SUBSTITUTE THE MECHANICAL OSCILLATION SYSTEM BY IMPOSING AMPLITUDE-MODULATED MAGNETIC FIELD OUTSIDE THE MOLD DURING CONTINUOUS CASTING

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So far, several kinds of alternative magnetic field have been tested in soft-contacted mould Electromagnetic Continuous Casting (EMCC) [1], such as, intermittent [2, 3], half-triangle [4] and quasi-sinusoidal [5] ones. On the base of these studies, a novel technology named Mould Oscillation-Less Electromagnetic Continuous Casting (MOLECC) Process [3, 6] has been proposed in order to substitute the huge and heavy mechanical mould oscillation system by a small and light electromagnetic one. However, only the amplitude-steady or intermittent magnetic field was adopted in this new technology. Obviously, it is necessary to explore the MOLECC process with other kinds of magnetic field, so that the behavior of meniscus during continuous casting can be controlled optimality by the magnetic field, and the billets quality be improved.

In this paper, a type of magnetic field named as Amplitude-Modulated Magnetic Field (AMMF) is proposed, whose amplitude is varied, i.e. a high frequency magnetic field (carrier wave) modulated by a low frequency periodic wave (modulated wave). Three kinds of AMMF, that is, rectangle, triangle and sine wave AMMF were applied in the experiment. The intermittent contacting distance in the mould under AMMF was measured. Further, the MOLECC experiments under the three wave kinds AMMF with Tin, as an analogue of steel, was carried out and the effects of AMMF type and modulated wave frequency on billets surface quality and cast withdrawing resistance was examined.

1. Experiments.

The experimental system and continuous casting condition were described in [7] in details.

The most important part in this system is a high frequency AMMF power source, which is specially designed to generate rectangle, triangle and sine wave AMMF.The main parameters of all three kinds of AMMF are adjustable, including the frequency, duty ratio of rectangle AMMF between 20 $\sim$ 80% and slope of the

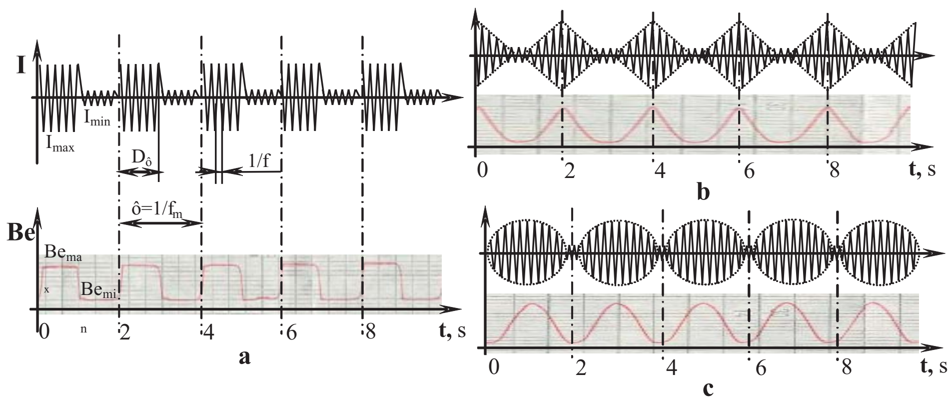

Fig. 1. Three kinds of amplitude-modulated magnetic field and their measurement results, the modulated waves are: (*a*) rectangle, (*b*) triangle and (*c*) sine wave.

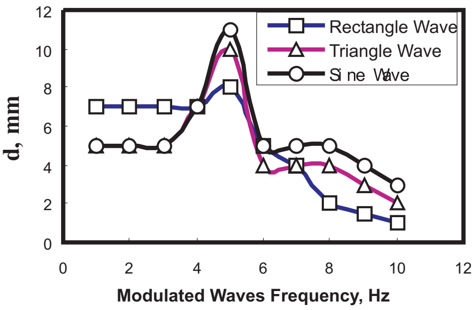

Fig. 2. Intermittent contacting distance under different AMMF.

triangle AMMF. Fig. 1 shows the typical waves of three kinds of AMMF and their measurement results in the mould when modulated wave frequency was $f_m = 0.5$ Hz, and the carrier wave frequency was $f = 18$ kHz. The rectangle wave AMMF duty ratio was 50% and the triangle wave AMMF was symmetrical.

Intermittent contacting distance [8] were measured, which is a key factor in the MOLECC process because it affects the mould flux's behavior of flow in and out of the mould flux channel between the early-solidified shell and mould [9].

In order to evaluate the effects of AMMF, the withdrawing resistance were measured by load cell during continuous casting and surface roughness of the billets was measured after casting.

2. Experimental results and discussion. Fig. 2 shows the relationship of intermittent contacting distance d and modulated wave frequency f_m under three kind waves AMMF when $B_{e\,\max} = 16.0$mT, $B_{e\,\min} = 5.3$mT (as shown in Fig. 1). The figure shows that d was the largest when $f_m = 5.0$ Hz under all three wave kinds of AMMF, and d decreased when f_m was over 5.0 Hz. The intrinsic frequency of a liquid metal filled in a cylindrical vessel (radius is R and liquid depth is H) is given as Eq.(1) [10].

$$f_{lm} = \frac{1}{2\pi}\sqrt{\left(gk_{lm} + \frac{\gamma}{\rho}k_{lm}^3\right)\tanh(Hk_{lm})}, \qquad \left(k_{lm} = \frac{\beta_{lm}}{R}\right) \tag{1}$$

Where, β_{lm} is the $m-$th positive root of the equation $\mathrm{d}J_l(x)/\mathrm{d}x = 0$, l and m represent the azimuthal and radial modes, $J_l(x)$ is l-th Bessel function. g, γ and ρ are the acceleration of gravity, liquid metal surface tension and density, respectively. From Eq. (1), it can be calculated that the 01 mode intrinsic frequency of the molten Tin in experimental mould is $f_{01} = 5.9$ Hz.

This result suggests that resonance happened between liquid Tin and variation electromagnetic force at 5.0 Hz, which was close to the intrinsic frequency of 5.9 Hz. The experimental results were accorded with the references [2, 9] in which only an intermittent magnetic field was concerned.

Fig. 2 shows that when f_m was less than the experimental resonance frequency, the intermittent contacting distance under the rectangle wave AMMF was larger than that under the triangle and sine wave AMMF. This is due to the longer time required for the magnetic force to push the meniscus away from the mould wall under rectangle wave AMMF for its greater duty ratio of $B_{e\,\max}$. However, at 5.0 Hz, the experimental resonance frequency, the sine wave AMMF obtained the greatest intermittent contacting distance, and the rectangle wave AMMF obtained the least. When f_m was greater than the experimental resonance frequency, intermittent contacting distance d decreased along with the increasing modulated waves frequency under all three wave kinds AMMF. This is because there was insufficient time for the liquid metal to respond to the electromagnetic force at high f_m.

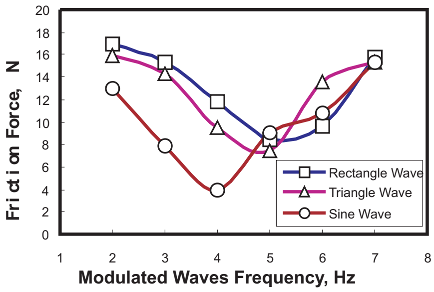

Fig. 3. Continuous cast with drawing resistance vs modulated waves frequency under three kinds of AMMF.

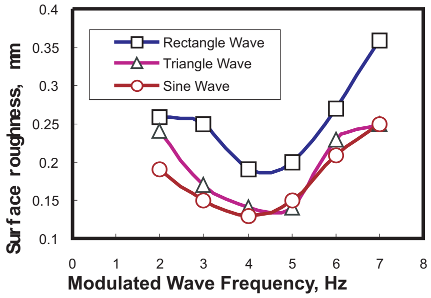

Fig. 4. Billets surface roughness vs modulated waves frequency under three kinds of AMMF.

Fig. 3 is the withdrawing resistance under three kind waves AMMF at different modulated wave frequencies. Fig. 4 is the relationship between billets surface roughness and modulated wave frequency under three kinds of AMMF. Figs. 3 and 4 show that when modulated wave frequency was slightly lower than the experimental resonance frequency, i.e. 4.0 ∼ 5.0 Hz, the withdrawing resistance was the least, and the surface roughness was the least also under all three kinds of AMMF. Away from the experimental resonance frequency, the withdrawing resistance became greater and the surface quality became worse. This phenomenon is due to the above experimental results regarding the intermittent contacting distance. As shown in Fig. 2, near the experimental resonance frequency, the intermittent contacting distance was the greatest, hence the mould flux channel was the widest. Therefore, mould flux flew in the channel most easily. The sine wave one was the best in view of reducing withdrawing resistance and improving surface quality as the same reason.

Fig. 5 shows photographs of cast billets under sine wave AMMF at different modulated wave frequencies. As can be seen, at 2.0 and 3.0 Hz of the modulated wave frequency, the billets surface showed obvious *oscillation marks* like defects, the periodicity of the *oscillation marks* was synchronized along with the frequency of the AMMF. This indicates that within one cycle of the electromagnetic force inducted by the AMMF, the early-solidified shell moved away and back to the mould wall once, then one *oscillation mark* formed. In the case of lower modulated wave frequency, the magnetic force may push the shell for a longer time and result in deeper oscillation marks. With a higher frequency of the modulated wave (i.e. 4.0 or 5.0 Hz), the intermittent contacting distance was the greatest and the lubrication was the best. Additionally, the alternation of the electromagnetic force

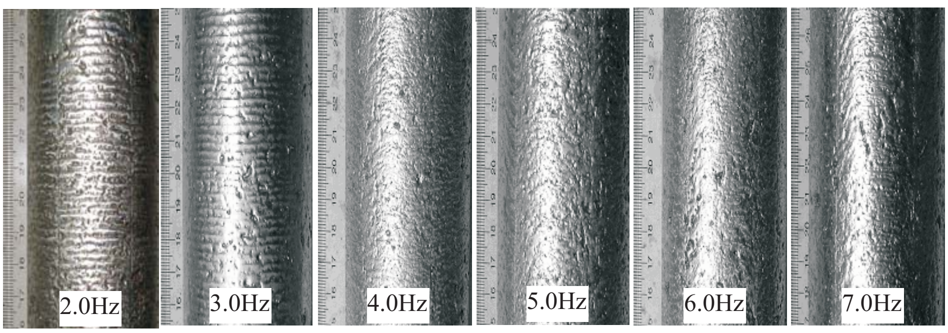

Fig. 5. The surface photos of Sn cast billets under sine wave AMMF at different modulated wave frequencies.

was so fast that the early-solidified shell can hardly followed. Therefore, regular oscillation marks were not easy to form and the surface quality was the best. However, when the modulated wave frequency exceeded the experimental resonance frequency (i.e. 6.0 or 7.0 Hz), the intermittent contacting distance decreased, the lubrication became worse, the early-solidified shell adheres to the mould wall and forms pinholes or depressed pits, the surface quality became worse.

According to the experiments, two aspects of influence of the AMMF must be considered in selection of its frequency. One aspect is that if the frequency is low, the mould flux flows fluently, but oscillation marks defect may form. The other is that if the frequency is high, the oscillation marks are abated, but the lubrication is too poor to obtain good surface quality. So there must be an optimization frequency to keep the balance between oscillation marks formation and lubrication. In our experiments, the optimization frequency was slightly lower than the intrinsic frequency of the experimental system.

3. Conclusion. Mould-less electromagnetic continuous casting with a high frequency AMMF power source that produces rectangle, triangle and sine wave AMMF were investigated experimentally.

During the MOLECC process under rectangle, triangle and sine wave AMMF, an modulated wave frequency slightly lower than the intrinsic frequency of the experimental system was the optimization frequency to obtain the greatest intermittent contacting distance, the best mould flux lubricating, the least continuous casting withdrawing resistance, and the best surface quality of billets.

Among the three kinds of AMMF, sine wave was the best in increasing the intermittent contacting distance, reducing the withdraw resistance and improving the billets surface quality.

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