portion outside diameter of 1400 mm, and the cross angle γ was 20˚, the inlet-side face angle was 3˚ and the outlet-side face angle was 4˚. The billet outside diameter draft Df at the plug tip was varied to 7 stages within the range of 2.0-7.0%.

[0121] For all the plugs, except for each front rolling section, the base material was a 3.0% Cr-1.0% Ni type steel and had a tensile strength of 30 MPa at 1100˚C. The front rolling section materials and the physical properties thereof were as follows. For the plugs Nos. C9 and C10, a material derived from the 3.0% Cr-1.0% Ni steel base material by scale formation thereon was used. A material derived from a 0.5% Cr-1.5% Mo-3.0% W type alloy steel by scale formation thereon was used for the plug No. C11 and the plug No. C11-1, configured identical to No.C11, an Nb-10.0% W-2.5% Zr type Nb alloy for the plug No. C11-2, a material derived from a 0.5% Cr-1.5% Mo-3.0% W type alloy steel by scale formation thereon for the plug No. C12 and the plug No. C12-1, configured identical to No.C12, and a Mo-0.5% Ti-0.08% Zr type Mo alloy for the plug No. 12-2,configured identical to No.C12.

[0122] The composition of the material used for the front rolling section of each plug, the tensile strength tested at 1100˚C of each front rolling section and the scale thickness on each base material as measured are shown in Table 12. The scale forming treatment was carried out in the temperature range of 1000˚C to 1100˚C, and the scale thickness was adjusted by adjusting the treatment time. As for the structure of each plug, the front rolling section was a replaceable one.

[0123] [Table 12]

Table 12

Plug No.	Front rolling section material	Physical properties of plug		Piercing/rolling conditions (cross angle γ = 20˚)						
		Tensile strength (1000˚C) (MPa)	Scale thickness (μm)	Billet outside diameter draft Df (%)						
				2.0	2.5	3.0	4.0	5.0	6.0	7.0
C9	3Cr-Ni	30	500	-	M◎	○	○	×	-	-
C10	3Cr-Ni	30	500	-	-	-	W	M×	×	×
C11-1	0.5Cr-1.5Mo-3W	42	500	-	P	P	-	-	-	-
C11-2	Nb-10W-2.5Zr	84	-	◎	◎	○	-	-	-	-
C12-1	0.5Cr-1.5Mo-3W	42	1200	P	◎	○	-	-	-	-

(continued)

Plug No.	Front rolling section material	Physical properties of plug		Piercing/rolling conditions (cross angle γ = 20˚)						
		Tensile strength (1000˚C) (MPa)	Scale thickness (μm)	Billet outside diameter draft Df (%)						
				2.0	2.5	3.0	4.0	5.0	6.0	7.0
C12-2	Mo-0.5Ti-0.08Zr	96	-	◎	◎	○	-	-	-	-

(Notes) :
The symbol ◎ indicates that no inner surface flaws developed.
The symbol ○ indicates that at most five trivial inner surface flaws developed.
The symbol × indicates that a large number, exceeding 5, of inner surface flaws developed.
The symbol M indicates that rolling was possible although there was some tendency toward insufficient billet onset-engagement.
The symbol W indicates that billet onset-engagement failure occurred, rendering further rolling impossible.
The symbol P indicates that the plug tip was damaged by meltdown wastage.

[0124] The results shown in Table 12 revealed the following facts. When the plug No. C9 satisfying the conditions defined in the fifth aspect of the invention was used, rolling was possible even at a billet outside diameter draft Df of 2.5%, although there was some tendency toward insufficient billet onset-engagement; the development of inner surface flaws could be inhibited. On the contrary, when the plug No. C10, which was a conventional 2-zone type plug, was used, it was impossible to carry out rolling at a Df of 4.0% or less; the development of inner surface flaws could not be inhibited.

[0125] When the plugs Nos. C11-2 and C12-2 satisfying the conditions defined in the sixth aspect of the invention were used, it was possible to carry out piercing/rolling in a stable manner at a billet outside diameter draft Df of 2.5% or less and the development of inner surface flaws could be inhibited. On the contrary, when the plug No. C11-1 the front rolling section of which failed to meet the tensile strength (at 1100˚C) requirement defined in the sixth aspect of the invention and which had an ordinary scale thickness was used, the plug was damaged by meltdown wastage and it was impossible to inhibit the development of inner surface flaws.

[0126] When the plug No. C12-1, which had a thicker scale layer formed than a conventional one but the tensile strength of the plug front rolling section was less than 50 MPa, was used, the plug could be prevented from being damaged by meltdown wastage and the development of inner surface flaws could be inhibited. However, when such a plug was used at a billet outside diameter draft Df of 2.0%, the plug was damaged by meltdown wastage. The reason is that the decrease in Df resulted in a decrease in billet driving force and, as a result, the rolling time was prolonged.

INDUSTRIAL APPLICABILITY

[0127] The process for seamless pipe production according to the present invention, which comprises a continuous casting step in which round cast billet materials markedly reduced in axial center cracks acting as a factor causing hollow shell inner surface flaws can be cast and a piercing/rolling step in which hollow shells are produced by piercing/rolling using billets obtained from the round cast billet materials made in the above step, can produce both effects of preventing the mis-rolling events and inhibiting the development of hollow shell inner surface flaws and thus can produce high-quality products with a very low incidence of inner surface flaws with high productivity.

[0128] In particular, by piercing/rolling the round billets mentioned above under conditions in which the ratio of the number of billet rotations to the billet outside diameter draft is adjusted within an appropriate range depending on the ratio of the roll diameter at the inclined roll gorge portion to the inlet roll diameter at the inclined roll, a seamless pipe further reduced in the incidence of inner surface flaws can be produced without mis-rolling. Furthermore, by using, as a piercing plug, a suitably configured plug having a substantially round column-shaped front rolling section with a spherical tip face, it becomes possible to produce a seamless pipe much more improved in inner surface quality with no billet onset-engagement failure at all. Therefore, the process of the present invention can be widely applied as a process for producing a seamless pipe having good inner surface quality with high productivity.

Claims

1. A process for seamless pipe production, **characterized in that** the process includes a continuous casting step in

which a round billet material having a carbon content of not more than 0.1% by mass and having a cross-sectional diameter exceeding 300 mm is cast so that the whole of a central circular region, in terms of the billet cross section, which has a diameter of at least 60 mm may be constituted of an equiaxed crystal structure, while carrying out slow cooling the round billet material surface at a cooling rate of not more than 10˚C/minute during the period in which an axial central portion solid phase fraction is above 0 and increases up to 1.0.

2. The round billet material as cast by the continuous casting step according to claim 1, **characterized in that** axial center cracks occurring in an axial central portion of the billet material is restricted to a circular region with a radius not more than 15 mm from the center of the cross section.

3. A process for seamless pipe production, **characterized by** including a piercing/rolling step of a round billet obtained from the round billet material as cast according to claim 2, without going through a blooming/rolling step.

4. A process for seamless pipe production, **characterized by** including a piercing/rolling step in which a round billet obtained from the round billet material as cast according to claim 2 is rotated and moved through a unit comprising a pair or cone-shaped inclined rolls disposed as opposed to each other along the pass line and a plug disposed in a space between the inclined rolls along the pass line, wherein the ratio of the roll diameter Dg (mm) at the inclined roll gorge portion to the roll diameter D1 (mm) where roll-billet contacting starts at the inclined roll inlet, namely the ratio Dg/D1, and the ratio of the number N of billet rotations from the billet onset-engagement to the plug tip to the billet outside diameter draft Df (%), namely the ratio N/Df, satisfy the relation represented by one of the formulas (1) to (3) given below and, further, the ratio of the above-defined D1 to the billet outside diameter Bd (mm), namely the ratio D1/Bd, satisfies the relation represented by the formula (4) given below:

when $Dg/D1 < 1.1$,

$$23 \leq N/(Df/100) \leq 40 \quad (1);$$

when $1.1 \leq Dg/D1 < 1.5$,

$$20 \leq N/(Df/100) \leq 44 \quad (2);$$

when $1.5 \leq Dg/D1 \leq 1.8$,

$$20 \leq N/(Df/100) \leq 48 \quad (3);$$

$$D1/Bd \geq 2.5 \quad (4);$$

wherein, the distance Ld (mm) from billet onset-engagement to the plug tip along the pass line, the feed angle β (˚) of the inclined rolls and the inclined roll gap Rpg (mm) at the plug tip position satisfy the following formulas (5) and (6):

$$N = 2Ld/(\pi \cdot Bd \cdot \tan\beta) \quad (5);$$

$$Df = \{(Bd - Rpg)/Bd\} \times 100 \quad (6).$$

5. A process for seamless pipe production, **characterized by** including a piercing/rolling step in which a solid round billet with an outside diameter Bd (mm) obtained from the round billet material as cast according to claim 2 is pierced/rolled by an inclined roll type piercing/rolling machine using a plug consisting of: a front rolling section with a round column-like shape having a constant outside diameter d (mm) over its length or increasing in diameter toward the rear end in an axial direction, which has a length L2 (mm) in an axial direction and a front face spherically formed with a curvature of radius r (mm) and an axial length L1 (mm); a work section abutting the rear end of the front rolling section, which is formed of a curvature of a circular arc with a radius R (mm) and an axial length L3(mm)so as to increase in outside diameter thereof toward the rear end in an axial direction; and a reeling section abutting the rear end of the work section, which has a tapered round column-like shape with an included taper angle 2θ (°) and an axial length L4 (mm) so as to increase in outside diameter toward the maximum outside diameter D (mm) at the rear end in an axial direction, wherein the plug outside diameter d, curvature radius R, axial lengths L1, L2 and L3 and the solid round billet outside diameter Bd satisfy all the relations represented by the formulas (7) to (9) given below:

$$0.12 \leq d/Bd \leq 0.35 \qquad (7);$$

$$0.020 \leq (d/2Bd)/(R/L3) \leq 0.046 \qquad (8);$$

$$0.5d \leq L1 + L2 \leq 3d \qquad (9).$$

6. A process for seamless pipe production, **characterized by** including a piercing/rolling step in which the solid round billet with an outside diameter Bd (mm) obtained from the round billet material as cast according to claim 2 is pierced/rolled by an inclined roll type piercing/rolling machine using a plug consisting of: a front rolling section with a round column-like shape having a constant outside diameter d (mm) over its length in an axial direction or increasing in outside diameter toward the rear end in the axial direction, which has a length L2 (mm) in an axial direction and the front face spherically formed with a curvature of radius r (mm) and an axial length L1 (mm); a work section abutting the rear end of the front rolling section, which is formed of a curvature of a circular arc with a radius R (mm) and an axial length L3 (mm) so as to increase in outside diameter thereof toward the rear end in an axial direction; and a reeling section abutting the rear end of the work section, which has a tapered round column-like shape with an included taper angle 2θ (°) and an axial length L4 (mm) so as to increase in outside diameter toward the maximum outside diameter D (mm) at the rear end in an axial direction, wherein at least the front rolling section is made of material having a tensile strength of not less than 50 MPa at 1100°C, and wherein the plug outside diameter d, radius of curvature R, axial direction lengths L1, L2 and L3 and the solid round billet outside diameter Bd satisfy all the relations represented by the formulas (8) to (10) given below:

$$0.06 \leq d/Bd \leq 0.12 \qquad (10);$$

$$0.020 \leq (d/2Bd)/(R/L3) \leq 0.046 \qquad (8);$$

$$0.5d \leq L1 + L2 \leq 3d \qquad (9).$$

7. The process for seamless pipe production according to claim 6, **characterized in that** the front rolling section of the plug is replaceable.

FIG. 1

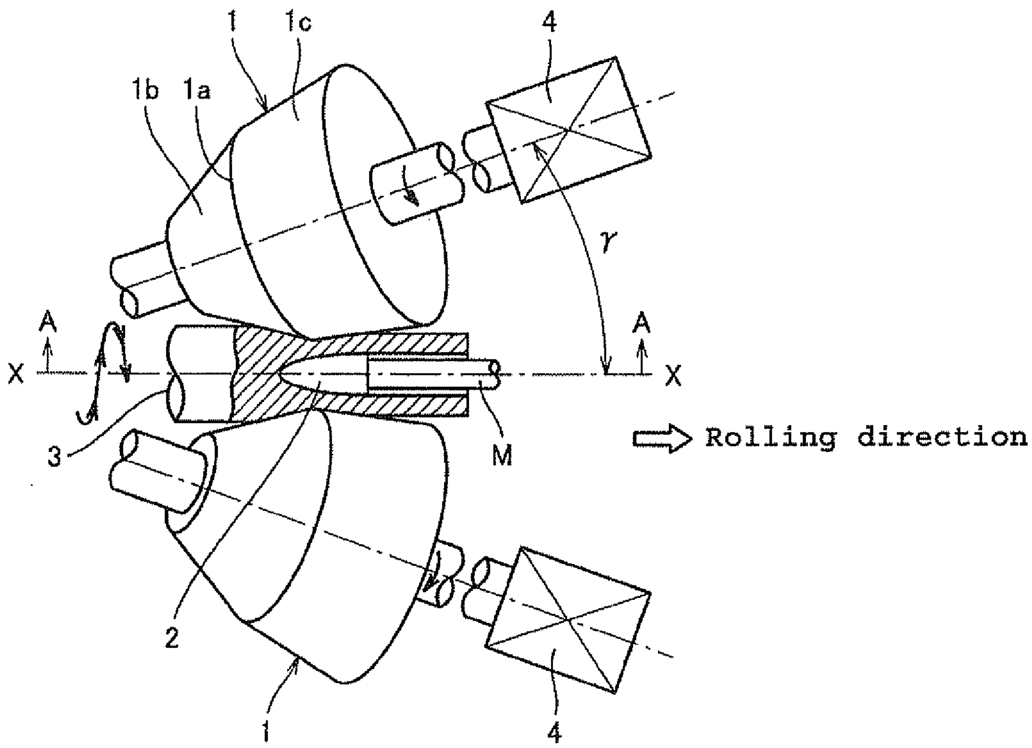

1
1c
4
1b
1a
γ
A
A
X
X
3
M
Rolling direction
2
1
4

FIG. 2

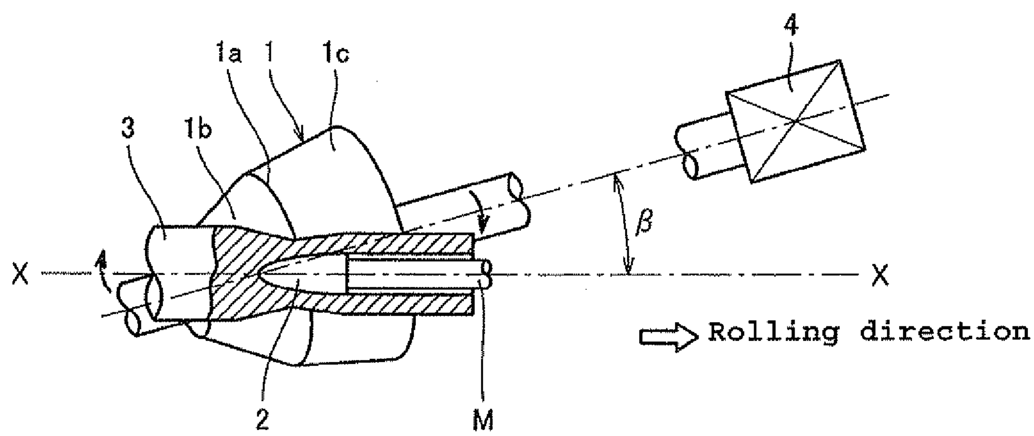

4
1a
1
1c
3
1b
β
X
X
Rolling direction
2
M

FIG. 3

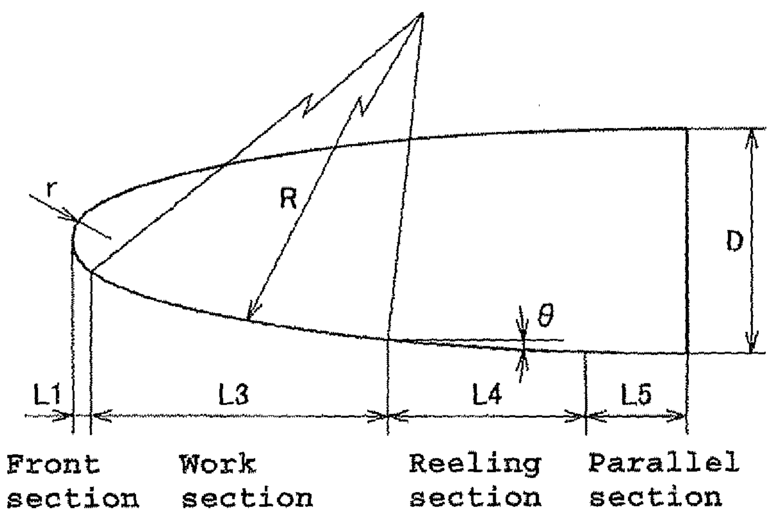

r
R
D
θ
L1
L3
L4
L5
Front section
Work section
Reeling section
Parallel section

FIG. 4

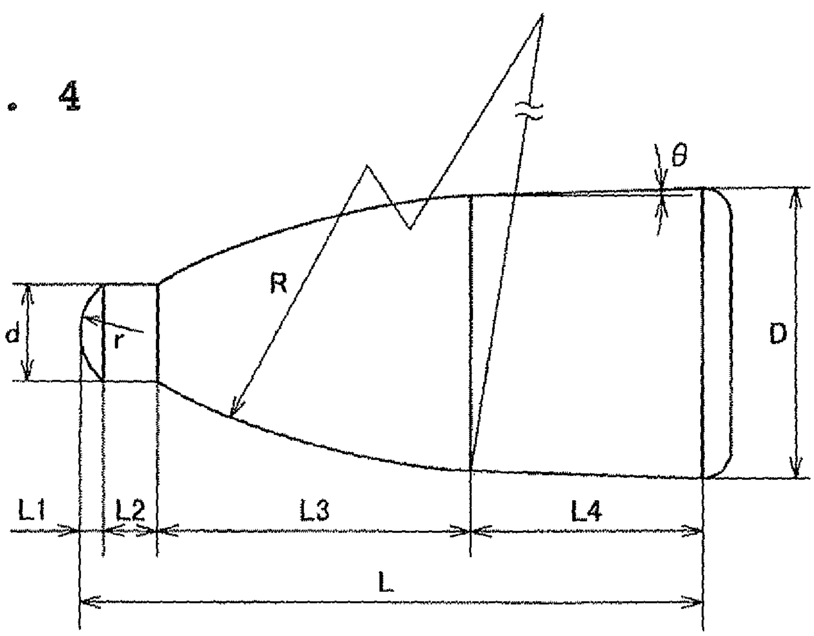

θ
R
d
r
D
L1
L2
L3
L4
L

FIG. 5

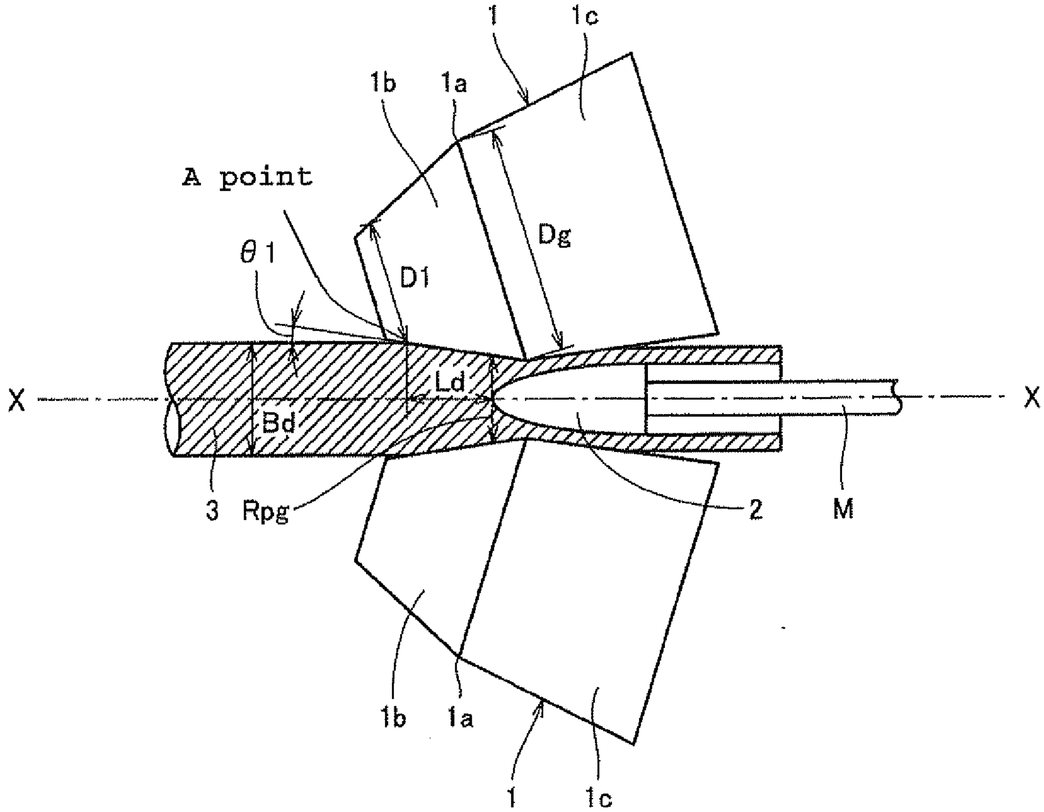
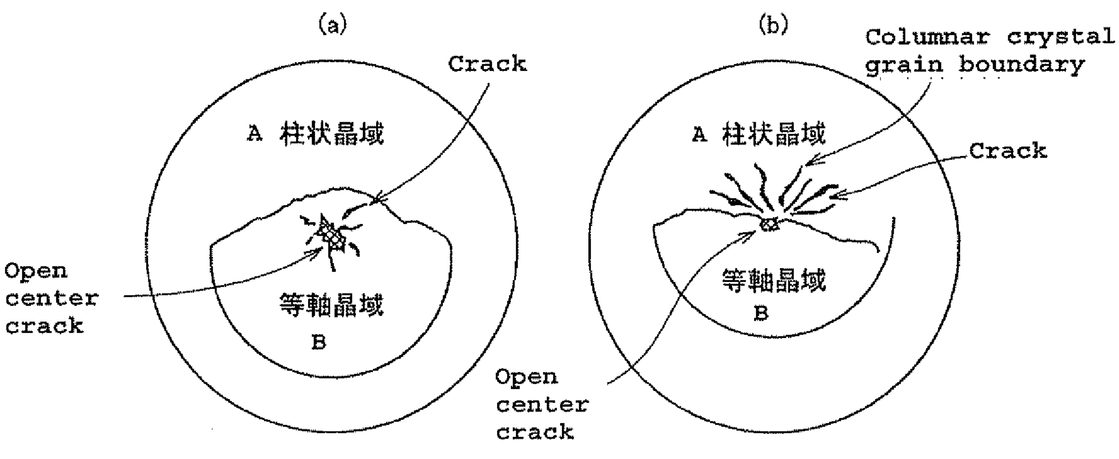


FIG. 6



A: Columnar crystal region
B: Equiaxed crystal region

A: Columnar crystal region
B: Equiaxed crystal region

FIG. 7

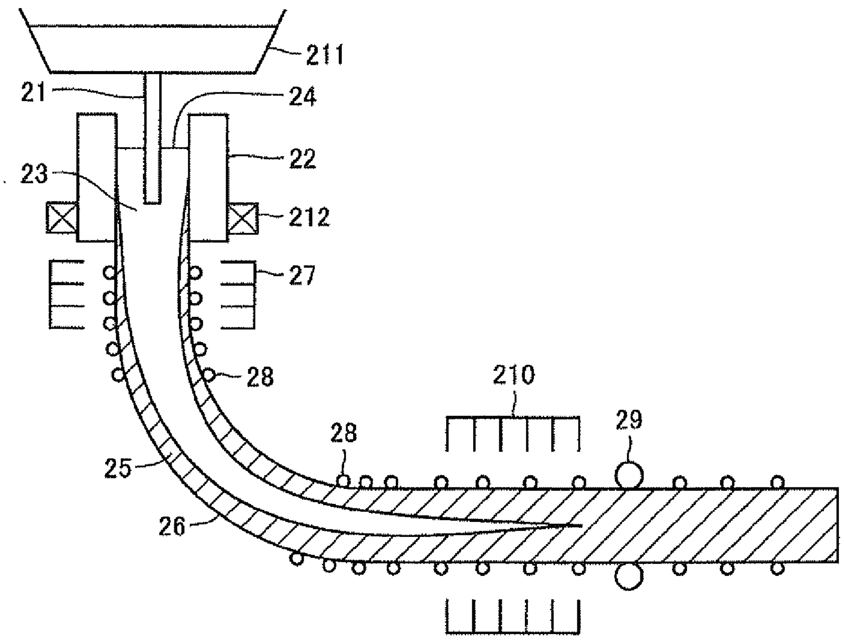
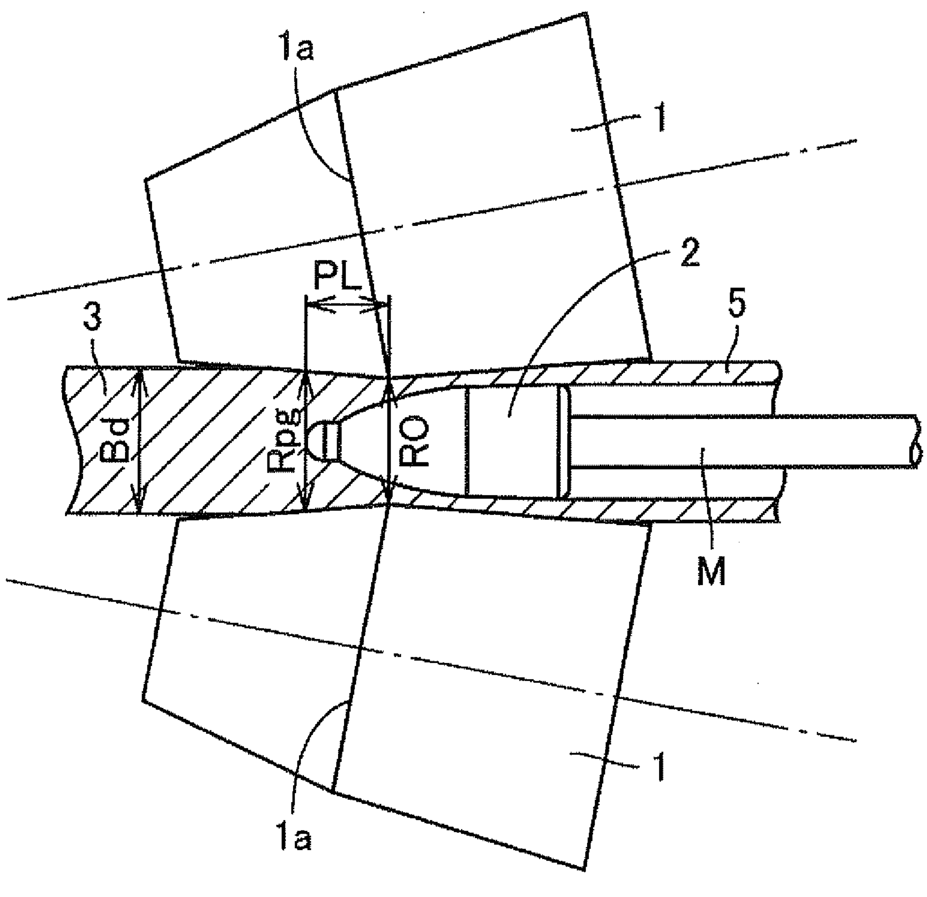


FIG. 8



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2006/306275

A. CLASSIFICATION OF SUBJECT MATTER
B21B19/04(2006.01), ***B22D11/00***(2006.01), ***B22D11/124***(2006.01), ***B22D27/04***(2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B21B19/04(2006.01), ***B22D11/00***(2006.01), ***B22D11/124***(2006.01), ***B22D27/04***(2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2006
Kokai Jitsuyo Shinan Koho	1971-2006	Toroku Jitsuyo Shinan Koho	1994-2006

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 8-332556 A (Sumitomo Metal Industries, Ltd.), 17 December, 1996 (17.12.96), Column 1, lines 1 to 20; column 2, lines 25 to 35; Fig. 2 (Family: none)	1-7
Y	JP 2002-361304 A (Sumitomo Metal Industries, Ltd.), 17 December, 2002 (17.12.02), Column 5, lines 16 to 19 (Family: none)	1-7

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
01 June, 2006 (01.06.06)	13 June, 2006 (13.06.06)

Name and mailing address of the ISA/	Authorized officer
Japanese Patent Office	
Facsimile No.	Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2006/306275

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2004/103593 A1 (Sumitomo Metal Industries, Ltd.), 02 December, 2004 (02.12.04), Claims & US 2006/65032 A1 & EP 1637244 A1	4
Y	WO 2004/052569 A1 (Sumitomo Metal Industries, Ltd.), 24 June, 2004 (24.06.04), Claims & US 2005/210944 A1 & EP 1593441 A1 & AU 2003/289244 A1 & BR 2003/17277 A	5-7
E,X	JP 2006-95565 A (Sumitomo Metal Industries, Ltd.), 13 April, 2006 (13.04.06), Claims (Family: none)	1-3

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- JP 2004330252 A **[0007]**
- JP 3013222 A **[0016] [0017] [0017]**
- JP 61003605 A **[0016] [0017]**
- JP 2000140911 A **[0016] [0017]**