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Continuous casting process of Incoloy800HT superalloy and its quality improvement with electromagnetic fields

Fei Wang, Yinglong Li, Anyuan Deng, Xiujie Xu, Xingwu Zhang, Engang Wang

Key Laboratory of Electromagnetic Processing of Materials (Ministry of Education)
Northeastern University, No. 3-11, Wenhua Road, Shenyang 110004, P. R. China

Correspondent: Engang Wang, professor, Tel: 024-83681739, E-mail: egwang@mail.neu.edu.cn

Abstract
The superalloy is generally produced in ingot casting mode, which generally brings a lower productivity rates, high costs and some casting defects. In this paper, the billets of Incoloy800HT superalloy are fabricated in a vertical pilot continuous caster with different frequency electromagnetic field, which is respectively applied on the mould zone and secondary cooling zone of continuous caster, and their effects were investigated at different process parameters. The research results show that electromagnetic stirring (EMS) can effectively restrain the dendrites growth and increase the ratio of equiaxed grains, and reduce the shrinkage porosity and segregation in the central of billets. The surface quality of billets also have a greatly improved as applied a high frequency electromagnetic field on the mould. The electromagnetic fields become the key techniques to control the internal and external quality of Incoloy800HT billets. Moreover, the mechanism of electromagnetic fields is analyzed based on the examination of billets.

Keywords: Superalloy; Continuous casting; Electromagnetic field; Solidification;

Introduction
Incoloy800HT is a single-phase austenitic solid solution Ni-based superalloy, which is extensively used in high temperature environments due to its advantages in high strength and corrosion resistance at high temperatures, such as steam generator tubes, reformer tubes, and gas turbines\cite{1-4}.

In order to decrease the production cost of the conventional casting of remelted superalloy ingots, a continuous casting process is being developed to replace the conventional casting. So a series of developments in the continuous casting of superalloys have been carried out. However, due to the alloy’s wider brittle range \cite{5,6} and solidification condition, some seriously internal and external quality issues of the continuously cast Incoloy800HT superalloy have been revealed, such as coarse column grains, cracks, segregation, coarse surface, etc.

Electromagnetic force generated by different frequency electromagnetic field can be used to control the solidification process for improving internal and external quality of the billets. Therefore, the aim of the present study is to investigate the effect of the combination of high frequency electromagnetic field and EMS on the internal and external quality of Incoloy800HT superalloy in the continuous casting process.

Experimental procedure
The chemical composition of Incoloy800HT used in the present study, given in mass percents, is: 0.08% C, 0.52% Si, 0.80% Mn, 0.023% P, 0.002%, 20.13% Cr, 30.88% Ni, 0.52% Ti, 0.28% Al and rest Fe. The Incoloy800HT bars were melted in a medium frequency induction furnace with a protective argon atmosphere. The melt was heated to 1425°C and then poured into the vertical continuous caster to obtain two 1200mm in length square billets. A high frequency electromagnetic field device and a rotary electromagnetic stirrer were respectively applied on the mould zone and secondary cooling zone of continuous caster. A schematic illustration for the experiment device was shown in Fig.1, and
the casting condition was listed in Table 1. To evaluate the influence of the electromagnetic field, all continuous casting parameters, including casting temperature, casting speed and cooling water flows, were held constant.

**Table 1 Continuous casting conditions**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>No.1/No.2</th>
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</thead>
<tbody>
<tr>
<td>High frequency electromagnetic field</td>
<td>0/1310</td>
</tr>
<tr>
<td>current, A</td>
<td></td>
</tr>
<tr>
<td>High frequency electromagnetic field</td>
<td>0/20</td>
</tr>
<tr>
<td>current frequency, KHz</td>
<td></td>
</tr>
<tr>
<td>EMS current, A</td>
<td>0/350</td>
</tr>
<tr>
<td>EMS frequency, Hz</td>
<td>0/5</td>
</tr>
<tr>
<td>Casting speed, mm/min</td>
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</tr>
<tr>
<td>Mold cooling water flow rate, m3/h</td>
<td>6.4</td>
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<tr>
<td>Secondary cooling water flow rate, m3/h</td>
<td>3.0</td>
</tr>
<tr>
<td>Mold dimension, mm</td>
<td>100×100×400</td>
</tr>
</tbody>
</table>

**Result and discussion**

Effect of high frequency electromagnetic field on the surface quality of Incoloy800HT superalloy square billets

Fig. 2 shows the appearance of the Incoloy800HT billets with and without high frequency electromagnetic field, respectively. As shown in Fig. 2(b), the surface quality of the Incoloy800HT billet under high frequency electromagnetic field is obviously improved that oscillation marks are suppressed and surface defects can be eliminated.

The reason is that high frequency electromagnetic field applied in the mold not only generate a electromagnetic force to reduce contact pressure on the mold, which results in a decreased friction force between the melt and the mold, but also produce Joule heating to heat the meniscus. As a result, the mold flux consumption is increased dramatically, (a)macrostructure, No EMS; (c), (d), (e) dendritic morphology, No EMS; (b) macrostructure, EMS; (f), (g), (h) dendritic morphology, EMS

Fig. 3 Dendrite evolution processes of Incoloy800HT billets without and with EMS
and a uniformly solidified shell is formed as well as oscillation marks are obviously suppressed, which greatly improve the surface quality of Incoloy800HT billet.

**Effect of EMS on the solidification structure of Incoloy800HT billets**

Fig. 3(a) and (b) show the solidification structure of Incoloy800HT billets with and without EMS, it can be seen that when EMS is applied, the ratio of equiaxed grain increased from 2.45% to 41.45%, and the average equiaxed grain size refine remarkably from 10.83mm to 1.28mm.

The dendrite morphologies at the various regions in the cross section can display the different solidification stages in Fig. 3(c)–(h). At the beginning of the solidification, it is observed in Fig. 3(c) that large numbers of equiaxed dendrites in the chill layer without EMS, whose growth directions are parallel to the temperature gradient, grow into unidirectional columnar dendrites towards the center of the billet, as shown in Fig. 3(d). Because of the high temperature gradient at the solidification front, the unidirectional columnar dendrites continuous grow up until the formation of few coarse equiaxed dendrites in the center of the billet. With the application of EMS, it is the same manner of the chill zone and the unidirectional columnar dendrites formation at the beginning of solidification in Fig. 3(f). However, with the evolvement of the solidification, the unidirectional columnar dendrites is prevented and plenty crossed dendrites emerge, presented in Fig. 3(g), and the columnar dendrites become less with no obvious orientation. In the center of the billet, a large number of fine equiaxed dendrites are formed and grow up, as shown in Fig. 3(h).

This phenomenon can be explained that the severe forced convection caused by EMS can generate the fragmentation of the dendrites, which is the remelting of the dendrite arms at its roots by thermal gradients and solute enrichment. The dendrite fragments are transported uniformly by forced convection and become effective nucleus, which increases the nucleation rate. Simultaneously, the forced convection can accelerate the heat transfer to promote the homogenization of the temperature and concentration field in the liquid region, which decreases the temperature gradient and increases the undercooling in the melt ahead of solid/liquid interface. All of the above factors favor the grain refinement and increase the ratio of equiaxed grains which enhance the transformation from columnar grain to equiaxed grain.

The shrinkage porosity and internal crack of continuous casting billets are familiar metallurgical defects, and its formation is often accompanied by serious marosegregation. As shown in Fig. 4(a) and 4(b), the central shrinkage porosity and the internal crack of the Incoloy800HT billet without EMS is very serious, while with the application of EMS, there is no obvious internal defects, the quality of the Incoloy800HT billet is remarkably improved. As solidification of the Incoloy800HT billet without EMS, the high speed growth of the columnar dendrites connect to form interdendritic bridging at the center which results in the formation of the shrinkage porosity by lacking melt to
feed, because of the large temperature gradient between the surface and center of the billet. Meanwhile the internal stress occurs by thermal contraction as well as by solidification shrinkage and it can induce to produce internal crack. Applying EMS can generate the forced convection to break the columnar dendrites for preventing interdendritic bridging, and promote the solidification feeding. Simultaneously, the forced convection improves the heat transfer to reduce the thermal stress, which results in suppressing the internal crack formation.

The segregation index is used to analysis the carbon segregation distribution. Fig. 5 shows that the positive segregation of C elements reaches the maximum 1.49 in the center of the billet without EMS, while the maximum C segregation index of the billet with EMS is only 1.16, so the centerline segregation of the billet without EMS is rather serious. This result show that more uniform carbon distribution and less segregation can be obtained and the concentration gradient of solute elements are significantly reduced by applying EMS. It is considered that the forced convection generated by EMS constantly scour the solute-rich liquid in the mushy zone and accelerates the transport of the solute elements, which reduces the solute-enrichment degree at the solidification front and homogenizes the molten pool composition.

Conclusions
(1) The application high frequency electromagnetic field in the continuous casting process produces the high quality surface of Incoloy800HT billet. The oscillation marks and some surface defects are remarkably suppressed and the external quality of the Incoloy800HT billet is obviously improved.
(2) By applying EMS in the continuous casting process of Incoloy800HT billet, the macrostructure is significantly refined. The fraction of the equiaxed grain increases from 2.45% to 41.45%, and the equiaxed grain size decreases from 10.83mm to 1.28mm.
(3) The application of EMS for Incoloy800HT billet can restrain the formation of shrinkage porosity, internal cracks and centerline segregation. The internal quality of the Incoloy800HT billet is remarkably improved.

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References