Investigation of waveform construction and dynamic characteristics for mould non-sinusoidal oscillation

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Abstract

Compared with sinusoidal oscillation, non-sinusoidal oscillation enhances the ability to control waveform and meets different oscillation requirements by adding an independent parameter, which is the key technology for high-efficiency continuous casting. A new waveform of mould non-sinusoidal oscillation is proposed in this paper, that is, a velocity waveform that is composed only of straight lines and parabolas, which not only has good dynamic characteristics, but also further enhances the feature of non-sinusoidal oscillation. Compared with sinusoidal oscillation, the negative strip time is reduced by 15.9%, the maximum negative strip velocity difference is increased by 38.3%, and the maximum positive strip velocity difference is decreased by 27.8%. The formulas of oscillation process parameters can be clearly deduced, and the isoplethic curves of oscillation process parameters when multi-parameter simultaneously changes are drawn. The negative strip time decreases as the modification ratio, frequency, and casting speed increase, but increases as stroke increases. In order to maintain the stability of negative strip time, an oscillation synchronous control model for optimising oscillation basic parameters was developed. Through practical application, the mean oscillation mark depths decreased by 10.1 µm and the flux consumption is increased from 0.37 kg/t to 0.45 kg/t in the non-sinusoidal oscillation model, which meets the requirements of normal production.

Keywords

continuous casting mould, non-sinusoidal oscillation, oscillation parameter

Introduction

Mould oscillation is the key technology for high-efficiency continuous casting. Its main purpose is to prevent billet from sticking to the mould wall. With the acceleration of production rhythm and the expectance of higher quality, it is necessary to ensure that the billet possesses good surface quality while realising demoulding, which puts forward higher requirements for mould oscillation technology. The investigation of mould oscillation technology has practical significance (Zhang et al., 2013; Suzuki et al., 1991; Zuo et al., 2016; Lei et al., 2004; Tsuprun et al., 2012; Zhou et al., 2019).

There are mainly two kinds of mould oscillation modes in general, i.e., sinusoidal and non-sinusoidal oscillation. Sinusoidal oscillation completely depends on frequency and stroke and has limited ability to control the oscillation waveform. There are disadvantages, such as longer negative strip time and larger negative strip velocity difference, which could make the breakout and surface quality control contradict each other, especially under high casting speed conditions. Non-sinusoidal oscillation introduces the modification ratio to enhance the ability of controlling waveform, and has the following advantages: (i) shorter negative strip time, reduces the depth of oscillation mark, (ii) longer positive strip time, increases powder consumption and improves lubrication effect of mould, (iii) larger negative strip velocity difference, helps billet demoulding and crack welding, (iv) smaller positive strip velocity difference reduces friction force to prevent billet cracking and improve surface quality, (v) higher flexibility of oscillation waveforms, which meets different oscillation requirement (Zang et al., 2008; Wang et al., 2010).

The construction of waveform function is the key technology to realise mould oscillation. Continuous casting researchers have done lots of study for non-sinusoidal oscillation waveform (Ma, 2014; Long, et al., 2008). The DynFlex function is composed of trigonometric functions with different frequencies, in which the rising-section frequency is lower, and the falling-section frequency is higher (Ma, 2014). Although oscillation is easy to control, its velocity waveform is not smooth at the junction. There is a sudden change in acceleration waveform, which causes flexible impact during oscillation. Based on trigonometric functions, Mannesman Demag, WISDRI ,and CISDI proposed integral Demag

Investigation of waveform construction and dynamic characteristics

function, WIS function, and CIS function, respectively (Long et al., 2008), which are simple in form and easy to control. The velocity and acceleration waveforms are continuous and smooth, and there is no oscillation shock problem. However, when the modification ratio is greater than a certain value, the acceleration waveform will appear as an inflection point instead of being monotonous, which will cause trembling of the oscillation device.

In view of the problem of previous non-sinusoidal oscillation functions, this paper proposes and constructed a new kind of non-sinusoidal oscillation function in the five-section form, of which the velocity waveform is only composed of straight lines and parabolas. It not only boasts good dynamic characteristics but also exhibits a significant improvement on the oscillation effect. The isoplethic curves of oscillation process parameters when multi-parameter simultaneously changes are drawn, which provide the convenient reference for the formulation of synchronous control model.

Construction of non-sinusoidal oscillation waveform

Figure 1 shows the waveform of displacement and velocity for two kinds of oscillation models, and the functions of displacement and velocity for sinusoidal oscillation can be expressed as Equations 1 and 2 in the following (Meng et al., 2013):

$$v(t)=\pi f h \cos(2\pi f t) \tag{1}$$

$$s(t)=\frac{h}{2}\sin(2\pi f t) \tag{2}$$

Where $v(t)$ is the mould velocity(mm/min), $s(t)$ is the mould displacement(mm), t is time(min), h is the oscillation stroke(mm), v and f is the oscillation frequency (cpm, i.e., count per minute).

Non-sinusoidal oscillation waveform was improved on the basis of sinusoidal oscillation waveform in this paper. Its velocity waveform is only composed of straight lines and parabolas, otherwise expressed as SLP function. The ab and fg sections are horizontal straight lines, and the bc, cde, and ef sections are parabolas. The velocity function is shown in Equation 3:

$$v(t)=\begin{cases} A & (0\le t\le t_b) \\ -k_1(t-t_b)^2+A & (t_b\le t\le t_c) \\ k_2(t-t_d)^2-B & (t_c\le t\le t_e) \\ -k_1(t-t_f)^2+A & (t_e\le t\le t_f) \\ A & (t_f\le t\le t_g) \end{cases} \tag{3}$$

Where k_1, k_2 is the undetermined constant (mm/min³), A and B are also the undetermined constant (mm/min), t_b, t_c, t_d, t_e, t_f, and t_g are the different time of velocity waveform for non-sinusoidal oscillation, respectively (min).

Compared with sinusoidal oscillation, non-sinusoidal oscillation adds the modification ratio α:

$$\alpha=\frac{t_m}{T/4} \tag{4}$$

Where t_m is lag time to reach maximum displacement for non-sinusoidal waveform relative to sinusoidal waveform (min), T is oscillation cycle (min), the relationship between oscillation cycle and frequency is $T=1/f$, and the value of α should be 0≤α<1.

By ensuring that the velocity waveform is continuous and smooth, and the ascending displacement and the descending displacement are equal, and the relationship between the openings of upward and downward parabola is $k_1=N' k_2$, the following relationship can be obtained by the aforementioned constraints:

$$N=\frac{3(\alpha+1)+\sqrt{(\alpha+1)^2+32\alpha}}{4(1-\alpha)} \tag{5}$$

$$A=\frac{hf(2N^2+1)}{N^2(\alpha+1)} \qquad B=NA \tag{6}$$

$$k_1=\frac{16Af^2(2N^2+1)^2}{9(\alpha+1)^2} \qquad k_2=\frac{k_1}{N} \tag{7}$$

$$t_b=\frac{(2N^2-2)(\alpha+1)}{4f(2N^2+1)} \quad t_c=\frac{(\alpha+1)}{4f} \quad t_d=\frac{1}{2f} \tag{8}$$
$$t_e=\frac{3-\alpha}{4f} \quad t_f=\frac{1}{f}-\frac{(2N^2-2)(\alpha+1)}{4f(2N^2+1)} \quad t_g=\frac{1}{f}$$

Taking the derivative of velocity function, the acceleration function $a(t)$ in each oscillation cycle is shown as Equation 9:

$$a(t)=\begin{cases} 0 & (0\le t\le t_b) \\ -2k_1(t-t_b) & (t_b\le t\le t_c) \\ 2k_2(t-t_d) & (t_c\le t\le t_e) \\ -2k_1(t-t_f) & (t_e\le t\le t_f) \\ 0 & (t_f\le t\le t_g) \end{cases} \tag{9}$$

Integrating the velocity function, the displacement function $s(t)$ in each oscillation cycle is shown as Equation 10:

$$s(t)=\begin{cases} At & (0\le t\le t_b) \\ -\frac{k_1}{3}(t-t_b)^3+At & (t_b\le t\le t_c) \\ \frac{k_2}{3}(t-t_d)^3-Bt+\frac{2}{3}A\sqrt{\frac{A}{k_1}}-\frac{2}{3}B\sqrt{\frac{B}{k_2}}+At_b+Bt_d & (t_c\le t\le t_e) \\ -\frac{k_1}{3}(t-t_f)^3+At-A\sqrt{\frac{A}{k_1}}-A(t_b+t_e) & (t_e\le t\le t_f) \\ At-A(t_b+t_f) & (t_f\le t\le t_g) \end{cases} \tag{10}$$

When stroke, frequency and modification ratio of oscillation are determined, N, k_1, k_2, A and B are all fixed values. The oscillation
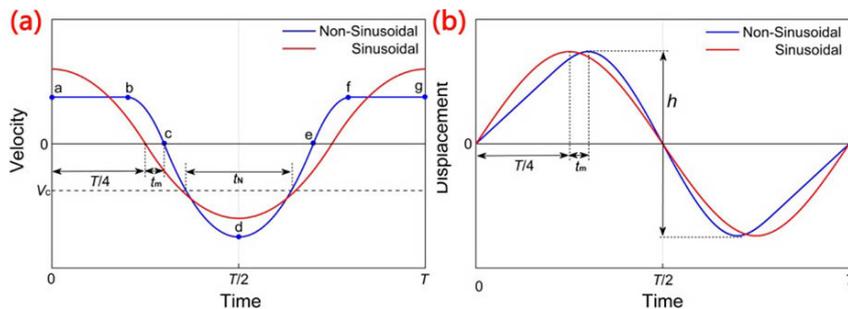

Figure 1—Schematic of sinusoidal and non-sinusoidal oscillation waveforms: (a) velocity waveform, (b) displacement waveform

Investigation of waveform construction and dynamic characteristics

waveform is completely determined and generated by computer, and the driving device is controlled by the oscillation waveform to make mould move accordingly.

Study on non-sinusoidal oscillation

Analysis of dynamic characteristics

The oscillation waveform is required to have good dynamic characteristics because of large mass and high frequency of mould (Yang et al., 2014). When the stroke is 8 mm and frequency is 120 cpm, the displacement, velocity, and acceleration waveforms with different modification ratios are as shown in Figure 2. There is no sudden change in velocity waveform and no infinite value in acceleration waveform, so the oscillation device is not subject to rigid impact. The velocity waveform is continuous and smooth, and the acceleration waveform is continuous although it has sharp points, so the oscillation device is also free from flexible impact. Therefore, the non-sinusoidal oscillation waveform boasts good dynamic characteristics.

The waveform should have a better non-sinusoidal oscillation feature under the premise of good dynamic characteristics. When the stroke is 8 mm, frequency is 120 cpm, and modification ratio is 0.2, the velocity waveform is as illustrated in Figure 3. Compared with sinusoidal function, the negative strip time is reduced by 15.9%, the maximum negative strip velocity difference is increased by 38.3%, and the maximum positive strip velocity difference is decreased by 27.8% when the casting speed is 1.0 m/min in this paper. The non-sinusoidal oscillation feature of SLP function is significantly improved by adjusting the velocity distribution in the downward oscillation period. Compared with Demag function, the negative strip time is increased by 6.1%, and the maximum negative strip velocity difference is reduced by 13.7%, and the maximum positive strip velocity difference is decreased by 7.3% when the casting speed is 1.0 m/min in this paper. Although the lubrication and demoulding effect of billet is weakened, the resistance of billet in mould is also significantly reduced for SLP function compared with Demag function. The formulas of oscillation process parameters for Demag function cannot be deduced, and the numerical solution can only be obtained by computer.

Determination of oscillation process parameters

The formulas of each oscillation process parameters can be clearly deduced to provide the convenient application of oscillation waveform in actual production. The oscillation process parameters mainly consider the negative strip time and the negative strip time ratio, which can better reflect the effect of oscillation basic parameters on the surface quality of billet. The negative strip time
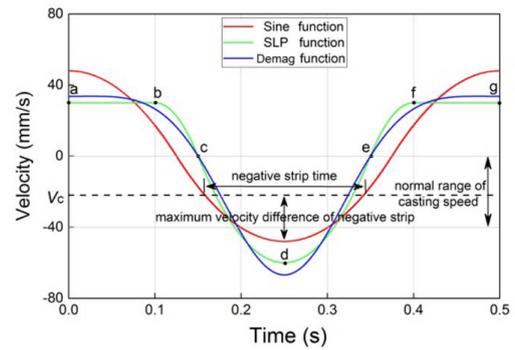
Figure 3—Comparison of velocity waveforms for different oscillation functions

is the period during which the mould moves downward relative to billet in each oscillation cycle, and the negative strip time ratio is the ratio of the negative strip time to half cycle. When casting speed is given, the negative strip time and the negative strip time ratio of SLP function can be expressed as Equation 11:

$$t_N = \frac{3(\alpha+1)}{2f(2N^2+1)}\sqrt{N^2 - \frac{NV_C}{A}} \qquad [11]$$

$$NSR = \frac{3(\alpha+1)}{(2N^2+1)}\sqrt{N^2 - \frac{NV_C}{A}} \qquad [12]$$

$$\Delta V_{max} = \frac{hf(2N^2+1)}{N^2(\alpha+1)} + V_C \qquad [13]$$

Where V_C is casting speed (mm/min), t_N is the negative strip time (min), NSR is the negative strip time ratio, and ΔV_{max} is the maximum velocity difference between oscillator and billet.

When casting speed, frequency, and stroke are constant, the negative strip time decreases and the negative strip velocity difference increases with the increase of the modification ratio, which significantly enhances the feature of non-sinusoidal oscillation and helps billet demoulding to improve surface quality, as shown in Figure 3 and Figure 4. The advantages of non-sinusoidal oscillation cannot be exerted with smaller modification ratio, but larger modification ratio would cause the significant increase in the maximum acceleration that determines the driving force and affects the oscillation stability of mould, as shown in Figure 4. The acceleration can take the maximum value at the point of c and e in Figure 1. According to previous studies, the modification ratio should be set to 0.1~0.4 (Meng et al., 2013). In order to control the maximum acceleration below 2 m/s², the modification ratio can be set to 0.1~0.2 in this paper.
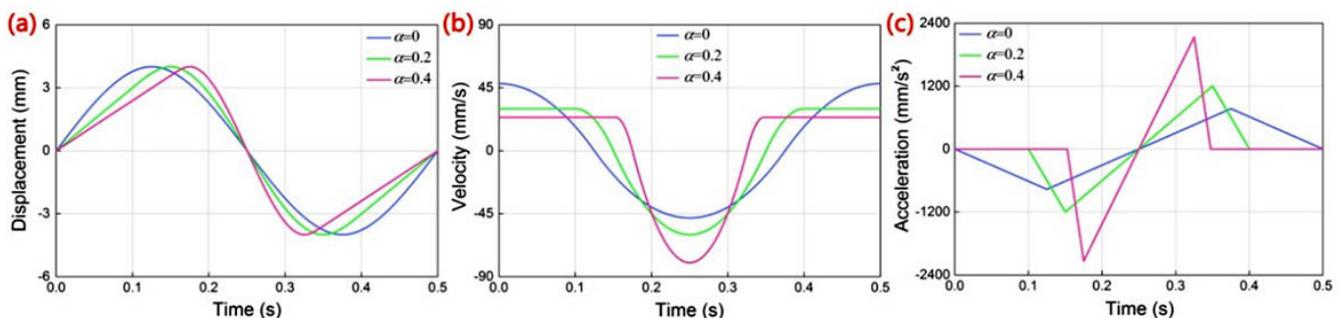
Figure 2—Waveforms of non-sinusoidal oscillation: (a) displacement waveforms, (b) velocity waveforms, (c) acceleration waveforms
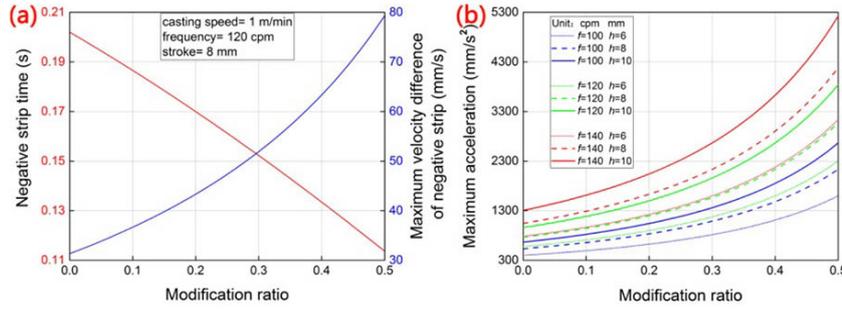
Figure 4—Effect of the modification ratio on non-sinusoidal oscillation: (a) negative strip time and the maximum negative strip velocity difference, (b) maximum acceleration
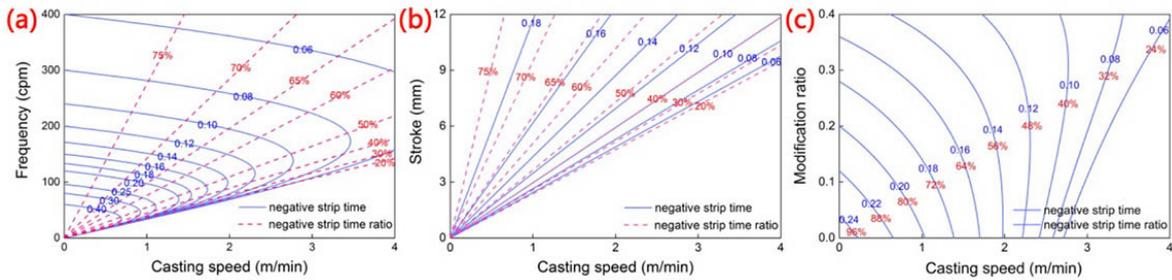

Figure 5—Isoplethic curves of multi-parameter variation: (a) V-f model, (b) V-h model, (c) V-α model

$$a_{max} = \frac{8hf(2N^2+1)}{3N^2(\alpha+1)^2} \quad [14]$$

Where a_{max} is the maximum acceleration of oscillation waveform(mm/min²).

Establishment of synchronous control model

During the process of production, casting speed usually varies with working conditions, such as casting temperature. If oscillation basic parameters remain unchanged, oscillation process parameters will inevitably be changed, which will affect the demoulding effect and surface quality of billet. After fixing two oscillation basic parameters, the isoplethic curves of the negative strip time and the negative strip time ratio when casting speed and the third oscillation basic parameter simultaneously change, are shown in Figure 5.

When casting speed is specified, the isoplethic curves of the negative strip time correspond to two frequencies in Figure 5(a). In the region near lower frequency, a small change of casting speed and frequency would lead to large fluctuation of the negative strip time. Therefore, the area of NSR below 50% is not the recommended area for modelling. In the region of NSR above 50%, the isoplethic curves of the negative strip time are approximately downward in Figure 5(a), upward in Figure 5(b), and downward in Figure 5(c), respectively. The negative strip time decreases as the modification ratio, frequency, and casting speed increase, but increases as stroke increases. If the casting speed is increased, in order to maintain the stability of the negative strip time, the modification ratio and frequency need to be decreased, and stroke needs to be increased properly. The following synchronous control model of oscillation basic parameters changing with casting speed can be established as shown in Equation 15:

$$\begin{cases} f = -m_1 * V_C + n_1 & (m_1 > 0) \\ h = m_2 * V_C + n_2 & (m_2 > 0) \\ \alpha = -m_3 * V_C + n_3 & (m_3 > 0) \end{cases} \quad [15]$$

Where m_1 and n_1 are the coefficients of the synchronous control model (i equals to 1, 2, and 3).

According to steel grade and section, the appropriate oscillation process parameters could be selected and the corresponding line segment in Figure 5 could be drawn to determine the coefficients of the synchronous control model. In an actual casting process, the modification ratio is often set directly, so the model can be simplified to a system containing two equations, as depicted by Equation 16:

$$\begin{cases} f = -m_1 * V_C + n_1 & (m_1 > 0) \\ h = m_2 * V_C + n_2 & (m_2 > 0) \end{cases} \quad [16]$$

Application and testing

In order to stabilise the negative strip time at 0.16 seconds when the modification ratio is 0.2, the conditions before and after optimisation are shown in Table 1. The synchronous control model can be established as shown in Figure 6. With the increase of casting speed, frequency decreases and stroke increases, which belong to the inverse synchronous control model (Spiess et al., 2005). The negative strip time basically remains unchanged and the positive strip time increases, which is conducive to stabilising the oscillation mark depth, enhancing the powder consumption and improving the demoulding effect of bloom. At the same time, the decrease of frequency is conducive to maintaining the oscillation stability of mould (Tsutsumi et al., 2007). Through the establishment of the synchronous control model, oscillation basic parameters such as the modification ratio, frequency, and stroke, could synergistically change with casting speed, so as to realise the stable metallurgical effect of mould oscillation.

According to the aforementioned analysis, this waveform of non-sinusoidal oscillation was applied on bloom continuous caster to evaluate the effect of non-sinusoidal oscillation on the lubrication of mould and the surface quality of bloom. The radius of the caster is 9 m, and the section is 180 mm×240 mm for casting C82DAD

Investigation of waveform construction and dynamic characteristics

Table 1

Technological parameters of sinusoidal and non-sinusoidal oscillation

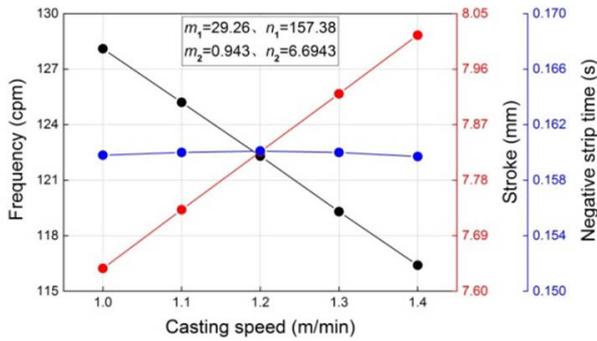| Oscillation mode	v(m/min)	α	f(cpm)	h(mm)	t_N(s)	$1/f\text{-}t_N$(s)
Sinusoidal	1.2	0	122	7.8	0.181	0.311
Non-sinusoidal	1.2	0.2	122	7.8	0.160	0.332

Figure 6—Oscillation synchronous control model

steel. The chemical compositions of steel and mould flux are shown in Table 2 and Table 3, respectively. The liquidus temperature is 1460°C for C82DAD steel, and the casting temperature is 1485°C.

The surface quality and the oscillation mark depths of bloom under the conditions of sinusoidal and non-sinusoidal oscillation model are shown in Figure 7. It can be seen that, compared with sinusoidal oscillation, the mean oscillation mark depths in non-sinusoidal oscillation mode decreased by 10.1 μm. The flux consumption is increased from 0.37 kg/t to 0.45 kg/t with the increase of the positive strip time. As shown in Figure 7(c), the surface temperature of bloom at the straightening position is 1103°C, which is conducive to avoiding the brittle transition temperature range and reducing the occurrence of surface cracks on the bloom. The effect of mould lubrication is improved significantly, and the possibility of surface defects is also controlled effectively. This waveform of non-sinusoidal oscillation meets the requirements of normal production and provides reference for the application of the oscillation mode.

Conclusions

A new waveform of mould non-sinusoidal oscillation is proposed in this paper. Its velocity waveform is only composed of straight lines and parabolas, and has many advantages such as simple form, easy adjustment, and convenient calculation.

➤ The waveform of mould non-sinusoidal oscillation not only has good dynamic characteristics but also exhibits significant improvement on the feature of non-sinusoidal oscillation by adjusting the velocity distribution. Compared with sinusoidal oscillation, the negative strip time is reduced by 15.9%, the maximum negative strip velocity difference is increased by 38.3%, and the maximum positive strip velocity difference is decreased by 27.8%.

➤ The formulas of oscillation process parameters can be clearly deduced, and the isoplethic curves of oscillation process parameters when multi-parameter simultaneously change is drawn. The negative strip time decreases as the modification ratio, frequency, and casting speed increase, but increases as stroke increases.

Table 2

Chemical compositions of steel(mass%)

C	Si	Mn	P	S	Cr	Ni	Cu
0.82	0.19	0.52	0.015	0.005	0.035	0.013	0.016

Table 3

Chemical compositions of mould flux(mass%)

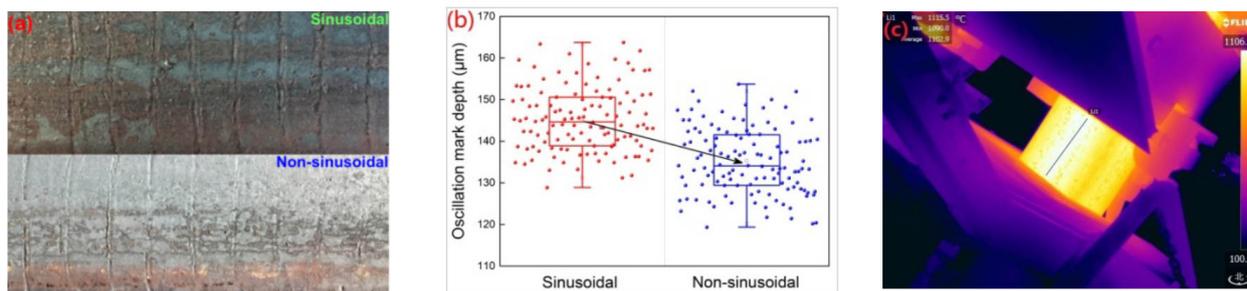| SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	F	C-tol
39.5	28.8	0.6	7.6	1.1	4.3	18.1

Figure 7—Oscillation effect of sinusoidal and non-sinusoidal model: (a) surface quality, (b) oscillation mark depth, (c) infrared temperature

Investigation of waveform construction and dynamic characteristics

➤ In order to maintain the stability of negative strip time, a synchronous control model for optimising oscillation basic parameters was developed. Through practical application, the mean oscillation mark depths decreased by 10.1 μm and the flux consumption is increased from 0.37 kg/t to 0.45 kg/t in the non-sinusoidal oscillation model, which meets the requirements of normal production.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

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