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Three-dimensional transient temperature analysis of cooling roller for preparing amorphous ribbon

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A R T I C L E I N F O

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A B S T R A C T

Planar flow casting (PFC) is a major method for industrial preparing amorphous ribbon. The key factors that affect ribbon formation in PFC are temperature and thermal stable time of cooling roller. This study proposes a new approach to investigate the transient three-dimensional temperature of the cooling roller using variable heat flux as the boundary condition. Firstly, the heat flux acted on the roller outer wall is calculated by two-dimensional heat transfer model. Employing the heat flux as the boundary condition, the three-dimensional transient temperature of the cooling roller is then analyzed. This study also examines the effects of the roller thickness and diameter on the temperature and stable time. Results show that the heat conduction in the roller not only in the radial direction but also in the width direction. The temperature is unevenly distributed, reaching the peak value in the middle width position, and the roller achieves thermal equilibrium after about 120 s of casting. In addition, the roller thickness mainly affects the stable time and the temperature of the inner wall; the diameter affects the stable time as well as the temperatures of both the inner and outer walls. Finally, the reliability of the simulation approach and results are verified by measuring the roller transient evolution temperature on the spot with the infrared thermal imager. This study provides the reference for the selection of roller parameters and the prediction of roller stable time during the PFC process.

1. Introduction

Amorphous ribbon has been widely used in electronics, aviation aerospace, and other fields owing to its excellent physical, mechanical, and magnetic properties. Among the various Fe-Si-B amorphous ribbon preparing methods, planar flow casting (PFC) is a major approach due to its mass production capability to produce wide, thin, and uniform amorphous ribbon [1]. During the PFC process, the stable temperature and constant gap between the roller and nozzle are basic conditions for preparing the desired ribbon with uniform thickness and high quality [2]. With the gradual increase of the roller temperature and thermal expansion at the initial time, the changed roller temperature and the gap can result in the produced ribbon is not available. In addition, the velocity of ribbon produced is about 30 m/s, the longer stable time, the more ribbons are discarded. Therefore, it is important to examine the temperature, and the stable time of the cooling roller, and their influencing factors.

Many studies have been conducted to analyze the puddle formation and temperature distribution with a simplified two-dimensional model in the PFC process for preparing amorphous ribbon [3–6]. The above analysis are limited in two-dimensional (2D) heat transfer in the PFC, without considering the distribution in the width direction. The roller temperature, however, is obviously three-dimensionally distributed also in the width direction in real conditions. The temperature analysis of the cooling roller was conducted employing the average heat flux as the boundary condition [7–9]. However, there is little information involves the heat flux distribution in the PFC process, and the extent of the average heat flux remains uncertain to reveal the actual phenomena. Recently, lots of the temperature measurement in the rotated roller have been conducted with the contact method by the thermocouple, owing to its high-accuracy in measurement, but it has some influence on interior temperature, as well as the trouble installation. In contrast, infrared radiation measurement can overcome the above problems due to its non-contact properties.

The purpose of this study is to propose a new simulation method to analyze the transient temperature of the cooling roller in the software CFX based on the variable heat flux, which is calculated employing 2D transient analysis by the software FLUENT. Meanwhile, the effects of different roller parameters such as thickness and diameter on the temperature and stable time are systematically discussed. Finally, a new non-contact method is presented to measure the roller temperature online to verify the reliability of simulation. Results can provide

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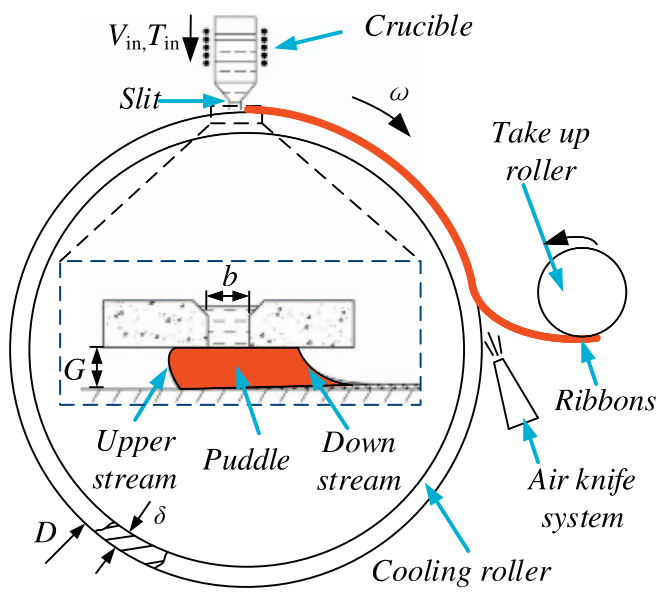

Fig. 1. Schematic of amorphous ribbon preparation in PFC process.

theoretical insights into the selection of the roller parameters and the prediction of stable time in the PFC process.

2. Model and calculation methods

2.1. Physical model of PFC

The scheme of preparing amorphous ribbon with the PFC method is illustrated in Fig. 1. The melt in the crucible is ejected to the cooling roller from the nozzle slit under the weight of the melt and the pressure of outside gas. The melt forms a puddle between the crucible and the outer wall of the cooling roller, and then cools rapidly at 10^6 K/s. A thin ribbon begins to form, is dragged from of the puddle, and attached with the cooling roller. Then, the ribbon is detached from the cooling roller by air knife system and wound up by take-up roller when the roller temperature and the gap reach steady state at about 1/4 arc of the cooling roller [10].

The geometrical parameters of the PFC in this study are as follows, roller diameter D is 1000 mm, roller width W is 200 mm, roller thickness δ is 50 mm, slit width W_r is 35 mm, nozzle slit width b is 0.25 mm, and gap G between the nozzle and the roller is 0.15 mm. The material properties of the alloy and cooling roller are presented as bellows in Table.1.

2.2. Heat conduction in the cooling roller

The temperature of the cooling roller is mainly affected by heat transfer with the puddle, ambient air, and cold water during the PFC process. In the previous study [6], the heat conduction in the roller is simplified as one-dimensional Fourier heat conduction only in the x-direction, and the cooling roller and the puddle are located at the two sides of the axis x, which as shown in Fig. 2. T_{10} and T_{20} are the initial temperature of the puddle and the roller, respectively. T_i is the temperature of the contact boundary.

Table 1
Parameters of material properties.

Materials	Fe-Si-B alloy	Copper roller
Density/kg m^{-3}	7180	8190
Specific heat/J kg^{-1} K^{-1}	544	381
Thermal conductivity/W m^{-1} K^{-1}	21	387.6

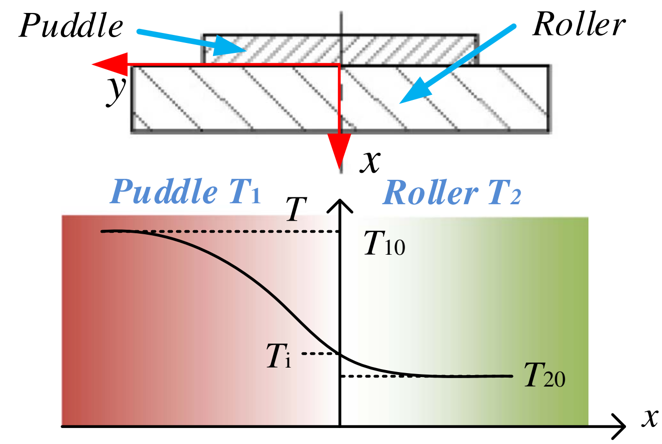

Fig. 2. The model of simplified one-dimensional heat transfer.

The simplified Fourier heat conduction equation is

$$\frac{\partial T}{\partial t} = \alpha \times \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where x is the distance from the interface in heat conduction direction/m, t is the cooling time/s, T is the temperature at a specific point/K, and α is the thermal diffusivity coefficient of the material/m^2 s^{-1}. The temperature of the cooling roller T_2 is

$$T_2 = T_i + (T_{20} - T_i) \times erf\left[\frac{x}{2\sqrt{\alpha_2 t}}\right] \tag{2}$$

$$T_i = \frac{b_1 T_{10} + b_2 T_{20}}{b_1 + b_2} \tag{3}$$

where T_2 is the temperature of the cooling roller; b is regenerative coefficient, and the $erf\,(x)$ is error function.

The calculation of the roller temperature in the above simplified Fourier heat conduction method, which involves a number of parameters and the heat conduction is limited in the x-direction.

However, the direction of the heat conduction is not only in the radial direction but also in the width direction. There is little information involves the heat conduction in the cooling roller, and the reliability of the one-dimensional Fourier heat conduction equation used in calculating the roller temperature is remains unclear.

2.3. Heat flux distribution

The presented approach to analyze the roller temperature with boundary condition of heat flux acted on the roller outer wall. The heat flux is examined in this section. The PFC process involves higher temperature melt flow, solidification, and roller heat transfer with cold water and ambient air. Therefore, the velocity, pressure, and temperature fields are coupled accurately in solving the equations of continuity, momentum and energy. The basic governing equations in the simulation are presented as follows:

a) Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{4}$$

b) Momentum equation:

$$\rho\left(\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j}\right) = \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial^2 u_i}{\partial x_i}\right)\right] - \frac{\partial P}{\partial x_i} + \rho g + f_\sigma \tag{5}$$

c) Energy equation: