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A Decoupling Control Model on Perturbation Method for Twin-Roll Casting Magnesium Alloy Sheet

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To better understand the twin-roll casting process, based on the analysis of the solidification phenomenon, the geometry shape of the molten metal pool, the continuity of metal and the balance of energy and momentum, five critical partial equations were established separately including the equations of pool level, solidification process, roll separating force, roll gap and casting speed. Meanwhile, to obtain a uniform sheet thickness and keep a constant roll separating force, a decoupling control model was built on the perturbation method to eliminate the interference of process parameters. The simulation results show that the control model is valuable to quickly and accurately determine the control parameters. Moreover, Mg alloy sheets with high quality were cast by applying this model.

1. Introduction

The strip casting combines two processes of continuous casting and hot rolling, which offers many advantages, such as less space requirements, lower investment cost, energy saving and lower atmospheric emissions compared with conventional continuous casting[1,2]. In addition, the mechanical properties of metallic materials can be increased owing to the rapid cooling in the casting process[3–5]. So the strip casting method has been regarded as the revolutionary technology in the metallurgical industry.

In 1846, Bessemer[6] proposed the basic concept of the twin-roll casting. While it had been a long time to implement the idea because there were many problems in control technology, measurement devices and theoretical model. In the last two decades, with the development of the related technology, twin-roll strip casting gradually has been a hot topic in the metal cast-rolling field. Bernhard et al.[7] described the automation of a twin-roll laboratory caster and developed a non-linear state-space process model which represented the dynamics of the solidification and forming process. Cao et al.[8] established the mathematical model of rolling force on the basis of viscous fluid mechanics and traditional hot rolling model, meanwhile, an intelligent algorithm was used to predict the rolling force. Some researchers considered the molten steel level control and respectively offered different fuzzy controller to solve the problem about non-linear uncertainty and time-variable in the casting process[9–11]. However, the complexity of the casting process results not only from the molten metal level and rolling force, but also from solidification process, roll gap and casting speed control. Isolated investigation on one component of the process is not enough to obtain casting quality.

Through analyzing the highly interaction and nonlinearity among the control variables in the casting process, John et al.[12] derived a 3 × 3 linearized model for control analysis, and the model was simplified to a 2 × 2 size on a justified basis. The model, which was calibrated by a pure static model experimentally validated, was considered to be a good approximation of the casting process during steady state and offered an important reference for the process control. Hong et al.[13] investigated a two-level control strategy of the twin-roll strip caster, in which the low level part was designed to control the gap, the pool level and casting speed, respectively, and the high level controller supervised the overall control performance that generated appropriate reference signals to the low level controllers. The simulations show the control

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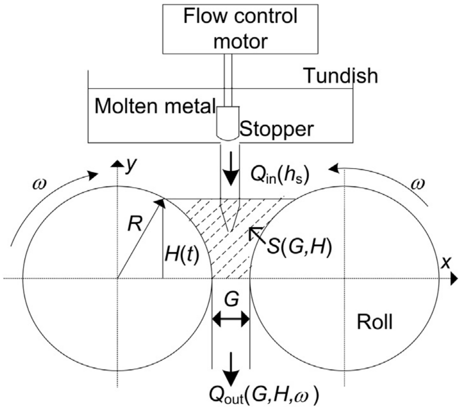

Fig. 1. Schematic diagram of the twin-roll casting process.

strategy is very effective to handle the multi-variable non-linear casting control problem. Although the above results make large contribution to simplifying model and the overall control strategy, they are very difficult to be applied in the real caster control due to too complicated theory or long data exchange time.

In the twin-roll strip casting process, these control features including complicity, non-linear, couple and time-delayed greatly restrict the industrialization of this new technology. In this study, firstly, based on analysis of the twin-roll casting process, the five physical equations are built, including the equations of molten metal level, solidification process, roll separating force, roll gap and casting speed. Secondly, in order to improve the product quality, the roll gap and the roll separating force keep constant. To fulfill the control requirement, a decoupling linearized overall twin-roll strip casting control model based on the perturbation method is established. Finally, the simulations based on the above model, give several appropriate control parameters. High quality Mg alloy sheets with the uniform thickness and good microstructure distribution have been produced by applying these parameters.

2. Casting Process Analysis

In the casting process, solidification of molten metal is completed rapidly and the process window is narrow. Small variation of the process parameters leads to severe defects of the casting strip, even leak of molten steel or break of the strip. So, to obtain a good control result and high quality strip, it is necessary to build particular process models.

A vertical twin-roll caster has been developed to produce thin strips continuously at thickness from 1 to 4 mm at casting speeds from 5 to 60 m/min in the Magnesium Alloy Cast-rolling Engineering Research Center of University of Science and Technology Liaoning. The schematic diagram is shown in Fig. 1.

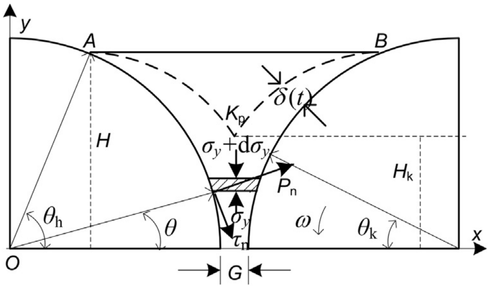

Fig. 2. Forming process of the kiss point and the force analysis on the differential units.

Molten liquid metal is poured from a tundish through a submerged nozzle into the wedge-shaped pool formed by two rolls rotating in opposite direction and two side dams. Once the liquid contacts the surface of rolls which are internally cooled with the circulated water, a thin solidification layer is formed and gets thicker as the two rolls rotate. At last, both two sides of shells weld together at a position above the roll nipper also called the kiss point. The flow rate of the liquid metal from the nozzle into the pool is controlled by adjusting the height of the stopper driven by a micro servo motor. The roll gap is adjusted by a hydraulic servo system. The casting speed is controlled by a DC-motor.

2.1. Molten metal level equation

In this section, the control equation for the molten metal level is described according to literature[9–11]. We assume that the metal density in the casting process keeps constant, so the continuity equation of the liquid metal presented by the volume change of the molten metal stored in the pool between the two rolls is described as

$$\frac{\mathrm{d}V}{\mathrm{d}t}=Q_{\mathrm{in}}-Q_{\mathrm{out}} \tag{1}$$

where Q_{in} and Q_{out} are the input flow and output flow of the pool between the two rolls, respectively.

The area of S in Fig. 1 can be expressed by

$$S=\int_0^H\left[G+2R-2\sqrt{R^2-H^2}\right]\mathrm{d}H \tag{2}$$

Synthesizing Eq. (1) and Eq. (2), Eq. (3) is gotten as

$$Q_{\mathrm{in}}-Q_{\mathrm{out}}=L\frac{\mathrm{d}S}{\mathrm{d}t}=L\left[H\frac{\mathrm{d}G}{\mathrm{d}t}+\left(G+2R-2\sqrt{R^2-H^2}\right)\frac{\mathrm{d}H}{\mathrm{d}t}\right] \tag{3}$$

where L, G, R, H are the roll width, the roll gap, the roll radius and the liquid metal pool height, respectively.

The input flow Q_{in} is simplified as a proportion loop of the stopper opening height h_{s}, that is presented as $Q_{\mathrm{in}}\approx k_{\mathrm{s}}h_{\mathrm{s}}$, where k_{s} is determined empirically. The output flow Q_{out} is given as $Q_{\mathrm{out}}=LG\omega R$, where ω is the casting angular speed. So the molten metal level equation is described as,

$$\frac{\mathrm{d}H}{\mathrm{d}t}=\frac{k_{\mathrm{s}}h_{\mathrm{s}}-LG\omega R-LH\frac{\mathrm{d}G}{\mathrm{d}t}}{L\left(G+2R-2\sqrt{R^2-H^2}\right)} \tag{4}$$

From Eq. (4), the molten metal level H can be adjusted by the stopper height h_{s}, but the roll gap and the casting speed have strong coupling relationship with the level.

2.2. Solidification process equation

On the basis of several research results[13,14], the dynamics equation of the kiss point is discussed. When the metal liquid contacts the surface of the roll, a solidification layer is formed. While the layer thickness gradually grows, finally both of shells touch and weld together at a position K_{p} called the kiss point that is above the roll exit. The stability of the kiss point assures a uniform separating force. The forming process of the kiss point is shown in Fig. 2.

In Fig. 2, in Lagrangian description, the thickness δ of the shell is described as