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Electromagnetic continuous casting by imposing multi-electromagnetic field ①

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[Abstract] In order to obtain cast metal of high quality, an investigation was carried out by simultaneous imposition of multi-electromagnetic fields from the outside of a cold-crucible copper mold. Sn-4.5%Pb as a simulator of high melting point metal was continuously cast under different conditions. The results show that multi-electromagnetic fields can eliminate surface defects, and coarse columnar grains of the solidification structure is turned into equiaxed crystal with the increase of magnetic flux density. Moreover, finer equiaxed crystal structure is obtained when rapidly solidified sheet is fed into the mold during continuous casting.

[Key words] continuous casting; multi-electromagnetic field; heredity effect; quality of cast metal

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1 INTRODUCTION

Surface quality of cast metals can be improved by imposing a high frequency magnetic field from outside of a mold, which is regarded as another great revolution in material processing and as a new casting process in the 21th century. Much research work was done in the field[1~6]. However, there are some problems, for example, coarse columnar grains appear in the solidified ingot cast by imposing high frequency electromagnetic field.

Electromagnetic stirring within the mold (M-EMS) can refine grains and decrease segregation in conventional continuous casting[6~10], but it is noted that the melt level in the vicinity of mold wall is higher than that near nozzle due to action of centrifugal force generated by EMS, which would decrease the flux channel between the melt and the mold and cause defects on surface of cast metal, and mold powder would be drawn into melt pool by center swirl motion.

In order to obtain high quality cast metal, a new process, i.e. imposing multi-electromagnetic field, which was realized by setting a high frequency electromagnetic coil (HFC) and a main frequency electromagnetic coil (MFC) around a mold, was developed. Through stipulating the distribution of multi-electromagnetic fields in the mold, the effect of simultaneous imposition of multi-electromagnetic fields on quality of billet was investigated. Furthermore, the effect of adding rapidly solidified metal sheet into the mold on quality of continuously cast metal was examined during continuous casting.

2 EXPERIMENTAL

The sketch of experimental apparatus is shown in Fig.1. Two copper coils were installed to the outside of the square copper mold of 30 mm × 30 mm, respectively. The upper is linked with a high frequency

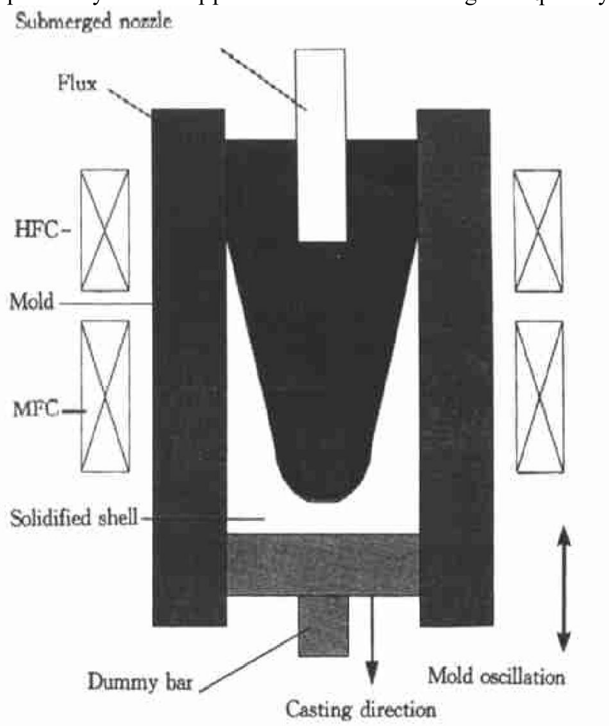

Fig.1 Sketch of experimental apparatus

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electric generator with maximum power capacity of 85 kW and maximum frequency of 80 kHz; the lower, which is connected to a main frequency electric generator with frequency of 50 Hz, serves as a stirrer. During continuous casting, Sn-4.5%Pb as a simulation alloy was poured into the mold through submerged entry nozzle, and rapidly solidified Sn-4.5%Pb sheet with size of 5 mm × 1 mm × 100 mm, which is made with a cooling rate of 3×10^5 ℃/s, was fed into the mold along mold wall at the same time. The meniscus level was kept at position of 10 mm from the top of the mold. The solidification structures of cast metal were observed. The experimental conditions are listed as follows:

Pouring temperature:	275 ℃
Billet size:	30 mm × 30 mm
Casting speed:	5 mm/s
Mold oscillation:	±3 mm (stroke), 50 Hz
Mold lubricant:	Silicon oil
Cooling speed:	80 L/h
Electric power:	6 kW, 30 kHz (HFC)
	0.1 kW, 50 Hz (MFC)

3 RESULTS

3.1 Distribution of multi-electromagnetic field in mold

Fig.2 shows the distribution of magnetic flux density without charge along the central axis of the mold, which was measured by a sensor coil[6]. Curves 1 and 2 indicate the magnetic flux density parallel and perpendicular to casting direction, respectively. It is noted that, in the upper part of the mold, magnetic flux density parallel to casting direction (B_Z) is larger than that perpendicular to casting direction (B_X), but in the lower part of the mold, B_X is larger than B_Z. It also can be found that in the vicinity of the meniscus B_Z is uniform, which is able to keep the meniscus stable; and the maximum value of B_X is at position of 70 mm from the top of the mold

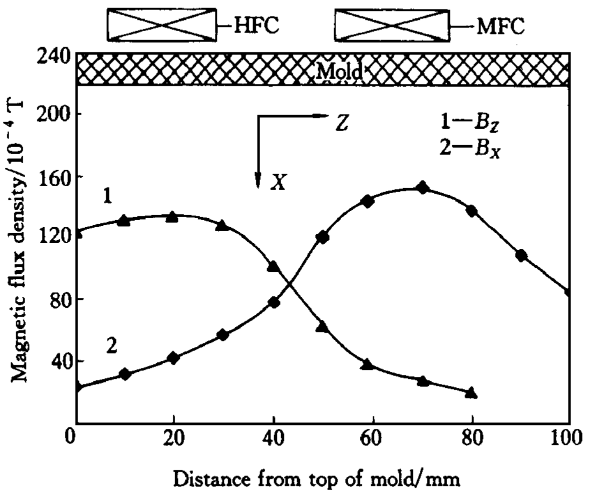

Fig.2 Distribution of multi-electromagnetic field

and produces a stirring force.

3.2 Effect of multi-electromagnetic field on quality of cast metal

The surface appearance of cast metal under conditions with and without multi-magnetic field was shown in Fig.3. In the case without multi-electromagnetic field, regular oscillation mark was found on the surface of cast metal; after imposing multi-electromagnetic field, the surface of cast metal becomes smooth. Fig.4 presents the surface roughness of the cast metals under the conditions with and without multi-electromagnetic field. The surface roughness of cast metal, which was measured by a displacement sensor, was reduced from 150 μm to 30 μm in the case with power of 20 kW and frequency of 30 kHz.

Fig.5 shows the macroscopic structures of the cast metals under the conditions with and without multi-electromagnetic field. It was obvious that in the case without main frequency magnetic field, the macroscopic structure of the billet is mainly coarse columnar crystal; and after main frequency electromagnetic field was imposed, more equiaxed crystals

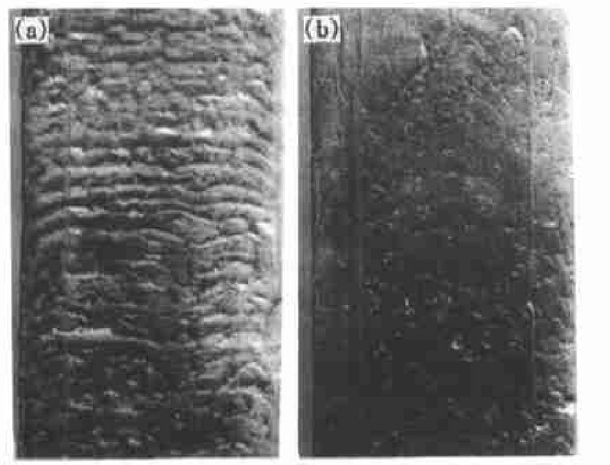

Fig.3 Macro-surface appearance of cast billet with multi-electromagnetic field
(a) — B_Z = 0 T, B_X = 0 T;
(b) — B_Z = 0.014 T, B_X = 0.015 T

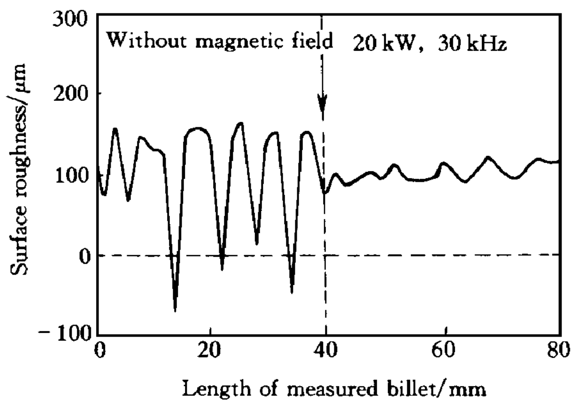

Fig.4 Effect of multi-electromagnetic field on surface roughness

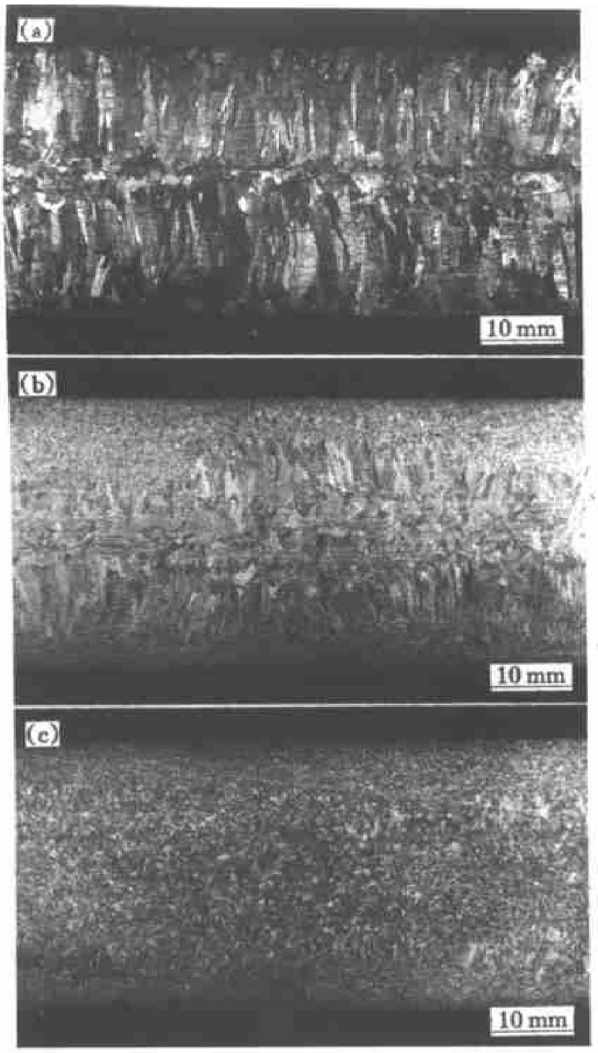

Fig.5 Macrostructures of cast metal under conditions with and without multi-electromagnetic field

(a) — $B_X = 0$ T, $B_Z = 0$ T; (b) — $B_X = 0.005$ T, $B_Z = 0.014$ T; (c) — $B_X = 0.015$ T, $B_Z = 0.014$ T

appear. The stronger the magnetic flux density, the higher the rate of equiaxed grains. When the magnetic flux density B_X was increased up to 0.015 T, the macroscopic structure of the cast metal is completely made of equiaxed grain.

3.3 Effect of adding rapidly solidified sheet on solidification structure

Fig.6 shows the effects of rapidly solidified sheet on macrostructures of cast metal. As illustrated in Fig.6(a), when adding the rapidly solidified sheet, even if magnetic field was not imposed much finer equiaxed crystals can be obtained compared with the magnetic field of 0.015 T as shown in Fig.5(c), but the distribution of equiaxed crystals is not uniform. When rapidly solidified sheet and magnetic field act simultaneously, solidification structure is fine equiaxed crystal, as shown in Fig.6(b).

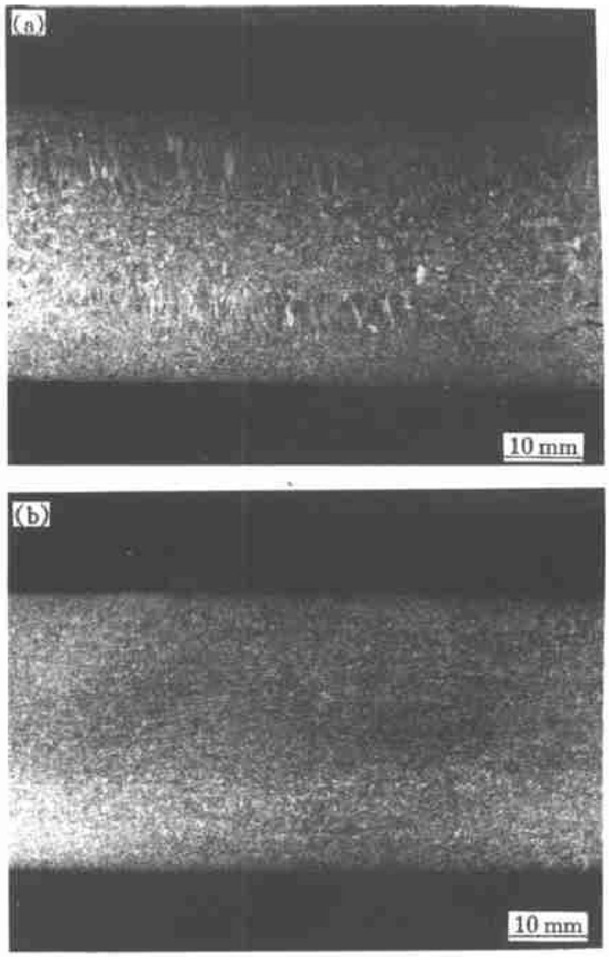

Fig.6 Macrostructures of Sn-4.5%Pb cast metal added rapidly solidified sheet

(a) — $B_X = 0$ T, $B_Z = 0$ T; (b) — $B_X = 0.015$ T, $B_Z = 0.014$ T

4 ANALYSES AND DISCUSSION

During conventional continuous casting, surface defect was caused by mold oscillation and chilling of the mold wall; and coarse columnar crystals appear in the cast metal due to unidirectional transfer of heat. The surface quality of cast metal can be improved by imposing the high frequency magnetic field at meniscus, but the coarse columnar grains were found in the solidification structure. Electromagnetic stirring within the mold can refine grains, but decrease the flux channel between the melt and the mold. When multi-electromagnetic field was imposed, electromagnetic stirring force $\boldsymbol{F} = \boldsymbol{J}_Z \times \boldsymbol{B}_X$, generated by main frequency magnetic field, would drive molten metal flow and decreased its temperature gradient of solidification direction; moreover, the stirring force could break the growing columnar crystals, which refined the solidification structure due to forming nonspontaneous nuclei. On the other hand, electromagnetic pressure $\boldsymbol{F} = \boldsymbol{J}_X \times \boldsymbol{B}_Z$, perpendicular to casting direction, which was generated by high frequency magnetic field, pushed the melt away from the mold wall and widened the flux channel, and the periodical deformation of the meniscus due to mold oscillation was restrained, so surface quality was improved greatly. Meanwhile, the electromagnetic pressure $\boldsymbol{F} = \boldsymbol{J}_X \times \boldsymbol{B}_Z$ also controlled the turbulence of the meniscus due to the stirring force generated by main frequency magnetic field and eliminated defects of cast metal.

In addition, effects of heredity of melt on solidification structure of cast metal were studied[11,12]. In this research, heredity theory was successfully applied to electromagnetic continuous casting, finer equiaxed crystals were obtained. Moreover, the EMS makes the solidification structure uniform.

5 CONCLUSIONS

1) The surface quality of cast metal is improved and the rate of equiaxed crystals in the solidification structure increases in case with imposing multi-electromagnetic field.

2) Much finer equiaxed crystals can be obtained by adding rapidly solidified sheet into the mold during continuous casting.

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