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# (54) METHOD OF CONTINUOUS STEEL CASTING

(57) A continuous casting method of steel is provided that can reduce segregation and center porosity by causing a slab to undergo impact vibration under optimum conditions. In the continuous casting method of steel in which a slab having a rectangular cross section is cast while causing vibration in the slab with liquid core by disposing impact-vibration equipments on both short side surfaces of slab and continuously impacting those surfaces, the method includes the steps of: adjusting a vibration energy, a distance between shafts of adjacent guide rolls and a liquid core thickness, so that, among intersections generated by the impacting of the short side surface, between a curve of displacement δ(x) of the long side slab surface in a slab thickness-wise direction as defined by the following formulas (1) and (2) and a straight line δ(x) = 0.10 mm, a distance from an impact position of the intersection farther away from the coordinate origin is at least 200 mm; and impacting the short side,

$$\delta(x) = \exp[-1.5 \times \{\ln(x/(200\times(\Delta R/\Delta R_0)^{0.587}))\}^2] \times \delta max \qquad (1)$$

$$\delta max = L_0 \times (E/E_0)^{0.5} \times (\Delta R/\Delta R_0) \times (t/t_0)^{0.446} \qquad (2).$$

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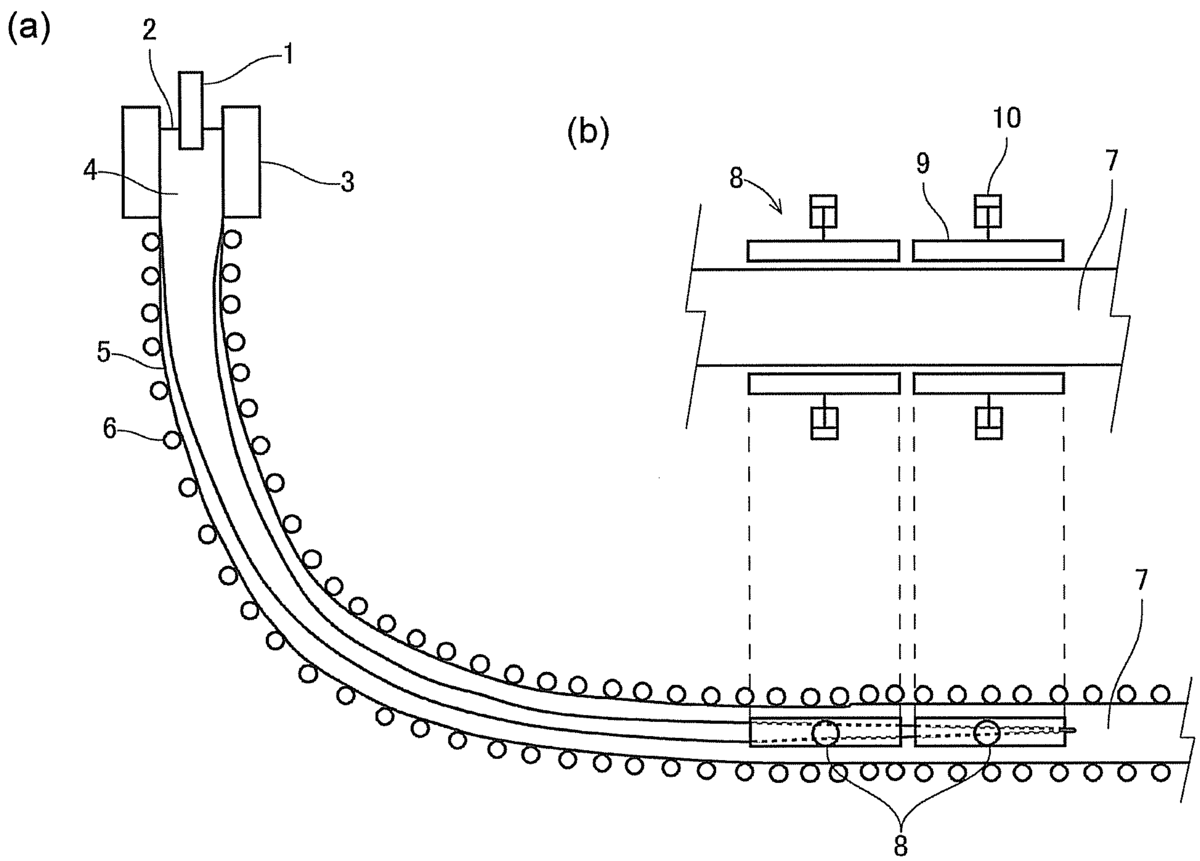
FIG. 1



## Description

TECHNICAL FIELD

**[0001]** The present invention relates to a continuous casting method of steel that casts while causing vibration in a slab by impacting a specific surface of the slab in a state containing a liquid core.

BACKGROUND ART

**[0002]** Internal defects that are macro segregation, called center segregation, V shape segregation or inverse V shape segregation, easily form in the central portion in a thickness-wise direction and in the vicinity thereof for the slab that is cast by continuous casting. Center segregation is an internal defect appearing due to solute elements that easily segregate (hereinafter also referred to as "segregation elements"), such as C, S, P, and Mn, enriching in the crater end of a slab, and V shape segregation and inverse V shape segregation are internal defects appearing due to these segregation elements enriching in the vicinity of the crater end of the slab in a V shape or inverse V shape.

**[0003]** In a product that is made by hot processing such a slab including these macro segregations, a decline in toughness, hydrogen induced cracking, and the like easily occur, and additionally, cracks easily occur when producing a final product by cold-rolling such product.

**[0004]** The mechanism of formation of segregation in a slab is considered to be as follows. Specifically, as solidification proceeds, segregation elements enrich between dendrite arms of columnar dendrite, which are a solidification structure. Molten steel in which these segregation elements have been enriched (hereinafter also referred to as "solute-enriched molten steel") oozes from between dendrite arms of columnar dendrite due to the amount of solidification contraction during solidification, swelling of the slab called bulging, or the like. The solute-enriched molten steel thus oozed flows toward the crater end of the slab to solidify in an as-is condition, thereby forming a region enriched with segregation elements. The region enriched with segregation elements formed in this way is segregation.

**[0005]** Preventing the movement of the solute-enriched molten steel remaining between dendrite arms of columnar dendrite, preventing this solute-enriched molten steel from concentrating locally, and the like are effective as segregation preventative measures for casting slabs, and various methods have been proposed thus far.

**[0006]** Then, in Patent Literature 1, the present inventors proposed a continuous casting method of steel, when casting a slab with a rectangular cross section, that casts while causing vibration in the slab by continuously impacting the short side of the rectangular thereof, using impact-vibration equipment disposed in at least one location on said short side, the slab including a liquid core having a solid fraction of 0.1 to 0.9 at the central portion in a thickness-wise direction.

**[0007]** In addition, in Patent Literature 2, the present inventors proposed a continuous casting method of steel, when performing reduction rolling along the withdrawing direction for a slab with a rectangular cross section, the slab containing a liquid core, with a plurality of pairs of guide rolls to be used for reduction rolling, is cast while causing vibration in the slab under rolling by continuously impacting at least one location on the slab surface within a region where reduction rolling is performed along the withdrawing direction.

**[0008]** According to these methods, a columnar dendrite at the stage of growth is made to break by impact vibration on a slab, whereby it is possible to prevent the generation of columnar dendrite. Furthermore, cavities/spaces are generated after bridging emerges in equiaxed structure, and, segregation is caused inside the cavities/spaces; however, these cavities are broken by impacting. As a result, the equiaxed structure is grown in high-density, and thus solute-enriched molten steel can be made to disperse finely between solidified grains, and the segregation such as center segregation, V shape segregation and inverse V shape segregation is reduced, whereby it is possible to obtain a slab with good internal quality.

CITATION LIST

PATENT LITERATURE

**[0009]**

PATENT LITERATURE 1: Japanese Patent No. 3835185
PATENT LITERATURE 2: Japanese Patent Application Publication No. 2003-334641

## SUMMARY OF INVENTION

### TECHNICAL PROBLEM

**[0010]** As an internal defect besides segregation, there is center porosity. Center porosity represents fine pores generated around width-wise end portions in the central portion in a thickness-wise direction thereof that is the final solidification point, due to solidification contraction while molten steel solidifies in continuous casting and due to thermal shrinking by cooling after solidification. It has been demanded to reduce segregation as well as center porosity in order to enhance the internal quality of cast slabs. In addition, it has been demanded to establish suitable vibration conditions by investigating the detailed relationship between the vibration conditions of the slab by impacting and the quality in the central portion of the slab, to improve the efficiency of continuous casting.

**[0011]** The present invention was made in view of the above-mentioned problems, and the object thereof is to provide a continuous casting method of steel that can efficiently obtain slabs with good internal quality without segregation and/or center porosity, by impacting a slab under suitable conditions to cause vibration therein.

### SOLUTION TO PROBLEM

**[0012]** The present inventors have studied continuous casting methods of steel for efficiently obtaining slabs with good internal quality without segregation and/or center porosity, and obtained findings in the following (A) and (B).

**[0013]** (A) In impacting a slab with liquid core at one position on the short side slab surface of the rectangular cross-section thereof, if a region in which the incurred-displacement of the slab in a thickness-wise direction thereof is at least 0.10 mm, and a maximum distance of such region in a normal direction to the short side, i.e. slab width-wise direction, is at least 200 mm away from the impact position, segregation inside the slab can be reduced.

**[0014]** (B) The incurred-displacement of the slab in a thickness-wise direction due to impacting varies depending on the distance between shafts of adjacent guide rolls, the impact energy, and the thickness of the liquid core at the impact position of the slab.

**[0015]** The present invention was accomplished based on the above-mentioned findings, and consists in a continuous casting method of steel according to the following first and second aspects.

**[0016]** According to a first aspect, in a continuous casting method of steel, when a slab having a rectangular cross section is cast while causing vibration in the slab with liquid core by disposing at least one pair of impact-vibration equipments on both short side surfaces of slab and continuously impacting those surfaces, the method is characterized in that: a vibration energy, a distance between shafts of adjacent guide rolls and a liquid core thickness are adjusted, so that the impacting of the short side surface causes a curve of displacement δ(x) of the long side slab surface in a slab thickness-wise direction as defined by the following formulas (1) and (2) to intersect a straight line δ(x) = 0.10 mm at two locations, and a distance of the intersection farther away from the coordinate origin in a slab width-wise direction, representing the distance from an impact position at the short side of the slab, is at least 200 mm; and the short side is impacted.

$$\delta(x) = \exp[-1.5 \times \{\ln(x/(200\times(\Delta R/\Delta R_0)^{0.587}))\}^2] \times \delta\max \qquad (1)$$

$$\delta\max = L_0 \times (E/E_0)^{0.5} \times (\Delta R/\Delta R_0) \times (t/t_0)^{0.446} \qquad (2)$$

Herein, each symbol in formulas (1) and (2) designates as follows:

x is a distance (mm) in a slab width-wise direction with the impact position on the short side of slab being 0,
δ(x) is a displacement (mm) of slab surface in a slab thickness-wise direction at the position x,
δmax is the maximum displacement (mm) in a slab thickness-wise direction,
ΔR is a distance between shafts of adjacent guide rolls (mm) at the position where impacting the short side,
E is impact energy per side per segment (J), and
t is a liquid core thickness of the slab at the impact position on the short side of the slab (mm),
wherein $E_0$ is 39 (J), $\Delta R_0$ is 245 (mm), $t_0$ is 26 (mm), and $L_0$ is 0.114 (mm).

**[0017]** According to a second aspect, in the continuous casting method of steel as described in the first aspect, by employing the same time phase in cyclically impacting opposing left and right short sides of the slab, the displacements δ(x) generated by impacting the left and right short sides, respectively, are combined with each other, and the resultant displacement δ(x) thus combined is at least 0.10 mm over the entire width of the slab at the impact positions.

ADVANTAGEOUS EFFECTS OF INVENTION

**[0018]** According to the present invention, since vibration having the displacement of the slab long side surface, caused by impacting the slab short side, of at least 0.10 mm can be generated over a wide range of the slab, segregation and/or center porosity is reduced, whereby a slab excelling in internal quality can be obtained.

BRIEF DESCRIPTION OF DRAWINGS

**[0019]**

FIG. 1 is a view showing a continuous casting machine that can adopt a continuous casting method of the present invention and a layout of impact-vibration equipment, with (a) showing a side view of the continuous casting machine, and (b) showing a plan view of a portion in which the impact-vibration equipment of the continuous casting machine is installed;
FIG. 2 is a cross sectional view of a slab, showing sampling positions of specimens for calculating specific volume of center porosity;
FIG. 3 is a graph showing a relationship between impact energy per side per segment and the reduction in specific volume of center porosity in a width-wise end portion of slab;
FIG. 4 is a schematic view of a vibration model according to the impact of a slab with a liquid core portion, with (a) showing a plan view, and (b) showing a view from the withdrawing direction;
FIG. 5 is a graph showing a relationship between a distance from a short side impact position and displacement of the slab long side surface in a thickness-wise direction;
FIG. 6 is a graph showing a relationship between the maximum displacement δmax in a thickness-wise direction of slab and the reduction in specific volume of center porosity, - $\Delta Vp$;
FIG. 7 is a graph showing a relationship between the impact energy per side per segment and the reachable distance of vibration;
FIG. 8 is a graph showing a relationship between the impact energy per side per segment and the reachable distance of vibration, and showing the influence of the distance between shafts of adjacent guide rolls; and
FIG. 9 is a graph showing the influence of impacting each short side surface which is a width-wise end of slab.

DESCRIPTION OF EMBODIMENTS

**[0020]** Hereinafter, reasons for specifying the method of the present invention as above and preferred embodiments of the method of the present invention will be explained.
**[0021]** The present inventors have analyzed on the effects of vibrations by performing continuous casting experiments while causing vibrations in a slab by impacting, thereby investigating the influence of vibrations on the internal quality of a slab, as described below.

1. Relationship between Slab Internal Quality and Impact Energy

1-1. Casting Experimental Conditions

**[0022]** FIG. 1 is a view showing a continuous casting machine that can adopt a continuous casting method of the present invention and a layout of impact-vibration equipment, with (a) showing a side view of the continuous casting machine, and (b) showing a plan view of a portion in which the impact-vibration equipment of the continuous casting machine is installed. The continuous casting machine shown in the same figure is of vertical bending type, and includes impact-vibration equipment for the casting slab.
**[0023]** Molten steel 4 poured from a tundish (not illustrated) into a mold 3 via an immersion nozzle 1 is cooled by the mold 3 and a water spray injected from secondary cooling spray nozzles (not illustrated) below thereof, whereby a solidified shell 5 is formed to be a slab 7. With liquid core remaining inside thereof, the slab 7 is withdrawn while being supported by guide rolls 6. The meniscus, which is a surface 2 of the molten steel 4, is shown in the mold 3 of FIG. 1. The guide rolls 6 are grouped into a plurality of segments and disposed (not illustrated).
**[0024]** Then, two pairs of impact-vibration equipments 8 are installed at a downstream site of the guide rolls 6 relative to the withdrawing direction, each pair being arranged in each segment composed of guide rolls, to impact the short sides of the slab 7. Each impact-vibration equipment 8 has a drive mechanism 10 and an impact effecting block 9

mounted to a leading end portion thereof.

**[0025]** In the present continuous casting experiments, a mold for a slab having a thickness of 300 mm was used as the mold 3. In order to examine the influence of impact vibration along a width-wise direction, a wider width slab of 2300 mm in width was used as the slab 7.

**[0026]** A steel grade of the following chemical composition for use in thick plates was adopted in the casting experiments. Specifically, it was a steel grade including, by mass, 0.05 to 1.00% of carbon, 0.04 to 0.60% of silicon, 0.50 to 2.00% of manganese, not more than 0.020% of phosphorus, and not more than 0.006% of sulfur, the remainder being iron and unavoidable impurities.

**[0027]** The casting velocity was set to 0.58 to 0.61 m/min, and the amount of secondary cooling water was set to 0.62 to 0.73 litter/kg-steel. The average temperature of the molten steel in the tundish was kept substantially constant with a superheat $\Delta T$ in the range of 30 to 50°C. $\Delta T$ is the difference between the actual molten steel temperature and the liquidus temperature of the molten steel.

**[0028]** The two pairs of impact-vibration equipments 8 were, respectively, disposed at positions of 22.5 m and 24.0 m downstream from the meniscus 2 in the mold 3 relative to the withdrawing direction, respectively, with each lengthwise mid point of the impact effecting block 9 along the withdrawing direction being used as a measured point. For the impact effecting blocks 9 of the impact-vibration equipments 8, the length of an impact effecting surface along the withdrawing direction was 1155 mm, the height in a vertical direction was 135 mm, and the mass was 500 kg. An air cylinder equipment was employed in the drive mechanism 10 of the impact-vibration equipments 8. The frequency of the impact vibration on the short sides of the slab 7 was set to 4 to 6 Hz, i.e. 4 to 6 times of impacting per second.

**[0029]** By impacting the short side of the slab, columnar dendrite at the stage of growth are made to break, which can prevent the generation of the columnar dendrite. Furthermore, after bridging occurs in equiaxed structure, cavities/ spaces generate, thereby causing segregation in the cavities. However, these cavities are destroyed by the impacting. As a result, abundant equiaxed structure is produced in a high-density, and thus solute-enriched molten steel can be made to disperse fmely between solidified discrete grains, and the segregation and/or center porosity can be reduced.

**[0030]** The solid fraction at the central portion in a thickness-wise direction of the slab 7 was calculated from the uni-directional heat transfer calculation in a thickness-wise direction of slab with the casting velocity and the amount of secondary cooling water being as main parameters, and based on the result thereof, the conditions for achieving a predetermined solid fraction at the central portion in a thickness-wise direction at an impacting position were obtained. Then, continuous casting was performed at the conditions while impacting the short sides of the rectangular slab.

1-2 Estimation of Internal Quality of Slab

**[0031]** Estimation of the internal quality of the slab obtained by the continuous casting performed while impacting short sides of the rectangular slab was carried out by estimating the status of the center porosity generation.

1-2-1 Estimation method of generation status of center porosity

**[0032]** The generation status of the center porosity was estimated by the following method. Taking into consideration the accuracy of the measurement of specific gravity, the specimen for calculation of the specific volume of center porosity sampled from a slab was made a rectangular solid with a length of 50 mm (thickness-wise direction of slab), width of 100 mm (width-wise direction of slab), and thickness of 7 mm (withdrawing direction of slab), and the surface finish was made based on JIS Standard for Surface Roughness to the surface roughness represented by triangle mark ∇ ∇ ∇: maximum surface roughness of 3.2 $\mu$m. The generation status of the center porosity was estimated from the specific volume of the center porosity calculated from the density at the central portion in a thickness-wise direction, while the density at a position of one-fourth of the thickness in a thickness-wise direction (hereinafter also referred to as "one-fourth thickness position") from the surface of the slab being a reference since no significant generation of center porosity should occur there. The specific volume of center porosity Vp was defined by the following formula (1) using the average density $\rho_0$ at the one-fourth thickness position and the average density $\rho$ in the central portion in a thickness-wise direction.

$$Vp \equiv 1/\rho - 1/\rho_0 \qquad (1)$$

**[0033]** FIG. 2 is a cross sectional view of a slab, showing sampling positions of specimens for calculating specific volume of center porosity. A region representing a width-wise end portion in the cross section being normal to the withdrawing direction of the slab, is fragmentarily shown in FIG. 2. The average density $\rho_0$ at the one-fourth thickness position of the slab was calculated by collecting a specimen 7a at one location in each width-wise end portion of slab, totaling two, and measuring and averaging the respective densities. The average density $\rho$ in the central portion in a thickness-wise direction was calculated by collecting specimen 7b, 7c and 7d at three locations in a width-wise end portion of slab, totaling six, and measuring and averaging the respective densities. The sampling positions are nearby the short side of slab, wherein positions at which the specimen 7a to 7d were collected were such that specimens 7a and 7b are 190 mm away from the short side of slab, specimens 7c being 320 mm therefrom, and specimen 7d being 425 mm therefrom, which represents the distance from each length-wise center of the specimen to the short side of slab, respectively.

**[0034]** Then, based on the specific volume of center porosity $Vp_0$ of a slab free of impacting and the specific volume of center porosity $Vp_1$ of a slab subjected to impacting, the reduction in specific volume of center porosity, $-\Delta V_p$, was defined by the following formula (2).

$$-\Delta Vp \equiv Vp_0 - Vp_1 \qquad (2)$$

1-2-2 Estimation results of generation status of center porosity

**[0035]** FIG. 3 is a graph showing a relationship between impact energy per side per segment and the reduction in specific volume of center porosity in a width-wise end portion of slab. In the same graph, the reduction in specific volume of center porosity, $-\Delta Vp$, was calculated for each slab subjected to impacting with different impact energies, and plotted. From the relationship shown in the same graph, a relationship was confirmed in which the specific volume of the center porosity reduces at a slab width-wise end portion of the slab when the impact energy E per side per segment exceeded 25 J. When calculating the regression equation for the relationship between the impact energy E per side per segment and the reduction in specific volume of center porosity, $-\Delta Vp$, in the same graph, the following formula (3) was yielded.

$$-\Delta Vp\ [cm^3/g] = 0.0049347 \times E\ [J] - 1.297487 \qquad (3)$$

**[0036]** Then, obtained from FIG. 3 is the finding that a reducing effect on the center porosity in the level of $-\Delta Vp = 0.57 \times 10^{-4} cm^3/g$ in terms of specific volume of center porosity is obtained when the impact energy E is 39 J. In addition, as a result of observation of the macro structure, a trend was recognized of the granular segregation being less for the slab subjected to impacting than the slab free of impacting.

2. Generalization of Relationship between Internal Quality of Slab and Impact Energy

**[0037]** Based on the above finding, the present inventors further studied generalization of the above-mentioned result relating to impacting the short sides of the rectangular cross sectional slab.

**[0038]** FIG. 4 is a schematic view of a vibration model according to the impact of a slab with a liquid core portion, with (a) showing a plan view, and (b) showing a view from the withdrawing direction. In the same figure, the solidified shell 5 of the slab 7 is in a state of being restrained by the guide rolls 6. In this state, the short sides of the slab 7 are impacted by the impact-vibration equipment 8.

**[0039]** The shape of the impact effecting block 9 of the impact-vibration equipment 8 was made in the form of a rectangular solid with a length a of 1200 to 1600 mm along the withdrawing direction, a thickness c of 140 mm, and a width b of 200 mm in a slab thickness-wise direction. In addition, the slab 7 measures a width of 2300 mm and a thickness of 300 mm. Using such a three-dimensional model, numerical analysis was performed for displacement of the impacting surface (long side surface) of the slab 7 by vibration.

**[0040]** The present inventors obtained from the numerical analysis results of the surface displacement of the slab 7 incurred by impact vibration such that the maximum displacement $\delta max$ of the slab in a thickness-wise direction was substantially equal to the value $\delta_{x=200\ mm}$ at a position of 200 mm, in a normal direction to the short side (i.e., slab width-wise direction), away from the impact position at the short side.

**[0041]** In addition, the present inventors found that, according to past studies on the relationship between the variable range L of displacement at a position on the interface between liquidus and solidus and several factors having an effect thereon, the variable range L of displacement within the vibration region is adjusted by the impact energy E caused by the impact effecting block, and that the relationship thereof can be described by the following formula (a) Hereinafter, each symbol with subscript 0 indicates a representative condition.

$$L/L_0 = (E/E_0)^{0.5} \quad (a)$$

**[0042]** Furthermore, it was found that the influences on the variable range of displacement by the distance ΔR between shafts of adjacent guide rolls and the liquid core thickness t of the slab at the impact position on the short side of the slab can be adjusted independently, and the variable range of displacement of the long side surface in a slab thickness-wise direction at a position 200 mm, in a normal direction to the short side, from the impact position at the short side changes substantially in direct proportion to ΔR. Based on this knowledge, the following formula (b) extended from formula (a) was obtained as an estimation equation of the variable range L of displacement.

$$L/L_0 = (E/E_0)^{0.5} \times (\Delta R/\Delta R_0) \times f(t,t_0) \quad (b)$$

Herein, $f(t,t_0)$ represents the effective term of the thickness of the liquid core of the slab. When $f(t,t_0)$ was assumed to be proportional to the exponent of the dimensionless value $t/t_0$, the following formula (c) was obtained from the experiment simulation results as one example of f function.

$$f(t,t_0) = (t,t_0)^{0.446} \quad (c)$$

**[0043]** Then, substituting formula (c) into formula (b), the following formula (4) was ultimately obtained as an estimation equation of the variable range L of displacement (= δmax).

$$\delta max \approx \delta_{x=200\ mm} = L_0 \times (E/E_0)^{0.5} \times (\Delta R/\Delta R_0) \times (t/t_0)^{0.446} \quad (4)$$

Herein, each symbol in the above formula (4) indicates the various amounts below:

E: impact energy per side per segment (J);
ΔR: distance between shafts of adjacent guide rolls at an impact position on the short side (mm); and
t: thickness of liquid core of slab at an impact position on the short side of slab (mm).

In addition, $E_0$, $\Delta R_0$ and to are numerical values of the condition at which the center porosity reducing effect of E, ΔR, and t is the largest, respectively, and $L_0$ is a representative condition of the maximum displacement in a thickness-wise direction of the slab when the center porosity reducing effect is the largest, and each is the constant as follows (5). Hereinafter, these conditions are also referred to as Condition (5).

$$E_0=39\ (J),\ \Delta R_0=245\ (mm),\ t_0=26\ (mm),\ L_0=0.114\ (mm) \quad (5)$$

**[0044]** The present inventors found that, when the displacement 5(x) in a thickness-wise direction of the slab surface (i.e., long side) at a position which is in a normal direction to the short side of slab and away from the impact position at the short side of the slab by a distance x, calculated by numerical analysis, is approximated according to the logarithmic normal distribution, it is possible to generalize as the following formula (6), using the δmax of the above formula (4).

$$\delta(x) = \exp[-1.5 \times \{\ln(x/(200\times (\Delta R/\Delta R_0)^{0.587}))\}^2] \times \delta max \quad (6)$$

**[0045]** FIG. 5 is a graph showing a relationship between a distance from a short side impact position and displacement of the slab long side surface in a thickness-wise direction. The horizontal axis in the same graph is the distance x from the impact position at the short side of the slab in a normal direction to the short side, and the vertical axis is the dimensionless displacement in a slab thickness-wise direction of the slab surface (dimensionless value where dividing δ(x) by δmax to let the maximum displacement to be one (1)). In the same graph, the open circle marks indicate values calculated according to numerical analysis, and the solid circle marks indicate values approximated according to the logarithmic normal distribution. It is evident from the results shown in the same graph that the values calculated according to numerical analysis are precisely approximated by logarithmic normal distribution.

3. Relationship between Internal Quality of Slab and Displacement of Slab Surface by Impact

**[0046]** FIG. 6 is a graph showing a relationship between the maximum displacement δmax in a thickness-wise direction of slab and the reduction in specific volume of center porosity, - ΔVp. The relationship shown in the same graph was prepared by seeking the relationship between δmax and -ΔVp from formula (3) and formula (4) while setting ΔR to 245 (mm) and t to 26 (mm) by adopting the Condition (5). For the liquid core thickness t of the slab at the impact position on the short side of the slab, the liquid core thickness at the entrance of the segment in which the impact-vibration equipment 8 are disposed was calculated from heat conduction and solidification analyses for the case of the casting velocity of 0.7 m/min to be used.

**[0047]** The present inventors have found from the results of FIG. 6 that, when δmax is at least 0.10 mm, the specific volume of center porosity decreases for a slab with a thickness of 300 mm and width of 2300 mm.

**[0048]** In addition, the present inventors have advanced the study further on the relationship between the internal quality of a slab and displacement of slab surface by impacting, and have found that, when δmax is at least 0.10 mm and the distance x occurring δmax from the short side is at least 200 mm, or alternatively, the distance x occurring δmax is less than 200 mm and the displacement δ(x) at x = 200 mm is at least 0.10 mm, the segregation and center porosity can be made to decrease over a wide range of the slab interior, and the internal quality of the slab can be improved. In addition, although the present continuous casting experiments were performed by installing two pairs of impact-vibration equipments, it was confirmed that an effect of improving the internal quality of the slab is obtained even in case of one pair or three or more pairs, similarly to the case of two pairs of impact-vibration equipments.

4. Relationship between Impact Energy and Reachable Distance of Vibration by Impacting

**[0049]** If solving the above formula (6) for x, the following formula (7) is obtained as a function of the displacement δ in a thickness-wise direction of slab and the distance between shafts of adjacent guide rolls ΔR at the impact position on the short side surface.

$$x = 200\times(\Delta R/\Delta R_0)^{0.587} \times \exp[\{-\ln(\delta/\delta max)/1.5\}^{0.5}] \qquad (7)$$

**[0050]** FIG. 7 is a graph showing a relationship between the impact energy per side per segment and the reachable distance of vibration. The maximum value x* of the distance x of a region in which the displacement δ in a slab thickness-wise direction due to impacting is at least 0.10 mm, as being from the impact position on the short side of the slab in a normal direction to the short side, is defined as the reachable distance of vibration. The solid circle mark in the same graph is the result, in the case of impacting while adopting Condition (5), setting the thickness of the slab to 300 mm, the impact energy E per side per segment for the short side of the slab to 40 J, showing that x* is 200 mm. In addition, the curve in FIG. 7 was calculated from the above formula (7) and conditions of the solid circle mark. It is understood from the relationship shown in the same graph that it becomes possible to increase the reachable distance of vibration x* by increasing the impact energy E. For example, the reachable distance of vibration x* increases 25% from 200 mm to 250 mm by increasing the impact energy E from 40 J to 65 J. In other words, by increasing the impact energy E, a quality improvement in the central portion in a slab thickness-wise direction is possible in the vicinity of an slab width-wise end portion in which center porosity easily generates due to delayed solidification under complex casting conditions.

5. Relationship of Distance between Shafts of adjacent guide rolls to Reachable Distance of Vibration by Impacting

**[0051]** FIG. 8 is a graph showing a relationship between the impact energy per side per segment and the reachable distance of vibration, when the distance between shafts of adjacent guide rolls is varied. FIG. 8 is a graph for the case of impacting with the same conditions as FIG. 7, except for the distance between shafts of adjacent guide rolls ΔR being 245 mm or 400 mm. It is understood from the relationship shown in the same graph that the reachable distance of vibration x* increases when the distance between shafts of adjacent guide rolls AR is widened from 245 mm to 400 mm. In other words, in the case of the slab whose ratio of the long side length to the short side length is large, the slab width is large, and bulging between shafts of adjacent guide rolls easily occurs; therefore, it is not possible to adopt a large distance between the adjacent guide rolls ΔR. On the other hand, in the case of the slab whose ratio of the long side length to the short side length is small (i.e., in such case, the slab is referred to as bloom), the bloom width is narrow, and the bulging between shafts of adjacent guide rolls is little; therefore, it is possible to adopt a large distance between shafts of adjacent guide rolls $\Delta R$, which is advantageous from the viewpoint of being able to obtain the effect of impacting in a wide range.

6. Effect of Impacting from Both Short Sides

**[0052]** FIG. 9 is a graph showing the influence of impacting each short side surface which is a width-wise end of slab. The same graph defines the horizontal axis as the distance in a normal direction to the short side from the width-wise center of slab, and defines the vertical axis as the displacement $\delta$ of slab surface in a thickness-wise direction of slab. Calculation results are shown for cases of impacting: only the left short side that lies left with respect to the withdrawing direction of slab; only the right short side; and both short sides simultaneously, wherein the casting slab is a bloom of approximately 400 mm in width, the distance between shafts of adjacent guide rolls $\Delta R$ is 400 mm, and an impact energy per side per segment is 45 J. It is understood from the results shown in the same graph that, when the left side impacting displacement $\delta_L$ which is the one in a thickness-wise direction of slab in the case of impacting only the left short side with respect to the withdrawing direction and the right side impacting displacement $\delta_R$ which is the one in a thickness-wise direction of slab in the case of impacting only the right short side on the right side are combined together, the resultant becomes equivalent to the displacement $\delta_D$ in a thickness direction of slab in the case of impacting both short sides of slab simultaneously.

**[0053]** In the case of impacting only the left short side with respect to the withdrawing direction or only the right short side, the horizontal length of the territory in which the displacement $\delta$ in a slab thickness-wise direction is at least 0.10 mm, is approximately 300 mm, which is the slab width-wise length in a normal direction to the short side, and the displacement $\delta$ cannot be made at least 0.10 mm over the entire width. However, by simultaneously impacting the short sides on both sides, the displacement $\delta$ can be made at least 0.10 mm over the entire width of the impact position. In addition, as understood from FIG. 9, in the case of simultaneously impacting both short sides, a maximum value of displacement $\delta$ at the central portion in a width-wise direction of the slab reaches 0.40 mm, and thus the displacement $\delta$ can be increased drastically, and it is possible to achieve a further improvement in the internal quality of the casting slab.

INDUSTRIAL APPLICABILITY

**[0054]** According to the method of the present invention, since impacting the slab short side surface causes vibration having a displacement of the long side slab surface of at least 0.10 mm over a wide range of the slab, the segregation and/or center porosity is reduced, and thus a slab excelling in interior quality can be obtained. Therefore, the method of the present invention can be widely applied as a continuous casting method of casting slabs of preferable internal quality.

REFERENCE SIGNS LIST

**[0055]** 1: immersion nozzle, 2: molten steel surface (meniscus), 3: mold, 4: molten steel, 5: solidified shell, 6: guide roll, 7: casting slab, 7a, 7b, 7c, 7d: casting slab specimen, 8: impact-vibration equipment, 9: block, 10: drive part

**Claims**

**1.** A continuous casting method of steel in which a slab having a rectangular cross section is cast while causing vibration in the slab with liquid core by disposing at least one pair of impact-vibration equipments on both short side surfaces of slab and continuously impacting those surfaces, **characterized in that**:

a vibration energy, a distance between shafts of adjacent guide rolls and a liquid core thickness are adjusted, so that the impacting of the short side surface causes a curve of displacement $\delta(x)$ of the long side slab surface in a slab thickness-wise direction as defined by the following formulas (1) and (2) to intersect a straight line $\delta(x) = 0.10$ mm at two locations, and a distance of the intersection farther away from the coordinate origin in a slab width-wise direction, representing the distance from an impact position at the short side of the slab, is at least 200 mm; and
the short side is impacted,

$$\delta(x) = \exp[-1.5 \times \{\ln(x/(200\times(\Delta R/\Delta R_0)^{0.587}))\}^2] \times \delta\max \qquad (1)$$

$$\delta max = L_0 \times (E/E_0)^{0.5} \times (\Delta R/\Delta R_0) \times (t/t_0)^{0.446} \qquad (2)$$

where each symbol in formulas (1) and (2) designates as follows,
x is a distance (mm) in a slab width-wise direction with the impact position on the short side of slab being 0,
δ(x) is a displacement (mm) of slab surface in a slab thickness-wise direction at the position x,
δmax is the maximum displacement (mm) in a slab thickness-wise direction,
ΔR is a distance between shafts of adjacent guide rolls (mm) at the position where impacting the short side,
E is impact energy per side per segment (J), and
t is a liquid core thickness of the slab at the impact position on the short side of the slab (mm),
wherein Constants are defined as $E_0$ = 39 (J), $\Delta R_0$ = 245 (mm), to = 26 (mm), and $L_0$ = 0.114 (mm).

**2.** The continuous casting method of steel according to claim 1, further **characterized in that** the same time phase is employed in cyclically impacting opposing left and right short sides of the slab, so that the displacements δ(x) generated by impacting the left and right short sides, respectively, are combined with each other, and the resultant displacement δ(x) thus combined is at least 0.10 mm over the entire width of the slab at the impact positions.

FIG. 1

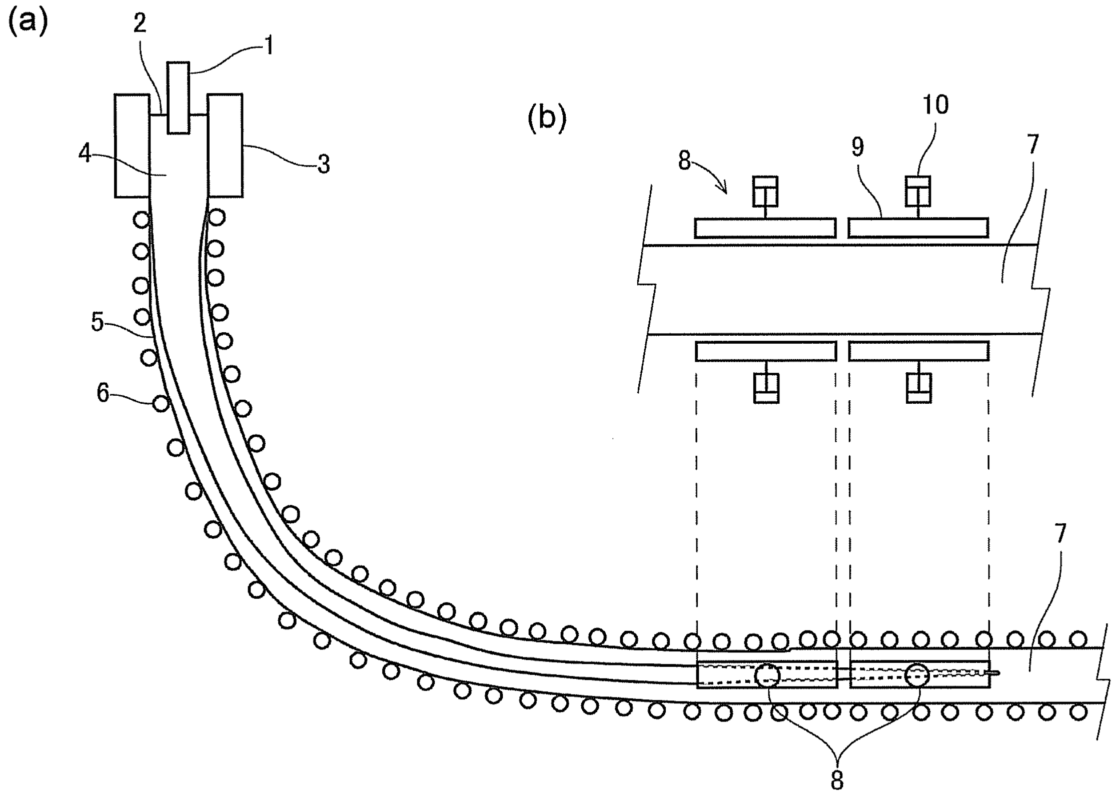

(a)
(b)
1
2
3
4
5
6
7
8
9
10

FIG. 2

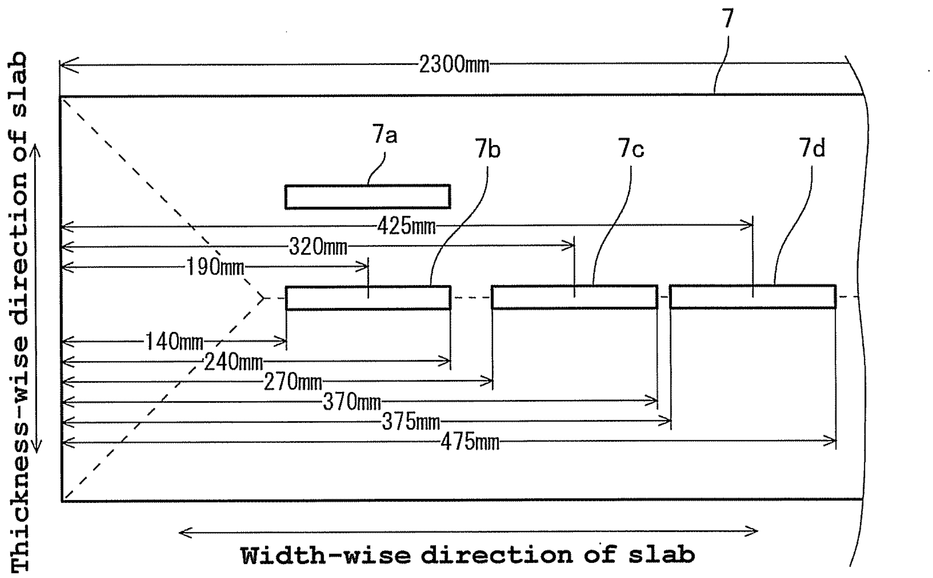

7
2300mm
7a
7b
7c
7d
425mm
320mm
190mm
140mm
240mm
270mm
370mm
375mm
475mm
Thickness-wise direction of slab
Width-wise direction of slab

FIG. 3

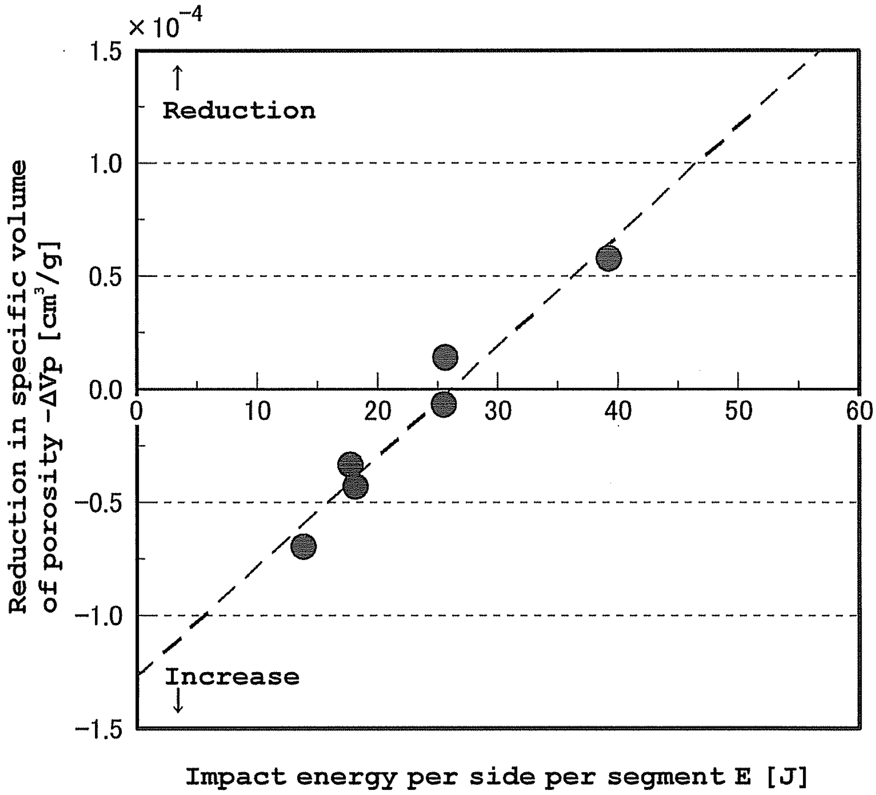

×10⁻⁴
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
10
20
30
40
50
60
↑ Reduction
Increase ↓
Reduction in specific volume of porosity -ΔVp [cm³/g]
Impact energy per side per segment E [J]

FIG. 4

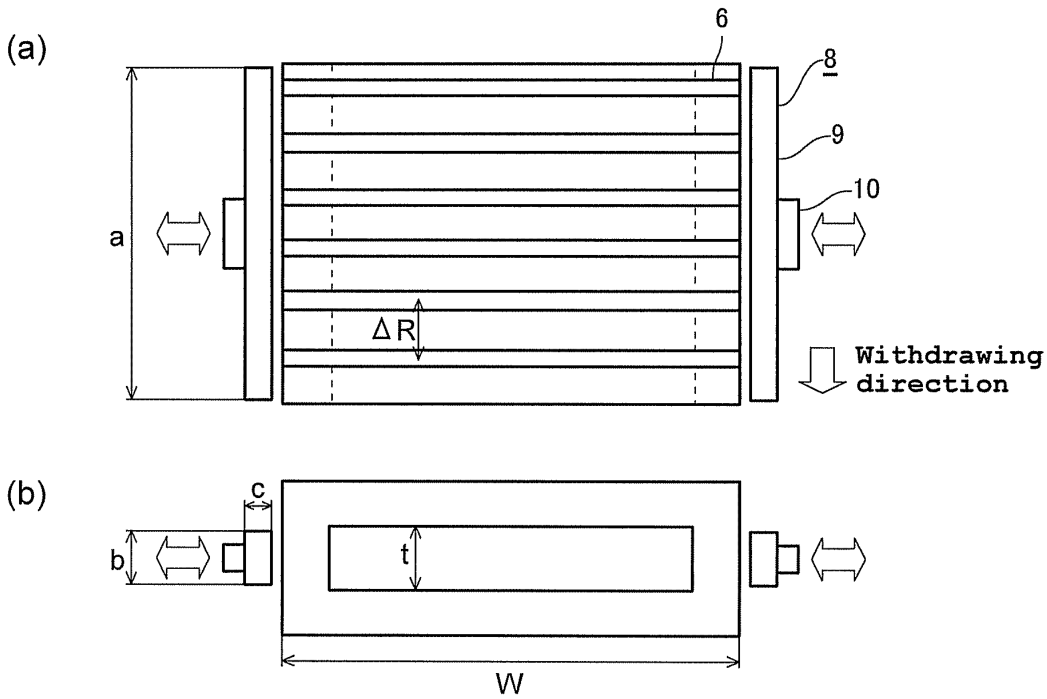

(a)
6
8
9
10
a
ΔR
Withdrawing direction
(b)
c
b
t
W

FIG. 5

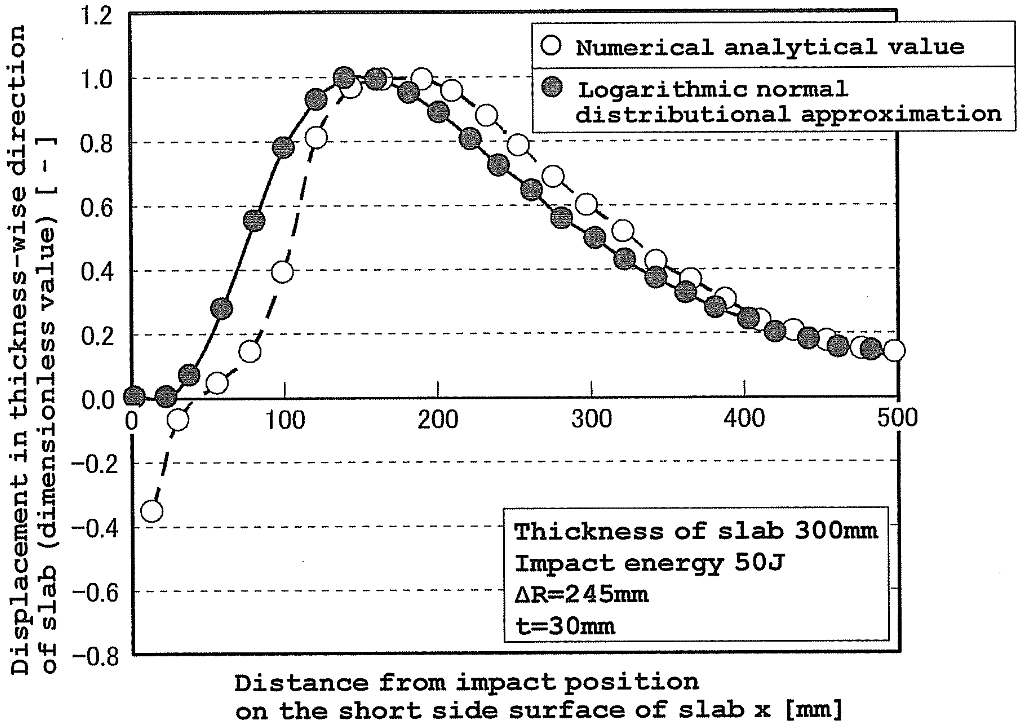

Displacement in thickness-wise direction of slab (dimensionless value) [ - ]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
0
100
200
300
400
500
Numerical analytical value
Logarithmic normal distributional approximation
Thickness of slab 300mm
Impact energy 50J
ΔR=245mm
t=30mm
Distance from impact position on the short side surface of slab x [mm]

FIG. 6

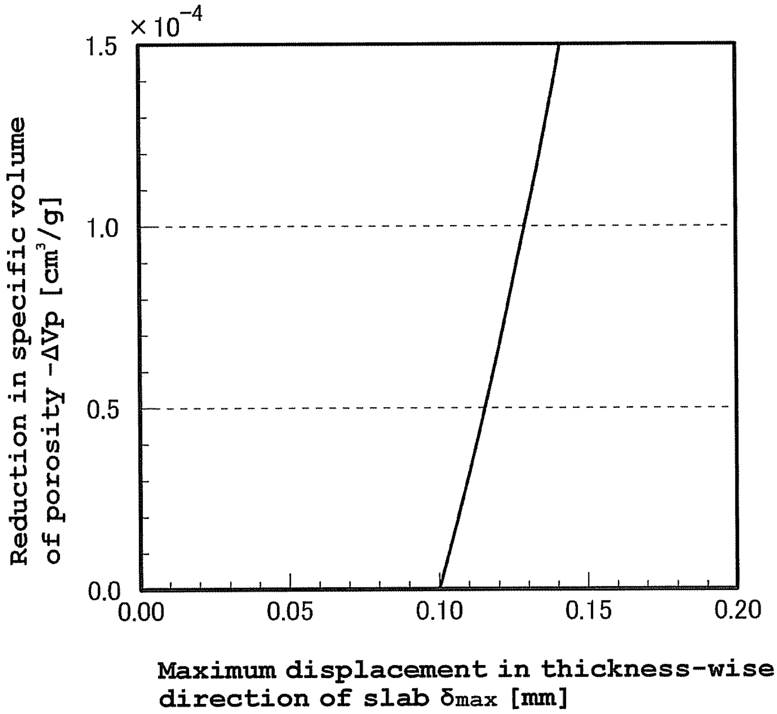

×10^−4
1.5
1.0
0.5
0.0
0.00
0.05
0.10
0.15
0.20
Reduction in specific volume of porosity -ΔVp [cm³/g]
Maximum displacement in thickness-wise direction of slab δmax [mm]

FIG. 7

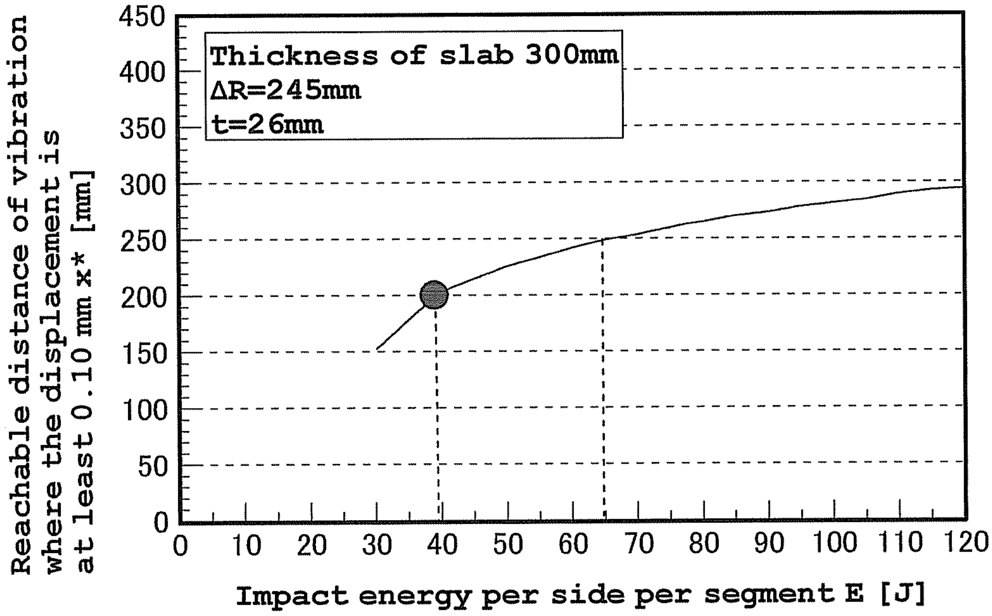

Thickness of slab 300mm
ΔR=245mm
t=26mm
Reachable distance of vibration where the displacement is at least 0.10 mm x* [mm]
0
50
100
150
200
250
300
350
400
450
0 10 20 30 40 50 60 70 80 90 100 110 120
Impact energy per side per segment E [J]

FIG. 8

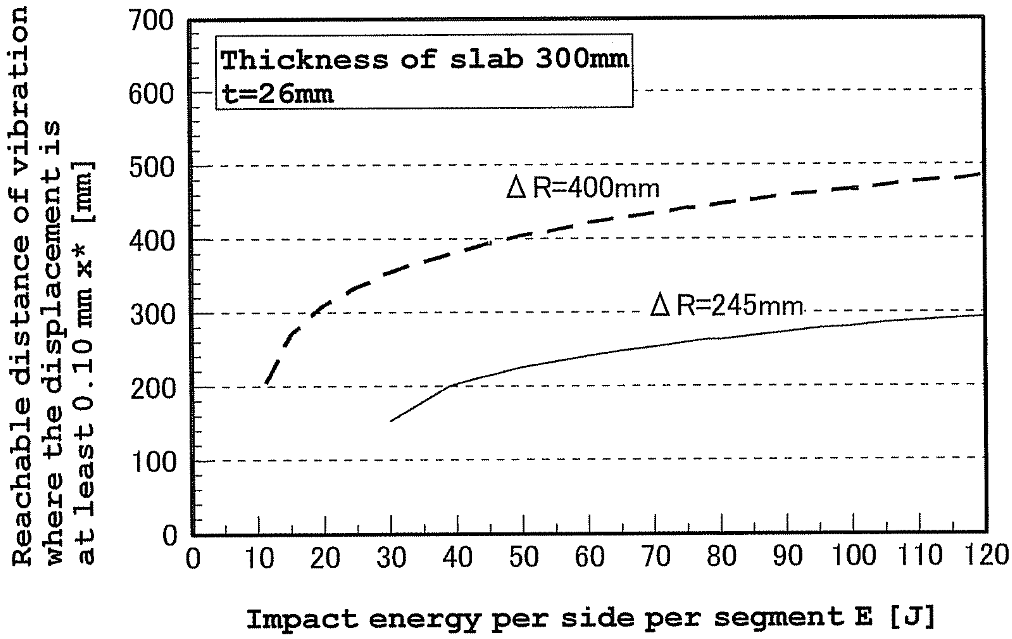
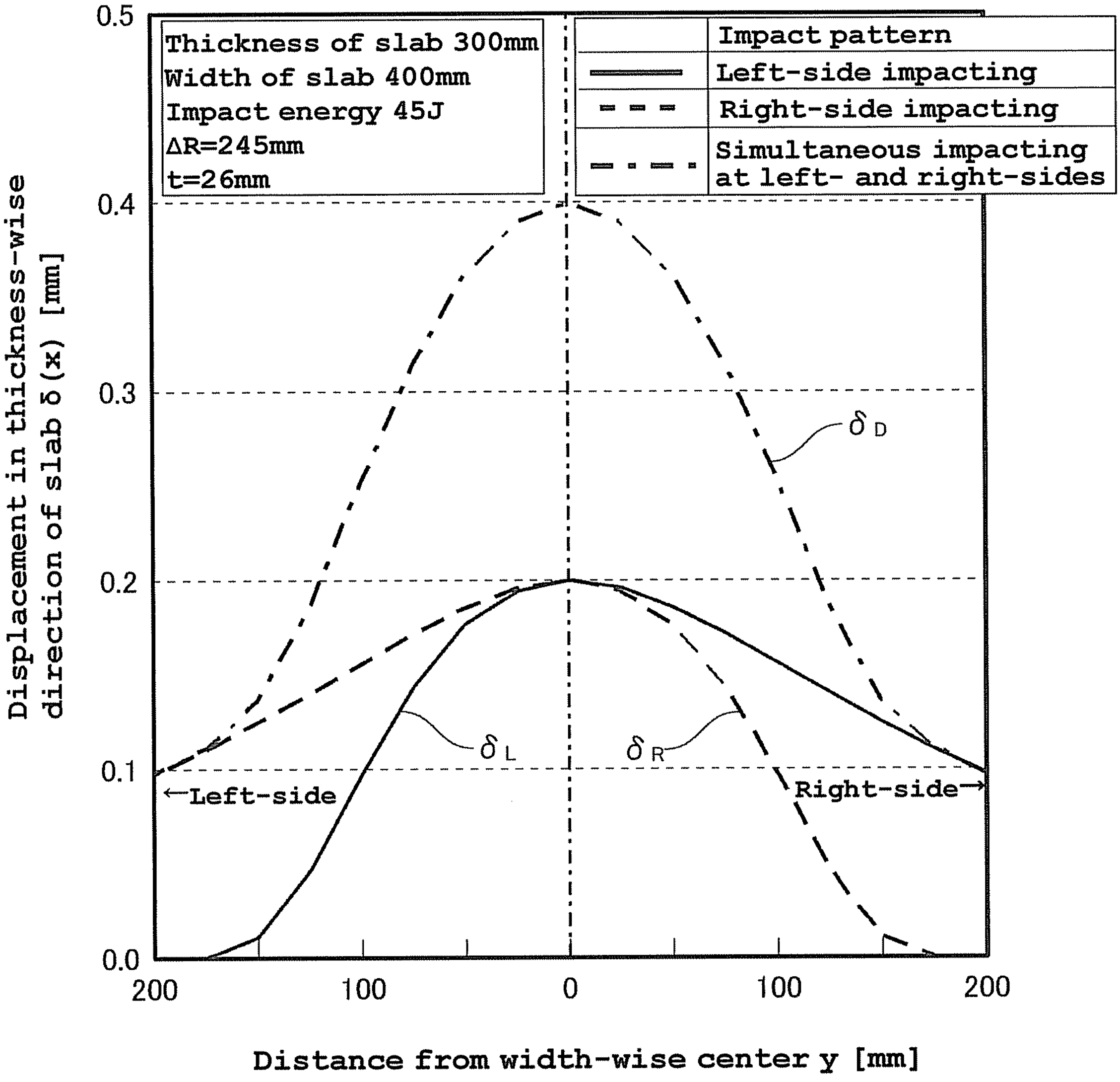

Thickness of slab 300mm
t=26mm
ΔR=400mm
ΔR=245mm
Reachable distance of vibration where the displacement is at least 0.10 mm x* [mm]
0
100
200
300
400
500
600
700
0 10 20 30 40 50 60 70 80 90 100 110 120
Impact energy per side per segment E [J]

FIG. 9


Thickness of slab 300mm
Width of slab 400mm
Impact energy 45J
ΔR=245mm
t=26mm
Impact pattern
Left-side impacting
Right-side impacting
Simultaneous impacting at left- and right-sides
δ D
δ L
δ R
←Left-side
Right-side→
0.5
0.4
0.3
0.2
0.1
0.0
200
100
0
100
200
Displacement in thickness-wise direction of slab δ(x) [mm]
Distance from width-wise center y [mm]

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2009/068462

A. CLASSIFICATION OF SUBJECT MATTER
*B22D11/128*(2006.01)i, *B22D11/16*(2006.01)i, *B22D11/20*(2006.01)i

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)
B22D11/128, B22D11/16, B22D11/20

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 | 1996-2009 |
| Kokai Jitsuyo Shinan Koho | 1971-2009 | Toroku Jitsuyo Shinan Koho | 1994-2009 |

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. |
|---|---|---|
| A | JP 2007-229748 A (Sumitomo Metal Industries, Ltd.), 13 September 2007 (13.09.2007), claims; paragraphs [0052] to [0061] (Family: none) | 1,2 |

☐ 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 |
|---|---|
| 08 December, 2009 (08.12.09) | 15 December, 2009 (15.12.09) |
| Name and mailing address of the ISA/ Japanese Patent Office | Authorized officer |
| Facsimile No. | Telephone No. |

Form PCT/ISA/210 (second sheet) (April 2007)

## REFERENCES CITED IN THE DESCRIPTION

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### Patent documents cited in the description


- JP 3835185 B **[0009]**
- JP 2003334641 A **[0009]**