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THEORETICAL ANALYSIS OF THE RIBBON FORMATION USING THE MODEL OF THE BASIN WITH COLD BOTTOM

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A model of the basin describing the ribbon formation by Planar Flow Casting is presented in the paper. The theoretical analysis has shown that the control parameters are the time period, during which the solidification front penetrates into the melt, the temperature gradient inside the melt, and the latent heat. The theoretical predictions are compared with the experiment.

1. Introduction

The process of the ribbon formation is affected by a number of parameters and it has not been clear up to now which of them are the basic ones controlling the quality of final product.The process of the formation of the amorphous ribbon differs substantially from that of the crystalline one. Therefore to built successfully a model, one needs to analyse very carefully the technical and physical aspects of the ribbon casting . Usually several models and calculation methods have to be used to characterise all aspects of the technological process.

Two models were investigated by analytical methods, namely the model of the molten layer on the cold substrate [1-6] and the model of the basin with cold bottom in the simplified version [6,7]. Most of the previous analytical calculations were concentrated on the temperature distribution or estimation of the cooling rate.

The ribbon casting represents a broad class of the elementary processes that should be investigated individually. A model of every process should be found and every process should be optimized according to the characteristic parameters. The quality of the final products depends strongly on the technological procedure. The casting of an amorphous ribbon requires different technological regime in comparison to the casting of the crystalline one. Therefore we try to distinguish the basic phases of the ribbon casting to which a specific attention should be paid, according to the structure (amorphous or crystalline). Generally, the casting of the ribbon can be divided into three phases (Figure 1).

The first phase is the formation of the stationary puddle between the nozzle and the surface of the cooling wheel. The ribbon formation is the second phase and depends

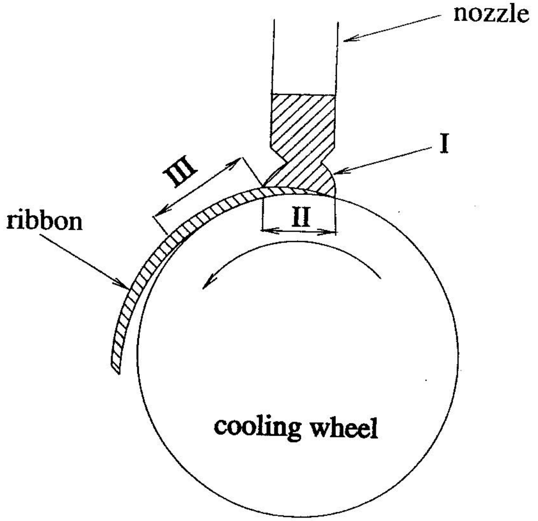

Fig. 1. Three phases of the ribbon casting. I–formation of the stationary puddle, II–solidification process or ribbon formation, III–structural relaxation.

on the rapid solidification process. The rapid solidification influences primarily the properties of the ribbon. The third phase represents the cooling of the ribbon from the temperature of the solidification (transformation temperature of the amorphous ribbon or crystallization temperature of the crystalline ribbon) to room temperature.

In the present paper we will discusse a model of the basin with the moving bottom shown in Figure 2. The model characterises the ribbon formation. The solidification starts at the right side of the basin during contacting the melt with the cold bottom provided the bottom moves in the direction shown. The solidified material is extruded by the moving bottom. The solidification front is spreading upwards from the cold bottom into the melt. This process continues up to the moment when contact of the solidification front with the melt is interrupted at the left side due to moving bottom. The puddle is represented by the basin and the cooling wheel by the cold bottom. The shape of the puddle is formed by the surface tension. Therefore it is assumed that the side surfaces of the puddle strengthened by the surface tension are represented by the side walls of the basin . The thickness of the ribbon depends on the depth of the penetration of the solidification front into the melt that depends on the crossection of the basin (the shape of the puddle) and on the velocity of the bottom (surface velocity of the cooling wheel). The model is applicable for a low surface velocity in comparison to the spreading velocity of the solidification front into the melt.

2. Theory of model

The model of a basin with the cold moving bottom is shown in Figure 3. The solidification of the elementary volume of the melt will be analyzed to obtain the main control

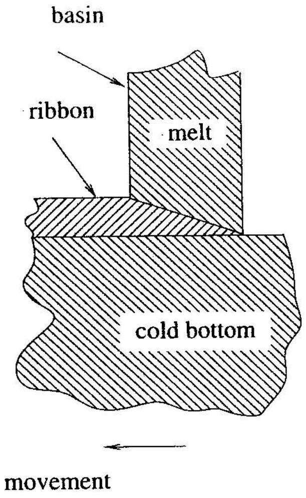

Fig. 2. Model of the basin with the cold bottom.

parameters. The thermophysical parameters of the solid and of the melt are $c_1, \rho_1, a_1, \lambda_1$ and $c_2, \rho_2, a_2, \lambda_2$, respectively, where c_i is specific heat, a_i is thermal diffusivity, l_i is thermal conductivity, ρ_i is density $(i = 1, 2)$.

Introducing the parameters characterizing the process of the ribbon formation one obtains

- $p_c = c_1/c_2$ - parameter characterizing the difference between the specific heat of the solid and that of the melt

- $p_a = a_1/a_2$ - parameter characterizing the difference between the thermal diffusivity of the solid and that of the melt

- $p_T = T_0/T_s$ - parameter characterizing the difference between the temperature of the melt and that of the solidification front, where T_0 is the initial temperature of the melt and T_s is the temperature of the solidification front

- $p_Q = \frac{L\rho_1 dX}{c_1\rho_1 T_s dX} = \frac{Q_L}{Q_T}$ - parameter characterizing the difference between the heat of the solidification and the heat corresponding to the heat capacity of the solid phase, where L is the latent heat of the solidification and dX is the elementary layer of the volume element. The parameter ranges in the wide interval from 0 to 100 having the value $p_Q = 0$ for the formation of the amorphous structure (latent heat L tends to zero, $L \to 0$).

The temperature distribution in the solid and in the melt is given by the functions [8]

$$\frac{T_1(x,t)}{T_0} = \frac{1}{p_T} \frac{\Theta\{\frac{x}{2\sqrt{a_1 t}}\}}{\Theta\{\gamma\}} \tag{1}$$

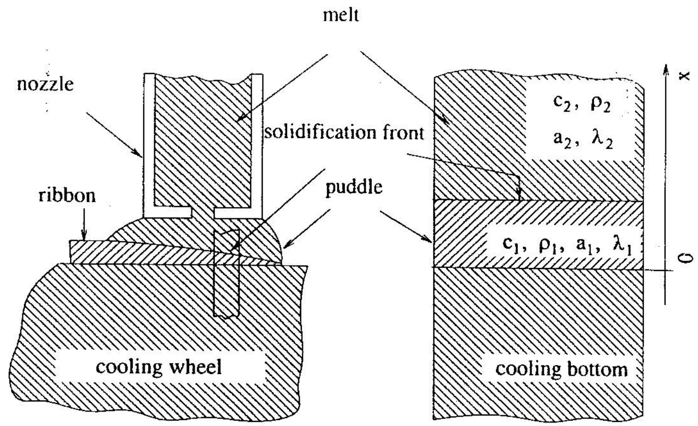

Fig. 3. Experimental arrangement of the ribbon casting and the model of the basin with cold bottom. c_1, ρ_1, a_1, λ_1 and c_2, ρ_2, a_2, λ_2 are thermophysical characteristics of the solid and of the melt, respectively.

and

$$\frac{T_2(x,t)}{T_0} = 1 - (1 - \frac{1}{p_T})\frac{\Theta^*\{\frac{p_Q x}{2\sqrt{a_2 t}}\}}{\Theta^*\{\gamma\sqrt{p_a}\}} \tag{2}$$

respectively where γ is the root of the transcendental equation

$$\frac{\exp(-\gamma^2)}{\Theta\{\gamma\}} - \frac{p_T - 1}{p_c\sqrt{p_a}}\frac{\exp(-\gamma^2 p_a)}{\Theta^*\{\gamma\sqrt{p_a}\}} = p_Q\gamma\sqrt{\pi}$$

where $\Theta\{x\} = \frac{2}{\pi}\int_0^x \exp(-\xi^2)dX$ and $\Theta^*\{x\} = 1 - \Theta\{x\}$ The functions (1) and (2) are the solutions of the partial differential equation for the heat conduction and fulfil the boundary conditions

$$T_1(x,t) = 0, \quad x = 0, \quad t > 0,$$

$$T_1(x,t) = T_2(x,t) = T_s, \quad x = X(t), \quad t > 0,$$

$$\lambda_1\frac{\partial T_1}{\partial x} - \lambda_2\frac{\partial T_2}{\partial x} = L\rho\frac{\partial X(t)}{\partial t}$$

The spreading of the solidification front is described by the relation

$$X(t) = 2\gamma\sqrt{a_1 t}$$

and the initial condition has the form

$$T_2(x, t = 0) = T_0, \quad X = 0, \quad t = 0$$

For the simplicity, the difference of the density between the solid and the melt is neglected, i.e. $\rho_1 = \rho_2 = \rho$.

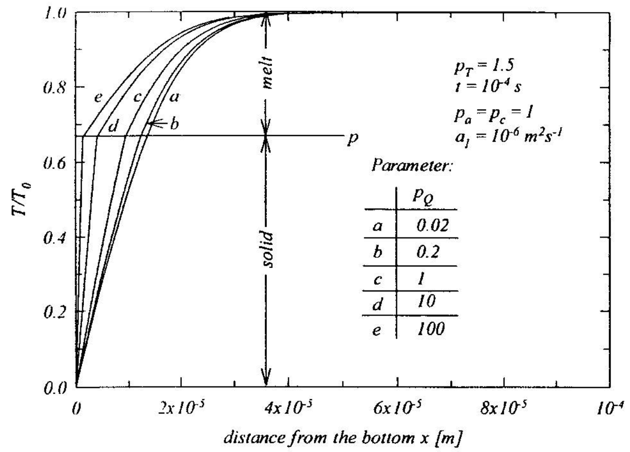

Fig. 4. The temperature distribution in the basin as a function of the distance from the cooling bottom. Parameter $p_Q = Q_L/Q_T$ characterises the latent heat. The calculations are valid for the parameters given in the figure.

The analysis of the functions (1) and (2), when choosing the suitable set of the graphs, gives a real picture of the processes of the ribbon formation assuming that the characteristic parameters correspond to a real experimental arrangement.

3. Discusion

The temperature distributions in the solid and in the melt for various values of the parameter p_Q (various latent heats) are shown in Figure 4. The parameter p_Q is connected with the latent heat i.e. with the crystallization kinetics. The presented calculations of the temperature distribution in the puddle assumed that the latent heat is constant during the ribbon formation. For an amorphous structure no latent heat is assumed. The crystallization kinetics is slow to let develop the process of the crystallization in the full range and throughout the considered volume. The apparent reduction of the latent heat may start because of the quick spreading of the solidification front. Depending on the composition and the casting conditions the compositional separation or even partial crystallization might occur. Therefore the latent heat involved in our calculation can range in a broad interval depending on the crystallization kinetics and the spreading of the solidification front into the melt.

The set of the curves in Figure 4 is valid for $p_a = p_c = 1$ and $p_T = 1.5$. The temperature distribution curves correspond to five different values of p_Q. The line "p" divides the Figure 4 into two areas belonging to the melt and to the solid. The crossing of the line with the curves belonging to various values of the parameter p_Q gives the thickness of the ribbon. The ribbon thickness is always smaller for the solidification process in which the partial crystallization is involved assuming that all the technological parameters have the same values (surface velocity of the cooling wheel, shape of the

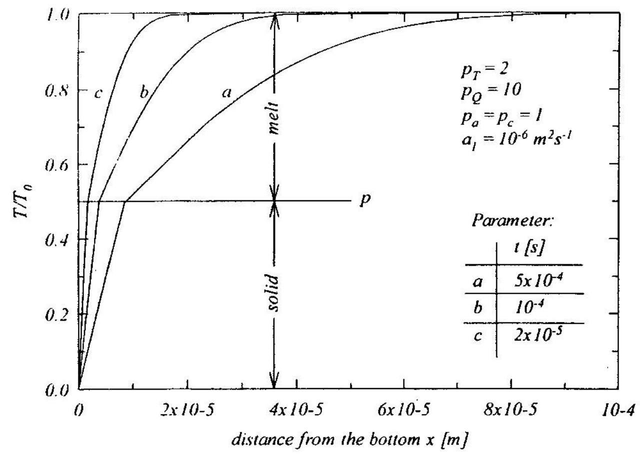

Fig. 5. The temperature distribution in the basin as a function of the distance from the cooling bottom for various time periods of the spreading of the solidification front into the melt. The calculations are valid for the parameters shown in the figure.

puddle, temperature of the melt, etc.). To obtain the same ribbon thickness for various contents of the crystallized phase, one needs to adjust the surface velocity of the cooling wheel or to adjust the puddle shape to keep the contact of the solidification front with the melt for an appropriate period of time. Both operations give the same result.

In the next, the development of the temperature gradient in the process of the ribbon formation is considered. The temperature gradient of the volume element in various distances from the right side of the basin (see Figure 3) is analyzed. A set of the curves corresponding to various time periods of the solidification process (different positions of the elementary volume element in the basin) is shown in Figure 5 in which non-dimensional temperature as a function of the distance from the bottom of the basin is plotted. For the simplicity, the parameters p_a and p_c are set to unity, i.e. $p_a = p_c = 1$ and $p_T = 2$. The crossing of the line "p" with the curve characterizing the temperature distribution in the solid and in the melt gives the penetration depth of the solidification front into the melt or the thickness of the solidified phase (variable x). The points along the line "p" represent the different penetration depths of the solidification front into the melt. The temperature distribution in the solid and in the melt for various points of the line "p" is different. Several curves of the temperature distribution corresponding to three different time periods or to three positions of the volume element in the basin are shown in Figure 5.

Figure 5 shows that the solidification of the melt in various distances from the bottom proceeds with different temperature gradients. This fact has a great consequence for practice. The form of the temperature gradient affects primarily the structure of the solidified phase. A large temperature gradient causes the freezing of the melt while a small temperature gradient could initiate the redistribution of the components of the melt and the nucleation and crystal growth depending on the composition. While the amorphous structure from the side of the cooling wheel can solidify, the compositional inhomogenous or even the crystalline structure can be found on the opposite side of the ribbon. The thickness of the ribbon determines how much the temperature gradient during the solidification can vary or how big the structural inhomogenities might be expected. The shape of the puddle and the surface velocity of the cooling wheel are the parameters that influence the thickness and the structure of the ribbon.

The temperature gradient can also influence on the structure of the ribbon. A large temperature gradient causes the freezing of the melt. Small temperature gradient represents the states that are not far from the thermodynamic equilibrium. The compositional separation, the formation of the nuclei or even the crystallization can take place for small temperature gradients. As a result, the ribbon with the inhomogenous cross section can be obtained.

4. Conclusions

The model of the basin with the cold bottom is discussed in the paper. The model is treated analytically as the solution of the partial differential equation for the heat conduction utilizing the boundary and initial conditions that consider the practical aspects of the ribbon casting.

The model presented gives several important conclusions:

- The thickness of the ribbon depends on the shape of the puddle and the surface velocity of the cooling wheel. The existence of the latent heat retards the penetration of the solidification front into the melt and this results in the casting of a thinner ribbon.
- The structure of the ribbon depends primarily on the composition. The phase diagram in question should be carefully considered. Pure substances or alloys far from eutectics, generally, give the crystalline ribbons while, at least for simple binary alloys, the compositions around eutectics could give amorphous ribbons. The alloy composed of many components give amorphous ribbon, too. Although the mentioned statements are generally known it should be stressed that the composition has be very carefully considered in the framework of the model presented as due to the temperature gradient it determines the structure of the final product.
- The homogenity of the ribbons depends on the temperature gradient during the solidification process. The temperature gradient changes during the solidification process and it is influenced by the time period during which the solidification is preceded, by the temperature of the melt, and by the temperature of the solidification front.

The model of the basin with cold bottom shows that the main control parameters are the time period, during which the solidification front penetrates into the melt, and the temperature gradient inside the puddle. The former depends on the surface velocity of the cooling wheel or on the diameter of the puddle and influences mainly the ribbon thickness while the latter influences the structure of the ribbon. The latent heat significantly influences the thickness of the ribbon.

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