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Effects of vertical electromagnetic stirring on grain refinement and macrosegregation control of bearing steel billet in continuous casting

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ABSTRACT

The grain refinement and macrosegregation control of GCr15 bearing steel were investigated under a type of rarely-used electromagnetic stirring, vertical electromagnetic stirring (V-EMS), in continuous casting. V-EMS can create an upward electromagnetic force and generate longitudinal loop convection, which enables the better mixing of the upper part with the lower part of the liquid steel. The results showed that applying V-EMS can enlarge the region of the equiaxed grain, decrease the secondary dendrite arm spacing (SDAS) and reduce the segregation of both carbon and sulfur. After applying V-EMS, liquid steel with a high solute concentration is brought to the dendrite tips, making the dendrite arms partially melt. The length of the dendrite fragment is approximately 1.8 mm, 10 to 12 times the SDAS. Upon increasing the amount of cooling water from 2.0 to 3.5 m^3/h, the dendrite fragments exhibit an obvious aggregation following V-EMS. Finally, a criterion for dendrite fragmentation under V-EMS was derived based on the dendrite fragmentation theory of Campanella et al.

1. Introduction

To increase the homogeneity of steels and limit the formation of internal defects, grain refinement and macrosegregation control are often desired in solidification processes, especially for high-carbon steel billets[1,2]. The application of electromagnetic stirring (EMS) in continuous casting process is an effective way to improve the solidification structure, enlarge the equiaxed zone, and reduce the center segregation and porosity[3-8]. As is generally known, two types of stirring are commonly used in practice, rotary electromagnetic stirring (R-EMS) and linear electromagnetic stirring (L-EMS). R-EMS is mainly used in round or bloom caster, and it produces a rotating magnetic field in the horizontal direction. A rotary motion is excited in the liquid steel, which enhances the heat-mass transfer processes in the molten steel and improves the inclusion distribution, segregation, and final solidification structure[9-11]. L-EMS is commonly applied in a slab caster and uses a travelling magnet to produce horizontal flow along the broad face of the slab, which can improve the internal solidification structure[12,13]. In the solidification of continuous casting, the upper part of the liquid steel has a higher temperature and lower solute concentration compared with the lower part. However, both R-EMS and L-EMS result in the horizontal movement of the liquid steel, so that the upper part and lower part of the liquid steel are not mixed well enough. In addition to the two types of EMS mentioned above, spiral electromagnetic stirring (S-EMS) is also used in some fields[14]. It makes the liquid steel spiral upward, but the upper part and lower part are not mixed enough yet.

Therefore, a type of vertical electromagnetic stirring (V-EMS) with a relatively simple configuration was proposed for continuous casting. The characteristic of V-EMS is that it creates an upward electromagnetic force and generates longitudinal loop convection, which provides better mixing of the upper part and lower part of the liquid steel. Strong turbulent convection increases the extent of the undercooling zone and thus the chance of dendrite fragments survival[15], and a small variation of the cooling rate or thermal gradient favors dendrite remelting through

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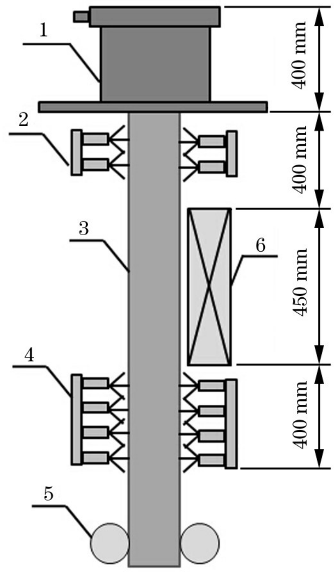
local increase in temperature or solute, which contributes to grain refinement[16,17]. In this paper, the technique of V-EMS was applied in continuous casting with solidifying GCr15 bearing steel. The macrostructure, microstructure, and segregation of the GCr15 bearing steel were investigated. Based on the dendrite fragmentation theory by Campanella et al.[18], the local remelting of dendrite arms resulting in the columnar-to-equiaxed transition (CET) under V-EMS was verified. This led to a clearer understanding of the grain refinement and macrosegregation control and helped produce high-quality GCr15 bearing steel in continuous casting.

2. Experimental Procedure

The GCr15 bearing steel was prepared by laboratory continuous casting. The chemical analysis showed that the billet contained 0.98 wt.% C, 0.20 wt.% Si, 0.30 wt.% Mn, 0.03 wt.% P, 0.03 wt.% S, and 1.48 wt.% Cr, and the balance was Fe. Fig. 1 shows a schematic representation of the electromagnetic continuous casting system. The GCr15 bearing steel (50 kg) was first melted in a medium frequency furnace, and then poured into a copper mold with inner dimensions of 0.1 m×0.1 m. Once the free surface of molten steel reached the pre-set location, a casting speed was applied to the continuous caster and the experiment started. The experimental conditions and operating parameters are shown in Table 1. The current intensity of the V-EMS was set to 250 A and



1—Mold; 2—Upper water spray system; 3—Billet; 4—Lower water spray system; 5—Roller; 6—V-EMS.

Fig. 1. Schematic representation of continuous casting system.

350 A, and the frequency was 12 Hz. Distribution of magnetic flux density was measured and the results are shown in Fig. 2. The maximum magnetic flux density was 0.07 T at 250 A and 0.09 T at 350 A in the centerline of the billet. To investigate the effect of the cooling rate on the solidification structure, the amount of the cooling water applied was set to 2.0 and 3.5 m^3/h (the second cooling intensity), as controlled by the lower water spray system in Fig. 1.

Table 1

Processing parameters applied in continuous casting

Cross-sectional size/(mm×mm)	Casting speed/(m · min^{-1})	Degree of superheat/K	V-EMS current/A	V-EMS frequency/Hz
100×100	0.6	40	0, 250, 350	12

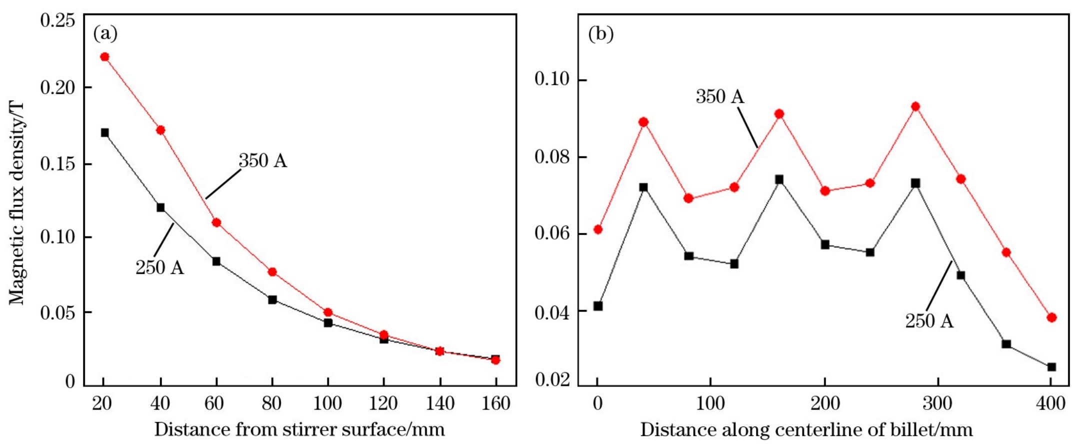


Fig. 2. Magnetic flux density distribution along stirrer surface to billet (a) and along longitudinal centerline of billet (b).

For each group of stirring parameters, samples with the length of 600 mm along casting direction were collected. The transverse and longitudinal section specimens were taken for inspection, as shown in Fig. 3. The macrostructure of the billets was ob-

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