

Solidification of horizontally continuous casting of super-thin slab in stable magnetic field and alternating current

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Abstract: The solidified structures of horizontally continuous casting (HCC) of super-thin slab and its relations with the current were studied under the electromagnetic vibration (EMV). The results show that, under the action of the periodical forces from EMV, the solidified structures of the super-thin slab of pure tin is greatly refined, and the extent of grain refinement is increased with the magnitude of alternating current. For the Sn-10%Pb alloy, it is shown that the EMV promotes the growth of equiaxed grains in the center of super-thin slab, and the grains are refined with the alternating current increasing. This is useful to prevent some solidification defects in the horizontally continuous casting of super-thin slab, such as columnar grains butting, porosity, inclusions and gases gathering, and composition segregation in the centre of slab.

Key words: horizontally continuous casting (HCC); super-thin slab; electromagnetic vibration (EMV); solidification

1 Introduction

Horizontally continuous casting (HCC) of super-thin slab, with the thickness in the domain of 10–20 mm, is the main mode and process of metallic sheet production. The remarkable advantage of HCC is that the rate of solidification of slab is quick, which results in the composition segregation in the casting to be decreased[1–2]. But there are also some disfigurements, which include cold shuts or small cracks on the slab surface, porosity in the slab center, as well as inter-crystalline segregation and columnar grains butting[3]. These phenomena, especially columnar grains butting, can result in the material properties anisotropic, and the inclusions and gases gathering on the interface of columnar grains butting, where porosity, hot cracks and composition segregation can be brought easily, which will cause the slab cracked and/or laminated in the subsequent processing and using[4]. Therefore, to form a layer of equiaxed grains in the center of super-thin slab and to refine the grain size can be an effective route to prevent above solidification defects in HCC of super-thin slab.

The previous studies indicated that, to apply an alternate or pulsing current and a static magnetic field,

which were perpendicular to each other in the solidifying metal, could bring on an electromagnetic vibration (EMV) in the metal, and the periodical vibration force in the same frequency of the current was acting on the mushy zone of solidification of metal. This made the columnar grains be suppressed and the equiaxed grains be promoted effectively. VIVES[5–7] studied the solidification of aluminum alloy in EMV and discovered that EMV could refine grains, remove gases, and disperse and homogenize impurity in the metals. Moreover, he considered that the mechanism of solidification structure improving is attributed to cavitation in the molten metals by EMV. Based on this viewpoint, AMANO et al[8] studied the propagation processes of compression wave in molten metals. RADJAI et al[9–11] studied the effect of EMV on the solidification of hypereutectic and hypoeutectic Al-Si alloys. They found the evidence of grains breaking. TAKAGI et al[12] analyzed the refinement mechanism of hypereutectic and hypoeutectic Al-Si alloys in EMV from the aspect of potential energy. SUGIURA and IWAI[13] studied the effect of EMV parameters on solidification of Sn-Pb alloys. It was indicated that the grains could only be refined by EMV in the initial stages of solidification of metals. ZHANG et al[14] studied the effect of EMV on continuous casting of round billet of

Al alloy 7075, including the solidification structures and the solute distributions in the billet, and pointed out that the frequency of electromagnetic field had an optimum range for metals, in which the solidified structures could be refined and the macro-segregation was restrained. WANG et al[15] studied the effects of EMV on the Al-6%Si alloy and its primary $\alpha(\text{Al})$ phase in solidification with the effect of coupling high magnetic field and alternating current, and the result showed that the size of primary $\alpha(\text{Al})$ phase could be enlarged slowly and changed to granular structure when the magnetic flux density was lower than 4 T, and there was no obvious effects when it was over 4 T. YU et al[16] also studied the effect of EMV on the solidified structure of aluminum, and pointed out that the reason of grains refining in EMV was due to the crystal nuclei detached from the nucleation sites in the action of the periodical vibration force, and then new crystal nuclei appeared continuously. Meanwhile, the primary crystal was broken up and proliferated also. So the crystal nuclei were increased rapidly in the molten metal.

In this work, we applied an electromagnetic vibration caused by a statically magnetic field and an alternating current, to the HCC processes of super-thin slab, and study the solidified structures as well as its relations with the current intensity. In the experiments, the width and thickness of the super-thin slab are 200 mm and 15 mm, respectively, the solidifying metals are Sn and Sn-10%Pb alloy, the maximum magnetic flux density in the mould is 115 mT, the alternating current is in the domain of 0–200 A and its frequency is 50 Hz.

2 Experimental

The experimental apparatus is shown in Fig.1. The mould with length of 150 mm consists of the inner graphite plates and outer copper plates. The size of the super-thin slab is 220 mm in width and 15 mm in thickness. In the mould, there are three pairs of Nd-Fe-B magnets to form a static magnetic field penetrating the super-thin slab perpendicularly through the wide surfaces, and a pair of electrodes to be set on the narrow walls, from which an alternating current, perpendicular to both the magnetic field and the casting direction, can be input to the solidifying metals, so that a periodical vibration force can be generated in the directions of withdrawing and pushing the slab. The experimental materials of casting are pure tin and Sn-10%Pb alloy, respectively. In the experiments, the tension leveler is driven by a timing electromotor, and the periodical basic movement of drawing is as the circulative procedure of “drawing for a time interval and stopping for another”.

The distributions of magnetic flux density in the center plane of mould were measured by a Tesla-meter, which is shown in Fig.2. From this figure, the peak value is 115 mT.

In the experiments, the metal was heated to the preset temperature (over its melting point), and then poured into the furnace. After holding for 5 min, the super-thin slab was started to withdraw. When the casting velocity was stable to the pre-determinate one, the alternating current was input, which controlled the

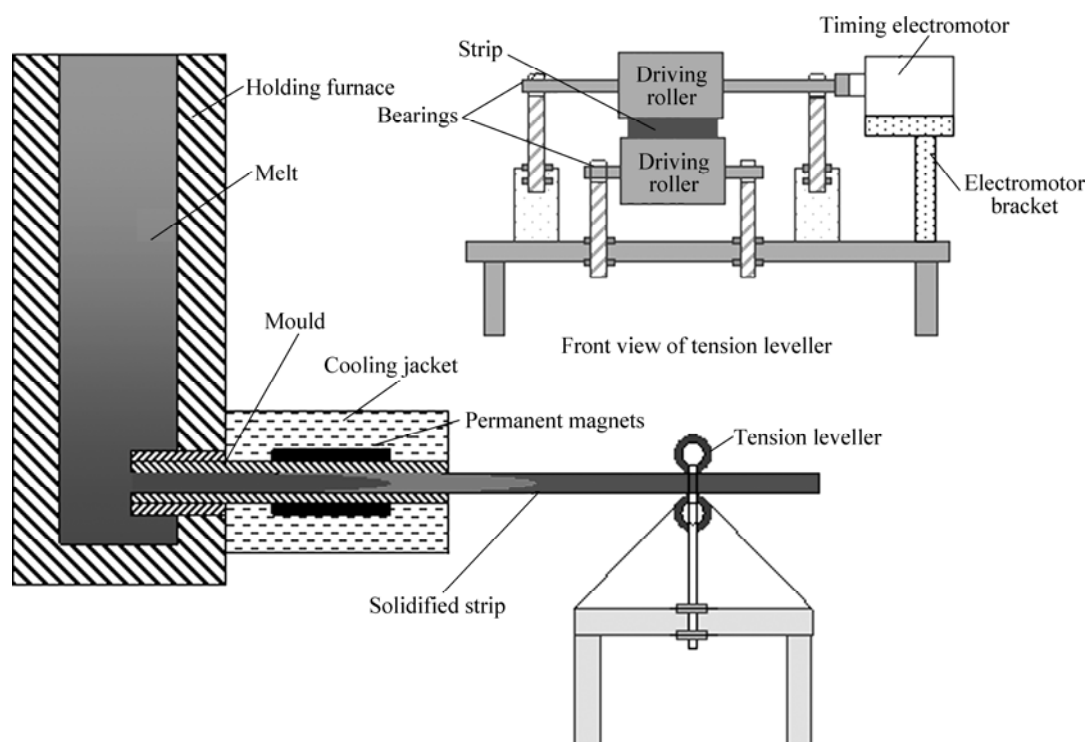


Fig.1 Experimental apparatus of horizontally continuous casting (HCC)

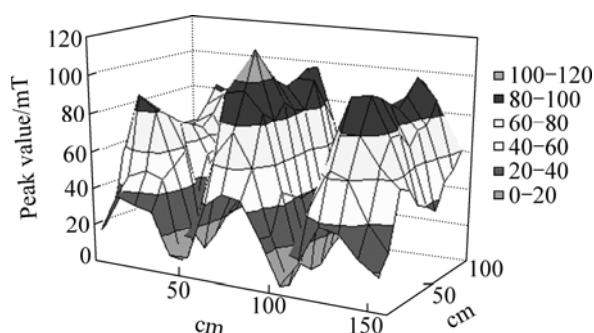


Fig.2 Distribution of magnetic flux density on center plane of mould

intensity of EMV in the casting processes. The technique parameters of this experiment are shown in Table 1. The alternating currents to be input were 0, 50, 100 and 200 A, respectively.

When the experiment was finished, a segment of sample with the length of 10 mm could be cut from the super-thin slab, which was used to observe the solidification structures and analyze its changing rules.

3 Results and discussion

3.1 Experiment of pure tin

Figure 3 shows that the solidification structures of pure tin are influenced by EMV in HCC of super-thin slab. Without the EMV (0 A), the solidified structures of the slab consists of large columnar grains, which can extend from the slab surface to the centre and butt each other; but when the EMV is applied, the columnar grains become small and fine with the current increasing. This result shows that the columnar grains become fine when the current is 50 A or 100 A, but they are still butting on the center layer of the slab, and when the current reaches 200 A, the grains are changed to equiaxed ones. In the picture of solidification structure from EMV with current of 200 A, it is obvious that the columnar grains are broken into equiaxed grains by the vibration force.

For solidification in EMV with current of 200 A, the morphologies of the dendrites on the surface and the equiaxed grains in the center of the slab are shown in Fig.4. It can be seen that in HCC with EMV, the columnar grains can be changed into small and fine dendrites, and the dendrite arms can be broken obviously; on the other hand, the equiaxed grains in the center of

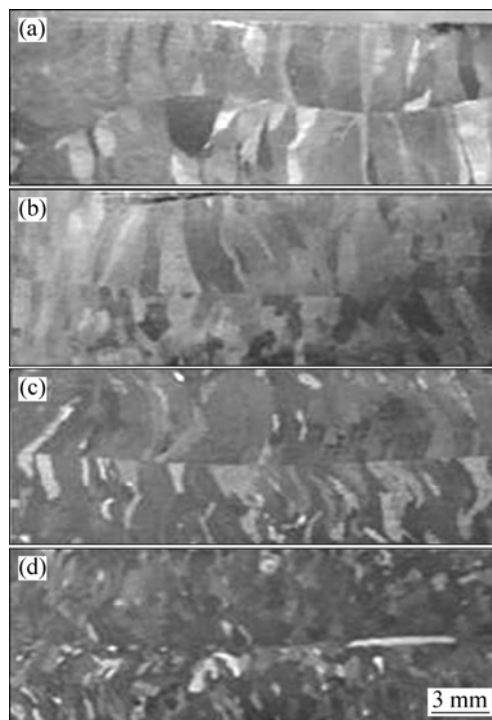


Fig.3 Effect of EMV on solidification structures of pure tin with different currents: (a) 0 A; (b) 50 A; (c) 100 A; (d) 200 A

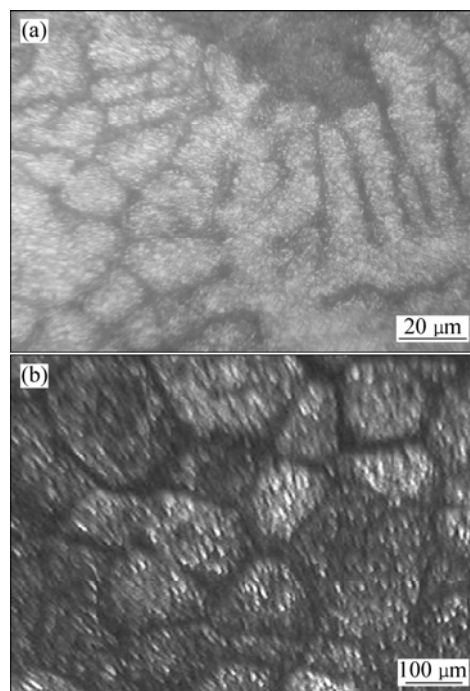


Fig.4 Microstructures on skin (a) and centre (b) of pure tin of slab casting by HCC with EMV at 200 A

Table 1 Experiment materials and technique parameters

Metals	Casting temperature/ $^{\circ}\text{C}$	Casting velocity/ $(\text{cm}\cdot\text{min}^{-1})$	Cooling Water flow/ $(\text{L}\cdot\text{h}^{-1})$	Drawing period/s	Stopping period/s
Sn	280	24	45	2.5	1.0
Sn-10%Pb	230	12	50	2.0	3.0

slab present to be sand-shape, and the sizes are homogeneous relatively. Comparing the solidification structures shown in Fig.4(a) and (b), it is found that under the action of EMV, the periodical vibration force makes the columnar grains transform into fine dendrites and their arms be broken usually. These breaking arms are in free-state in the molten metal, so they can grow into equiaxed grains or re-melt into liquid.

For statistics of the grain average size and its relation with the alternating currents, some square samples with the cross section of 10 mm×10 mm were cross-cut from the super-thin slab casting by HCC in EMV. According to the grains number on the diagonals in the cross section, the average size of grains was evaluated, which is shown in Fig.5. In this figure, the relation of average grain size with the alternating current is linear approximately.

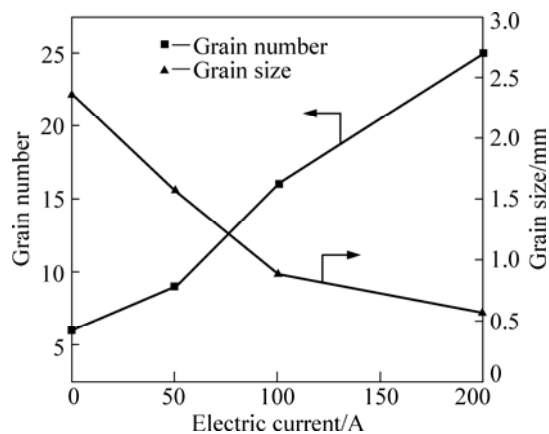


Fig.5 Relation of grain number and average size with current

3.2 Experiment of Sn-10%Pb alloy

For HCC experiments of super-thin slab of Sn-10%Pb alloy in EMV, the solidification structures with various alternating current are shown in Fig.6. It can be seen that the structures in cross section of slab consists of irregular columnar grains when EMV is off, but when EMV is used, the columnar grains transform to equiaxed ones and are refined with the alternating current increasing. In this experiment, when the current is 50 A, compared with that in EMV-free case, the columnar grains become smaller, and a layer of equiaxed grains appear in the center of slab; when the current increases to 100 A and higher, the solidified structure is basically composed of equiaxed grains (the columnar grains are not obvious), and the grains trend to become small and fine with the current increasing. The morphologies in the center layer of super-thin slab of Sn-10%Pb alloy casting by HCC with and without EMV can be seen in Fig.7, in which the currents are 0 and 200 A, respectively. From this figure, it can be observed that with EMV turning on, the periodically electromagnetic

vibration force makes the grains change from irregular granular shapes to the similarly rosaceous ones.

3.3 Discussion

From above experiments, during the solidification

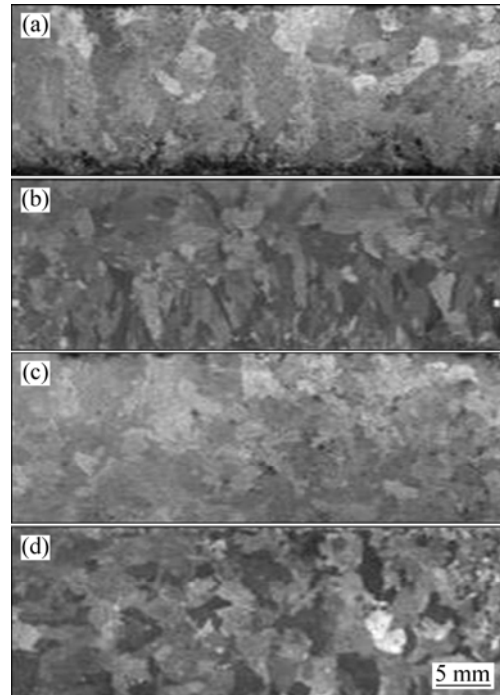


Fig.6 Effects of EMV on solidification structures of Sn-10%Pb with different currents: (a) 0 A; (b) 50 A; (c) 100 A; (d) 200 A

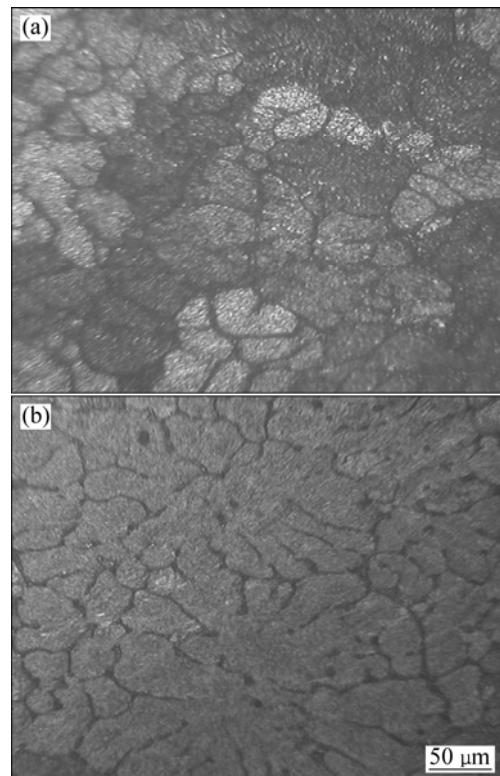


Fig.7 Morphologies in center region of Sn-10%Pb alloy of super-thin slab casting by HCC: (a) 0 A; (b) 200 A

of HCC of super-thin slab, EMV can effectively suppress the growing of columnar grain, refine the grains, and facilitate the formation of equiaxed grains. EMV is effective on improving the solidified structures of billet cast in the cases of high temperature gradient, high casting velocity and/or short solidification time, such as HCC of super-thin slab, so that it has the practicability and technical feasibility in industry.

For the mechanism of EMV, we think that the electromagnetic force caused by EMV makes molten metal and the initially solidified shell vibrate periodically, which results in the actions of drawing, compressing and/or shearing alternately to the primary crystals. The frequency of this vibration is the same as that of alternating current. In the casting processes, EMV results in the primary grains to be exfoliated from the mould and the solidified wall of metal, and the dendrite arms to be broken into the crystal nuclei in the molten metal in free-state. At the same time, the oscillating effect of EMV can homogenize the temperature and the solute concentration in the molten metal, which results in the compositional under-cooling decreasing and the equiaxed crystals growing.

When the intensity of EMV is large enough, electromagnetic force can cause the cavitation effect in the molten metal. The studies[6–7, 10, 16] indicated that, there was a critical value of 0.1 MPa for the periodically electromagnetic pressure in the molten metal. When the electromagnetic pressure is smaller than 0.1 MPa, the grains refining is mainly from the mechanical effects of drawing, compressing and shearing on primary grains; and when it is larger than 0.1 MPa, the cavitation has the main effect on grain refinement.

According to electromagnetism, the electromagnetic force is simplified as:

$$F = BIL \sin 2\pi ft \quad (1)$$

And the electromagnetic pressure can be described as:

$$P = (BI / H) \sin 2\pi ft \quad (2)$$

where B is the magnetic flux density, I is the current, f is the frequency, L and H are the width and the thickness of the slab, respectively.

Therefore, the electromagnetic force and electromagnetic pressure increase linearly with the magnetic field and alternating current, which means that the intensity of EMV is also proportional to these parameters. From the magnetic flux density measured and the alternating current input in the experiments, we can calculate the maximal electromagnetic pressure in the molten metal, which is at the level of 1.53 kPa and far lower than the critical one, so we think that there is no action of cavitation in above experiments. The equiaxed crystallization and refining in solidification structures are from the increasing of primary crystal nuclei,

homogenization of temperature and solutes caused by EMV.

Taking pure tin as an example, in the experiments, when the current is at the lower level of 50 A and 100 A, EMV makes the columnar grains be fine and the grain number increase. This indicates that the periodical vibration force makes the number of nuclei increase fast, but in this time it cannot change the temperature gradient on the front of solidification greatly. When the current increases up to 200 A, there are a large number of equiaxed grains in the center of the super-thin slab. This means that EMV makes the temperature and solutes be homogenized, and the nuclei increase in the solidification front of the molten metal. Also, in the casting experiment of Sn-10%Pb alloy, the results show that the trend of equiaxed crystallization is more evident in EMV with lower level currents, where the section of super-thin slab is almost covered by equiaxed grains. The results can be related to the conductivity of metals. The conductivity of Sn-10%Pb alloy is 35% higher than that of pure tin, so that it can get a higher Joule heat and a larger force in EMV at the same level of currents.

From the above results, it can be concluded that in solidification of metals, the function of EMV with low intensity is to disturb the molten metal and the primary crystal, which can result in the homogenous distribution of temperature and solutes, and more nuclei, so the grains grow uniformly and equiaxedly. In the experiments, the changing trend of solidification structures in the super-thin slab cast by HCC in EMV can be described as following: with the increase of alternating current, grains change from columnar to small and fine, but they are still butting; then, they change progressively to local equiaxed grains in the center; and finally to total equiaxed grains in the section of the slab.

4 Conclusions

1) The experiments show that it is effective to refine grains by applying EMV to HCC of super-thin slab. The problems of columnar grains butting, and porosity or segregation in the center of the slab can be solved, and the solidification structures of the slab can be also improved.

2) The formation of refining and equiaxed grains is related to the intensity of EMV, the physical properties of molten metal, (such as electrical conductivity and thermal conductivity), and the technique parameters of casting (such as the drawing velocity and cooling water flow).

3) In the case of EMV, with the intensity increasing, the solidified structures of slab change in a progress from large columnar grains to small grains, to equiaxed grains in center, and to equiaxed grains in total section, in

which the growth of equiaxed grains eliminates the butting of columnar grains in the center of super-thin slab.

4) Because of the periodical actions of tension, compress, and/or bend from the electromagnetic force on the primary columnar grains, and the homogenizations of temperature and compositions in the region of solidification front of molten metal, the primary columnar grains are broken into nuclei partially, and the temperature gradient and the compositional cooling are decreased, thus the columnar gains are suppressed and the equiaxed grains are formed and refined.

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静磁场和交流电耦合作用下超薄板坯水平连铸的凝固组织

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摘 要: 研究在电磁振荡作用下, 金属超薄板坯水平连铸的凝固组织及其与电流强度的关系。结果显示, 在静磁场和交流电正交所产生的电磁振荡力的作用下, 水平连铸纯 Sn 超薄板坯的凝固组织明显细化, 且细化效果随所施电流的增大而增强; 而对 Sn-10%Pb 合金超薄板坯, 则显著地促进其等轴晶组织的形成, 使其中心层面出现等轴晶区, 该等轴晶层的厚度随电流强度增大而增加。实验结果表明, 电磁振荡作用有利于抑制柱状晶对穿、中心疏松、夹杂和/或气体聚集、以及偏析等超薄板坯水平连铸中常见的凝固缺陷。

关键词: 水平连铸; 超薄板坯; 电磁振荡; 凝固

(Edited by YUAN Sai-qian)