Effect of electromagnetic stirring on solidification structure of austenitic stainless steel in horizontal continuous casting

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Abstract: An investigation on the influence of low frequency rotary electromagnetic stirring on solidification structure of austenitic stainless steel in horizontal continuous casting was experimentally conducted and carried out on an industrial trial basis. The results show that application of appropriate electromagnetic stirring parameters can obviously improve the macrostructure of austenitic stainless steel, in which both columnar and equiaxed grains can be greatly refined and shrinkage porosity or cavity zone along centerline can be remarkably decreased due to eliminating intracrystalline and enlarging equiaxed grains zone. The industrial trials verify that the electromagnetic stirring intensity of austenitic stainless steel should be higher than that of plain carbon steel. Electromagnetic stirring has somewhat affected the macrostructure of austenitic stainless steel even if the magnetic flux density of the electromagnetic stirring reaches 90 mT (amplitude reaches 141 mT) in average at frequency f=3–4Hz, which provides a reference for the optimization of design and process parameters when applying the rotary electromagnetic stirrer

Key words: horizontal continuous casting; austenitic stainless steel; electromagnetic stirring; equiaxal grain; center porosity

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Horizontal continuous casting was originated in the 1970s and applied to produce non-ferrous metal firstly. Afterward, it was developed rapidly to apply to production of ferrous metal. Now industrialization of common steel and special steel produced by horizontal continuous casting has been realized [1-2], but owing to the lower thermal conductivity of austenitic stainless steel (much smaller compared with that of plain carbon steel), pronounced defects during horizontal continuous casting of austenitic stainless steel, such as coarse columnar and equiaxed zones, and centerline porosity, significantly have a negative influence on the microstructure and mechanical property of finished products.

A widely used technique in metallurgy is the inductive drive of molten metals using rotational or traveling magnetic fields. Recently rotary electromagnetic stirring has been applied to continuous casting steel, molding and solidifying of casting, and purifying of liquid melt, which has been more attractive to professionals in materials field. Successful fruits in both technology development and theoretical study have been achieved. Electromagnetic stirring (EMS) of steel in the continuous casting billet and slab is a well established technique for improving the quality of cast products [3-5] and is becoming widespread in industry. However, very few literatures on the effects of EMS on casting austenitic stainless steel have been reported. The aims of the present article are as follows: (a) to systematically study the effect of intensity and frequency of EMS on the solidification structure of austensitic stainless steel; (b) to discuss the mechanisms of electromagnetic stirring on solidification of casting billet.

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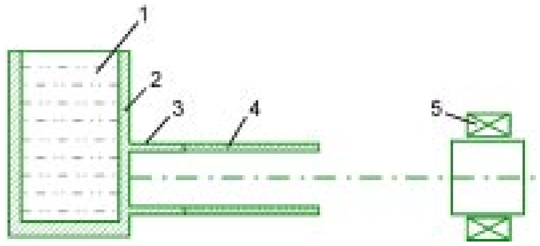
1 Experimental procedure

1.1 Experimental apparatus

The experimental equipment consist of 10 t tundish, rotary EMS, and mold. Rotary EMS with inside diameter of 325 mm, outside diameter of 800 mm and length of 450 mm was installed beneath the mold (from 1 900 mm mold exit). The mold consists of copper portion with length of 200 mm and a wall thickness of 8 mm and graphite portion with a length of 1 000 mm. The frequency of rotary EMS is modulated in the range of 0 to 10 Hz. The current of EMS is modulated in the range of 0 to 300A. The schematic diagram of the experimental apparatus is shown in Fig 1.



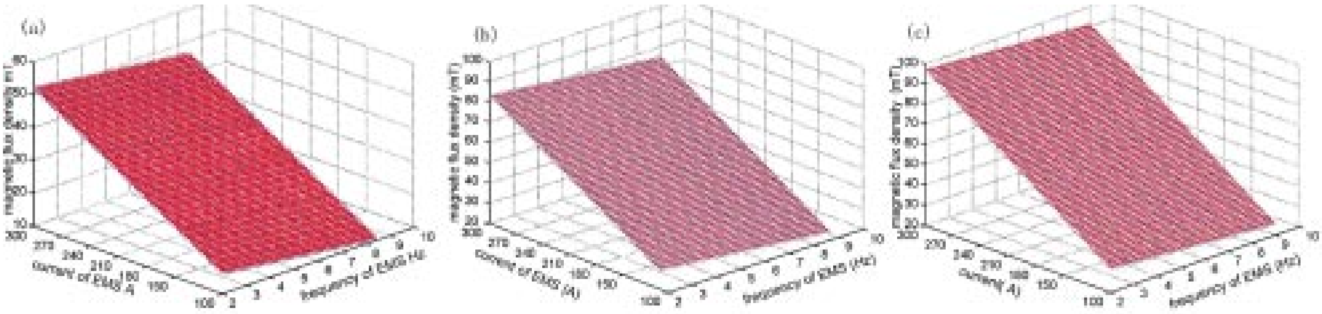
1. Stainless steel liquid, 2. Tundish, 3. Copper mould, 4. Graphite mould, 5. Rotary EMS

Fig. 1 The schematic diagram of the experimental apparatus

1.2 Measurements and analyses

The positioning of the EMS is critical. Proper position of EMS can greatly improve the effect of stirring on the quality of billet at a given kVA input, so it is important to consider the evolutions of magnetic flux density varied with frequency and current. Magnetic flux density is measured within copper mold and graphite mold and beneath mold (from 1 900 mm mold exit) with different frequency and current by moving rotary EMS respectively, and the measurement result of magnetic flux density is shown in Fig. 2.

Figure 1 shows that, at a given kVA input and stirrer diameter, the attenuation of magnetic flux by the mold increases with the increasing of its electrical conductivity such as copper and graphite, which will cause the losses of magnetic flux density to increase. According to actual measurement result with respect to magnetic flux density and shell thickness at the mold exit, the position beneath mold (from 1 900 mm mold exit) is suitable for EMS, where shell thickness is 15 mm or so.



(a) In copper mold (b) In graphite mold (c) From 1 900 mm mold exit

Fig. 2 Evolutions of magnetic flux density with frequency and current

2 Experiment results

The stainless steel was refined and then poured into a tundish, and then, the Φ 180 mm and 150 mm × 150 mm billets were produced. To assess the effects of EMS on the macrostructure of austenitic stainless steel more accurately, a plant trial was performed with two strands cast at the same time with EMS and without EMS, separately, by applying casting speed of 1.0–1.4 m/min and superheat value of (50 ± 5)℃.

2.1 Macrostructure of direct chill and electromagnetic stirring billet

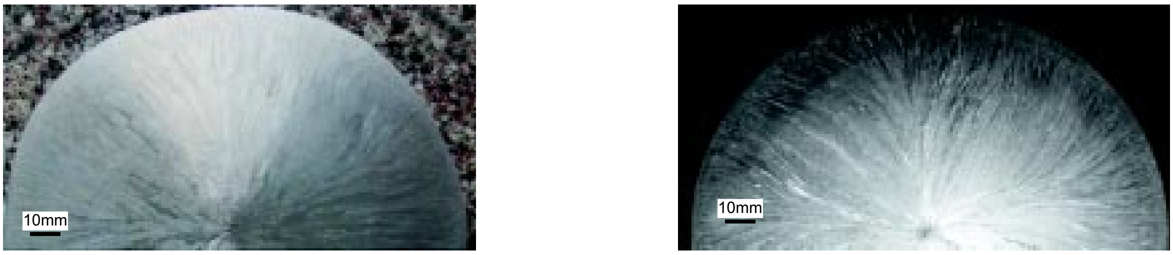
From the results of all the experiments, it is noticed that the macrostructure of the billets with the electromagnetic stirring is finer than that of the billets with direct chill process. Figure 3(a) shows the coarse macrostructure of direct chill billet. Apparently, the macrostructure are characterized by coarse columnar grains, shrinkage cavity and columnar grains spreading over the almost entire of billet. As contrast, casting under an electromagnetic field, however, the macrostructure of the billet is dominated by fine columnar and equiaxed grains as shown in Fig3(b,c and d). In addition, EMS reduces centerline porosity and shrinkage cavity and eliminate intracrystalline.

2.2 Effect of magnetic flux density on the macrostructures

Because the macrostructures of EMS billets are with fine columnar and equiaxed grains as shown above, the macrostructures of the billets, in cross-section only, produced at various magnetic flux density are reported. Fig.3 (b, c and d) show the transition from very coarse columnar grains to finer columnar and to equiaxed grains as the magnetic flux density increasing from 0 mT to 70 mT. But, when the magnetic flux density reaches to a certain degree such as 90 mT, the grain morphologies show apparent alternations, somewhat like the grains of the direct chill billets as shown in Fig. 3 (b and d).

(a) B=0 mT f=0 Hz, Φ=150 mm

(b) B=68 mT f=5 Hz, Φ=180 mm



(c) B=70 mT f =7 Hz, Φ =180 mm

(d) B=90 mT f =3 Hz, Φ =180 mm

Fig. 3 Macrostructure of roughcast cross sectional view

3 Discussions

3.1 Effect of intensity and frequency of magnetic field on solidification structure

Generally, solidification in the study leads to two types of grain morphologies: columnar and equiaxed. Heat flows from the crystal into the undercooled melt (temperature gradient G<0) and growth is generally equiaxed. Heat flows from the superheated melt into the cooler mold (G>0) and growth is generally columnar [6]. According to solidification theory [7], the driving force for crystallization is:

$$\Delta G \approx \frac{\Delta H_m \Delta T}{T_m} \qquad (1)$$

and the degree of solute supercooling is:

$$\Delta T_c = \frac{mc_0(1\text{-}k)}{k}(1\text{-}e^{-\frac{Rx}{D}})\text{-}Gx \qquad (2)$$

Where, ΔT_c is the degree of supercooling, ΔH_m is solidification latent heat, k is alloy constant, m is liquidus slope, R is growth rate, G is temperature gradient ahead of the solidification front, c_0 is solute concentration, D is solute diffusion coefficient (in liquid).

According to equation (1) and (2), with the decreasing of G, ΔT_c and ΔG will increase. Therefore, temperature gradient (G) directly influences the types of grain morphologies. As shown in Fig3 (a), the solidification structure at the cross section of the billet without EMS is coarse columnar grain. This is mainly due to considerable temperature gradient (G) at the interface in mold. The Fig3 (b, c and d) is different for the magnetic flux density of EMS. The result suggests that the magnetic flux density of EMS has obvious effect on the solidification structure.

Under the effect of the alternative current, the inductor generates a variable magnetic field in the melt, which, in turn, gives rise to a type of induced current as well as an electromagnetic volume force. The force consists of two parts: the horizontal component and the vertical component. The vertical component of electromagnetic volume force is a rotational force derived from the inclination of the magnetic field lines toward the axis of the billet symmetry, which makes the low temperature melt near the mold, moving inwards into the center, and high temperature melt moving outwards to the border. These results in a forced convection flow in the melt and a reduction of the temperature gradient ahead of the solidification front, which had been identified experimentally [8]. Therefore, the ideal flow pattern in the melt will be achievable when the overheated melt driven from the center region of the melt to the periphery. All the effects can effectively refine the microstructures and broaden the equiaxed zone, for example, the dendrites can be remelted, detached and carried away by convection from the solidifying shell to the inner region of the melt, therefore, promote heterogeneous nucleation. So the structure of the casting billets with EMS is much finer than that of direct chill billet, as shown in Fig. 3. When the magnetic flux density of EMS keeps increasing, however, the solidification structure of austenitic stainless steel has no obvious alternation until magnetic flux density reach 90 mT as shown in Fig. 3 (d), which indicates that the volume force is too small. The electromagnetic stirrer is typically a multiphase induction motor. The average volume force for a two-pole axisymmetric system is given by [9]:

$$F=J \times B= \sigma\omega B^2\delta =2B^2\sqrt{\pi f\sigma/\mu} \qquad (3)$$

Where, B is magnetic flux density, f is the frequency of current, and σ and μ are the electrical conductivity and permeability of the liquid metal respectively.

According to equation (3), the notably increased volume force to the melt may be mainly attributable to an appropriate higher or an optimal frequency utilized in Fig. 3(c). Therefore, these parameters will determine the input in kVA needed to generate required volume force. The effect of each of these parameters on the stirrer characteristics as well as metallurgical performance shall be considered in context of their interaction rather than as an independent impact.

Figure 3(d) shows that the solidification structure of the solidifying shell has no obvious effect, in spite of magnetic flux density growing. This is due to the too weak stirring intensity. In order to enlarging equiaxed zones, reduce bridging and refine grain, the stirring intensity of the stirrer (i.e., the volume force) will be increased rather than magnetic flux density to be increased only. Optimum frequencies and magnetic flux density can obtain a maximum internal volume force with a given kVA input and electrical conductivity. However, typically, the actual operating frequencies are determined experimentally.

3.2 Effect of thermophysical properties of austenitic stainless steel on solidification structure

As seen in Fig. 3, with application of electromagnetic stirring, the equiaxed and columnar grain sizes were found to be decreased, but the increase of the area of equiaxed grain zone is not obvious. There are mainly two reasons for this effect. Firstly, due to the low thermal conductivity of stainless steel, as shown in Table 1, a reduction of the temperature gradient in stainless steel melt by the magnetic forced convection being too small. Secondly, because of the high kinematic viscosity of stainless steel, as shown in Table 1, in the low frequency and low induction limit, the magnetic Taylor number T_a can be taken as the characteristic non-dimensional parameters to describe the flow field. The Taylor number is given as:

$$T_a = \frac{\sigma\varpi B^2 R^4}{2\rho\upsilon^2} \qquad (4)$$

Where ρ and υ denote the density and the kinematic viscosity of the fluid.

Table 1 Thermophysical properties of the steel melt used in calculation [10,11]

Thermophysical properties	Austenitic stainless steel	Plain carbon steel and alloy steel
Thermal conductivity at solidus, W/(m·K)	14–17	47–58
Thermal conductivity at liquidus, W/(m·K)	30.3	120–170
Electrical conductivity, $\Omega^{-1}\cdot m^{-1}$ (10^5)	7.20	7.14
Kinematic viscosity, m^2/s (10^{-7})	11.26	8.57
T_a (70 mT, 7 Hz, R = 70 mm) (10^9)	2.09	3.59

The heat transfer coefficient, due to convection, increases with increasing of Tayor number. A distinct reduction of the temperature gradient with growing Taylor number becomes visible, indicating a thermal homogenization of the melt. Based on equation (4), the magnetic Taylor number T_a of stainless steel is 40% lower than that of plain carbon steel at a given kVA input and dimensional parameters of the stirrer. Moreover, due to a higher viscosity, rotating speed of molten stainless steel was 20%–30% lower than that of molten carbon steel in the same magnetic flux density [12], so a reduction of the temperature gradient of stainless steel billets is low and leads to growth of columnar grains generally.

4 Conclusions

(1) Under the low frequency rotational electromagnetic stirring, the rotary volume force produces a forced convection flow in the melt as well as a reduction of the temperature gradient ahead of the solidification, which facilitates heat transfer and mass transfer as well as uniformity of solidifying shell.

(2) Stirring intensity produced by EMS and its metallurgical performance at a given kVA input are determined by the relationships between intensity and frequency of magnetic field and the electrical conductivity of the melt.

(3) EMS with appropriate electromagnetic stirring parameters reduces centerline porosity and shrinkage cavity, removes intracrystalline, improves the width of equiaxed grains zone, and provokes a distinct grain refinement, but the increase of the equiaxed grain zone is not obvious as expected.

(4) Electromagnetic stirring has somewhat affected the macrostructure of austenitic stainless steel, even if the magnetic flux density of the electromagnetic stirring reaches 90 mT in average (amplitude reaches 141 mT) at frequency f=3–4 Hz.

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