CONTROL OF COLUMNAR-TO-EQUIAXED TRANSITION IN CONTINUOUS CASTING OF 16% Cr STAINLESS STEEL

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In continuous casting of 16%Cr ferritic stainless steel, columnar grains undesirably forming among equiaxed grains make non-uniform microstructure and degrade ridging property. Since this phenomenon results from the change of solidification condition during continuous casting, we focused on Cellular-to-Equiaxed Transition (CET) in continuous casting of 16%Cr ferritic stainless steel to control the microstructure of as-cast slab. In order to find the CET condition, we carried out the one dimensional heat transfer analysis of the melt, and predicted the CET condition by Hunt's model. It was revealed that the secondary columnar grains usually formed at 0.5~0.8 solid fractions, and the formation of them resulted from a steep increase of G/V1/2 value as the melt was getting out of EMS field; however the increase of G/V1/2 was readily controlled by changing EMS pattern and the secondary cooling intensity. In result, secondary columnar grains were eliminated by optimizing the upper and lower EMS intensity, and increasing secondary cooling intensity. We also investigated the effect of solidification parameters including superheat and casting speed as CET condition in continuous casting process, and the results were also discussed by the terms of thermal condition of melt.

KEYWORDS: Ferritic stainless steel, continuous casting, ridging, columnar-to-equiaxed transition (cet), secondary columnar structure, solidification parameters

INTRODUCTION

Recently, market demand of austenitic stainless steel has been in stagnation due to higher Ni price in contrast to higher market demand of cheaper ferritic stainless steel with superior anti-stress-corrosion property. However, ferritic stainless steel is inferior to austenitic stainless steel in anti-corrosion and forming properties, so many engineering attempts are focused on developing new ferritic stainless steel and production technique, and improving material quality.

In particular, ridging defect has been typical problem in forming process of ferritic stainless steel and it is the surface defect resulting from the plastic anisotropic difference between recrystallized and non- recrystallized structure[1,2], which is originated from the non-uniform microstructure made in continuous casting process[3]. Recent efforts have focused to increase equiaxed crystal ratio by restraining columnar grains based on the research, showing that anti-ridging properties showed significant improvement at about 40% of the equiaxed crystal ratio (ECR) in as-cast slab[4-7].

There were several ways to increase ECR in 400 type STS, for example, making the preferred condition for equiaxed growth by increasing constitutional undercooling or by increasing heterogeneous nucleation sites. This study focused on the solidification parameters to control the microstructure of as-cast slab for increasing ECR. Typical macro-structure of as-cast slab of 16%Cr stainless steel exhibited in the order of 'columnar-equiaxed-secondary columnar-equiaxed' after surface chill layer as shown in Fig. 1. In particular, reappearance of columnar structure (C2) shown among equiaxed regions is problem, because

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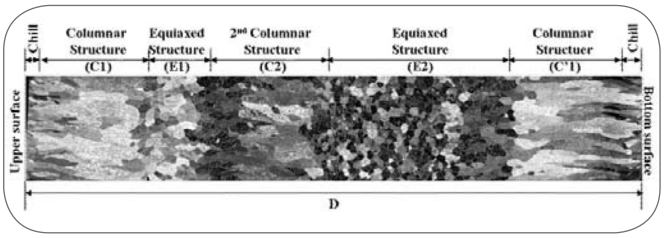

▲ *Fig. 1*

Typical macrostructure obtained in slab section of 16Cr stainless steel.

Macrostruttura tipica ottenuta nella sezione di bramma di acciaio inossidabile 16Cr.

Slab Thickness	Superheat	Casting Speed	2^{nd} cooling intensity	EMS Intensity	
				Upper	Lower
200~220 mm	*15~50*	*0.7~1.0 m/min*	*0.5~1.5 l/kg*	*0~1300A*	*1300 A*

Tab. 1

Experimental conditions for continuous casting of 16Cr stainless steel.

Condizioni sprimentali per la colata continua dell'acciaio inossidabile 16Cr.

the secondary columnar structure provokes non-uniformity of macro-structure, contributing the ridging defect somewhat. Thus, it is necessary to identify the forming condition of secondary columnar structure and find out the solution to prevent them from generating.

In addition, electromagnetic stirring (EMS) technology has been applied to ensure not only homogenous macro-structure, but equiaxed grain structure[8]. The main role of EMS is to redistribute heat and solute in the molten steel by inducing forced convection and it results to give significant influence on the formation of equiaxed crystal. Moreover, the optimum function of EMS comes from harmony with casting conditions. Therefore, we investigated the correlation between EMS and solidification condition, and found out the optimum condition for maximizing ECR considering CET condition.

EXPERIMENTAL METHOD

The conditions of continuous casting and EMS of 16Cr stainless steel are shown in Tab. 1. In this study, two parts of EMS were applied, upper part to control solidification condition at the early stage of solidification and lower part for the control at midterm stage.

Each part of EMS was controlled independently and the effect of the pattern of EMS was investigated, which is the combination of EMS power at upper and lower part, on CET condition. After continuous casting, slab samples were cut at the location of 1/4 and 1/2 of the slab width in the thickness direction, and macro structure are examined. Evaluation of equiaxed crystal ratio is defined in Eq. (1) as the ratio of equiaxed zone to total thickness of slab. The symbols in equation 1 are noted in Fig. 1. The variation of ECR is defined as ECR index based on the averaged value of ECR without EMS at the casting speed of 0.9m/min.

$$ECR(\%) = \frac{\left[Sum\ of\ equiaxed\ dendrite\ region,\ \sum(E1+E2)\right]}{\left[Slab\ thickness,\ D\right]}\times 100 \qquad (1)$$

RESULTS

Effect of superheat

Fig. 2 shows the variation of ECR as the degree of superheat. The increase of superheat resulted to decrease ECR. However, it was shown that superheat effect became weak as EMS was applied.

Effect of casting speed

The effect of casting speed to ECR was similar to the cases with/without the EMS application. As the casting speed increase from 0.8m/min to 0.9m/min in Fig. 3, ECR was decreased by 5% in average.

Effect of EMS pattern

The effect of EMS pattern was examined by changing the power intensity of upper and lower electromagnetic stirrer independently. Fig. 4 shows that higher ECR existed at the condition of low or no power of upper electromagnetic stirrer, in contrast to lower ECR at strong power at

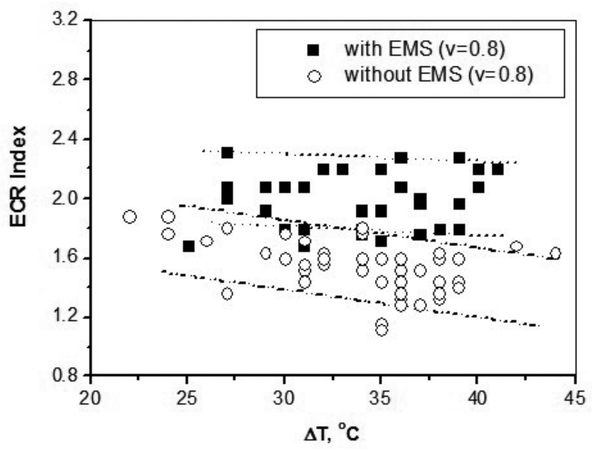

Fig. 2

Effect of superheat in Tundish on ECR.

Effetto del surriscaldamento nella paniera.

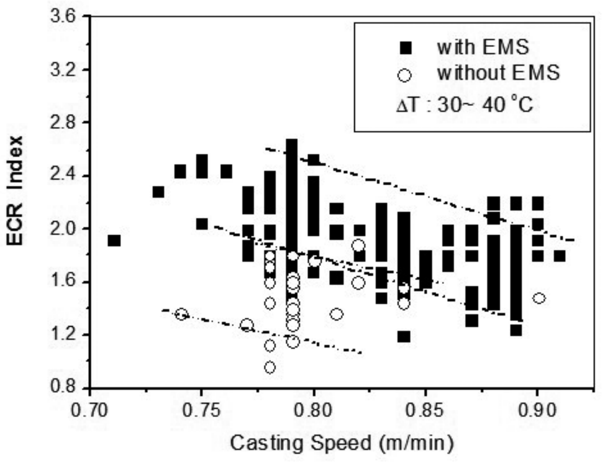

Fig. 3

Effect of casting speed on ECR.

Effetto della velocità di colata sull' ECR.

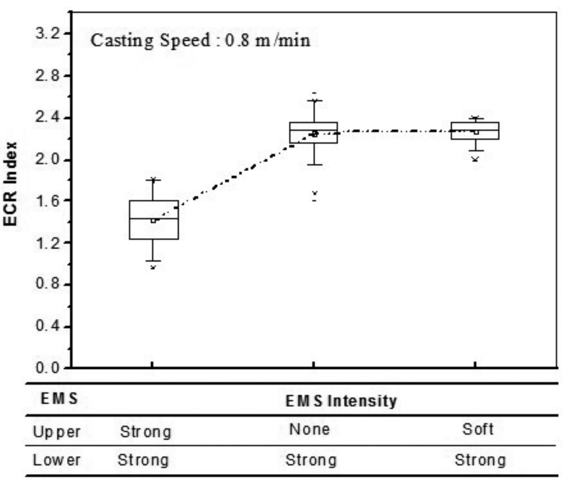

Fig. 4

Effect of EMS pattern and intensity on ECR.

Effetto di schema e intensità dell'EMS sull' ECR.

both electromagnetic stirrers when the lower electromagnetic stirrer was applied same power for both cases. In addition, the combination of high power at upper electromagnetic stirrer and low power at lower one gave lower ECR.

Effect of secondary cooling intensity

ECR increased by 20% when the secondary cooling condition was changed from soft to strong cooling condition (Fig. 5). The previous study showed that there was no significant change of ECR at strong cooling condition [5], but this work showed obvious effect of the secondary cooling condition. This result may originate from the strong relation between CET and secondary cooling condition.

DISCUSSION

Forming mechanism of secondary columnar structure

Many theories were reported for the transition from columnar to equiaxed structure, and also there have been many researches for the prediction of microstructure based on constitutional undercooling theory [9], which was referred to this analysis. Growing columnar grains capture or push equiaxed grains and continuously grow when the number of generated equiaxed grains was small, but they will be suppressed by equiaxed grains occupying remained liquid phase when the volume of equiaxed grains is larger than the specific value to the liquid phase volume. J.D. Hunt suggested the transition condition from columnar to equiaxed structure as CET model [10], and the condition is defined as below,

$$G < 0.617 N_0^{-1/3}\left[1-\left(\frac{\Delta T_N}{\Delta T_C}\right)^3\right]\Delta T_C \qquad (2)$$

where, G is the temperature gradient at the dendrite tip, N0 is the nucleation density of delta ferrite (mm-3),   is the constitutional undercooling at the dendrite tip, and

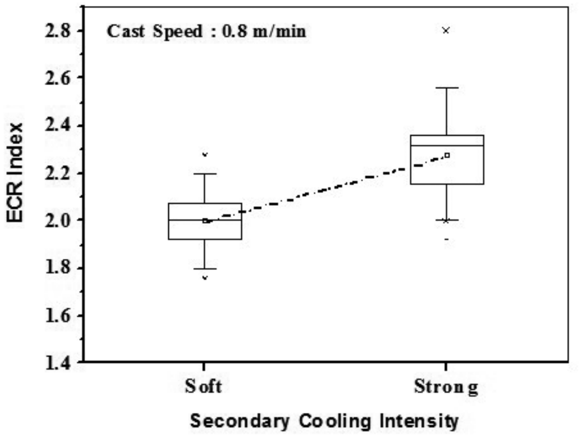

Fig. 5

Effect of secondary cooling intensity on ECR.

Effetto dell' intensità di raffreddamento secondario sull' ECR.

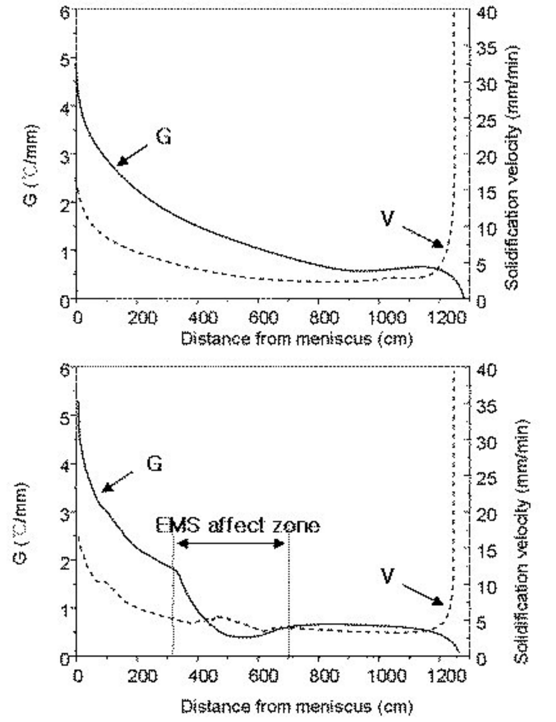

Fig. 6

Change of growth condition during casting (a) without EMS (b) with EMS.

Cambiamento delle condizioni di crescita durante la colata (a) senza EMS (B) con EMS.

is the undercooling for nucleation. With the assumption of   is much smaller than , the Eq. (2) can be simplified as below[6], and it can be expressed by measurable parameters, i.e. temperature gradient and growth rate.

$$\frac{G}{V^{1/2}} < 0.617 N_0^{-1/3}[C_0/A]^{1/2}$$
$$A = D/[8m(k-1)\Gamma] \qquad (3)$$

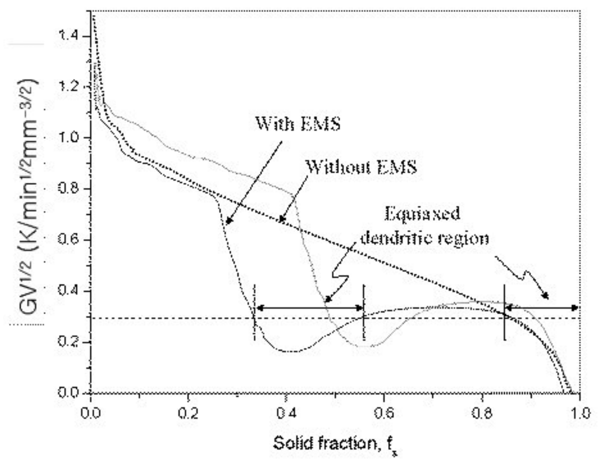

Fig. 7

Effect of EMS on $G/V^{1/2}$ with solid fraction.

Effetto dell'EMS su $G/V^{1/2}$ con frazione solida.

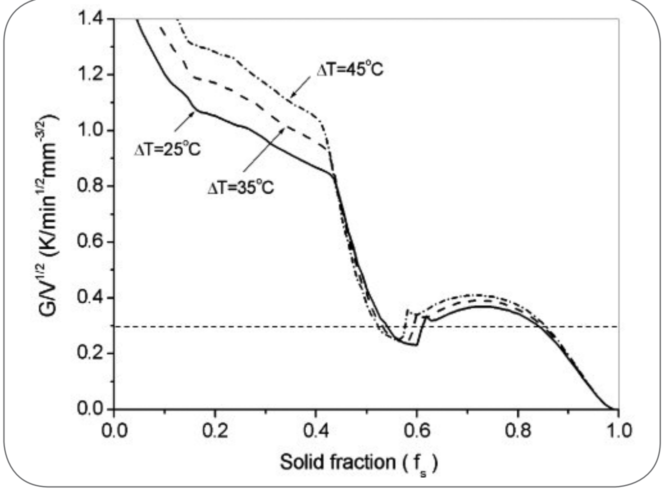

Fig. 8

Effect of superheat on $G/V^{1/2}$ with solid fraction.

Effetto di superheat su $G/V^{1/2}$ in relazione alla frazione solida.

where, V is the growth rate at the dendrite tip, D is the diffusivity of molten steel, C0 is the initial concentration of liquid phase, k is the effective distribution coefficient, and Γ is the Gibbs-Thomson constant.

To predict CET condition based on Eq.(3) in actual continuous casting process, it is necessary to predict temperature gradient and growth rate. In this study, one-dimensional heat transfer simulation was carried out in continuous casting process, and it was enabled to predict temperature gradient and solidification speed at the specific location.

Fig. 6 shows temperature gradient and growth rate at the given point with and without EMS application. Temperature gradient without EMS is about 5°C/mm at the early stage of solidification, and becomes smaller as the solidification proceeds (Fig. 6a). In the case of EMS application(Fig. 6b), steep drop to smaller temperature gradient and increase of growth rate were observed in the region of EMS applying, and higher temperature gradient and decrease of growth rate were observed outside of EMS field.

The variation of G/V1/2 with solid fraction was calculated by applying temperature gradient and growth rate variation to Eq.(3). The area with stable columnar structure exists in the case of higher G/V1/2 than critical value, and equiaxed growth is more stable when the value of G/V1/2 is lower than critical value. The critical value of CET is a criterion to define stable equiaxed region, and 0.3 is acquired in this study by comparing calculated G/V1/2 with real macrostructure of as-cast slab. The obtained value in this study is similar to the results of other researchers [6].

Without applying EMS, grains grew as columnar structure until the last stage of solidification (fs=0.9), thereafter CET occurred as shown in Fig. 7. On the other hand, CET occurred after fs=0.3 with EMS, and transition to columnar structure occurred again at fs=0.55 with good agreement with observed value from real macrostructure of as-cast slab at both cases.

From the results, it can be explained why secondary columnar structure generates, as follows. Strong convection occurs in the region of EMS application, resulting to lower temperature gradient at the growing interface. It brings steep decrease of G/V1/2 value, which gives the condition for equiaxed grain generation and CET occurs. However, temperature gradient and growth rate at the S/L interface will be recovered when the melt leaves the EMS field; accordingly secondary columnar structure develops again due to the change of growth condition.

Effect of casting condition on CET

In order to increase ECR, two concepts were applied in this study. One is to suppress the generation of secondary columnar structure and the other is to make the condition of the equiaxed crystal generation at early stage of solidification. Based on this model, it was able to predict the

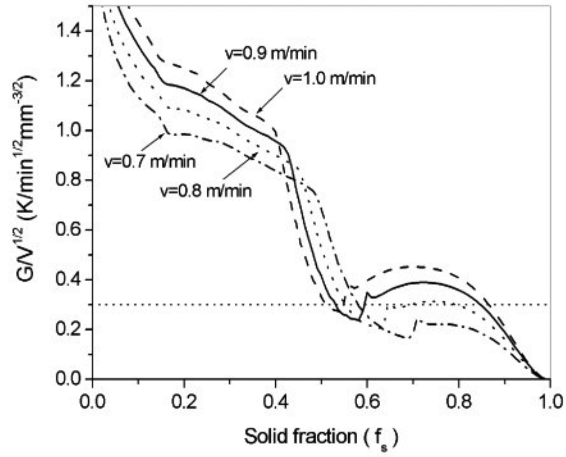

Fig. 9

Effect of casting speed on $G/V^{1/2}$ with solid fraction.

Effetto della velocità di colata su $G/V^{1/2}$ con frazione solida.

macrostructure of as-cast slab from calculated results and these were compared with experimental one.

Effect of superheating

Fig. 8 shows the variation of G/V1/2 as superheat. With higher degree of superheat, the G/V1/2 value has larger one in the initial solidification, but the superheat effect becomes weak as the solid fraction increases. The area of secondary columnar structure generation becomes narrow as superheat decreased even though the effect is not significant. It corresponds with the results that the effect of superheat on the variation of CET is not dominant with EMS application.

The effect of casting speed

As shown in the experimental results, it was obvious that the effect of casting speed was significant to CET condition. With increase of casting speed, the growth of columnar dendrite in the early stage of solidification is suppressed due to increase of heat transfer to the mold, resulting to have shorter primary columnar grains with assumption of same CET condition.

However, the increase of casting speed enlarged the area of secondary columnar structure as shown in Fig. 9, which brings totally smaller ECR. It is estimated that the critical casting speed for free-secondary columnar structure is 0.8m/min at given conditions.

Fig. 10 shows the forming range of secondary columnar structure with superheat at tundish. The secondary columnar structure existed between 0.6~0.9 for solid fraction, which correspond with the value of 65~90mm of observed sample, improving the reliability of calculated results. Hence, decrease of ECR with increasing casting speed is originated from the expansion of secondary columnar region, so it is required to decrease temperature gradient for restrain of columnar growth.

Effect of secondary cooling condition

Fig. 11 shows the variation of G/V1/2 with secondary cooling condition. In the condition of 0.9m/min growth rate and soft cooling condition, early generation of secondary columnar grains was observed with broader area.

Increase of cooling intensity at the same growth condition delayed generation of secondary columnar grain and it can be explained from Fig. 11.

Temperature distribution of liquid phase describes a polynomial decay of G/V1/2 as the increase of solid fraction as shown in Fig. 11. With applying EMS, temperature distribution becomes uniform by forced convection in EMS field resulting to lower temperature gradient; thereafter temperature decreased steeply again when the melt got out of EMS field and columnar growth is to be preferred due to the increase of temperature gradient.

In this condition, increase of cooling rate at the same EMS pattern brings overall decrease of melt temperature; in particular, temperature gradient at the outside of EMS field will be smaller by having rather low melt temperature. As a result, the generation of secondary columnar grains can be delayed; moreover lowering casting speed helps to suppress secondary columnar growth.

In the experimental results, the secondary columnar growth was completely restrained by applying strong cooling intensity at 0.8m/min casting speed and sound slabs having higher ECR over 60% were able to obtain. Briefly, to suppress the secondary columnar grains completely, it is proposed to optimize secondary cooling condition in the V, VI region, in which secondary columnar grain used to generate as shown in Fig. 11.

CONCLUSION

In this study, parametric study was performed such as EMS, casting condition, and secondary cooling to increase equiaxed crystal ratio of as-cast slab in ferritic stainless steel, and the following conclusion was derived.

The secondary columnar grains, decreasing equiaxed crystal ratio, was observed in the area of absence of EMS stirring(6~10m from the meniscus), in which the growth

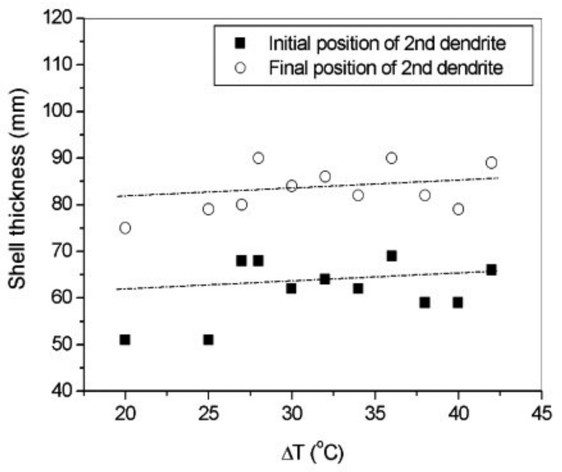

Fig. 10

Forming range of secondary columnar structure.

Range di formazione della struttura colonnare secondaria structure.

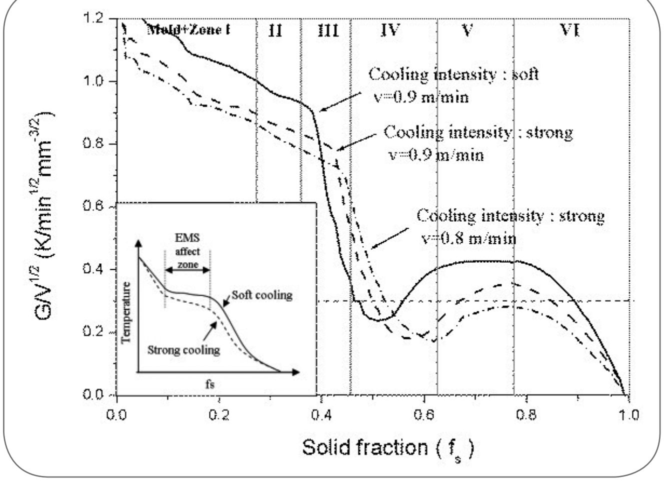

Fig. 11

FEffect of secondary cooling intensity on $G/V^{1/2}$ with solid fraction.

Effetto dell'intensità di raffreddamento secondario su $G/V^{1/2}$ in relazione alla frazione solida.

condition of dendrite transits from equiaxed to columnar manner as increasing temperature gradient and decreasing growth rate, resulting to the generation of secondary columnar structure.

With EMS application, effect of superheat on CET condition is no longer significant. On the other hand, decrease of casting speed effectively restrained the generation of secondary columnar grains having a tendency increase the equiaxed crystal ratio. In addition, strong secondary cooling was another way to increase equiaxed crystal ratio, enabling to suppress columnar grains completely at 0.8 m/min casting speed. For the EMS pattern effect, it is observed that secondary columnar grains were promoted with application of high power of upper electromagnetic stirrer due to increase of melt temperature by flow pattern and the optimum combination of EMS pattern for higher equiaxed crystal ratio is low power of upper electromagnetic stirrer and full power of lower one.

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ABSTRACT

CONTROLLO DELLA TRANSIZIONE COLONNARE-EQUIASSICO NELLA COLATA CONTINUA DELL'ACCIAIO INOSSIDABILE 16% CR

Parole chiave: acciaio, colata continua, solidificazione

Nella colata continua dell' acciaio inossidabile ferritico 16% Cr, gli indesiderabili grani colonnari che si formano tra i grani equiassici rendono la microstruttura non uniforme e compromettono le proprietà di "ridging". Poiché questo fenomeno deriva dal cambiamento delle condizioni di solidificazione durante la colata continua, si è concentrata l'attenzione sulla Transizione Cellulare-Equiassico (CET) nella colata continua dell' acciaio inossidabile ferritico 16% Cr per controllare la microstruttura della bramma "as-cast". Per trovare la condizione CET, nello studio è stata effettuata una analisi del trasferimento di calore monodimensionale del metallo fuso, e una previsione della condizione CET secondo il modello di Hunt. Si è osservato che i grani colonnari secondari - solitamente presenti in ragione di una frazione tra 0,5 e 0,8 - e la loro formazione sono il risultato di un brusco aumento del valore G/V1/2 al momento dell'uscita del metallo fuso dal campo EMS; tuttavia l'aumento del valore G/V1/2 è stato prontamente messo sotto controllo cambiando la configurazione dell'EMS e aumentando l' intensità di raffreddamento secondario. In conclusione, i grani colonnari secondari sono stati eliminati ottimizzando l'intensità superiore e inferiore di EMS e aumentando l'intensità di raffreddamento secondario. Si è inoltre investigato l' effetto dei parametri di solidificazione inclusi il surriscaldamento e velocità di colata in termini di transizione CET nel processo di colata continua, e i risultati sono stati anche discussi in termini di condizione termica di colata.