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Parametric investigation on an industrial electromagnetic continuous casting mould performance

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ABSTRACT

This research aimed at conducting a quantitative investigation of process parameters on the magnetic field contribution in an electromagnetic continuous casting mould. The Taguchi method (4 factors and 3 factor value levels: L9 orthogonal array) was adopted to design matrix of the simulation runs and the analysis of variance was used to evaluate the contributions of each control factor. The simulations were conducted based on the finite element method and the numerical set-up was validated by the designed experiment. The results showed that the applied alternating current magnitude contributed most (76.64%) to the magnetic field level in the mould, compared to the other control factors. It was followed by the slit length (17.72%), the alternating current frequency (4.17%) and the slit width (1.57%).

1. Introduction

The electromagnetic continuous casting (EMCC) technique was first applied in the aluminium casting (Vives & Ricou, 1985) and then the technique was adopted in steel making process (Yasuda, Toh, Iwai, & Morita, 1997). The depth of oscillation mark (OSM) on the billets was decreased from 0.45 (±0.15) mm to 0.15 (±0.05) mm (Park et al., 2003; Park, Jeong, Kim, & Kim, 2002) for 0.08–0.1%C steel (round billets) by using EMCC technique. For the square billets, similar results were obtained: OSM decreased from 0.65 mm to 0.06 mm (Xu, 2011). The improvement of billet surface quality simplified the following manufacturing process before the billets were rolled: the billets scalping process was avoided (Bermudez, Muniz, & Salgado, 2003). Therefore, the energy consumption was decreased.

The basic principle of EMCC technique was discussed by professor Vives (1985) and the metallurgy effect of this technique depends on several factors: the electric control and mould structure parameters, for instance. Therefore, the investigation on these issues are critical in terms of enhancing the mould performance. Plenty of research has been carried out to focus on the effect of alternating current magnitude on the magnetic field level in the EMCC mould. The results unveiled that the magnetic field was enhanced as the current value was increased. A wide range of alternating current frequencies from 60 Hz (Toh, Takeuchi, Hojo, Kawai, & Matsumura, 1997) to 2500 Hz (Wang, 2009) and further to 100 kHz (Nakata, Inoue, Mori, Murakami, & Mominami, 2002) was investigated. The billet surface quality was improved for all the cases. However, for low frequency case, more fluctuations existed due to the electromagnetic stirring (EMS) effect. The EMCC mould (usually made of copper alloy) should have a slit-segment structure ("cold-crucible" structure) (Yasuda et al., 1997), which is due to the skin effect of copper under the high frequency electromagnetic field. The slit allows the magnetic field to permeate to the mould centre and act on the liquid steel. Zhou et al. experimentally studied the magnetic field distribution with different values of round mould slit width: 0.4 mm, 0.8 mm and 1.2 mm, respectively (Zhou, Zheng, Jun, Li, & Qu, 2001). Numerically, Zhang et al. investigated influence of the slit width (0.3 mm and 0.5 mm) on the magnetic field level in a round EMCC mould (Zhang, Wang, Deng, & He, 2006). Both studies showed that the magnetic field increased as the slit width value was increased, however, the uniformity of magnetic field along the circumferential direction may worsen. For the slit length, similar results were obtained for both square (Yu, Jia, Wang, He, Zhang, & Chen, 2002) and rectangular (Deng, Wang, He, Meng, Zhang, & Chen, 2003) EMCC mould: the magnetic field level was enhanced as the slit length values were increased.

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From the short literature review above, the research showed that the magnetic field level was in proportion to the applied alternating current magnitude, the slit width and length values, respectively. This raised a question:

- what is the exact quantitative contribution of the main control parameters on the magnetic field in the EMCC mould?

Little research has been conducted on this issue in the previous study. Answering the above question can help to figure out the contributions to the magnetic field of each parameters and therefore to find the most dominant one. The results could further help to design of experiments (DoE). That is the problem shall be tackled in the present research. The Taguchi method (Taguchi, 1985) basic principles discussed in Section 3.1 were used to design the simulation matrix. The reason for this selection was because that Taguchi method has been well validated in a wide field, e.g. for injection moulding process (Mehat & Kamaruddinb, 2011; Tang et al., 2007) and evaporative pattern casting process (Kumar, Kumar, & Shan, 2008).

The outline of the present paper is as follows. The configuration and numerical system are introduced Sections 2.1 and 2.2, respectively. To obtain the precise simulation results, an experimental validation for the numerical set-up is discussed in Section 2.3. In Section 3, a detailed Taguchi analysis is conducted. Main conclusions are summarised in Section 4.

2. Configuration and numerical system

2.1. Configuration

An industrial round EMCC mould supplied by a company, with an inner diameter 0.356 m, was adopted in the present research. The mould had a slit-segment structure and 32 slits were distributed equally along the circumference direction. Therefore, only 1/32 region (11.25°) of the EMCC mould system was investigated, as shown in Fig. 1. The dimensions (in millimetre) of the steel simulator, the mould and induction coil, along with their relative locations were also shown in the figure. The x- and y-axis are in the radial and the axial (casting) direction. I and II denote the symmetric surfaces of the steel simulator and the mould. III and IV denote the surfaces where applied alternating current flows in and out. The mould and induction coil were made of copper alloy and the steel simulator was made of stainless steel. The detailed material properties were listed in Table 1.

Table 1
Material properties of the copper and steel.

Materials	Relative permeability (–)	Conductivity (S/m)	Density (kg/m^3)
Copper Fort, Garnich, and Ymyshyn (2005)	1	4.5×10^7	8890
Steel Deng, Xu, Wang, and He (2014)	1	7.14×10^5	7020

2.2. Numerical system

The simulations were conducted by Ansoft Maxwell® (version 16.0) based on finite element method. The simulation was based on the following assumptions (ANSYS Maxwell Online Help, 2012):

1. all the electromagnetic fields pulsate with the same frequency;
2. no moving objects in the simulation domain;
3. all the material properties are assumed to be linear.

The control equation for the conducting region can be expressed as follows (ANSYS Maxwell Online Help, 2012):

$$\nabla \times \left(\frac{1}{\sigma + j\omega\epsilon_0}\nabla \times \mathbf{H}\right) = j\omega\mu_0\mathbf{H}, \tag{1}$$

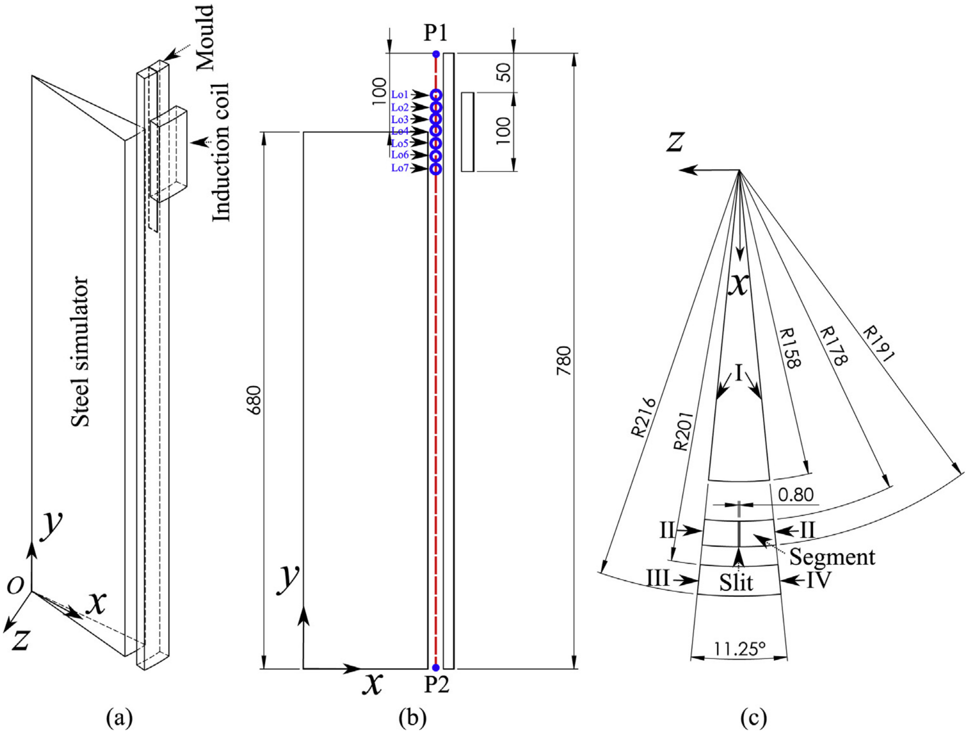

Fig. 1. The configuration of EMCC mould system: the steel simulator, the mould and the induction coil. 3D view (a), front view (b) and top view (c), respectively. I and II denote the symmetric surfaces of the steel simulator and the mould, respectively. III and IV denote the surfaces for the external applied alternating current in and out, respectively. Dimensions are in millimetre.