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Progress of some techniques on electromagnetic metallurgy

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Abstract
Some of the electromagnetic metallurgy techniques are introduced in this paper. One is the vertical electromagnetic brake (V-EMBr) which have some different effects with Ruler-EMBr and FC-Mold on the control of fluid flow in continuous casting mould. Another is the vertical continuous casting of nickel-based superalloy with high frequency electromagnetic field in the mould and lower frequency electromagnetic stirring (EMS) in second cooling zone of pilot continuous casting machine, that have apparently improved the surface and internal quality of superalloy billets.

Key words: Fluid flow; V-EMBr; EMS; Superalloy; Solidification; Continuous casting;

Introduction
During the past decades, the Division of Electromagnetic Metallurgy on Steel, Key Laboratory of Electromagnetic Processing of Materials (Ministry of Education), Northeastern University, P. R. China, has focused on the research of EPM field. The different electromagnetic field, such as high frequency, lower frequency electromagnetic fields and DC field, were respectively applied to investigate their influence on the fabrication processing, qualities and properties of materials. In recent years, we also have some progress about the high magnetic field on the fabrication of Fe-based magnetic nanocomposites\(^1\), the solidification, precipitation and properties of Cu based composites\(^2\), and the amorphous state of bulk metallic glass during annealing process\(^3\).

In this paper, a new pattern of electromagnetic brake (EMBr) device is introduced, which was firstly proposed in EPM 2009 conference\(^4\) and it is called the vertical electromagnetic brake (V-EMBr). The metallurgical effects of V-EMBr to control the fluid flow in continuous casting mould are presented by numerical simulation methods. On the other hand, the metallurgical effects of continuous casting of nickel-based superalloy, which is generally fabricated by ingot casting, are presented with high frequency electromagnetic field in the mould and lower frequency electromagnetic stirring (EMS) in second cooling zone of pilot continuous casting machines.

Effect of V-EMBr in continuous casting mould
In continuous casting of steel, some patterns of EMBr, such as EMBr Ruler and FC-Mould, are used to control the fluid flow in the mould, which generally have the level patterns of magnetic poles in the wide side of the mould (Fig. 1). However, these magnetic poles are fixed in a certain height of the mould, which generally couldn’t fit the intermittently change of the depth and angle of submerged entry nozzle (SEN) during the casting process, so it will reduce the effect of EMBr and even bring some negative effect. The proposed new pattern of V-EMBr, which has two pairs of magnetic poles vertically installed on the narrow sides of the mould from the meniscus to the impinge point of melt from the outlet of SEN (Fig. 2). The important characteristic of V-EMBr is that it covered the meniscus and the initial solidifying shell near the narrow sides of mould which generally brings the surface fluctuation, powder flux engulfment, and subsurface defects in slabs owing to the bubbles and inclusions are captured by initial solidifying shell, moreover their control effect to fluid flow is not affected by the change of melt surface level, the outlet depth and angle of SEN.
Fig. 3 shows the flow field of molten steel in mould with different casting speed when the depth of SEN is 170mm and the average value of magnetic flux density $B_{ave}$ in the covered region by magnetic pole is 0T and 0.3T respectively. Fig. 4 and Fig. 5 respectively show the distributions of molten steel velocity on the free surface of mold and turbulent kinetic energy in the narrow side of mould under the same processing conditions.

The numerical simulation results show that the flow of molten steel in the mold is enhanced as the casting speed increasing, it presents that the vortex center in lower recirculation zone is moved down (Fig. 3a), and the flow velocity of free surface is gradually increased (Fig. 4a), and the velocity and turbulent kinetic energy near the impact points of molten steel jet from the SEN in the narrow of mould is also gradually increased (Fig. 5a). That mean the chance is increase to have the powder flux engulfment in the mold surface and involve inclusions and bubbles to the slabs. After applying V-EMBr under different casting speed in continuous casting process, the fluid flow in upper recirculation zone is remarkable reduced and the vortex center in lower recirculation zone is obviously moved upward (Fig. 3b). The flow velocity of molten steel in the free surface of mould is significantly reduced (Fig. 4b). The flow field near the impact points in the narrow side of mould forms a regular flow field moved upward and downward (Fig. 5b) contrast to irregular divergence flow without EMBr (Fig. 5a), it proves that proposed V-EMBr can significantly reduce the impact of molten steel jet to the narrow side and the meniscus of mould, and further prevent the surface fluctuations and powder flux engulfment in the mold. The numerical simulation results proved that the V-EMBr device can play a effect control to the molten steel in the continuous casting mould.
Fig. 5 Distribution of velocity and turbulent kinetic energy in narrow side of mold with and without V-EMBr (B_{ave}=0.3T)

The numerical simulation results show that when the submergence depth of SEN changes from 200mm to 170mm, which is the conventional operation in the continuous casting, the flow velocity of molten steel in the free surface is increased, especially the region which velocity is over 0.4m/s is also increased (Fig. 6a). That mean the chance to bring the powder flux engulfment near the meniscus of mold is increased. After applying the V-EMBr (B_{ave} is 0.3T), the flow velocity of molten steel in the free surface is not over 0.4m/s as the SEN depth is 170mm and 200mm (Fig. 6b), that is helpful to prevent the surface fluctuations and powder flux engulfment in the mold, and it also proved that the control effect to fluid flow of V-EMBr is a few affected by the depth and outlet angle of SEN.

Fig. 6. The velocity distribution of molten steel on the free surface of mold with and without V-EMBr (B_{ave}= 0.3T)

Fabrication of superalloy strands in continuous casting with electromagnetic fields

Incoloy 800 is a kind of Ni-based superalloy, which is widely used in steam generator, nuclear reactor, petrochemical industrials and solar energy systems due to its high strength at high temperatures and the ability to resist oxidation and high-temperature corrosion. However, Incoloy 800H strands is traditionally fabricated by ingot casting, which not only brings a higher production cost and also has a series of quality problems such as serious segregation, coarse grain and serious cracks. In this paper, the fabrication of rectangular strands and billets of Incoloy800 superalloy were carried out in a vertical pilot continuous caster in Northeastern University, China. To improve the quality of Incoloy800 strands, the electromagnetic fields are applied, one is the high frequency electromagnetic field in mould to improve its surface quality and another is electromagnetic stirring (EMS) in the secondary cooling zone to control the solidifying structure and segregation of elements in the strands.

Fig. 7 shows the solidification macrostructure of Incoloy800 slabs (225mm×100mm) casted in the vertical pilot continuous caster without and with EMS. It is shown that the solidification structure of Incoloy800 transverse section without EMS is mainly consists of the unidirectional column grains and a few fine equiaxed grains in the surface of strands, and the serious transgranular phenomenon is appeared in the center of strands (Fig. 7a). When EMS is applied, the transgranular phenomenon is disappeared and the equiaxed ratio in the transverse section of Incoloy800 strands is increased to 31% (Fig. 7c) and the average equiaxed grain size in the central area of slabs is apparently refined.

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Fig. 8 shows the macrostructure of Incoloy800HT billets (100mm×100mm) in longitudinal section casted in the vertical pilot continuous caster without and with EMS. It is also shown the transgranular phenomenon no EMS is applied in the center of strands and the small shrinkage or porosity and internal crack between the column grains (Fig. 8a). When the EMS is applied, the growth of columnar dendrites were apparently restrained and many of fine equiaxed grains are formed in the center of billets, the transgranular phenomenon, shrinkage and internal crack are eliminated, the internal quality of the Incoloy800HT billet is remarkably improved.

In order to improve the serious surface defects of Incoloy800HT billets (100mm×100mm) such as oscillation mark (Fig. 9a), etc, a high frequency electromagnetic field (20Hz) was applied near the meniscus zone of the mould during continuous casting process. The experimental results show that appearance of Incoloy800HT billets is significantly improved with high frequency electromagnetic field, the oscillation marks are suppressed and surface defects can be eliminated.

Conclusions
1) A new pattern of electromagnetic brake (so-called V-EMBr) is proposed and the numerical simulation results show that the V-EMBr can significantly reduce the impact of molten steel jet to the narrow side and the meniscus of mould and the velocity of molten steel in the free surface of mould, that further prevent the surface fluctuations and powder flux engulfment in the mold. Moreover the control effect of V-EMBr to fluid flow is few affected by the depth and outlet angle of SEN.
2) By applying of high frequency electromagnetic field and electromagnetic stirring, the internal and external quality of Incoloy800HT billets could be improved greatly in the continuous casting.

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References