Article ID: 1003 - 6326(2005)03 - 0548 - 05

Effects of alternative electromagnetic field on surface tension and filling ability of molten metal ①

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Abstract: Surface tension and filling ability of molten metal play an important role on the shaping of the molten metal. The surface tension was calculated from wetting angles of the molten metal by the sessile drop method. The specimen for filling ability was designed and the filling ability experiments under the alternative electromagnetic field were performed. The results show that the intensity and frequency of the alternative electromagnetic field have significant effects on the surface tension of the molten metal. The surface tension of Al-6% Si alloy decreases with increasing the intensity of the electromagnetic field. For pure Sn, the surface tension decreases gradually when the frequency of electromagnetic field is reduced. The filling ability is improved by applying the alternative electromagnetic field.

Key words: electromagnetic field; surface tension; filling ability; wetting angle; Al-Si alloy; pure Sn
CLC number: TG113.2 **Document code:** A

1 INTRODUCTION

Interface is defined as the surface of liquid or solid contacted with air or vacuum. Interface has some particular features which result in some special phenomena. The molecule or atom in the liquid is in equilibrium state, while the molecule or atom on the surface of the liquid is in the non-equlibrium state, leading to a resultant force toward the liquid. This is the reason why the surface tension is produced. The surface tension can be understood as a force applied on a unit length of the surface:

$$\sigma = \frac{N}{m} \qquad (1)$$

where N is the applied force, N; m is the length, m.

Surface tension is characterized by the wetting angle, as shown in Fig. 1.

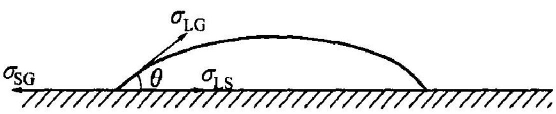

Fig. 1 Schematic of surface tesnion

When surface tension reaches the equilibrium state, the following equations are obtained:

$$\sigma_{SG} = \sigma_{LS} + \sigma_{LG} \cdot \cos\theta \qquad (2)$$

$$\cos\theta = \frac{\sigma_{SG} - \sigma_{LS}}{\sigma_{LG}} \qquad (3)$$

where θ is the wetting angle; σ_{LS} is the surface tension between liquid and solid; σ_{LG} is the surface tension between liquid and air; and σ_{SG} is the surface tension between solid and air.

The surface tension of molten metal plays an important role in the shaping of molten metal and has significant effects on the filling and solidifying of the molten metal. During the filling process of molten metal, the greater the surface tension, the larger the applied pressure required to fill the mould cavity. This usually leads to some defects, such as misrun, cold shut and rough surface. Smaller surface tension is favourable for rising gas and inclusion in the molten metal, lessening the formations of pore and inclusion defects.

There are a lot of studies about the effects of electromagnetic field on solidification behavior[1-3], solidification defects[4, 5] and solidification microstructures[6-14]. Effects of alternative electromagnetic field on surface tension and filling ability of molten metal are mainly investigated in this study.

2 EMPERIMENTAL

2.1 Experimental sets

2.1.1 Experimental apparatus

The schematic of measurement of the wetting angle is shown in Fig. 2.

2.1.2 Set of alternative electromagnetic field

Fig. 3 shows the set of alternative electromagnetic field.

2.2 Experimental method

2.2.1 Measurement of surface tension

① **Received date:** 2004 - 12 - 29; **Accepted date:** 2005 - 05 - 30
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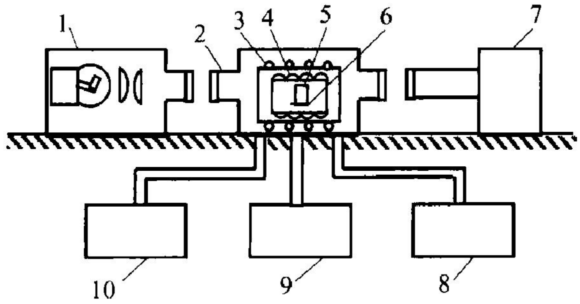

Fig. 2 Schematic set up of sessile drop method
1 —Light source; 2 —Furnace; 3 —Induction coil;
4 —Heating furnace tube; 5 —Specimen;
6 —Backup plate; 7 —Photographic part;
8 —Control part; 9 —Vacuum pump;
10 —Alternative electromagnetic field

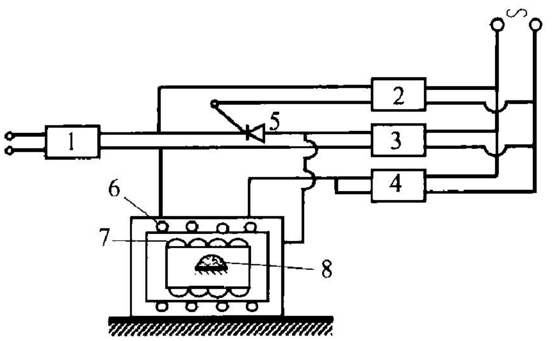

Fig. 3 Set up of alternative electromagnetic field
1 —Voltage regulator; 2 —Trigger circuit; 3 —Ondoscope;
4 —Recorder; 5 —Silicon control; 6 —Inductor;
7 —Heating tube; 8 —Molten metal

A sessile drop method was used to measure the surface tension of the molten metal. The specimen with size of $d2$ mm × 2 mm was cut from the metal material measured. The specimen was put on the backup plate which was made from the compact material with higher melting point than that of the tested material. The specimen and the backup plate were put into the vacuum furnace together. As the vacuum furnace was heated to the desired temperature, the metal drop was formed on the backup plate. The photography of the wetting angle was taken and the surface tension was calculated by measuring the wetting angle.

2. 2. 2 Measurement of filling ability

Fig. 4 shows the specimen designed for filling ability measurement of molten metal. Mould material was silicate bonded sand. The upper part of the mould was a cylindrical cavity with size of $d80$ mm × 60 mm. Three fine holes were distributed equidistantly in the bottom part of the mould. The diameters of three fine holes were 2. 5, 1. 8 and 1. 1 mm, respectively, and they were all 100 mm in depth. The filling ability was measured by comparing method. Under the same environmental conditions, the molten metal was poured under gravity field, and electromagnetic field respectively.

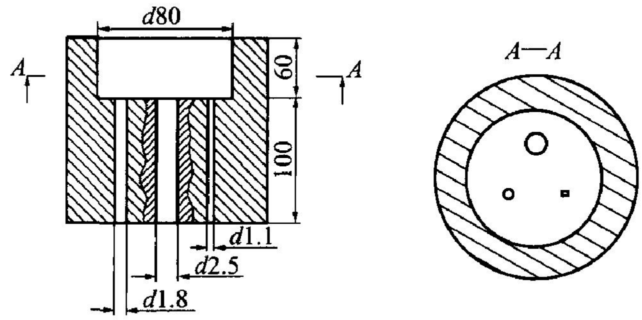

Fig. 4 Mould diagram for filling ability measurement

3 RESULTS AND DISCUSSION

3. 1 Effect of intensity of electromagnetic field on surface tension

The measured material was Al-6% Si and the material of the backup plate was graphite. The measured temperature was 800 ℃. Vacuum degree was 6.67×10^{-3} Pa. The frequency of the electromagnetic field was 50 Hz. The intensity of the electromagnetic field was changed from 0 to 0. 072 T. The wetting angles measured under different electromagnetic field intensities are shown in Fig. 5. The calculated surface tensions are given in Table 1.

Table 1 Relationship between wetting angle and electromagnetic intensity

Electromagnetic field intensity/ T	Time/ min	Wetting angle/ (°)	Surface tension/ (10^{-3} N • m^{-3})
0	5	124	840. 0
0. 018	5	123	813. 1
0. 036	5	106	511. 2
0. 072	5	76	298. 2

The results show that both the wetting angle and the surface tension of Al-6% Si alloy are reduced with increasing electromagnetic field intensity.

3. 2 Effect of frequency of electromagnetic field on surface tension

The used material was pure Sn and the material of the backup plate was pure copper. Vacuum degree was 6.67×10^{-3} Pa and the temperature was 650 ℃. The intensity of the electromagnetic field was fixed at 0. 05 T. The frequency of electromagnetic field was varied from 0 to 50 Hz. The wetting angles measured are shown in Fig. 6. The surface tensions calculated are given in Table 2. It is obvious from the results listed in Table 2 that the surface tension of the molten metal reduces with the reduction of the frequency of the electromagnetic

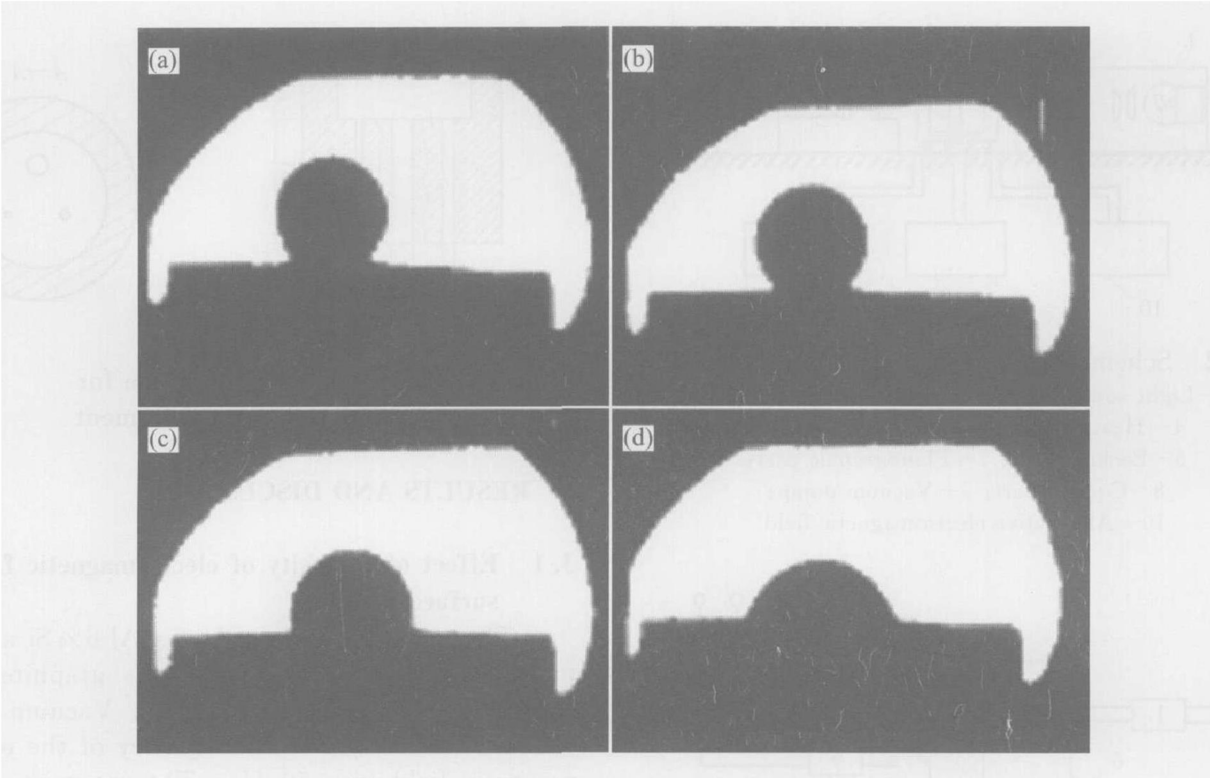

Fig. 5 Wetting angles under different electromagnetic field intensities
(a) —0 T; (b) —0.018 T; (c) —0.036 T; (d) —0.072 T

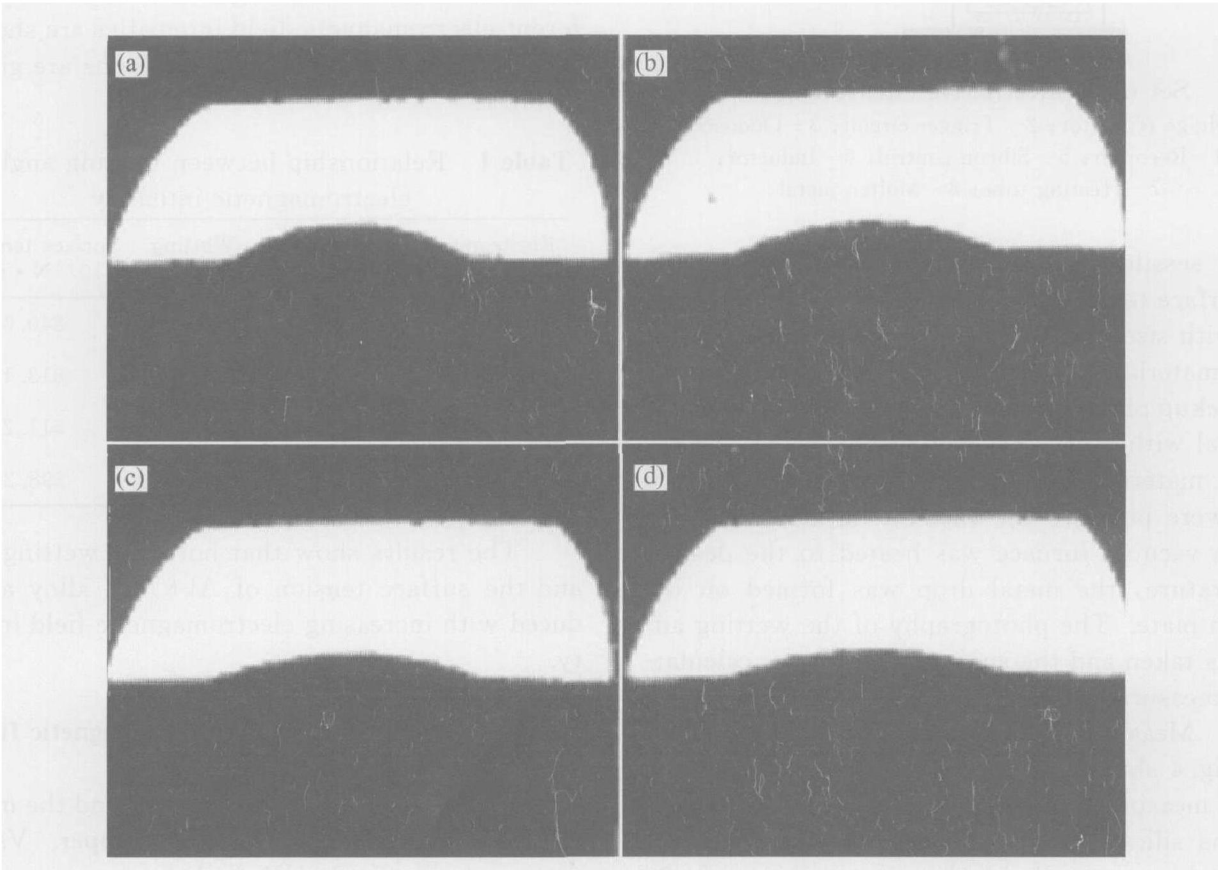

Fig. 6 Effect of frequency on wetting angle
(a) —0 Hz; (b) —50 Hz; (c) —30 Hz; (d) —10 Hz

field.

It is indicated that the alternative electromagnetic field can decrease the surface tension of molten metal. The higher intensity and/or the lower frequency of the electromagnetic field are favourable for the decrease of the surface tension of molten metal.

3.3 Effect of alternative electromagnetic field on filling ability

The material used was Al-6% Si alloy. The pouring temperature was 800 ℃. The results of filling ability measurement are shown in Fig. 7.

The experiments were repeated several times. The details of the results are given in Table 3.

Table 2 Relationship between wetting angle and frequency

Frequency/Hz	Time/min	Wetting angle/(°)	Surface tension/(10^{-3}N · m^{-1})
0	0	35	500.0
50	4	27	481.0
30	4	21	470.4
10	4	18	466.2

Table 3 Data for filling ability measurement

No	Condition	Filling samples size		
		d2.5 mm	d1.8 mm	d1.1 mm
1	GF	47.00	5.50	0
	EF	51.00	48.30	23.50
2	GF	49.00	6.00	0
	EF	50.10	43.00	20.50
3	GF	45.10	4.30	0
	EF	53.10	45.30	28.00
Average	GF	47.00	5.27	0
	EF	51.53	45.53	24.00

GF —Gravity field; EF —Electromagnetic field

The experimental results in Table 3 show that the filling ability is imporved under the electromagnetic field. According to the theory of double electronic shells put forward by Barnak et al[2], surface tension can be regarded as the potential barrier of a condenser on the unit surface:

$$\sigma = \varphi \cdot \eta \quad (4)$$

where η is the electronic charge on the unit surface in the condenser; φ is the electric potential difference between two electrodes.

$$\eta = \frac{ze}{R^2} \quad (5)$$

$$\varphi = E \cdot R = 4\pi\eta R = \frac{4\pi ze}{R} \quad (6)$$

Based on Eqns. (4), (5) and (6), σ can be expressed as

$$\sigma = \varphi \cdot \eta = \frac{4\pi ze}{R} \cdot \frac{ze}{R^2} = \frac{4\pi z^2 e^2}{R^3} \quad (7)$$

where R is the distance between atoms; e is the electric charge; z is the valency; E is the intensity of electric field.

The surface tension is proportional to the square of electric charge and is inversely proportional to the cube of distance. When the molten metal solidifies under the electromagnetic field, an additional electromagnetic energy is created. As a result, both the thermodynamic potential of the molten metal and the internal energy of the atom are improved, which leads to an increase in the distance between atoms, i. e. the value of R increasing. According to Eqn. (7), the surface tension of molten metal is reduced.

In general, the fluidity of molten metal is related to the effective pressure head. The greater effective pressure head results in the better fluidity. When the effective pressure head reaches zero, the flow of molten metal is stopped. The effective pressure head can be expressed as

$$H_e = H_s + H_d - \sum H_r \quad (8)$$

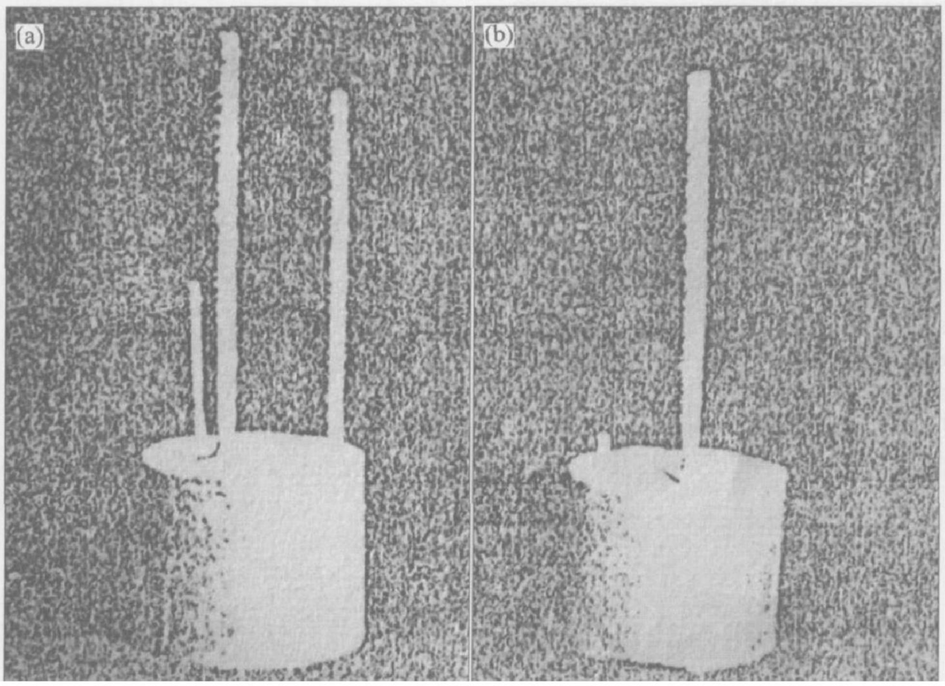

Fig. 7 Compared specimens for filling ability
(a) —Under electromagnetic field; (b) —Under gravity field

where H_e is the effective pressure head at the flow orientation; H_s is the static pressure head; H_d is the dynamic pressure head; $\sum H_r$ is the sum of all resisting forces.

While the sum of all resisting forces can be expressed as

$$\sum H_r = H_g + H_\sigma + H_\xi + H_\eta \tag{9}$$

where H_g is the anti-pressure at the flow orientation; H_σ is the surface resisting force at the fluid orientation caused by surface tension of the molten metal; H_ξ is the resisting force at the flow orientation caused by the friction between the moving molten metal and mould plus resisting force at the corners; H_η is the resisting force caused by the change in viscosity of the molten metal.

From Eqns. (8) and (9), we have

$$H_e = H_s + H_d - H_g - H_\sigma - H_\xi - H_\eta \tag{10}$$

The alternative electromagnetic field mainly affects H_d and H_σ[15]. From Table 1, the surface tension of molten Al-6% Si alloy is 840×10^{-3} N/m, while it reduces to 298.2×10^{-3} N/m as the intensity of the electromagnetic field is 7.2×10^{-2}T. The decreased surface tension produces a reduction in resisting forces, resulting in an increased H_e. Therefore the filling ability is improved.

4 CONCLUSIONS

1) Alternative electromagnetic field can decrease the surface tension of molten metal.

2) Effect of the alternative electromagnetic field on the surface tension of molten metal is related to the intensity and frequency of the alternative electromagnetic field. The greater intensity and the lower frequency of the alternative electromagnetic field are favourable for the decreasing of the surface tension of molten metal.

3) The filling ability of the molten metal is improved under the alternative electromagnetic field.

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(Edited by YANG Bing)