Analysis on the characteristics of pulsed electromagnetic force and the fluctuation behavior of molten metal free surface under pulsed magnetic field

Xinjiang Wu, Ruirui Liu, Jianjun Gao, Jian Luo and Haibin Geng

1 School of Engineering, Fujian Jiangxia University, 350108, Fuzhou, People’s Republic of China
2 Capital Aerospace Machinery Corporation Limited, 100076, Beijing, People’s Republic of China
3 School of Mechanical Engineering and Automation, Fuzhou University, 350108, Fu Zhou, People’s Republic of China
4 Author to whom any correspondence should be addressed.

E-mail: gjj410zd@fzu.edu.cn

Keywords: pulsed electromagnetic force, molten metal fluctuation, pulsed magnetic field

Abstract
A self-made line laser liquid level measurement system was used to measure the fluctuation of molten metal free surface under pulsed magnetic field. The electromagnetic characteristics of pulsed electromagnetic force were mathematically analyzed. Results showed that the electromagnetic force presents oscillatory attenuation during a single pulse period. The electromagnetic force was composed of turning force $f_{\text{turn}}$ and non-turning force $f_{\text{non-turn}}$. The direction of $f_{\text{turn}}$ was always consistent with the melt circumferential direction, which turned the $f_{\text{non-turn}}$ consisted of electromagnetic pull and push forces, which caused the melt to oscillate. Under the pulsed magnetic field, the free surface formed a meniscus with a high middle, low side structure. With increased pulsed field intensity, the center surface of molten melt had an oscillation of $\pm 3.52$ mm at 0.187 T. The wave power density had only two spectral peaks (at 0.60 and 3.36 Hz) without a magnetic field. Under pulsed magnetic field, four spectral peaks were found at 0.40, 3.00, 6.50 and 13.00 Hz.

1. Introduction

Pulsed magnetic field applied to the solidification process of metals can significantly refine metal grains [1–4], which can improve the mechanical properties of metal and reduce macroscopic segregation and thermal cracking tendency. By imposing a magnetic field, the electromagnetic casting technology overcomes the contact pressure between the molten metal and the mold inner wall, which can control the initial solidification process and improve the casting quality [5].

Pulsed magnetic field technology can be mainly divided into high- and low- frequency pulse magnetic fields. When a low-frequency pulsed magnetic field is used, the melt is oscillated and stirred [6]. When the pulse discharge frequency coincides with a certain natural frequency of the solidification system, the resonance effect is induced and the effect on the pulse electromagnetic force is enhanced [7]. When a high frequency pulsed magnetic field is applied, the magnetic sound waves are produced in the melt [8]. Moreover, when the magnetic field is pulsing, the electromagnetic wave is either a sine or cosine [9]. However, the pulsed magnetic field presents attenuation with increasing time. Therefore, the electromagnetic signal must not be set as a sine or cosine.

Some free surface fluctuation is beneficial for promoting interface quality [10]. However, if the fluctuation of free surface is too sharp, it will likely cause the entrapped slag and gas to melt. Free surface under an alternating magnetic field has been studied [11–13]. Some studies focused on the calculation methods for melt shape [14].

This paper focuses on the characteristics of pulsed electromagnetic force and the fluctuation behavior of molten metal free surface under pulsed magnetic field. Based on the collected pulse signal data, the law of

© 2020 The Author(s). Published by IOP Publishing Ltd
impulse signals is fitted by a nonlinear fitting method. The expressions of low-frequency pulsed electromagnetic oscillation and stirring terms are deduced by mathematical analysis. The characteristics of low-frequency pulsed electromagnetic oscillation are analyzed. The effect of pulsed magnetic field on the wave behavior of molten metal surface is also studied.

2. Experimental

In this experiment, a self-made line laser liquid level measurement system was used to measure the fluctuations of different positions on the molten metal surface under pulsed magnetic field. The measurement of magnetic induction intensity was based on small coil electromagnetic induction method. Liquid level displacement was measured using the line laser (Oxlasers, OX-R100L-5) measuring system (figure 1). First, the liquid level fluctuation was recorded by a high-speed camera (Phantom, v2640). Second, image data processing was preformed using C# programming to obtain the fluctuation data recorded by the camera. As shown in figure 1, the relationship between liquid level height $h$ and beam displacement $l$ on the light curtains was $h = l/[2 \cos \theta_1 + 2 \sin \theta_1 \cot (\theta_1 - \theta_2)]$. At $\theta_1 = 0$, $h = l/2$ could then be obtained. Therefore, the liquid level fluctuation could be obtained by measuring the beam displacement $l$. Low-melting GaInSn alloy was used to simulate molten steel. Figure 2 shows the schematic of the experimental apparatus with pulsed magnetic field. A self-made pulsed power with a frequency of 1–100 Hz and a voltage reaching 3000 V was used to produce the pulsed electricity. The GaInSn alloy was heated to 100 °C and then poured into a 32 mm-wide, 50 mm-tall graphite crucible. The graphite crucible was kept warm by magnesia heat preservation. The magnetic field intensity was measured by electromagnetic induction. The test coil was placed in the middle of the experimental apparatus, where the graphite crucible was located. A signal conditioner was used to enlarge the measured signal. The oscilloscope connected with a computer was applied to record the measured signal. The induction coil had 100 turns and a diameter of 150 mm. The physical property of GaInSn alloy and molten steel are shown in table 1.

3. Experimental results and discussion

3.1. Analysis of pulsed electromagnetic force

The fitting results of pulsed magnetic induction intensity versus time are shown in figure 3(a). The intensity of pulsed magnetic field presents oscillatory decay with time. The fitting curve shows a good fit with the measured data of pulsed magnetic field intensity.

The pulsed magnetic induction intensity versus time can be fitted as followings:

$$B = \sum_{i=1}^{8} [a_i \cos(\omega t) + b_i \sin(\omega t)],$$

where, $t$ is the time; and $B$ is the pulsed magnetic induction intensity. $i$, $a_i$, $b_i$, and $\omega$ are the related parameters. The fitting results are listed in table 2.
The residual distribution of pulsed magnetic induction intensity versus time fitted by equation (1) is shown in figure 3(b). The residual values are uniformly distributed around 0. This finding demonstrates that equation (1) can be reasonably used to fit the curve of pulsed magnetic induction intensity versus time. The value of the residual sum of squares (RSS) and the squares of the multiple correlation coefficient (R-square) approximates 0 and 1, respectively. The values of RSS and R-square are 0.00349 and 0.993, respectively. Therefore, the curve of pulsed magnetic induction intensity versus time can be fitted by equation (1).

According to Hua [9], if the magnetic field only has the z component, then the diffusion equation of the magnetic field will be as follows:
where, $v_m$ is the diffusion coefficient, $v_m = (\mu_m \sigma)^{-1}$, $\mu_m$ is the permeability, and $\sigma$ is the conductivity.

The boundary condition of the magnetic field is

$$B_z = \sum_{i=1}^{8} [a_i \cos(i \omega t) + b_i \sin(i \omega t)], \quad z = 0$$

$$B_z = 0, \quad z \to \infty$$

Combined with equations (2) and (3), the instantaneous form of the magnetic field can be as follows:

$$B_z(x, t) = \left\{ \sum_{i=1}^{8} \left[ a_i \cos \left( i \omega t - \frac{x}{\delta} \right) + b_i \sin \left( i \omega t - \frac{x}{\delta} \right) \right] \right\} e^{-\frac{x}{\delta}},$$

where, $\delta$ is the skin layer thickness, $\delta = \sqrt{2/ \mu_m \omega \sigma}$, and $\omega$ is the angular frequency.

According to the Maxwell equation, the Lorentz force applied to a conductive melt per unit volume is as follows:

$$f = \frac{1}{\mu_m} (B^2 \nabla) B - \frac{1}{2 \mu_m} \nabla (B^2),$$

where, the first part in equation (5) is turning force $f_{\text{turn}}$, which drives fluid rotation, and the second part is non-turning force $f_{\text{nonturn}}$, which drives fluid oscillation.

When only the magnetic field in the $z$ component is considered, the turning force $f_{\text{turn}}$ is as follows:

$$f_{\text{turn}} = \frac{1}{\mu_m} (B^2 \nabla) B = \frac{1}{\mu_m} B_z \frac{\partial B_z}{\partial z},$$

Given that $\partial B_z / \partial z \approx B_z / L$ [15], the turning force $f_{\text{turn}}$ can be set as follows:

$$f_{\text{turn}} = \frac{B_z^2}{\mu_m L},$$

In addition, the non-turning force $f_{\text{nonturn}}$ is as follows:

$$f_{\text{nonturn}} = \frac{1}{2 \mu_m} \nabla (B^2) \approx \frac{1}{2 \mu_m} \frac{\partial B_z^2}{\partial x}$$

### Table 2. Fitting results of pulsed magnetic induction versus time.

| Fitting region | 0 s ≤ t ≤ 0.01 s |
|----------------|-------------------|
| Parameters     | Value             | Standard deviation |
| $a_1$          | 0.00151           | 8.84314E-4         |
| $a_2$          | -0.01146          | 0.00277            |
| $a_3$          | 0.02403           | 0.00806            |
| $a_4$          | -0.02505          | 0.00144            |
| $a_5$          | -0.0074           | 0.0021             |
| $a_6$          | -0.00233          | 0.00149            |
| $a_7$          | -0.00165          | 2.95523E-4         |
| $a_8$          | 0.00226           | 6.91102E-4         |
| $b_1$          | 6.30734E-4        | 6.09841E-4         |
| $b_2$          | -0.00079          | 0.00274            |
| $b_3$          | 0.1112            | 0.00354            |
| $b_4$          | 0.03059           | 3.54999E-4         |
| $b_5$          | 0.00827           | 5.58012E-4         |
| $b_6$          | 0.00305           | 8.90382E-4         |
| $b_7$          | 0.0023            | 0.00136            |
| $b_8$          | 0.00209           | 3.42923E-4         |
| $\omega$       | 509.38988         | 6.58369            |

$R$-square 0.9992

SSE 0.00349
Substituting equation (4) into equations (7) and (8) can obtain the following equations:

\[ f_{\text{turn}} = \frac{1}{\mu_0 L} k_1^2 e^{-\frac{2\pi}{\delta}} \]

\[ f_{\text{nonturn}} = \frac{1}{\mu_0 \delta} k_2 e^{-\frac{2\pi}{\delta}} \]

where, \( k_1 = \sum_{i=1}^{8} \left[ a_i \cos \left( i \omega t - \frac{\pi}{\delta} \right) + b_i \sin \left( i \omega t - \frac{\pi}{\delta} \right) \right] \), \( k_2 = \sum_{i=1}^{8} \left[ a_i \sin \left( i \omega t - \frac{\pi}{\delta} \right) - b_i \cos \left( i \omega t - \frac{\pi}{\delta} \right) \right] \).

\[ \frac{f_{\text{turn}}}{f_{\text{nonturn}}} \approx \frac{\delta}{L} \]

When the value of electromagnetic pulse frequency \( \omega \) is very small, \( \delta/L \approx 1 \), the turning force \( f_{\text{turn}} \) and non-turning force \( f_{\text{nonturn}} \) work. While the \( \omega \) is sufficiently large, \( \delta/L \ll 1 \), the non-turning force \( f_{\text{nonturn}} \) dominates. When the value of \( \omega \) approximates \( \nu / L \), \( \delta/L \gg 1 \), the turning force \( f_{\text{turn}} \) dominates. The result \( \delta/L = 2.139 \) can be obtained by correlation calculation. Therefore, turning force \( f_{\text{turn}} \) and non-turning force \( f_{\text{nonturn}} \) work on the molten melt under pulsed magnetic field.

The used melt is GaInSn alloy, and the diameter of the molten pool is 32 mm. The conductivity and relative permeability of melt are \( 3.4 \times 10^6 \text{ S/m} \) and 1, respectively. The nephogram of non-turning force \( f_{\text{nonturn}} \) (figure 4) can be obtained by considering the melt symmetry and substituting those parameters into equation (10). The non-turning force \( f_{\text{nonturn}} \) in three representative positions, namely, the surface \((x = 0 \text{ m})\), radial quarter \((x = 0.008 \text{ m})\), and center \((x = 0.016 \text{ m})\) of molten metal are illustrated in figure 5. The non-turning force causes the electromagnetic oscillation. At negative \( f_{\text{nonturn}} \) value, its orientation is from center to edge of the melt and presents push force. At positive \( f_{\text{nonturn}} \) value, its orientation is from the edge to the center of the melt and presents pull force. As shown in figures 4 and 5, the electromagnetic oscillation force in the melt surface is largest, while the closer to the internal melt, the smaller the electromagnetic force is due to the skin effect. Electromagnetic force decays with increasing discharge time. With increasing pulse discharge time, the electromagnetic force undergoes an alternate evolution from pull force to push force. The action time of pull force is longer than that of push force. Figure 6 shows that the maximum value of electromagnetic oscillation pull and push forces vary with the increasing time. The maximum value of pull force is larger than the push force. In addition, the maximum values in both the pull force and push forces decreases with increasing charge time. Table 3 shows the non-turning force \( f_{\text{nonturn}} \) in different distances from the edge of melt in the radial. The maximum value of pull force in the melt surface \((x = 0 \text{ m})\) is \(-309,261 \text{ mN m}^{-3}\), while the maximum of push force is 288,031.9 \text{ mN m}^{-3}. In the center of melt, the maximum values of pull and push forces are \(-105,823 \text{ mN m}^{-3}\) and 101609.4 \text{ mN m}^{-3}, respectively. Therefore, the pull force of non-turning force is dominate compared with the push force. The calculated turning force and non-turning force have the same order of magnitude compared with those in other works [9]. The combination of gravity, surface tension, and non-turning forces acts on the molten melt. When the non-turning force is sufficiently high, the melt is derived

![Figure 4. Nephogram of non-turning force \( f_{\text{nonturn}} \) in half of the molten melt at a single discharge period.](image-url)
far from the wall of molten pool. Given that the non-turning force presents oscillatory attenuation with increasing discharging time, the molten melt acted on by gravity and surface tension is pushed back to the wall of the molten pool, resulting in the reciprocating oscillation of molten melt.

The calculation process of turning force is similar to that of the non-turning force. When the relative parameters are substituted into equation (9), the nephogram of turning force $f_{turn}$ is obtained (figure 7). The turning force $f_{turn}$ in three representative positions, namely, the surface ($x = 0$ m), radial quarter ($x = 0.008$ m), and center ($x = 0.016$ m) of molten metal, are illustrated in figure 8. The electromagnetic turning force in the melt surface is largest, while the closer to the internal melt, the lesser the electromagnetic force. The value of $f_{turn}$ decreases with increasing charge time while maintaining the radial direction. Figure 9 shows that the maximum

---

**Table 3. Electromagnetic force in different positions away from the edge of melt in the radial.**

| Electromagnetic force $f_{nonturn}$ (mN m$^{-3}$) | Distance from the edge of melt (m) |
|-------------------------------------------------|-----------------------------------|
| $-x=0$  | $x=0$  | $x=0.008$  | $x=0.016$  |
| $f_{nonturn}^{max}$ | 288,031.9 | 167,079.3 | 101,609.4 |
| $f_{nonturn}^{-3}$ | $-309,261$ | $-178,949$ | $-105,823$ |

**Table 3.** Electromagnetic force in different positions away from the edge of melt in the radial.
value of $f_{\text{turn}}$ varies with the distance from the center to the edge of melt. With increasing distance, the maximum value of $f_{\text{turn}}$ decreases. As illustrated in table 3, the maximum value of $f_{\text{turn}}$ in the melt surface ($x = 0$ m) is 568,499.3 mN m$^{-3}$. The maximum value of $f_{\text{turn}}$ is larger than that in the $f_{\text{nonturn}}$, and this finding demonstrates that the turning force is dominate in working on molten melt compared with the non-turning force.

### 3.2. Effect of pulsed magnetic field on the fluctuation of molten melt

Figure 10 shows the 3D diagram of molten melt fluctuation varying with time at different intensities of magnetization. The free surface of molten melt is not stationary without pulsed magnetic field. The free surface of molten melt maintains the oscillation state under the pulsed magnetic field, and the molten melt in the middle of the pool fluctuates sharply. The surface of molten melt in the middle bumps up and is sunken at the edge. This phenomenon illustrates that the free surface of molten melt has a meniscus [16]. The amplitude of surface oscillations increases with increasing magnetic field intensity [17]. The fluctuation amplitude is largest at 0.187 T magnetic field intensity. The non-turning force urges molten melt to reciprocate oscillation. When the non-turning force reaches maximum, the molten melt in the middle of the surface locates the highest position. With the combination of non-turning force and turning force, the molten melt in the surface presents reciprocating oscillation and rotary movement. The fluctuation of molten melt is related to the increasing electromagnetic force by increasing the pulsed current [18]. However, this fluctuation causes the unstable deformation of the
meniscus and even deteriorates the initial solidification status, which negatively affects the improvement of improving the surface quality of casting [19]. Figure 11 shows the waveform of the oscillations obtained at the center of molten surface with different magnetization intensities. The surface in the center of the molten pool has a fluctuation amplitude of ±1.13 mm without pulsed field action. This wave maybe produced by uneven heating. Fluctuation increases with pulsed field intensity. The molten metal in the surface center has an oscillation of ±3.52 mm at 0.187 T.

Fourier transform is often used to analyze the regularity of wave motion on free surface. The law of liquid level fluctuation under pulsed magnetic field can be reflected by its power spectral density distribution. Figure 12
shows the power spectral density obtained at different magnetic field intensities. The power spectral density is distributed symmetrically and increases with increasing of magnetic field intensity. This result illustrates that the displacement in the central point fluctuates violently with increasing magnetic field intensity (figure 10).
The eigenfrequency of surface waves on a cylindrical pool is expressed as follows [20]:

\[
f_{mn} = \frac{1}{2\pi} \sqrt{\left(\rho g \cdot \frac{1}{\rho r^3} + \sigma \frac{k_{mn}^3}{R}\right)} \tanh \left(\frac{k_{mn} H}{R}\right)
\]  

(12)

where, \(m\) and \(n\) are the azimuthal and radial numbers, respectively; \(\rho\) is the liquid density; \(g\) is the gravitational acceleration; \(r\) and \(H\) are the radius and depth of the pool, respectively; \(\sigma\) is the surface tension; and \(k_{mn}\) is the \(n\)th zero of the first derivative of the \(m\)th-order Bessel function of the first kind. The calculated eigenfrequency frequencies are listed in table 4.

The statistical results of power spectral density in the center fluctuation under different magnetic field intensities are summarized in table 5. Only two spectral peaks (at 0.60 and 3.36 Hz) of the fluctuation power density are observed without pulsed magnetic field. The first peak (at 0.6 Hz) approaches the eigenfrequency (table 4) calculated by equation (12). When applied in pulsed magnetic field, four spectral peaks are observed (appear at 0.40, 3.00, 6.50 and 13.00 Hz). With increasing magnetic field intensity, the position of the four spectral peaks almost remains constant, but the power spectral density increases with magnetic field intensity. Compared with those without magnetic field, the dominant frequencies of the oscillations at the center are reduced by imposing a pulsed magnetic field. The wave frequency of the molten melt in the center of molten pool is different with the frequency of pulsed magnetic field. This result is attributed to the wave of melt being associated with the combined action of pulsed electromagnetic, surface tension and gravity recombination. The melt flow at the free surface must be controlled to obtain stable free surface [19]. Because the wave of melt increases with increasing magnetic field intensity, and these phenomenon results in the large liquid level deformation. The magnetic field should be controlled appropriately to decrease the fluctuation degree of the liquid level. The increasing fluctuation of liquid level causes dross and gas on the surface of molten melt. These may be involved in casting embryo, which reduces the casting embryo quality.

### 4. Results

Based on the measuring pulsed magnetic intensity signal, the pulsed electromagnetic force was deduced by mathematical analysis. The effect of pulsed magnetic field on the wave behavior of molten metal surface was also studied. The following conclusions were drawn:

1. The electromagnetic force was composed of turning force and non-turning force by mathematical analysis. At 0.154 T, the maximum values of turning force in the surface and center were 568,499.3 mN m\(^{-3}\) and down to 192,646 mN m\(^{-3}\), respectively. The maximum values of non-turning force in the surface and center were –309,261 mN m\(^{-3}\) (pull force), and down to 101,609.4 mN m\(^{-3}\) (push force), respectively.

2. The molten melt in surface fluctuated disorderly without electromagnetic field. Applied by the electromagnetic field, it formed a meniscus. The fluctuation increased with increasing pulsed field intensity. The molten metal in center of the surface had an oscillation of ±3.52 mm at 0.187 T.

| \(n\) | \(n\) |
|---|---|
| 1 | 3.43 | 1.45 | 1.65 | 2.29 | 1.18 | 1.01 | 1.85 | 1.14 | 0.62 |

**Table 4.** Calculated eigenfrequencies of the molten metal pool.

| B/T | \(f/Hz\) | Power | \(f/Hz\) | Power | \(f/Hz\) | Power | \(f/Hz\) | Power |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.60 | 0.27 | 3.36 | 0.30 | – | – | – | – |
| 0.143 | 0.41 | 6.17 | 2.97 | 2.18 | 6.76 | 2.12 | 13.10 | 1.63 |
| 0.154 | 0.40 | 10.60 | 2.98 | 5.32 | 6.62 | 5.42 | 13.42 | 4.60 |
| 0.187 | 0.41 | 28.88 | 3.55 | 3.09 | 6.50 | 2.67 | 13.35 | 19.00 |

**Table 5.** Statistical results of power spectral density of center fluctuation under different magnetic field intensity.

The eigenfrequency frequency of surface waves on a cylindrical pool is expressed as follows [20]:
(3) Compared with those without magnetic field, the dominant frequencies of the oscillations at the center was reduced by imposing a pulsed magnetic field, and four spectral peaks (appear at 0.40, 3.00, 6.50 and 13.00 Hz) of power spectral density were found on the fluctuation of center surface.

Acknowledgments

This work is financially supported by National Natural Science Foundation of China (No. 51905103).

ORCID iDs

Jianjun Gao @ https://orcid.org/0000-0002-4402-3138
Jian Luo @ https://orcid.org/0000-0002-4546-5739
Haibin Geng @ https://orcid.org/0000-0002-4405-337X

References

[1] Yin W S and To S 2019 Effects of magnetic field on microstructures and mechanical properties of titanium alloys in ultra-precision diamond turning Mater. Res. Express 6 056553
[2] Gao Y L et al 2007 Comparative study on structural transformation of low-melting pure Al and high-melting stainless steel under external pulsed magnetic field Mater. Lett. 61 4011–4
[3] Chen Q and Shen H 2018 Numerical study on solidification characteristics under pulsed magnetic field Int. J. Heat Mass Transfer 120 997–1008
[4] Bai Q et al 2018 Nucleation and grain refinement of 7A04 aluminum alloy under a low-power electromagnetic pulse J. Mater. Eng. Perform. 27 857–63
[5] Vives C 1989 Electromagnetic refining of aluminum alloys by the CREM process: Part I. Working principle and metallurgical results Metall. Trans. B 20B 623–9
[6] Sun J et al 2018 Fine equiaxed dendritic structure of a medium carbon steel cast using pulsed magneto-oscillation melt treatment Advances in Manufacturing 6 189–94
[7] Guglielmi M 2018 Optimization of Pulsed Magnetic Field application for electromagnetic stirring during the continuous casting [D] University Degli Studi Di Padova Leibni Universitat Hannover
[8] Gong Y Y et al 2008 Structure refinement of pure aluminum by pulse magneto–oscillation Materials Science and Engineering A 497 147–52
[9] Hua J et al 2011 On the characteristics of pulsed electromagnetic force: Theoretical analysis Journal of Northeastern University (Natural Science) 32 72–7 (in Chinese)
[10] Deng A Y et al 2011 Oscillation Characteristics of molten metal free surface under compound magnetic field J. Iron. Steel Res. Int. 18 25–30
[11] Karcher C, Kocourek V and Schulze D 2003 Experimental investigations of electromagnetic instabilities of free surfaces in a liquid metal drop International Scientific Colloquium, Modelling for Electromagnetic Processing. 105–10
[12] Fautrelle Y, Etay J and Daugan S 2005 Free-surface horizontal waves generated by low-frequency alternating magnetic fields J. Fluid Mech. 527 285–301
[13] Fautrelle Y, Perrier D and Etay J 2003 Free surface controlled by magnetic fields ISIJ Int. 43 801
[14] Zha X R, Harding K A and Campbell J 1997 Calculation of the free surface shape in the electromagnetic processing of liquid metals Appl. Math. Modell. 21 207–14
[15] Asai S 1989 Birth and recent activities of electromagnetic processing of materials ISIJ Int. 29 981–92
[16] Zhang B et al 2002 Research of surface stability of molten metal under alternative magnetic field Zhuzhao jishu (Foundry Technology) (China) 23 388–9
[17] Deng A Y, Wang E G and He J C 2006 Meniscus behavior in electromagnetic soft-contact continuous casting round billet mold J. Iron. Steel Res. Int. 13 13–6
[18] Kolesnichenko A F, Podoltsev A D and Kucheryavaya I N 1994 Action of pulse magnetic field on molten metal ISIJ Int. 34 715–21
[19] Xu X J et al 2009 Evolution mechanism of surface oscillation marks on round billet during soft-contact electromagnetic continuous casting Acta Metall Sin 45 664–9
[20] Negrini F et al 2000 Electromagnetic control of the meniscus shape during casting in a high frequency magnetic field Energy Convers. Manage. 41 1687–701