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Theoretical analysis and experiment research of electromagnetic casting of steel by electromagnetic dimensionless number

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Electromagnetic processing of materials is greatly highlighted due to its outstanding performance to enable the product quality and the productivity to be enhanced [1, 2]. As one of such technologies, the electromagnetic casting technology is considered as a potential process to drastically improve the surface quality of its products and to eventually increase the productivity of the continuous casting process [3, 4]. Attainment of the electromagnetic casting technology has been mainly dependent upon the role of magnetic force/pressure of the electromagnetic field.

Fig. 1 shows the principle of the electromagnetic casting process [5].

The important technique occurring in the electromagnetic casting is the support of the molten metal by electromagnetic force. The equilibrium between electromagnetic force and the static pressure of molten metal is the key to attain electromagnetic casting.

But the distinct physical properties of the different metals, such as electric conductivity, magnetic conductivity and specific weight, make the difference of the feasibility of the different metal to achieve electromagnetic casting, such as the feasibility between the aluminum and steel.

The paper has developed an original mathematical model, the Electromagnetic dimensionless Number (EMDN), on the basis of the principle of the Electromagnetic Casting to estimate the feasibility of electromagnetic casting of steel. The veracity of the EMDN has been proved by the experiments of Aluminum and Sn-3%Pb alloy. By the discussion of EMDN of Sn-3%Pb alloy and Steel, it can be noticed that the two metals have a uniform feasibility of EMC. Then by the experiments of Sn-3%Pb alloy substituted for Steel the parameters required for EMC of steel can be deduced.

The equations describing the electromagnetic field are the Maxwell's equations, shown as follows:

$$\nabla \times \dot{H} = \dot{J}$$
$$\nabla \times \dot{E} = -j\omega\dot{B}$$
$$\nabla \cdot \dot{B} = 0 \qquad (1)$$
$$\dot{B} = \mu\dot{H}$$
$$\dot{J} = \sigma\dot{E}$$

The electric field in Equation 1 can be approximately expressed as [6]: $E = \omega B\delta$, then the induction current density is: $J = \sigma\omega B\delta$. The electromagnetic force density can be expressed as:

$$F = J \times B = \sigma\omega B^2\delta = 2B^2\sqrt{\pi f\sigma}/\mu \qquad (2)$$

And the gravity force density is:

$$p = \rho g$$

As a first approximation, dynamic pressure and the surface tension effects can be neglected. Assuming that the height of the molten metal confined with electromagnetic force is h, and the integral distance of electromagnetic force is t. Then the equilibrium between the electromagnetic force and the static pressure is the prerequisite to achieve the electromagnetic casting.

$$\int_0^t F\,\mathrm{d}x = \int_0^h p\,\mathrm{d}y \qquad (3)$$

substituted (2) to (3) then:

$$\int_0^t 2B^2\sqrt{\pi f\sigma}/\mu\,\mathrm{d}x = \int_0^h p\,\mathrm{d}y \qquad (4)$$

Assuming $\bar{B}$ is the average magnetic intensity of the integral distance in the metal surface, then making integral of (4), the following equation is obtained:

$$\frac{2\bar{B}^2\sqrt{\pi f\sigma}/\mu}{\rho g} = \frac{h}{t} \qquad (5)$$

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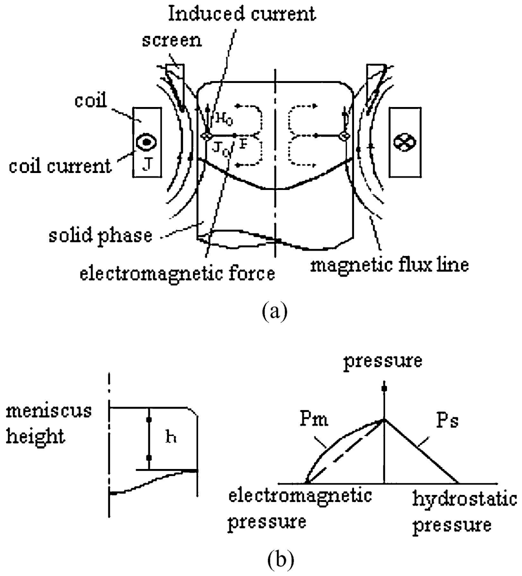

Figure 1 (a) Schematic illustration of electromagnetic casting and (b) its principle.

During the process of the electromagnetic casting, the height of the molten metal refined by electromagnetic force was generally required $h > 30$–50 mm. To ensure that the electromagnetic body force could be considered as a surface force, it was considered that t is less than 5 mm. Here, it is considered that $h = 50$ mm and $t = 5$ mm, taking all assumption into consideration, the Equation 5 can be expressed as follows:

$$\frac{2\bar{B}^2\sqrt{\pi f \sigma/\mu}}{\rho g} > \frac{h}{t} \approx 10 \qquad (6)$$

Equation 6 is defined as the prerequisite of the electromagnetic casting.

Here, using

$$\xi = \frac{2\bar{B}^2\sqrt{\pi f \sigma/\mu}}{\rho g},$$

Then (6) can be represented as: $\xi > 10$.

Dimension of the physical properties used in the Equation 6 are shown in Table (A) at appendix.

Substituted dimension to Equation 6 it can be concluded that ξ is a dimensionless number. So ξ is named the electromagnetic casting dimensionless number or the Electromagnetic Dimensionless Number (EMDN) for short.

Considered the skin effect of the electromagnetic field, then the magnetic flux intensity in the metal can be shown as:

$$B(x) = B_0 e^{-\sqrt{\pi f \mu \sigma}\cdot x}$$

where, $B(x)$ is the magnetic flux density at the x position inside of metal; B_0 is the magnetic flux density virtual value at the surface of the molten metal; The average of magnetic intensity in the integral distance can be calculated by the following expression:

$$\bar{B} = \frac{\int_0^t B(x)\mathrm{d}x}{t} = \frac{B_0\cdot(1-e^{-\sqrt{\pi f\sigma\mu}\cdot t})}{\sqrt{\pi f\sigma\mu}\cdot t} = \begin{cases} B_0\cdot\dfrac{1-e^{-\sqrt{\pi f\sigma\mu}\cdot t}}{\sqrt{\pi f\sigma\mu}\cdot t} & t<\delta \\ B_0\cdot\left(1-\dfrac{1}{e}\right) & t\geq\delta \end{cases} \qquad (7)$$

substituted (7) to (6), the EMDN can be expressed exactly as follows:

$$\xi = \begin{cases} \dfrac{2B_0^2\cdot(1-e^{-\sqrt{\pi f\sigma\mu}\cdot t})^2}{\rho g t^2\sqrt{\pi f\sigma\mu^3}} > 10 & t\leq\delta \\ \dfrac{2B_0^2(1-1/e)^2}{\rho g\mu t} > 10 & t>\delta \end{cases} \qquad (8)$$

The minimum magnetic flux intensity required for EMC of different metals can be estimated by EMDN. Table (B) at appendix shows the different physical parameters and electromagnetic parameters of Steel, Sn-3%Pb and Aluminum in the molten state.

Table I lists the minimum magnetic intensity calculated by EMDN for different metals to achieve EMC under middle frequency ($f = 2500$ Hz).

It can be seen from Table I that the magnetic intensity required for EMC of Steel and Sn-3%Pb alloy is approximate two times that of Aluminum, and the Steel and the Sn-3%Pb alloy require almost similar magnetic intensity to attain EMC.

Fig. 2 shows the relationship between the EMDN of the Steel and Sn-3%Pb and the frequency of the alternating current field (where the magnetic flux density is 0.09T). As represented in the Fig. 2, the value of EMDN increases with the increase of the frequency, and the increase ratio decreases gradually as the increase of frequency resulted from the decrease of the skin depth with the increase of the frequency. When frequency reaches a value, the effect of frequency on EMDN becomes little.

Fig. 3 shows the relationship between the EMDN and magnetic intensity of Steel, Sn-3%Pb and Aluminum when the frequency of alternating current is 2500 Hz. As shown in the Fig. 3, with the increase of magnetic intensity the feasibility of metal also will be improved. Obviously, the feasibility of EMC of Aluminum is

TABLE I Comparison of magnetic intensity required for EMC of different metal ($f = 2500$ Hz, $h = 50$ mm)

Parameter	Aluminum	Steel	Sn-3%Pb
Skin depth (mm)	5.13 (1)	11.9 (2.32)	14.5 (2.83)
EMDN	10.05	10.03	10.03
Magnetic intensity (T)	0.044 (1)	0.091 (2.07)	0.095 (2.16)

(i) The magnetic Intensity shown in Fig. 5 is the minimum to achieve EMC for the specific metals calculated by the EMDN.
(ii) The number in the parenthesis is the specific value on basis of the value of Aluminum.

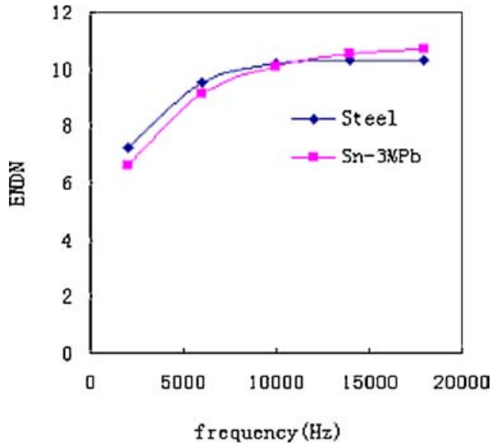

Figure 2 Effect of frequency on EMDN of Steel and Sn-3%Pb (B = 0.09T).

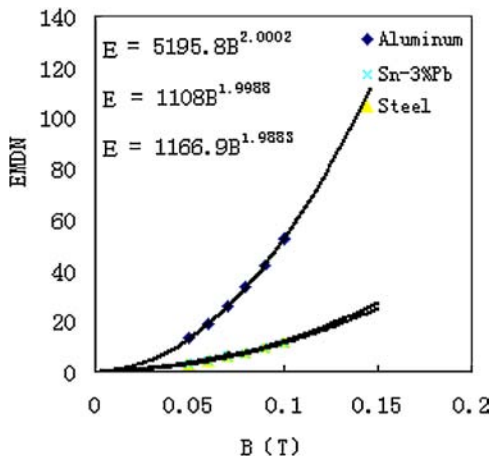

Figure 3 Effect of magnetic intensity on EMDN of different metals (f = 2500 Hz).

Figure 4 Sketch of experimental apparatus.

larger than that of Steel and Sn-3%Pb, and Steel has an almost familiar feasibility with Sn-3%Pb.

Some experiments have been taken exampled by Aluminum and Sn-3%Pb alloy to testify the veracity of the EMDN mathematical model.

TABLE II Experimental results

Metal	Aluminum	Sn-3%Pb
Output current	2200–2500	3400–4000
Magnetic intensity	0.036	0.087
Magnetic intensity calculated by EMDN	0.04	0.09

Fig. 4 shows the sketch of the experimental apparatus. The experimental power-supply was chosen the middle frequency power apparatus, and the frequency is 2500 Hz. The current imposed on the coil can be easily controlled and measured by DT266 Clamp Amperemeter. The slope-side coil has two coils and the slope is among 30–40°. The inner coil diameter is 112–114 mm and that of the crucible is 100 mm. The magnetic intensity induced by the coil was measured by a self-made small-induction coil and calculated by the equation as follows:

$$B = E/(4.44\,fNS)$$

In this experiment, $N = 10$, $S = 3.14 \times 10^{-6}$ m^2;

The meniscus shape is measured by the soakage method.

Figs 5 and 6 show the meniscus shape and the column height of Aluminum and Sn-3%Pb alloy under different current respectively.

Table II represents the experiment results of the output current and the magnetic intensity required for the EMC of the Sn-3%Pb and Aluminum respectively.

It can be noticed that when current reaches 2200–2500A and magnetic intensity is about 0.036–0.04T, the electromagnetic mold-less shaping of Aluminum can be approximately attained; While the electromagnetic mold-less shaping of Sn-3%Pb could be attained only when the magnetic intensity gets to 0.09T or so.

By the comparison of the experiment data with the calculated results of EMDN, there is a good agreement between the two results. Then the veracity and practicability of the EMDN model used to analyze and estimate the metal's feasibility of EMC have been proved.

Owning to the uniform feasibility between Sn-3%Pb alloy and Steel as the EMDN model represents, it is practicable to substitute Sn-3%Pb for steel to estimate the its feasibility of EMC.

Fig. 7 shows the meniscus shape of the Sn-3%Pb alloy under the different magnetic intensity.

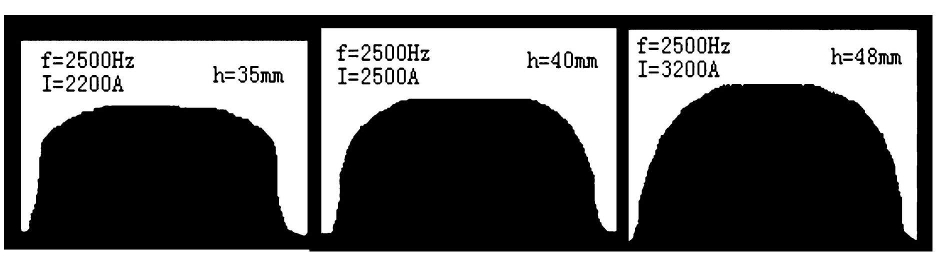

Figure 5 Effect of current on the meniscus shape and height of aluminum (f = 2500 Hz).

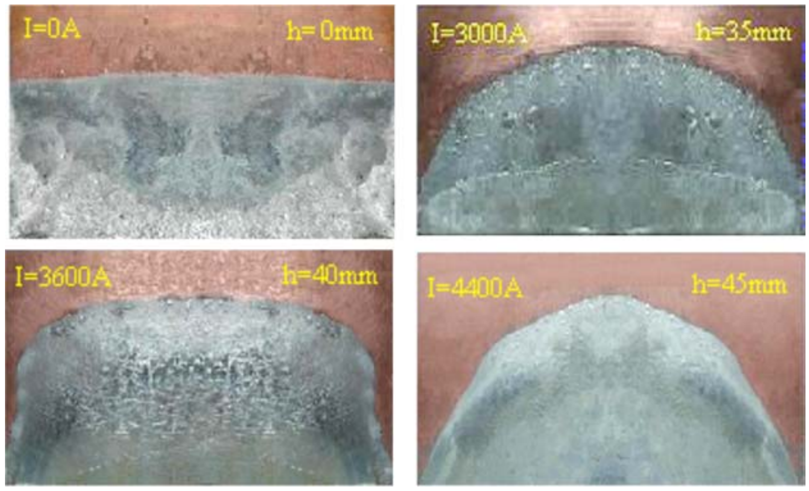

Figure 6 Effect of current on meniscus shape and height of Sn-3%Pb ($f = 2500$ Hz).

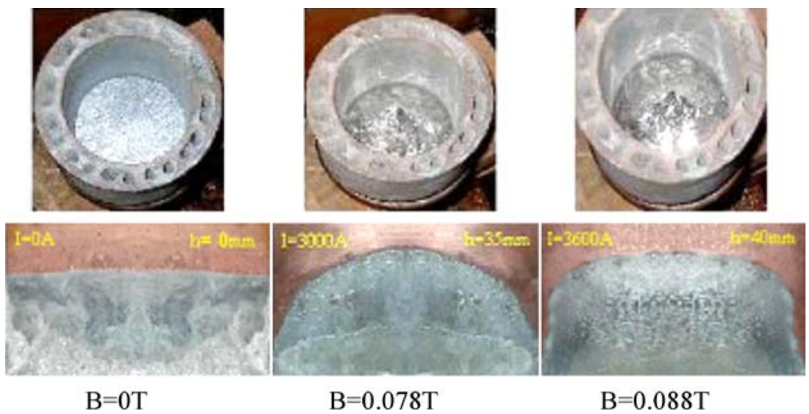

Figure 7 Relationship between magnetic intensity and meniscus shape of Sn-3%Pb.

By the experiments of Sn-3%Pb substituted for Steel, it can be deduced that the magnetic intensity required for EMC of steel is approximate 0.09T, much larger than that of Aluminum that is about 0.04T. Only when the magnetic intensity is higher than 0.09T or 0.1T can the electromagnetic casting of steel be achieved as far as the electromagnetic mold-less shaping or the electromagnetic dimensionless number is concerned.

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Appendix

TABLE A The dimension of the physical parameters used in the EMDN

Nomenclature	Symbol	Unit	Dimension
Magnetic flux identity	B	T	$MT^{-2}I^{-1}$
Electric conductivity	σ	S/m	$L^{-3}M^{-1}T^{3}I^{2}$
Magnetic permeability	μ	H/m	$LMT^{-2}I^{-2}$
Frequency of A.C. field	f	Hz	T^{-1}
Mass density	ρ	kg/m^3	$L^{-3}M$
Acceleration of gravity	g	m/s^2	MT^{-2}

TABLE B Physical parameters and electromagnetic parameters of steel, Sn-3%Pb and aluminum

	Electric conductivity σ (S/m)	Magnetic permeability μ (H/m)	Mass density ρ (kg/m^3)
Aluminum	3.85×10^6	$4\pi \times 10^{-7}$	2300
Steel	7.14×10^5	$4\pi \times 10^{-7}$	7400
Sn-3%Pb	4.8×10^5	$4\pi \times 10^{-7}$	7130

List of symbols

$\dot{B}$: Magnetic flux density (T)
B: Magnetic flux density on the surface of the molten metal (T)
$\dot{H}$: Magnetic field intensity ($\mathrm{AT \cdot m^{-1}}$)
$\dot{E}$: Electric field intensity ($\mathrm{V \cdot m^{-1}}$)
$J, \dot{J}$: Current density ($\mathrm{A \cdot m^{-2}}$)
F: Electromagnetic force density ($\mathrm{N \cdot m^{-3}}$)
δ: Magnetic skin depth $\delta = \sqrt{1/\pi f \sigma \mu}$(m)
μ: Magnetic permeability ($\mathrm{H \cdot m^{-1}}$)
σ: Electrical conductivity ($\mathrm{S \cdot m^{-1}}$)
ω: Angular frequency $\omega = 2\pi f$ ($\mathrm{rad \cdot s^{-1}}$)
f: Frequency of A.C. fields ($\mathrm{s^{-1}}$)
p: Gravity force density ($\mathrm{N \cdot m^{-3}}$)
ρ: Density of the metal ($\mathrm{kg \cdot m^{-3}}$)
g: Acceleration due to gravity ($\mathrm{m \cdot s^{-2}}$)
N: Coil quantity;
S: Coil-section area, m^2;

j: Imaginary number (−)

Superscript $\dot{}$ means the variable is a vector.

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