EFFECTS OF ELECTROMAGNETIC FIELD ON CASTING-ROLLING STRIP BREAKDOWNS[①]

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ABSTRACT The industrial-scale tests of the electromagnetic casting-rolling technology were described. The effects of electromagnetic field on the casting-rolling strip breakdowns were studied by analysing their microstructures and mechanical properties. The results show that the electromagnetic casting-rolling can effectively refine the grain size to ASTM grain size number grade 1, eliminate horseshoe cracks, improve dendritic segregation, and suppress the gas passages defects caused by the hanging slags on the casting nozzles. Using electromagnetic field to replace the Al-Ti-B wire modificator can not only reduce the earing ratio of the casting-rolling strip and improve the deep drawing property, but also reduce the production cost by 60～70 RMB Yuan/t.

Key words electromagnetic field continuous casting-rolling process mechanical properties microstructure

1 INTRODUCTION

The continuous casting-rolling process is a relatively new production technology. Compared with the conventional hot-rolling technology, this technology has the advantages of less capital investment, shorter production period and less energy-consuming. However, the unmodified casting-rolling strip breakdowns are composed of coarse columnar crystals and have poor deep-drawing property, thus the quality of the products is seriously affected. At the present, Al-Ti-B modificator is widely added to obtain fine grains. However, the Al-Ti-B modificator is expensive and its addition may cause alloying pollution for some high-purity aluminium products. In addition, the deep-drawing property of the strip needs to be further improved. Therefore, it's necessary to develop new technologies so as to reduce the production cost, to further improve the product quality and to find more applications for the casting-rolling process. The electromagnetic casting-rolling process described in this paper is a try for a new technology.

2 INDUSTRIAL TESTS

The industrial tests were carried out on a standard Hunt casting-rolling machine (d 650 mm × 1 600 mm). Besides the original equipment, a set of self-made electromagnetic induction generator and power supply electric control system were disposed. In order to avoid magnetic by-pass, magnetism proofing was made on the bearing pedestal and the bed piece of upcast hydro-cylinder.

A board computer was used to select the frequency of the variable-frequency current and the guide frequency of the electromagnetic induction generator, thus a comprehensive magnetic field composed of travelling-wave component and pulsed component was obtained in the casting-

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rolling zone[1].

2.1 Experimental details

(1) The temperature of the aluminium melt and the melting technology were controlled as usual. (2) A proper margin between the supply nozzle and the rollers was a key factor to ensure successful casting-rolling process and had to be regulated carefully. (3) The intensity and frequency of the current were key factors which determined the quality of the strip breakdowns and had to be controlled in a reasonable region. (4) L2 and L4 aluminium alloys, which are prone to form coarse grains, were selected as test materials. The aluminium melts were divided into normal burden and holding burden. (5) After the strip breakdown was set up from the casting-rolling zone, cooling water ran through the roller cases and the water pressure was stable at 4.0×10^5 ~ 4.2×10^5 Pa; the liquid surface of the front box was controlled at 15 ~ 16 mm; the casting-rolling rate was controlled at 15 ~ 16.3 mm/s.

In order to compare the effect of applying electromagnetic field with that adding Al-Ti-B wire modificator, applied electromagnetic field in the first to the third casting-rolling reels and made follow-up sampling, then made blank sampling by stopping applying the electromagnetic field in the casting-rolling process; in casting-rolling the fourth reel, canceled the electromagnetic field and added the Al-Ti-B modificator as usual and sampled by shearing.

2.2 Experimental results

2.2.1 Grain refinement effect

Applied an electromagnetic field at the solidification front of the casting-rolling zone. When the magnetic field intensity reaches a certain value, the grain size can be effectively refined, and the coarse columnar crystals can be transformed into fine equiaxed grains to a grain fineness number grade 1, see Fig. 1 and Fig. 2. The effect of the electromagnetic field on the grain refinement increases with increasing exciting current and is closely related with the frequency of the current. The experimental results show that satisfying grain refinement effect can be obtained in the current frequency range of 10 ~ 20 Hz.

2.2.2 Apparent quality

If the molten aluminium without addition of Al-Ti-B modificator in the furnace(≥12 h), not only coarse columnar crystals appear, but also a large number of horseshoe cracks are formed. When an eletromagnetic field is applied, the horseshoe cracks will disappear immediately.

But in some cases, if the electromagnetic field is unreasonably designed or the electromagnetic parameters do not match the technological parameters, the exciting floor and the casting system will produce low-frequency vibration, which will accelerate the folding of the oxide films on the casting-rolling strip breakdowns

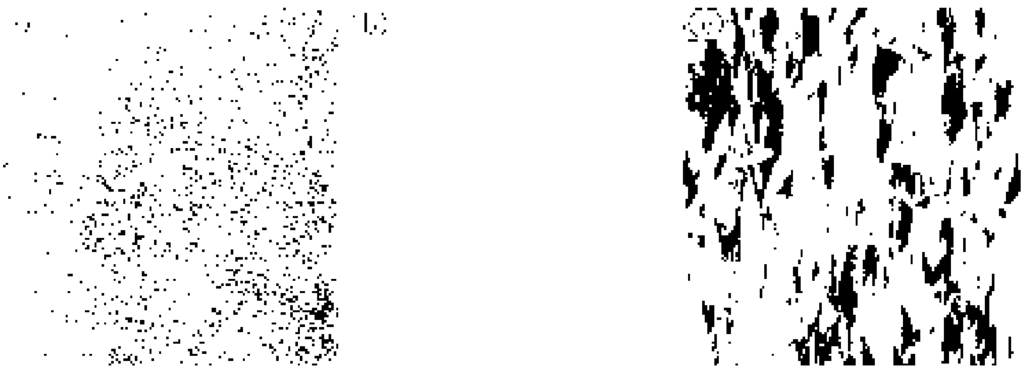


Fig. 1 Low-magnification optical morphology of strip breakdown surfaces under different production conditions, ×1

(a) —Electromagnetic casting-rolling sample;
(b) —Adding imported Al-Ti-B modificator sample; (c) —Blank sample

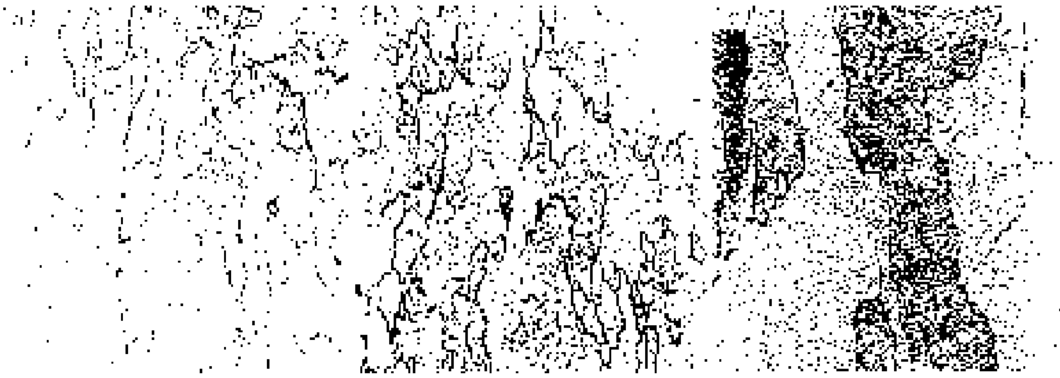


Fig. 2 High-magnification optical morphology of cross-sections of strip breakdowns under different production conditions, ×120

(a) —Electromagnetic casting-rolling sample;
(b) —Adding imported Al-Ti-B modificator sample; (c) —Blank sample

and then affect the deformability of the subsequent rolling of the foils. If the electromagnetic field is reasonably designed, the electromagnetic parameters match the technological parameters and the equipment is properly regulated, the folding of the oxide films can be eliminated completely and the surface will be smooth.

2.2.3 Improvement of dendritic segregation

When the contents of the alloying elements or the impurities are high, the fractional condensation caused by constituent undercooling is prone to form dendritic segregation. When an electromagnetic field is applied, the dendritic cells will degrade under the stirring action of the electromagnetic force (Fig. 3).

2.2.4 Elimination of gas passages defects

The conventional continuous casting-rolling process can easily produce gas passages. When there exist gas passages in the casting-rolling strip breakdowns, lamination will occur along the rolling direction in the subsequent rolling of foils. This kind of lamination usually distributes along a straight line and may extend tens or hundreds of meters or even run through the whole reels. No gas passages defects have been found in the strip reels obtained by electromagnetic casting-rolling.

2.2.5 Mechanical properties of strip breakdowns (Table 1)

The measurements of the mechanical properties of the casting-rolling strip breakdowns show that, the anisotropy of the mechanical properties of the blank sample without adding Al-Ti-B modificator and applying electromagnetic field is very serious, the maximum differences of tensile strength and elongation along 0°, 45° and 90° to the rolling direction are 12% and 47% respectively, while those of the electromagnetic casting-rolling strip breakdowns are 3% and 8.7% respectively, which can match those added with imported Al-Ti-B modificator.

Sampling from the 1.0 mm product strip and deep-drawing shows that the earing ratio of the electromagnetic casting-rolling strips in the

Table 1 Mechanical properties of casting-rolling strip breakdowns

Sample	Thickness/mm	σ_b/MPa			δ/%		
		0°	45°	90°	0°	45°	90°
Blank	7.30	79.1	76.1	69.8	33.3	23.8	17.5
Electromagnetic casting-rolling	7.32	78.4	77.3	79.8	36.6	34.1	33.4
Adding Al-Ti-B modificator	7.28	84.7	80.0	83.6	34.2	32.8	32.0

Fig. 3 High-magnification optical morphology under different casting-rolling conditions
(a) —Blank sample;
(b) —Electromagnetic casting-rolling sample

cold-working condition is 14.5%, while that of the adding Al-Ti-B modificator casting-rolling strips is 13%; the earing direction and number of both samples are 45° × 4. However, after annealing at 360 ℃ for 60 min, the earing ratio of the former is reduced to 3.2%, that of the latter is reduced to 10%; the earing direction and number of both samples are 0° × 2, 90° × 2. This indicates that the electromagnetic field affects not only the grain size but also the textures of the strip breakdowns.

2.2.6 Reduction of production cost

Using electromagnetic field to replace Al-Ti-B modificator can reduce the product cost by 60~ 70 RMB Yuan/t.

3 DISCUSSION

3.1 Effect of electromagnetic field on solidification crystallization

In the continuous casting-rolling process, the molten aluminium in the casting-rolling zone experiences rapid cooling, and the cooling rate can reach 10^2 ~ 10^3 ℃/s, which is higher than that of conventional water cooling semicontinuous casting by two orders of magnitude[2]. Therefore, the temperature gradient of the molten aluminium is larger, as a result the microstructure of the casting-rolling strip breakdowns obviously has the characteristic of directional solidification, that is to say, the directionality of crystal growth is strong and the columnar crystals are well-developed. In order to refine the grain size, it's necessary to add Al-Ti-B modificator in the production so as to increase the heterogeneous nuclei.

When applying electromagnetic field to the solidification-front of the casting-rolling zone, the electromagnetic force will not only change the temperature field and concentration field of the molten aluminium, but also make the molten aluminium oscillate in small displacements along the roll axial direction so as to fragment the growing dendrites or even the columnar crystals and distribute the fragments dispersively in the metastable molten aluminium. These fragments will act as new nuclei and grow into grains. The action of the electromagnetic field is very rapid; its effect of grain refinement appears immediately when applied. Fig. 4 shows the low-magnification structures of the casting-rolling strips; the left is columnar crystals without applying electromagnetic field, the right is fine equiaxed grains applied electromagnetic field; there is an obvious boundary between them.

In the electromagnetic casting-rolling process, the effect of grain refinement increases with exciting current, i.e. the higher the magnetic intensity, the finer the equiaxed grains[3]. This is due to the fact that the higher the magnetic-field intensity, the stronger the oscillation and stirring of the molten aluminium, as a result the larger the changes of the concentration field and the temperature field, the better the dendritic fragmentation, i.e. the more the nuclei increment and the more dispersive the distribution of the nuclei in the molten aluminium, ultimately the finer the grains[4]. It is worth noting that overhigh magnetic-field intensities are likely to rupture the surface film which connects the solid phase and liquid phase, as a result wave-like oxide film foldings or cracks will be produced on the surface of the casting-rolling strips[5].

The grain sizes of the strips are closely related to the frequency of the electromagnetic field. When the frequency of the alternating magnetic field is lower than 10 Hz, the effect of

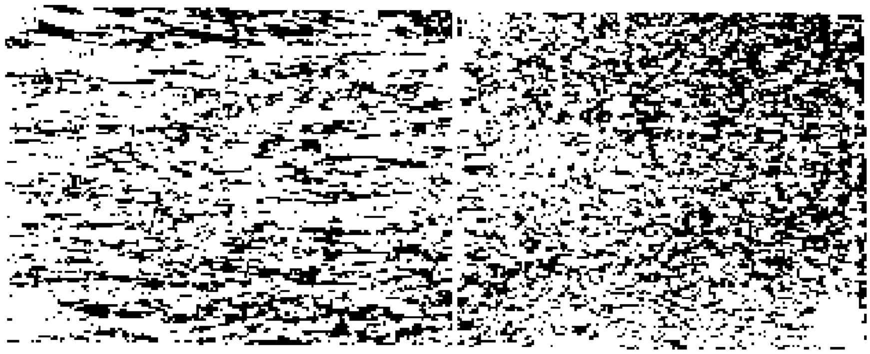


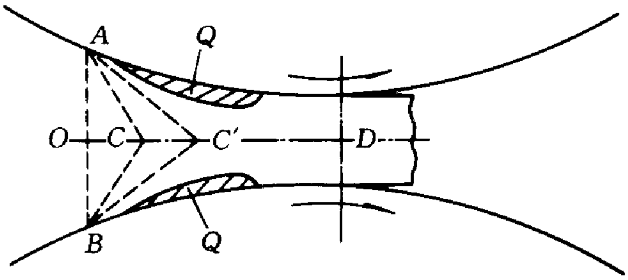
Fig. 4 Low-magnification structure of casting-rolling L4 alloy, × 1
Left —without applying electromagnetic field;
Right —applying electromagnetic field

grain refinement will be significantly weakened; when the frequency is lower than 5Hz, the electromagnetic field almost has no effects on the grain size and shape[6]. When the frequency is too low, the crystallization of the molten aluminium is dominated by static nucleation and can not effectively suppress the growth of the columnar crystals and dendrites. With increasing frequency, the fragmented crystals increase and the molten aluminium transforms from low-speed laminar flow to high-speed turbulent flow under the action of electromagnetic force; the fragments which fall away from the solid diffuse rapidly to the melting bath, thus there are a large number of nuclei in the melt, which will change their orientations in the stirred melt. This whole process can be described as a dynamic nucleation and crystallization process which includes crystallization, fragmentation, stirring and crystallization, and will transform the initial columnar crystals into fine equiaxed grains. When the frequency of the alternating electromagnetic field is in the range from 10 to 20Hz, obvious grain refinement effect can be obtained. However, when the frequency becomes larger, the effect of the electromagnetic field on the grain refinement will become significantly weak, which is due to the fact that the molten aluminium has a high viscosity, thus there appears a lagging phenomenon, i. e. the flow of the melt falls behind the change of the direction of the electromagnetic field. As a result, the dendrites can not be effectively fragmented and no obvious grain refinement effect will be realized.

The combination patterns of the electromagnetic field also affects the microstructures of the strips. Although single pulsed magnetic field can also refine the grains, the grains are likely to be non-uniform along the strip. The combinaton of travelling-wave magnetic field with pulsed magnetic field can give rise to good grain refinement effect[7].

3.2 Effect of electromagnetic field on horseshoe cracks

Horseshoe cracks are frequently formed in the casting-rolling process of pure aluminium and aluminium alloys if they are not modified, and the longer the holding time of the melt in the furnace, the more serious the horseshoe cracks. This is due to the fact that the adhesive zone formed in the casting-rolling process doesn't slip along the roll surface and deform plastically, only the central zone deforms under the pressure of the rolls, shearing flow occurs between the adhesive zone and the central zone and an extra shearing stress arises. When this stress exceeds the strength of the as-solidified metals, cracks will emerge. Because the strength near the solid-liquid boundary is the lowest, it is most likely to form cracks at this location. Additionally, the deeper the liquid pool, the more serious the horseshoe cracks. Fig. 5 shows the schematic diagram illustrating the formation of the horseshoe cracks. Fig. 6 shows the low-magnification structures along the longitudinal section, which indicates that when the other conditions are the same, the angles included between the fibrous structures for the blank sample is 20° ~ 22°, while that for the electromagnetic casting-rolling sample is 30°~ 38°. It can be proved that applying an electromagnetic field in the casting-rolling process can smoothen the liquid pool and reduce its depth. Industrial scale tests demonstrate that after 24 h holding in the furnace, the blank sample will form horseshoe cracks on the strip surface, while applying an electromagnetic field, the horseshoe cracks will disappear right away.



Fi. 5 Schematic diagram illustrating formation of horseshoe cracks

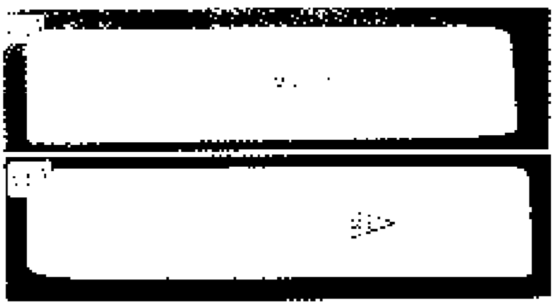


Fig. 6 Low-magnification of longitudinal section of strip breakdowns, × 2
(a) —No electromagnetic field applied;
(b) —Electromagnetic field applied

3.3 Effect of electromagnetic field on dendritic segregation

The dendritic segregation is mainly caused by constituent under cooling. Under the condition that the solute transfer is realized only through diffusion, the constituent undercooling condition can be expressed as[8]

$$\frac{G}{V} < \frac{mC_0(K_0 - 1)}{DK_0} \qquad (1)$$

where m is the slope of the liquidus, C_0 is the average concentration of the solute, D is the diffusivity of the solute, G is the temperature gradient in the liquid, V is the crystal growth rate. For a definite solution system, the right side of expression (1) is a constant. When this expression is satisfied, constituent undercooling will occur, as a result, cellular microstructure or cellular-dendritic microstructure will be probably formed, consequently the mechanical properties of the strips will present strong directionality. In the electromagnetic casting-rolling process the stirring in the melt pool is strengthened, therefore the solute transfer is realized not only by diffusion but also by forced convection. Under the condition of forced convection transfer, the condition for constituent undercooling will become

$$\frac{G}{V} < \frac{mC_0(K_0 - 1)}{D[K_0 + (1 - K_0)\exp(-\frac{V}{D}\delta)]} \qquad (2)$$

where δ is the thickness of the solute layer.

The electromagnetic stirring will greatly increase the D value and reduce the δ value. For a definite solution system, the right side of expression (2) is also a constant, but much smaller than that of expression (1). If the crystal growth rate is not increased, i. e. the cooling intensity in the casting-rolling process is not increased, then it is possible for the left side in expression (2) to be larger than the right side, thus there is no constituent undercooling zone and no cellular microstructure or cellular-dendritic microstructure will be formed.

3.4 Effect of electromagnetic field on gas passages

The casting-rolling is a continuous process. With increasing production time, it is likely to form precipitates in the casting nozzles and at the nozzle lips and most of the precipitates are oxides of Ti and B or other compounds. The streamlines of the aluminium melt will change when it is hindered by the compound precipitates. Because the hanging slags cannot be wetted by the liquid aluminium, the locations below the fluid are likely to act as bubble nuclei, the hydrogen dissolved in the melt diffuses to them after precipitation, and the bubbles will grow up gradually and be pulled to become gas cones. When the gas cones enter the casting-rolling zone, gas passages will form in the strips. The hanging slags in the casting nozzles can also cause segregation bands, passage cracks, cold shuts and other defects.

When applied an electromagnetic field, there is strong electromagnetic-field intensity in the casting nozzles or at the nozzle lips, due to act of inducting force, thus it is difficult for the oxides of Ti and B to accumulate in the casting nozzles, so that the formation of bubbles are suppressed. The experimental results show that applying a travelling electromagnetic field will immediately eliminate the gas passages defects caused by the accumulation of brush slags from the casting-rolling strip breakdowns.

4 CONCLUSIONS

(1) Applying an electromagnetic field to the casting-rolling zone in the continuous casting-rolling process can effectively refine the grains. The intensity, frequency and combination pattern have obvious effects on the grain refinement of the casting-rolling strip breakdowns.

(2) The electromagnetic casting-rolling can eliminate the horseshoe cracks in the casting-rolling strips. Even when the holding time of the aluminium melt in the furnace is longer than 24 h, the horseshoe cracks can also be eliminated at once.

(3) The electromagnetic field strengthens the stirring effect in the melt pool, so that it can control the constituent undercooling zone in the crystallization process, avoid the formation of cellular crystals or cellular-dendritic crystals and improve dendritic segregation. In the mean time, it can also suppress the hanging slags on the casting nozzles and bubble sources and get rid of the brush slags at the casting nozzle lips, thus eliminating the gas passages defects.

(4) The electromagnetic casting-rolling process can significantly improve the mechanical properties of the casting-rolling strip breakdowns and their quality, in the mean time it can save a lot of Al-Ti-B modificator so as to reduce the production cost.

REFERENCES

1 Zhao Xiaolin, Mao Daheng and Chen Qiangen. The Chinese Journal of Nonferrous Metals, (in Chinses), 1995, 5(4): 145- 149.

2 Ma Xiliang. Continuous Casting-Rolling Production of Aluminium Strip Breakdowns, (in Chinese). Changsha: Central South University of Technology Press, 1992.

3 Zhong Jue, Yan Hongzhi and Mao Daheng. Journal of Central South University of Technology, (in Chinese), 1995, 26(Suppl 1): 84- 88.

4 西村章, 川野丰. 轻金属, (in Japanese), 1983, 33(9): 503- 507.

5 Mao Daheng, Zhong Jue *et al*. Journal fo Central South University of Technology, (in Chinese), 1995, 26(Suppl 1): 89- 94.

6 Mao Daheng and Yan Hongzhi. Processing Technologies of Light Metals, (in Chinese), 1991, 19(4): 10 - 16.

7 Mao Daheng, Zhong Jue *et al*. Metallurgy and Mining Engineering, (in Chinese), 1996, 16(2): 68- 71.

8 Wang Jiaxin, Huang Jirong and Lin Jiansheng. Solidification and Control of Metals. Beijing: Mechanical Industry Press, 1983: 66- 67.

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