High-quality Work Roll Manufacturing Technology Using New Electro Slag Remelting (ESR)

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Because cold rolling requires work rolls of high quality in their surfaces and interiors, the rolls are generally made from electro-slag-remelting (ESR) ingots which ensure a stable outcome. In order to produce rolls with excellent dendrite pattern, a fine and uniform dendrite structure with no flow pattern is required. Segregation lines, which may appear as "freckles" on the roll surface, are sometimes generated in the ingots. Such segregation lines should not exist within the use depth of the rolls. In recent years, Kobe Steel has upgraded its ESR apparatus and achieved a significant improvement in the quality of the surface and interior.

Introduction

Work rolls are used for cold-rolling steel plates into thin sheets and have to meet demanding standards for their surface and interior quality. Thus, they are typically made from steel ingots produced by electro slag re-melting (ESR), ingots which can consistently provide the desired quality. To ensure high resistance to surface deterioration, the surfaces must have fine and homogeneous dendrite structures without flow patterns. Some ingots may have internal segregation lines, which can appear as "freckles" on their surfaces, depending on the type of steel. Such segregation lines must not exist in the effective use depth of the rolls. To meet such demanding quality requirements, Kobe Steel renewed its ESR apparatus in 2007 and has significantly improved the surface and interior qualities, as reported in this paper.

1. Method for making work rolls for cold rolling and characteristics required for rolls

The work rolls for cold rolling (hereinafter simply referred to as "work rolls") are made according to the following steps:

Melting by electric furnace (EF) → Refining in ladle furnace (LF) → Bottom teeming & Ingot making → ESR → Forging & Heat treatment → Machining
ESR is a type of re-melting technique which involves a target metal used as a consumable electrode, and a water-cooled mould holding a layer of molten slag, in which the slag layer conducts a large electric current and generates resistance heat to melt the electrode. The droplet of molten steel passes through the slag layer and sequentially solidifies into a steel ingot. The steel ingot thus obtained has a superior cleanliness and is used for high-value-added products such as work rolls and aircraft members.

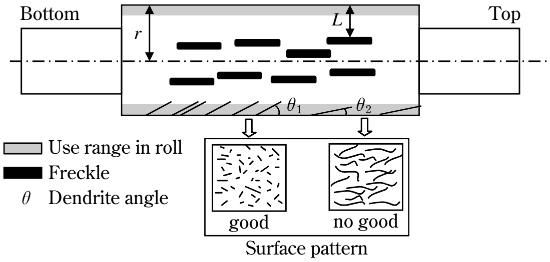


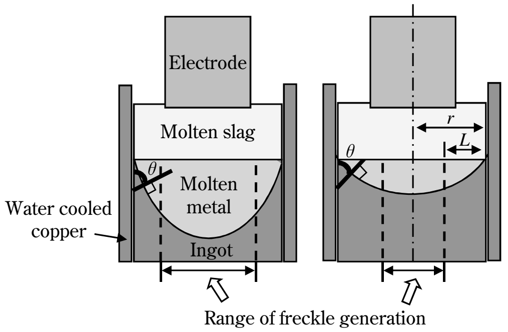
Fig. 1 Necessary quality for roll material

The quality of work rolls is largely affected by the quality of the steel ingots made by the ESR process. Here, the dendrite structure of the ingot surface must be fine and homogeneous, and, to prevent freckles, there should be no positive segregation of the additives in the steel within the use range (depth). Depending on the intended applications, the rolls have differing quality requirements. Tinplate roll for beverage cans especially requires fine and homogeneous dendrite structures on the rolls' surfaces. In addition to the stringent quality requirement for the surface, some such rolls are reworked for reclamation after use and must be free from freckles even after twice as deep a layer is removed from the surface, compared with other types of rolls.

In order to refine the structure of surface dendrite, a large enough angle must be retained between the mould wall and the dendrite growth direction in a steel ingot (the angle hereinafter referred to as "dendrite angle"). This dendrite angle enables the evaluation of the surface structure of rolls. The present paper uses dendrite angle θ as the evaluation index of the surface quality and depth of the freckled region (hereinafter referred to as freckled depth, L/r (L; the distance between the ingot circumference and the depth where freckles appear: r; steel ingot radius) as the evaluation indices of interior quality (**Fig. 1**). The following describes the improvement of these indices.

2. Relationship between dendrite angle and freckled depth

Dendrites grow vertically from the solidification interface in the pool of molten steel[1), 2)]. Thus, in order to increase the dendrite angle, the lateral face of the molten steel pool must be kept parallel to the mould surface as much as possible. In general, the higher the melting rate, the deeper the molten steel pool becomes, which increases the dendrite angle. Freckles, on the other hand, are caused by condensed molten steel floating up and being trapped in the solidified layer. Thus, the shallower the molten steel pool, the less likely they are to appear [3), 4)]. To maintain the pool of molten steel shallow enough, the melting rate must be kept low. In other words, there is a trade-off relationship between the dendrite angle and freckled depth: i.e., a higher melting rate results in a larger dendrite angle θ and shallower L/r, and vice versa (**Fig. 2**). **Fig. 3** shows the relationship between the dendrite angle θ and freckled depth (L/r). Here, the dendrite angle is defined by the average of the angles measured at the depth of 30mm from the steel ingot surface (assuming that the measured points will lie on the outer surface at the time of shipment) and the angle measured at the depth of 90mm (assuming that the points will lie on the outer surface at the time of disposal). This figure also indicates that controlling the melting rate alone cannot improve the dendrite angle and freckled depth at a time.



Melting rate	High	Low
Molten metal depth	Deep	Shallow
Dendrite angle (θ)	Big(good)	Small(no good)
Depth of freckled region (L/r)	Small(no good)	Big(good)

Fig. 2 Relationship between melting rate, molten metal depth, dendrite angle (θ), and depth of freckled region (L/r)

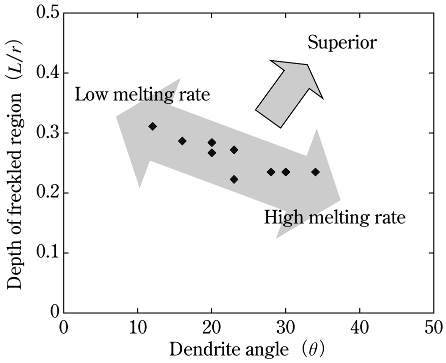


Fig. 3 Relationship between dedrite angle and depth of freckled region (L/r)

3. Decreasing thickness of slag skin

In addition to the melting rate, various other melting conditions can affect the quality of steel ingots made by ESR; e.g., flux composition, the amount of flux, electric current, voltage, cooling capacity of the mould and fill ratio. Aiming at improving both the dendrite angle and freckled depth simultaneously, Kobe Steel focused on the heat transfer of the slag skin formed between the ingot and water-cooled copper mould. A method was devised for thinning the slag skin to increase the cooling rate of the steel ingot and for making the lateral face of the pool of molten steel almost parallel to the mould surface to decrease the overall depth of the pool (**Fig. 4**).

The thickness of the slag skin is largely affected by the slag composition and immersion volume of the electrode. Thus, for thinning the slag skin, it is effective to use flux with a low melting point and/or to decrease the immersion volume of the electrode. Such a flux can be found in a $CaO-Al_2O_3-CaF_2$ series with high CaF_2 content. However, when used in an insulated system in which the mould and steel ingot are insulated from each other, the flux can result in arcing caused by the potential difference between the mould and steel ingot. Thus such flux cannot be used for the conventional apparatus. To enable the use of flux with such a low melting-point, the mould and steel ingot must have the same electrical potential (**Fig. 5**). The new ESR adopts a live mould which allows electrical conduction and enables the use of flux with a low melting point (1,290℃).

Immersing a large volume of electrode into the slag layer increases the amount of heat extracted by the electrode, which lowers the temperature of the slag layer and increases the thickness of the slag skin. Thus it is preferable to keep the immersion volume of

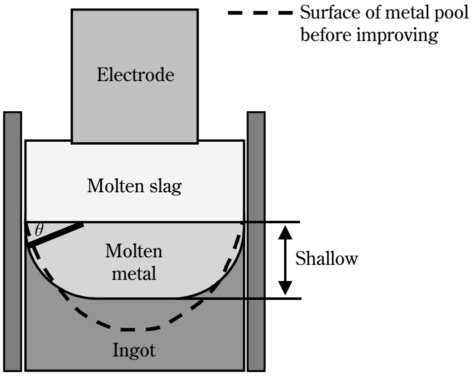


Fig. 4 Ideal shape of molten metal

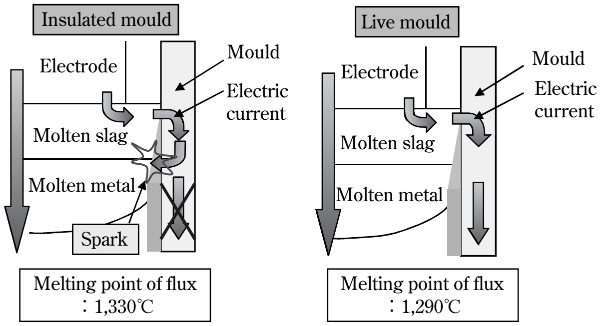


Fig. 5 Pattern diagrams of insulated mould and live mould in ESR melting

the electrode as small as possible. This was difficult to achieve in the conventional apparatus, in which the electrode was suspended by a wire with poor responsivity, making it difficult to precisely control the electrode position. In addition, the conventional electrode positioning system, involving voltage swing, suffered from difficulties caused by slag composition, electrical conductivity and slag volume, all of which change during the process. In addition, the changing lengths of electrode and ingot accompany changes in the impedance and voltage, causing difficulties. To avoid this, a resistance swing method was employed for the new electrode positioning (**Table 1**). **Fig. 6** summarizes these and other features of the ESR apparatus before and after the renewal.

Table 1 Electrode positoning control

	Conventional ESR	New ESR
Electrode positioning control	Voltage swing	Resistance swing
Electrode positioned by	Winch hoisting	Ball screw
Amount of immersion	10mm	1～3mm

4. Quality of steel ingots produced by new ESR

The following evaluates the quality of steel ingots produced by conventional and new ESR apparatuses and discusses the optimum operating conditions.

4.1 Experimental method

A steel ingot having an extra portion 500mm in length at the top was prepared by the new ESR. Specimens, as shown in **Fig. 7**, were prepared for macroscopic observation: i) a ϕ810×30mm transverse cross-section specimen; and ii) a 810×470×30mm longitudinal section specimen.

Among the segregation spots observed on the transverse cross-section specimen, spots having average diameters greater than 2mm were determined to be freckles, and their locations were recorded. The angles of dendrite growth directions were determined on the longitudinal section.

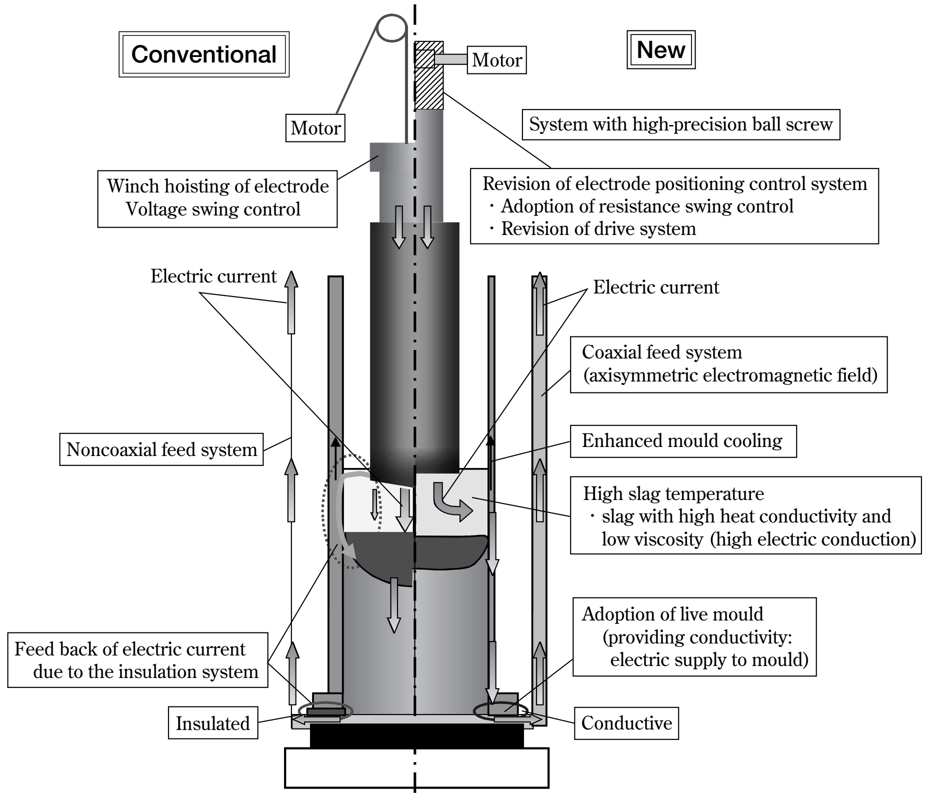


Fig. 6 Features of conventional and new ESR

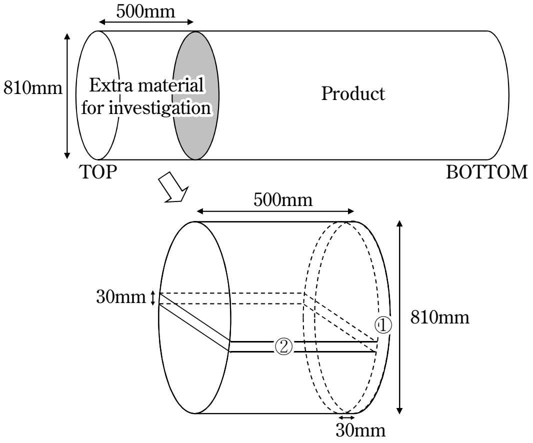


Fig. 7 Specimens for investigation of ESR

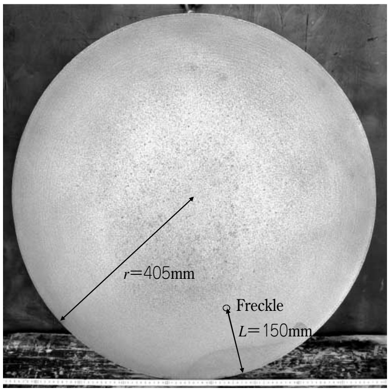


Fig. 8 Photograph of typical cross-sectional macro structure 〔Freckled region:150mm deep from the surface (L/r=0.370)〕

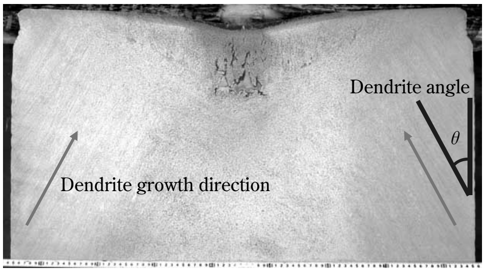


Fig. 9 Photograph of typical longitudinal sectional macro structure

4.2 Results

Fig. 8 and **9** show typical macroscopic structures observed on transverse and longitudinal cross-sections, respectively. **Fig.10** shows the relationships between the dendrite angle and freckled depth in the ingots prepared by the new and conventional ESR apparatuses, respectively. It should be noted that the new system has improved both the dendrite angle and freckle depth significantly compared with the conventional system.

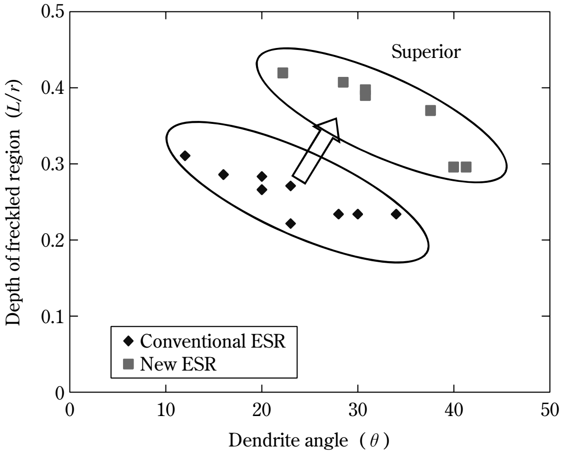


Fig.10 Relationship between dendrite angle (θ) and depth of freckled region (L/r) in the ingot produced by New ESR

5. Theoretical verification of improvement in internal quality of steel ingots

The present modification of the ESR apparatus has changed the conventional casting conditions, such as control method, slag composition, slag temperature, molten steel temperature, slag skin thickness and mould structure. Thus it is envisaged that the solidification profile has also been changed. To theoretically verify the quality improvement of the steel ingot achieved thanks to this modification, a numerical analysis (heat-transfer calculation) was conducted to determine the shape of the molten steel pool (i.e., dendrite angle). The calculation result was compared to the results for the steel ingot quality described in section 4.

An FEM program for solidification analysis, "Casting Analysis System" (CASTEM), developed by Kobe Steel[5)], was used for calculating the advancement of the solidification interface and the shape of the molten steel pool in the ESR. The CASTEM allows resolving thermal conduction equations in non-steady state, taking into account the release of latent heat during solidification, as follows:

$$\rho C\frac{\partial T}{\partial t}-\rho L\frac{\partial f_s}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)$$

wherein T represents temperature, t represents time, C represents specific heat, ρ represents density, L represents latent heat, f_s represents solid phase ratio and λ represents thermal conductivity.

Table 2 shows the physical properties used for the heat-transfer analysis. The melting rates were set to three conditions, i.e., 600kg/h, 700kg/h and 920kg/h. Since there is no measurement data for the melt temperature T (℃) at the surface of the molten steel pool, the melt temperature was calculated according to Formula (1). A slag temperature measured for a different type of steel produced by the

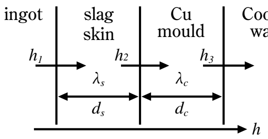
Table 2 Physical properties and experimental conditions used in heat transfer analysis

Liquid steel physical properties	Liquidus temperature	1,450℃		
	Solidus temperature	1,344℃		
	Heat conductivity	3.8×10^{-2}cal/(mm^2·s·℃)		
	Specific heat	0.17cal/g/K		
	Density	7.6×10^{-3}g/mm^3		
	Latent heat of solidification	65cal/g		
Coefficient of heat transfer	Ingot bottom	1.4×10^{-3}cal/(mm^2·s·℃)		
	Ingot side surface	2.7×10^{-4}cal/(mm^2·s·℃)		
Melting speed		600kg/h	700kg/h	920kg/h
Molten metal temperature		1,604℃+ α	1,628℃+ α	1,681℃+ α

conventional ESR was used for the calculation. Here, α represents a fitting parameter.

$$T\,(℃) = 0.24\times(\text{melting rate kg/h}) + 1460 + \alpha \cdots (1)$$

The overall heat transfer coefficient h between the lateral face of the steel ingot and the water-cooled copper mould was calculated using Formula (2) below.



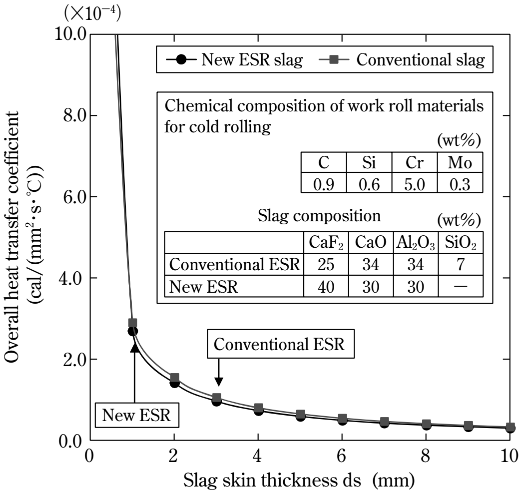
$$\frac{1}{h}=\frac{1}{h_1}+\frac{1}{\lambda_s/d_s}+\frac{1}{h_2}+\frac{1}{\lambda_c/d_c}+\frac{1}{h_3}\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Fig.11 shows the relationship between the slag skin thickness and overall heat transfer coefficient calculated under the above conditions. It appears that the slag skin thickness for the conventional ESR is approximately 3mm, while that for the new ESR is approximately 1mm, and the overall heat transfer coefficient is considered to have increased by approximately 2.5 times (**Table 3**).

Fig.12 shows examples of the metal pool shapes calculated. The calculation is based on a two dimensional axial symmetry model with the left side representing the ingot center and the right side representing the ingot surface. Each diagram includes metal pool shapes, which are determined by the temperature profiles of liquidus line and solidus line at given times.

Dendrite growth directions were calculated at the depth positions of 30mm and 90mm from the ingot surface, in the direction vertical to the molten metal pool determined by the profiles of the liquidus line. Dendrite angles are defined by the crossing angles between the dendrite growth directions and the ingot surface. The dendrite angles were determined by the average of angles obtained from the depth positions of 30mm and 90mm.

Fig.13 compares the calculated and measured



Chemical composition of work roll materials for cold rolling

(wt%)

C	Si	Cr	Mo
0.9	0.6	5.0	0.3

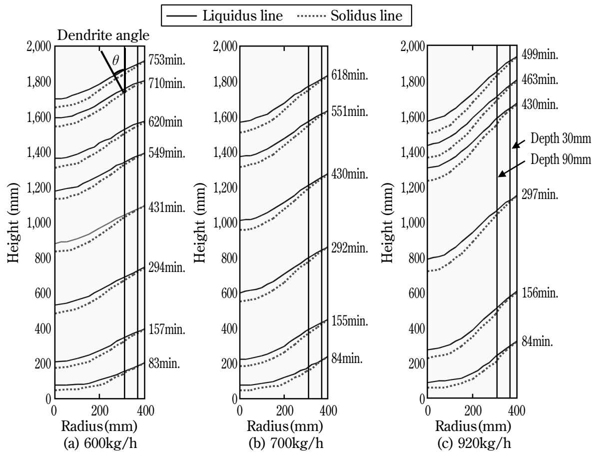
Slag composition (wt%)

	CaF_2	CaO	Al_2O_3	SiO_2
Conventional ESR	25	34	34	7
New ESR	40	30	30	—

Fig.11 Slag skin thickness and overall heat transfer coefficient

Table 3 Slag skin thickness and overall heat transfer coefficient

	Slag skin thickness (mm)	Overall heat transfer coefficient ($\times10^{-4}$cal/(mm^2·s·℃))
Conventional ESR	3	1.05
New ESR	1	2.68



(a) 600kg/h (b) 700kg/h (c) 920kg/h

Fig.12 Metal pool shapes at each melting speed (α =50℃)

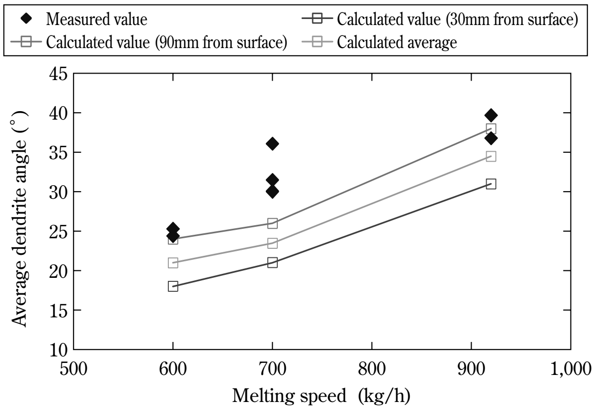


Fig.13 Calculated (Molten metal temperature α =0℃) and measured values of average dendrite angle

values of average dendrite angles. The figure indicates the difference between the calculated and measured values. It should be noted that the values in Fig.13 were calculated using the slag temperature measured for the conventional apparatus. The new apparatus is thought to have achieved a higher slag layer temperature (= molten metal temperature) as a result of the present renewal including the modification of electrode positioning control (employing a resistance swing control and a new electrode drive method), which decreased the immersion volume of the electrode.

Thus, the fitting parameter α in Formula (1) was set to 0℃, 50℃ and 100℃ to determine the molten metal temperature T (℃) at the pool surface for each condition. The dendrite angles were averaged for each condition and were compared to measured values as shown in **Fig.14** and **15** respectively.

The comparison with measured values indicates that, by setting α to a value in the range from 50~100℃, the calculated values for dendrite angles turn out to agree well with the measured values.

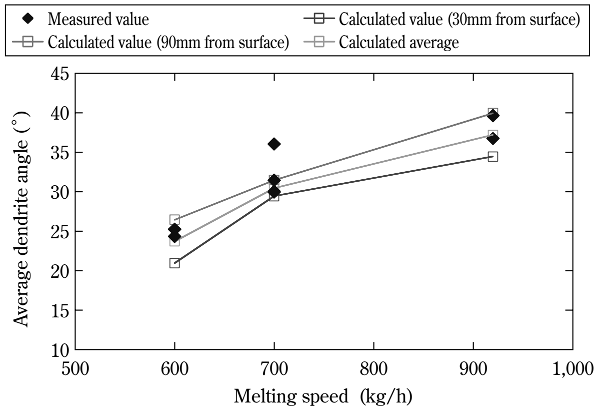


Fig.14 Calculated (Molten metal temperature α =50℃) and measured values of average dendrite angle

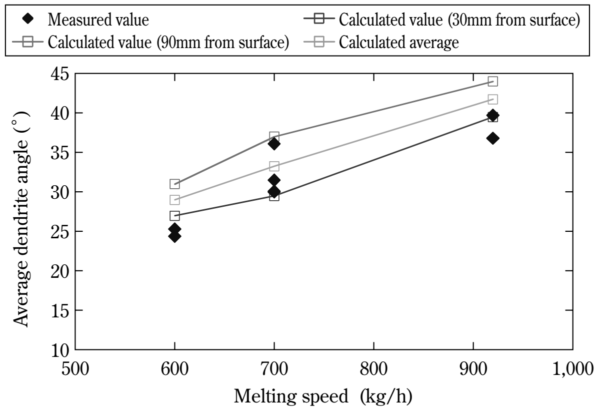


Fig.15 Calculated (Molten metal temperature α =100℃) and measured values of average dendrite angle

The above discussion indicates that the new ESR apparatus maintains the slag temperature 50~100℃ higher than the conventional apparatus. This produces a slag skin 1mm thick, which is less than the slag skin thickness of 3mm produced by the conventional apparatus. The thinner slag skin increases the cooling rate at the lateral face of the ingot, which improves the shape of the molten steel pool (Figure 4) and produces a steel ingot with a large dendrite angle and fewer freckle defects.

6. Summary

An ESR apparatus was renewed so as to produce high-quality rolls. The new apparatus was subjected to a study of the relationship between the melting conditions and the quality of the steel ingot interior. The following results were obtained:

(1) Significant improvements were obtained for the dendrite angle and depth of the freckled region in the new ESR, compared with the conventional one;
(2) the new ESR yielded a thinner slag skin of 1mm, as against the 3mm thick slag skin in the conventional ESR, and increased the overall coefficient of heat conduction by approximately 2.5 times; and
(3) the results of the studies on the quality of the ingot interior and solidification analysis indicate that the new ESR increased the slag temperature by 50~100℃, compared with the conventional ESR. It is contemplated that the higher slag temperature has enabled the thinning of the slag skin.

Conclusions

The quality evaluation and its results on the roll material produced by a new ESR apparatus have been outlined. The new apparatus further comprises an automatic melt control system which decreases the operator dependence of the outcome, enabling consistent production of high quality roll materials.

References

1) A. Suzuki et al., *Physical Chemistry of Electro Slag Remelting and Its Technical Issues* (1979), pp.132-133.
2) A. Masui et al., *Physical Chemistry of Electro Slag Remelting and Its Technical Issues*, pp.149-151.
3) H. Yamada et al., *Tetsu-to-Hagane*, No. 1 (1989), pp.97-104.
4) H. Yamada et al., *Tetsu-to-Hagane*, No. 1 (1989), pp.105-112.
5) T. So et al., *R&D KOBE STEEL ENGINEERING REPORTS*, Vol. 37, No. 4 (1987), pp.99-100.