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Courier Press, Leamington Spa, England.

Description

The present invention relates to a method of electromagnetic stirring intended to provide a satisfactory solidified structure in continuous casting, according to the preamble of claim 1.

Besides Fe, molten steel contains various alloying elements and impurity elements, and the solidification of molten steel is sometimes attended by appreciable segregation of segregative elements, such as C, P, and S, into the final solidifying portion of the steel ingot or cast slab or bloom. Products made of a material having such a segregated portion are inferior in their characteristics, due to non-uniformity of their mechanical properties, and experience case trouble during welding. Thus it is an important problem to decrease segregation. Particularly in continuous casting, noticeable segregation develops in a direction at right angles to the cast slab or bloom drawing direction. However, past examination of various operating conditions has not been successful in improving the mechanical properties of the cast slab or bloom.

The most promising of the measures heretofore taken is to stir the molten steel electromagnetically during solidification. Thus, DE—A—2 424 610 forming the first part of claim 1, discloses a method of electromagnetically stirring molten steel in continuous casting, wherein in producing a cast slab or bloom an electromagnetic stirring force is applied to the unsolidified molten steel in the cast slab or bloom being drawn by an electromagnetic stirrer installed, for example, at a drawing position where the unsolidified thickness at viewed in the direction of the thickness is 30% of the thickness of the cast slab or bloom.

Although this method has been recognized as having the effect of breaking, to some extent the columnar crystals which grow during solidification, the degree to which the columnar crystals are broken is insufficient to eliminate marked segregation. To enhance the stirring effect, an attempt has been made to increase the electromagnetic stirring force so as to provide an increased stirring force capacity, but this has the drawback of producing a white band in the form of negative segregation. The white band portion is not only lower in the percentages of alloying elements than their average values, forming a qualitative effect, but also presents an undesirable outside appearance.

The present invention, made with this serious situation in mind, is intended to establish electromagnetic stirring conditions for enhancing the effect of breaking columnar crystals to reduce negative segregation and avoid the formation of white bands.

According to the invention there is provided a method of the type disclosed in DE—A—2 424 610 characterised in that said electromagnetic stirrer or a plurality of such stirrers is or are installed within a region defined between drawing positions where said unsolidified thickness in 45% and 15%, respectively, of the thickness as viewed in the direction of the thickness of the cast slab or bloom and in that stirring in the casting direction is applied to the unsolidified molten steel in such a manner that the product of the magnetic flux density at the interface between the unsolidified and solidified portions and the stirring time, expressed as the ratio of the length in m. of the region of the cast slab to which electromagnetic stirring is applied to the casting speed in m/min, is 0.16 Tesla-min (1,600 gauss-min) or more per m^3 of the total volume of unsolidified molten steel present in a region extending to the drawing side of the electromagnetic stirrer or stirrers.

Preferably the electromagnetic stirrer is installed between drawing positions where the unsolidified thickness is 35% and 20%, respectively, of the thickness as viewed in the direction of the thickness of the cast slab or bloom.

The interface between the unsolidified and solidified portions is hereinafter referred to as the solidification interface.

The aforesaid conditions have been determined with the flow condition of molten steel during solidification taken into account. The arrangement and functions and effects of the invention will now be described along with the process of development of the invention.

In continuous casting, the cause of segregation taking place in the central portion of the cast slab or bloom is generally considered to be as follows.

It is known that although the central portion of the cast slab or bloom, when viewed in the casting direction (drawing direction), has very little temperature gradient, the flow of the solid-liquid coexistence layer in this portion can be induced by the so-called suction (a phenomenon of contraction of the solid-liquid coexistence layer taking place in the last stage of solidification of molten steel). However, all the solid-liquid coexistence layer does not flow at the same time, but, owing to solidification contraction which proceeds in the lower region (on the drawing side), the region which overlies the same (mould side) flows downward, and as this flowing region solidifies, the region which overlies the same flows downward and solidifies. Such stepwise flow is repeated, whereby the periodicity of V segregation is formed. This situation will now be described more schematically. The solid-liquid coexistence condition is established in several regions along the cast slab or bloom drawing direction and these regions flow in block but the flow of these regions takes place successively with some time lag, with the lower side flowing first. Therefore, between adjacent regions, the dendrites separate from each other in accordance with the flow time lag, so that cavities with some periodicity are formed. Such a cavity has a temperature gradient in a direction at right angles to the cast slab or bloom drawing direction and a flow of molten steel is formed between the dendrites, so that the aforesaid suction effect becomes greater toward the centre of the cast slab or bloom. Under these influences, the aforesaid cavities assume a V-shape inclined toward the centre axis, and it seems that the surrounding segregated liquid present between the dendrites flows into the V-shaped cavities, resulting in V segregation.

On the basis of this analysis, the present invention aims to reduce segregation in the central portion of the cast slab or bloom by adjusting the electromagnetic stirring force so as to change the aforesaid solidification mechanism.

The region where V segregation takes place is, after all, a region with little temperature gradient. The factors which determine the size of this region are supposed to include the molten steel composition (particularly the carbon concentration) and super-heating of molten steel, but a statistical examination of regions where V segregation is formed has revealed that even the maximum value does not exceed 45% of the thickness as viewed in the direction of the thickness of the cast slab or bloom.

The invention will now be described in more detail below with reference to the accompanying drawings, wherein:

Fig. 1 is a graph showing the relationship between the carbon concentration and the percentage of equiaxed crystal zone on the upper curve side in continuous casting;

Fig. 2 is a schematic view showing the effect of the present invention;

Figs. 3—7 are schematic views showing how the invention is embodied;

Fig. 8 is a graph showing the relationship between the unsolidified molten steel volume and the stirring force, associated with the presence or absence of the effect of the invention; and

Fig. 9 is a graph showing the effect of the invention on C segregation evaluation.

Fig. 1 is a graph showing the relationship between the carbon concentration in molten steel and percentage of equiaxed crystal zone on the upper curve side. As can be seen in the graph, the percentage of equiaxed crystal zone on the upper curve side is low in the low and high carbon ranges but very high in the medium carbon range. It is thought that this is because the solidification of single phases δ and γ, in the low and high carbon ranges results in the formation of fewer equiaxed crystals, whereas in the medium carbon range the two-phase solidification, liquid + δ phase → γ phase, takes place, so that a long time is expended in the course of this transformation, resulting in the survival of more of the nuclei for equiaxed crystals. It is also thought that the heat locally generated by peritectic reaction remelts the dendrite branches starting at their roots, thereby providing nuclei for equiaxed crystals. The percentage of equiaxed crystal zone corresponds to the distance from the centre axis of the cast slab or bloom to the portion where V segregation takes place, expressed in terms of its ratio to the thickness as viewed in the thickness of the cast slab or bloom, and the results of continuous casting under the conditions shown in the figure (v is the cast slab or bloom drawing speed and Δt is the superheating of molten steel) have led the present inventors to the conclusion that the region where V segregation takes place extends from the centre axis up to 45%, preferably 35% of the thickness as viewed in the direction of the thickness as viewed in the direction of the thickness of the cast slab or bloom. Thus, the present inventors have thought that to eliminate said V segregation by electromagnetic stirring, it is necessary to stir said region and reached the conclusion that it is suitable to locate an electromagnetic stirrer at a position nearer to the drawing side than a position were the unsolidifed thickness is 45%, preferably 35%, of the thickness as viewed in the direction of the thickness of the cast slab or bloom.

For the reasons described above, the upper limit of the proportion of the unsolidified thickness to the thickness of the cast slab or bloom is 45%, preferably 35% The lower limit must be 15%, perferably 20%. The reason for this is that the amount of unsolidified molten steel remaining in the cast slab or bloom in the region where the proportion is below said lower limit is relatively small and its temperature has dropped so that the viscosity of the molten steel itself is high, which means that stirring is difficult and that the improvement effect on the quality of the cast slab or bloom is lessened.

Fig. 2 is a schematic view for explaining a V segregation reducing mechanism according to the present invention, wherein *A* refers to an instance applying no electromagnetic stirring, *B* refers to an instance using a conventional electromagnetic stirring technique, and *C* refers to the present invention; in each case, the cast slab or bloom moves vertically downward. An examination of the macro-structure in the case of *A* has revealed that columnar crystals extend as far as the centre of the cast slab or bloom thickness, forming centre porosities at their junction, and in the case of *B* equiaxed crystals are multiplied by the breakage of columnar crystals, and the solidified structure in the centre part is reduced greatly but not to the extent of eliminating V segregation and micro-porosities. In the case of *C* according to the method of the invention, however, the V-shaped segregation angle is changed to an extremely sharp angle; in other words, the end edges are successfully turned parallel with the surface of the cast slab or bloom or orientated in the cast slab or bloom drawing direction. Thus, the electromagnetic stirring according to the invention causes the flow of the V segregation forming region in the casting direction to diffuse rather than gathering toward the centre, and more particularly it causes said flow due to the contracting force exerted in the last stage of solidification to be artificially diffused in a direction perpendicular to the cast slab or bloom drawing direction by forming a temperature gradient in said perpendicular direction. Therefore, the segregated liquid formed in the last stage of solidification is circumferentially diffused and solidified without being allowed to produce V-shaped segregation. In addition, such an artificial flow could be produced in the direction opposite to the cast slab or bloom drawing direction, but this is economically disadvantageous, for example as regards the power source capacity. Thus, advantageously, it should be produced in the cast slab or bloom drawing direction.

Figs. 3—7 are schematic views showing how the present invention is embodied. One or more electromagnetic stirrers 2 are installed at a position nearer to the drawing side than is the position which satisfies said conditions. To achieve the intended object of the invention, however, it is necessary to determine more concrete conditions for electromagnetic stirring. We have concluded that the product (B T) of the magnetic flux density (ß gauss) at the solidification interface and the stirring time (T.min.) should be 0.16 Tesla-min (1,600 gauss-min.) or more per m^3 of the volume of the unsolidified molten steel. The circumstances that have led us to this conclusion will now be described on the basis of experimental

Table 1 shows conditions where, in the continuous casting of cast bloom having a cross-section of 380 mm × 550 mm, an electromagnetic stirrer having a stirring effective length l of 1,300 mm is installed at a position 13 m (Test No. 1—8) or 17 m (Test No. 9—12) apart from the meniscus [which position satisfies the aforesaid installation condition (45% or less)] and the output is changed. The mm notation in the solidified portion indicates the thickness. For example, the solidification percentage when the casting speed is 0.45 m/min. is calculated as follows.

$$\frac{125 + 125}{380} \times 100 = 65.8\%$$

Further, the unsolidified volume from the stirrer is calculated as follows, on the assumption that this portion is pyramidal.

$$(0.38-2 \times 0.125) \times (0.55-2 \times 0.125) \times 17 \times \tfrac{1}{3} = 0.22 \text{ m}^3$$

The gauss values used in the calculations are those shown in Table 2. In Table 1 the values of BT are in gauss-min. (i.e. Tesla-min × 10^4).

TABLE 1

Test No.	Drawing speed V m/min.	Solidified portion mm%	Unsolidified mass Length(m)	Unsolidified mass Volume(m³)	Stirring time 1,300mm/v	250A BT	500A BT	750A BT	1000A BT	1200A B T		1800A B T	Remarks
1	0.45	125 65.8	17.0	0.22	2.89 min	159	275	405	535	650		867	Gauss for a shell thickness of 125 mm
2	0.5	119 62.6	20.0	0.30	2.60	143	247	364	481	585		780	"
3	0.55	113 59.5	23.6	0.39	2.36	130	224	330	437	531		708	"
4	0.60	108 56.8	26.9	0.49	2.17	152	260	401	521	630		825	Gauss for a shell thickness of 100 mm
5	0.65	102 53.7	30.2	0.61	2.0	140	240	370	480	580		760	"
6	0.70	96 50.5	33.5	0.75	1.86	130	223	344	446	539		707	"
7	0.75	90 47.3	36.9	0.91	1.73	121	207	320	415	501		657	"
8	0.80	85 44.7	40.0	1.06	1.63	114	196	302	391	473		619	
9	0.45	150 78.9	13.0	0.087	2.89	88.7	178	266	1000A* 355	426		639	
10	0.55	136 71.5	19.6	0.196	2.36	100	200	300	400	480	1500A* 600	720	
11	0.60	130 68.4	22.9	0.266	2.17	81.3	102.5	243	325	390		1800A* 585	
12	0.55	136 71.5	19.6	0.196	2.36	100	200	300	400	1200A* 480		720	

TABLE 2

Shell thickness \ Current	250A	500A	750A	1000A	1200A	1800A
125 mm	55	95	140	185	225	300
100 mm	70	120	185	240	290	380

In addition, the magnetic flux density B at the solidification interface is given by the following equation.

$$B = Boe\,\frac{\tau}{\delta}$$

where

Bo is the magnetic flux density (gauss on the electromagnetic stirrer surface
τ is the pole pitch (mm) in the electromagnetic stirrer
δ is the depth of penetration (mm)

$$\delta = 5.04\,\frac{\rho}{f}$$

ρ: specific resistance (μΩ)
f: frequency (Hz)

Fig. 8 shows the values of Table 1 plotted in a graph, the vertical axis indicating the stirring force (B.T) and the horizontal axis the unsolidified molten steel volume (mm^3). The mark ○ refers to cases where the central V segregation was reduced and the mark ● refers to cases where there was no such effect. The longitudinal/horizontal axis ratio (unit:gauss—min/m^3) for each plot is also shown in the graph. We have concluded from Fig. 8 that the V segregation reducing effect is remarkable if the value of B. T/m^3 is 1,600 ot more.

Fig. 9 shows an example in which a cast slab or bloom with a superheating of molten steel ΔT of 15—40°C and a cross-section of 380 × 550 (mm) was continuously cast at a casting speed of 0.6 m/min. The mark ● refers to a comparative example using no electromagnetic stirring and the mark ○ refers to an example of the present invention wherein an electromagnetic stirrer is installed at a position where the unsolidified thickness is 40%. As is clear from Fig. 9, whereas the comparative example exhibited extremely noticeable C segregation, the example according to the invention yielded a cast slab or bloom having little C segregation. Further, is did not develop negative segregation, either, nor did it form a white band.

The use of the present invention makes it possible to prevent formation not only of V-shaped segregation in the central portion of the cast slab or bloom but also of negative segregation, thereby improving the mechanical properties of continuously cast products.

Claims

1. A method of electromagnetically stirring molten steel in continuous casting, wherein in producing a cast slab or bloom an electromagnetic stirring force is applied to the unsolidified molten steel in the cast slab or bloom being drawn by an electromagnetic stirrer installed for example, at a drawing position where the unsolidified thickness as viewed in the direction of the thickness is 30% of the thickness of the cast slab or bloom, characterised in that said electromagnetic stirrer or a plurality of such stirrers is or are installed within a region defined between drawing positions where said unsolidified thickness is 45% and 15%, respectively of the thickness as viewed in the direction of the thickness of the cast slab or bloom, and in that stirring in the molten steel in such a manner that the product of the magnetic flux density at the interface between the unsolidified and solidified portions and the stirring time, expressed as the ratio of the length in m. of the region of the cast slab to which electromagnetic stirring is applied to the casting speed in m/min, is 0.16 Tesla-min (1,600 gauss-min) or more per m^3 of the total volume of unsolidified molten steel present in a region extending to the drawing side of the electromagnetic stirrer or stirrers.

2. A method as claimed in claim 1, wherein the or each electromagnetic stirrer is located between drawing positions where the unsolidified thickness is 35% and 20%, respectively, of the thickness as viewed in the direction of the thickness of the cast slab or bloom.

Patensansprüche

1. Verfahren zum elektromagnetischen Rühren von geschmolzenem Stahl beim Stranggguß, wobei bei der Herstellung eines gegossenen Stranges oder Blockes auf den nicht erstarrten, geschmolzenen Stahl, der in dem gegossenen Strang oder Block, der gezogen wird, vorhanden ist, durch einen elektromagnetischen Rührer, der beispielsweise bei einer Ziehlage angebracht ist, wo die in der Richtung der Dicke betrachtete Dikke des nicht erstarrten Teils 30% der Dicke des gegossenen Stanges oder Blockes beträgt, eine elektromagnetische Rührkraft ausgeübt wird, dadurch gekennzeichnet, daß der erwähnte elektromagnetische Rührer oder mehr als ein solcher Rührer innerhalb eines Bereichs, der zwischen Ziehlagen festgelegt ist, wo die erwähnte Dicke des nicht erstarrten Teils 45% bzw. 15% der in der Richtung der Dicke betrachteten Dicke des gegossenen Stranges oder Blockes beträgt, angebracht ist oder sind und daß der nicht erstarrte, geschmolzene Stahl in der Weise in der Gießrichtung gerührt wird, daß das Produkt der magnetischen Flußdichte an der Grenzfläche zwischen dem nicht erstarrten und dem erstarrten Teil und der Rührdauer, die als das Verhältnis der Länge (in m) desjenigen Bereichs des gegossenen Stranges, auf den das elektromagnetische Rühren angewandt wird, zu der Gießgeschwindigkeit (in m/min) ansgedrückt wird, 0,16 Tesla·min (1600 Gauss·min) oder mehr je m^3 des Gesamtvolumens des nicht erstarrten, geschmolzenen Stahls beträgt, der in einem Bereich vorhanden ist, der sich bis zu der Ziehseite des elektromagnetischen Rührers oder der elektromagnetischen Rührer erstreckt.

2. Verfahren nach Anspruch 1, bei dem sich der oder jeder elektromagnetische Rührer zwischen Ziehlagen befindet, wo die Dicke des nicht erstarrten Teils 35% bzw. 20% der in der Richtung der Dicke betrachteten Dicke des gegossenen Stranges oder Blockes beträgt.

Revendications

1. Procédé de brassage électromagnétique d'acier fondu en coulée continue, selon lequel pour la fabrication d'une brame ou d'un bloom coulé, on applique une force de brassage électromagnétique à l'acier fondu non solidifié, qui est situé dans la brame ou le lingot coulé et qui est tiré par un agitateur électromagnétique installé par exemple dans une position de traction, dans laquelle l'épaisseur à l'état non solidifié, considérée suivant la direction de l'épaisseur, est égale à 30% de l'épaisseur de la brame ou du bloom coulé, caractérisé en ce que ledit agitateur électromagnétique ou une pluralité de tels agitateurs est ou sont installés à l'intérieur d'une zone définie entre des positions de traction, dans lesquelle ladite épaisseur à l'état non solidifié est égale respectivement à 45% et à 15% de l'épaisseur considérée suivant la direction de l'épaisseur de la brame ou du bloom coulé, et en ce que le brassage dans la direction de coulée est appliquée à l'acier fondu non solidifié de telle manière que le produit de la densité de flux magnétique au niveau de l'interface entre les parties non solidifiées et les parties solidifiées par la durée de brassage, exprimée par le rapport de la longueur en m de la zone de la brame coulée, à laquelle l'agitation magnétique est appliquée, à la vitesse de coulée en m/mn, est égal à 0,16 teslas-mn (1600 gauss-mn) ou plus par m^3 du volume total d'acier fondu non solidifié présent dans une zone s'étendant jusqu'au côté de traction du ou des agitateurs électromagnétiques.

2. Procédé selon la revendication 1, selon lequel chaque agitateur électromagnétique est située entre des positions de traction, dans lesquelles l'épaisseur à l'état non solidifié est égale respectivement à 35 et 20% de l'épaisseur considérée suivant la direction de l'épaisseur de la brame ou du bloom coulé.

F I. G. I

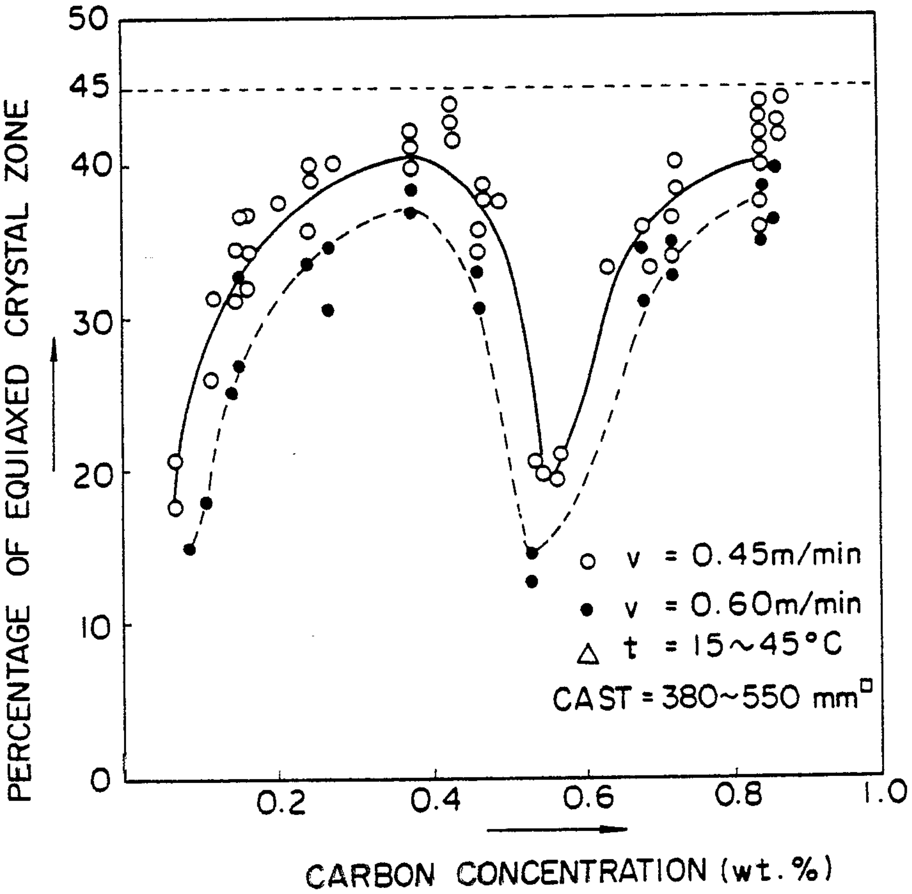

PERCENTAGE OF EQUIAXED CRYSTAL ZONE
50
45
40
30
20
10
0
0.2
0.4
0.6
0.8
1.0
CARBON CONCENTRATION (wt.%)
○ v = 0.45m/min
● v = 0.60m/min
△ t = 15~45°C
CAST = 380~550 mm□

FIG. 2

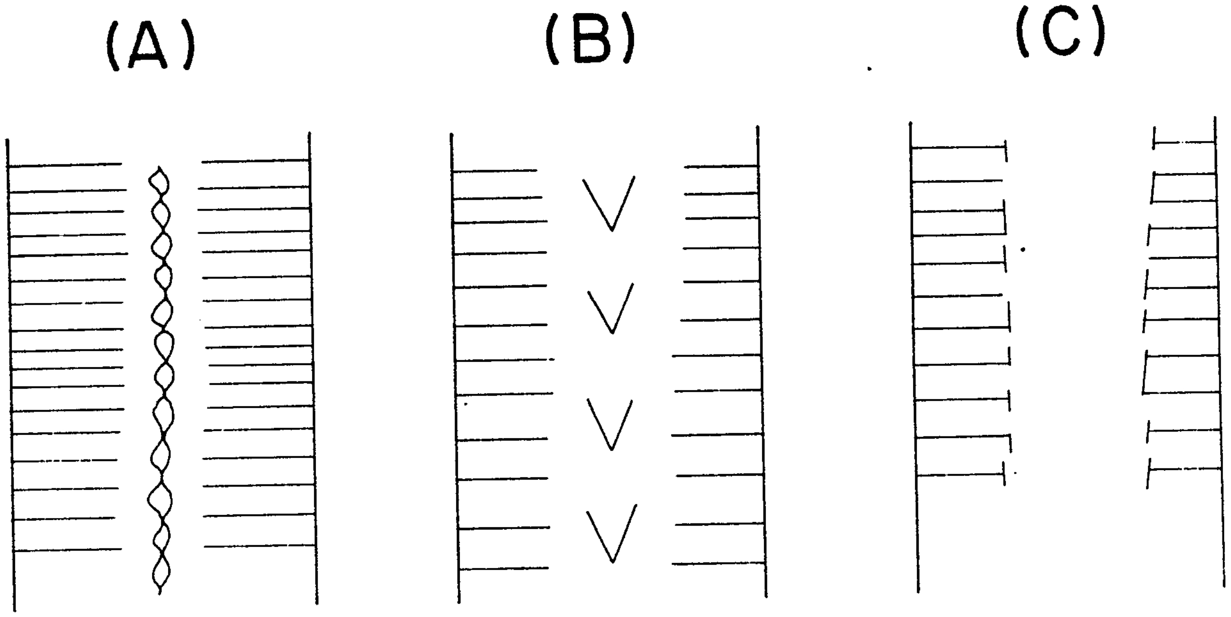


FIG. 3

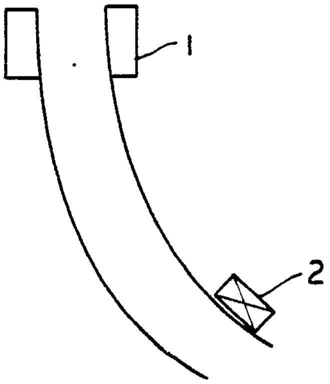


FIG. 4

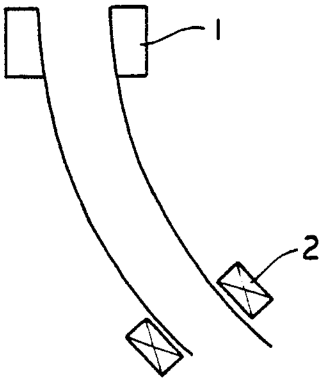


FIG. 5

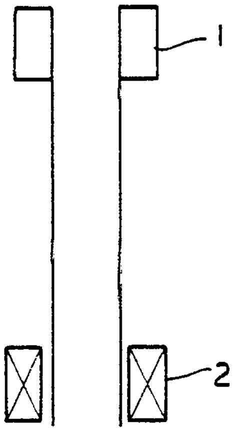


FIG. 6

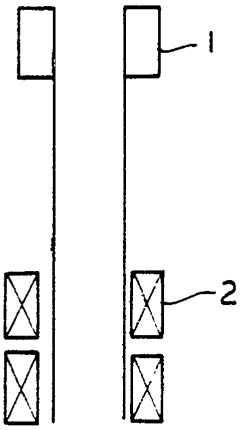


FIG. 7

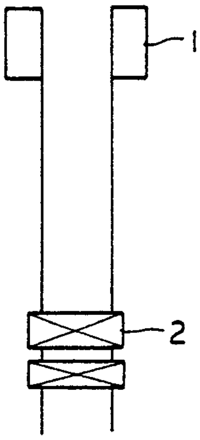
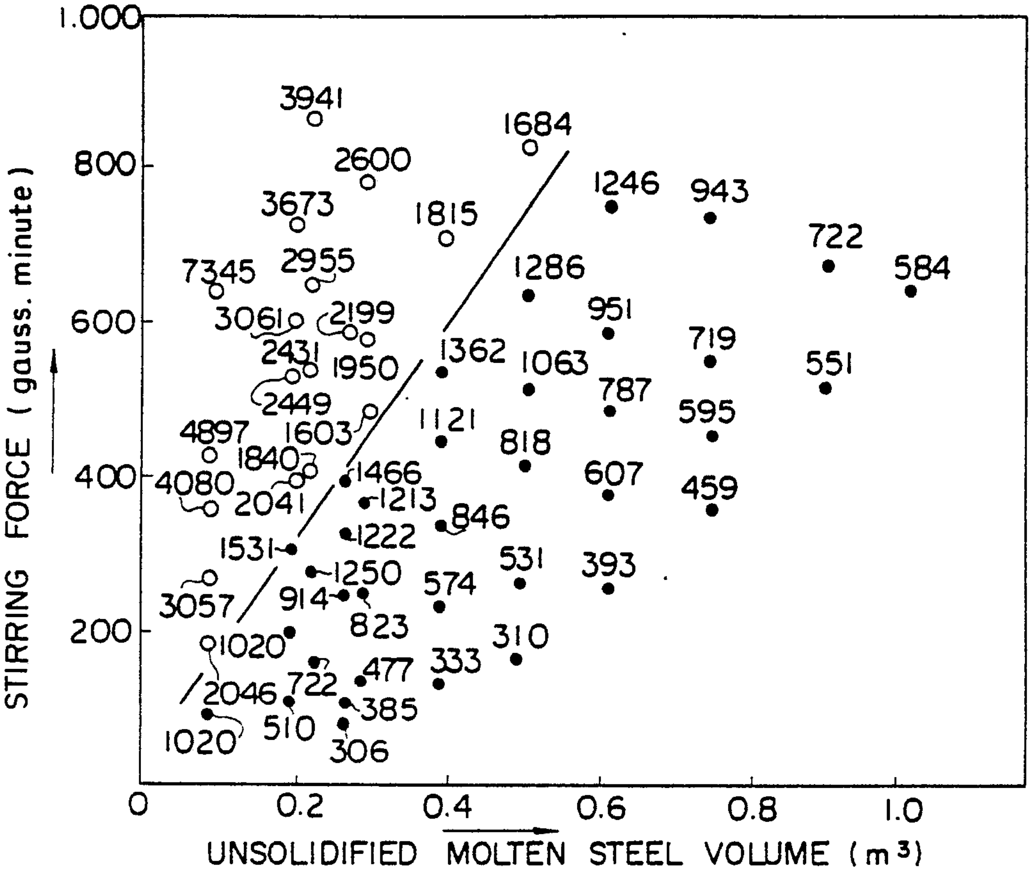


FIG. 8


1.000
800
600
400
200
0
0.2
0.4
0.6
0.8
1.0
STIRRING FORCE (gauss. minute)
UNSOLIDIFIED MOLTEN STEEL VOLUME (m³)
3941
1684
2600
1246
943
3673
1815
722
2955
1286
584
7345
3061
2199
951
719
2431
1950
1362
1063
551
2449
787
595
4897
1603
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818
1840
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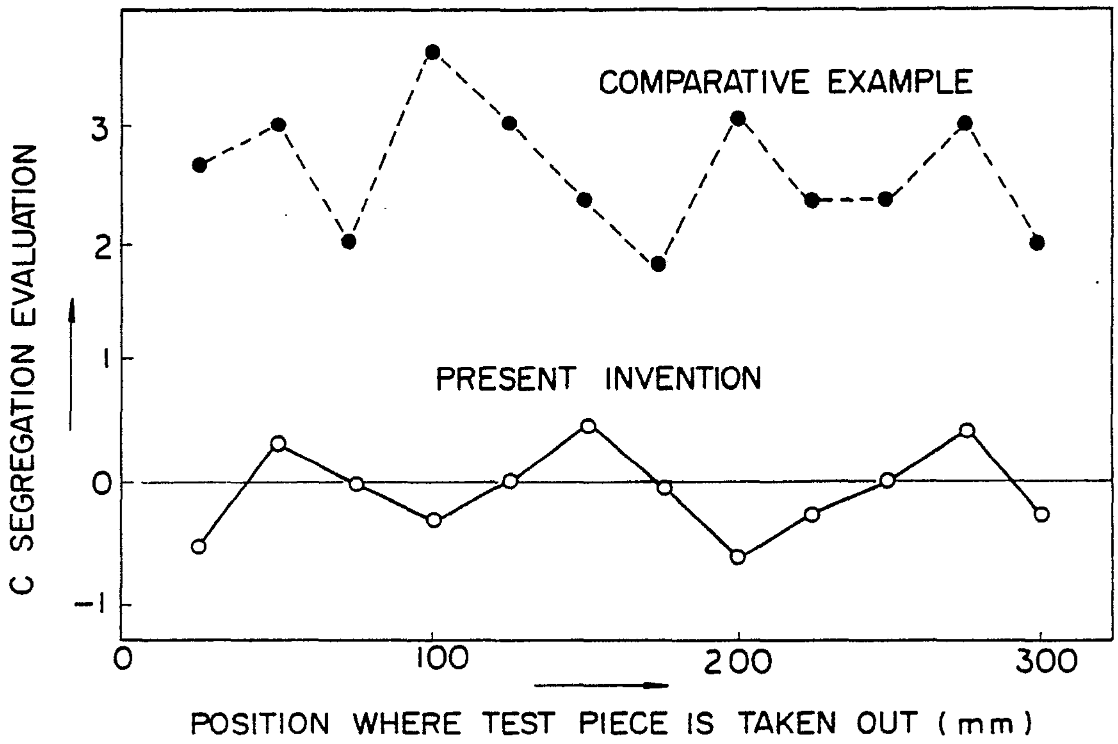
FIG. 9


COMPARATIVE EXAMPLE
PRESENT INVENTION
C SEGREGATION EVALUATION
3
2
1
0
−1
0
100
200
300
POSITION WHERE TEST PIECE IS TAKEN OUT (mm)