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Numerical analysis of temperature field and structure field in horizontal continuous casting process for copper pipes

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ABSTRACT

To efficiently utilize energy, refrigeration industries, including air conditioning, have put forward higher and higher requirements for the performances of copper pipes used for heat exchangers. Horizontal continuous casting of pipe blank is a key process in production of copper pipes, and optimization of its technological parameters has positive effects on improving the structure uniformity of casting blank. The stability of the performances of pipe blank also directly influences the quality of subsequent machining process. In this paper, numerical analysis was carried out for the temperature field and structure field during solidification of pipe blank in the crystallizer for horizontal continuous casting, and the steady-state sump depth and morphology in the crystallizer for continuous casting, which could be used to evaluate production safety, were obtained. Quantitative analysis was conducted for the laws of influence of different casting technological parameters, such as cooling water flow rate, withdrawal speed, and casting temperature, on the sump morphology in the crystallizer for casting blank and the final distribution of structure field in casting blank. Metallographic experiment was carried out for casting blank, and the results were compared visually with the structure field from simulation calculation, to provide measurable reference bases for further optimizing the horizontal casting technological parameters for copper pipes.

1. Introduction

As people constantly pay attention to environmental protection and efficient utilization of energy, copper pipes, as piping used for refrigerators on a large scale, have been developed towards thin wall and light weight [1–3]. Since copper pipes are mounted inside a heat exchanger, they, if broken, will bring about great troubles for repair. Previous research results have shown that various defects occurring at the casting stage, e.g., air hole, inclusion, and microstructure ununiformity existing in castings, will not be able to be eliminated completely in subsequent processes [4,5]. These defects may carry over to subsequent processes, e.g., forming [6,7], and heat treatment [8,9]. Horizontal continuous casting is the first process in production of copper pipes, and the processing quality directly influences the grade of finished copper pipes [10,11]. In particular, the uniformity degree of solidified microstructure directly influences the stability of the peripheral mechanical performances of the pipes [12,13].

In production of copper pipes, the casting and rolling method is a relatively advanced production method at present. This method has such advantages as short process flow, little energy consumption, small footprint of equipment, convenient maintenance, and high metal utilization rate. However, the casting process has some shortages, mainly including many quality factors for pipe blank, relatively difficult technological control, frequent graphite replacement, and complex operation and control. The copper pipe casting process is shown in Fig. 1.

In this paper, numerical simulation and analysis were conducted for the temperature field and structure field at the continuous casting stage of copper pipe with the casting software PROCAST based on the features of horizontal continuous casting [14], and metallographic experiment was carried out for comparison. Analytical study on the horizontal casting process for copper pipes can provide basic theoretical data for further improving the processing technology for copper pipes and raising the quality of the pipes, to decrease the scrap rate, reduce the energy consumption and raise the productive efficiency as much as possible. In addition, it is probable to reduce the accident rate of copper pipes during operation of refrigerators.

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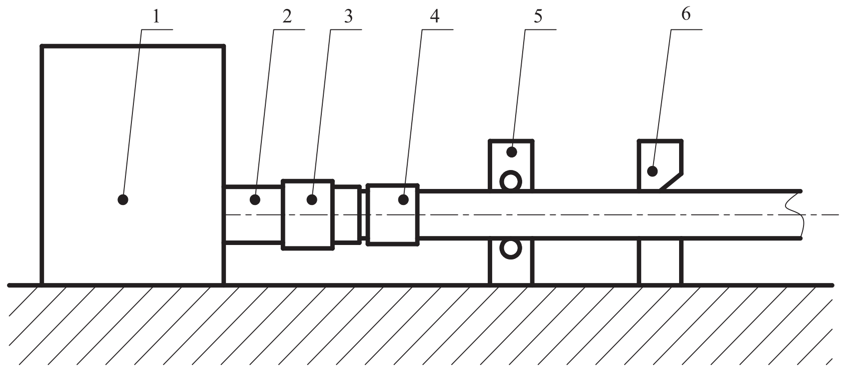

Fig. 1. Schematic diagram of casting process. (1) Smelting furnace; (2) Crystallizer; (3) Primary cooling system; (4) Secondary cooling system; (5) Traction machine; (6) Shearing machine.

2. Mathematical model

In horizontal continuous casting, after the copper liquid enters the crystallizer from the smelting furnace, there will be complex changes, including heat transfer, and phase change, in the solution, due to cooling effect. Therefore, the laws of distribution of the temperature field of pipe blank must be analyzed with the transient heat transfer equation. Boundary conditions are applied in the calculation so that the convective effects are taken into account; the variable finally influenced by the convective effects is the change of temperature field, and the change of structure field is obtained from coupling temperature field.

The temperature field control equation used for the horizontal continuous casting process for copper pipes is a non-steady-state heat transfer partial differential equation:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial x}\left(k_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial x}\left(k_z\frac{\partial T}{\partial z}\right)+q_b=\rho c\frac{\partial T}{\partial t}. \quad (1)$$

where

$T=(x,y,z,t)$ - Temperature varying with space and time (°C);
ρ - The density of copper liquid (g/cm^3);
c - The specific heat of pipe blank (J/(kg·°C));
k_x, k_y, k_z - The conductivity coefficients of pipe blank in X, Y, and Z directions;
q_b - The latent heat of crystallization released during solidification of copper liquid.

During the crystallization and solidification of horizontal continuous casting copper liquid, it was assumed that the heat transfer is isotropic, in other words, the thermal conductivity of one node is approximately believed to be identical in x, y and z directions at a given temperature [15], then the transient heat transfer equation can be simplified as follows:

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=\rho c\frac{\partial T}{\partial t}, \quad (2)$$

The heat transfer model in the Procast software is to conduct heat flow calculation by solving the Fourier's heat conduction equation, and the release of latent heat of phase change during solidification of pure copper casting liquid is taken into account in the calculation. The settings of simulation parameters of the structure field of copper pipe blank are shown in Table 1.

Table 1
Parameters values of structure field.

Parameter	Value
Liquidus temperature	1082 °C
Solute diffusion coefficient	3×10^{-9} m^2·s^{-1}
Gibbs-Thompson coefficient	0.9×10^{-7} k·m
$\Delta T_{s,max}$	1 °C
$\Delta T_{s,\sigma}$	0.5 °C
$n_{s,max}$	1.50×10^7
$\Delta T_{v,max}$	3 °C
$\Delta T_{s,\sigma}$	0.5 °C
$n_{v,max}$	5.10×10^8
a_1	2.102×10^{-6} m·s^{-1}·K^{-2}
a_2	6.137×10^{-7} m·s^{-1}·K^{-2}

3. Establishment of simulation model

Main horizontal continuous casting equipment includes smelting furnace, holding furnace, crystallizer, and cooling system; in this paper, the change of melting copper liquid in a crystallizer was primarily studied, and the field measurement data in a factory was used to establish a model, as shown in Tables 2 and 3.

In meshing with the dedicated pre-processing module MeshCAST of PROCAST, triangular plane meshes were generated first on the surfaces of the crystallizer, copper sleeve, and copper pipe, respectively, and then tetrahedral meshes were generated. Finally, the volumetric meshes of all parts were assembled in a mesh assembler, to complete the meshing of casting process, as shown in Fig. 2. Establishment of meshes mainly includes the following processes: generation of plane meshes, generation of volumetric meshes, evaluation of mesh quality, and mesh smoothing; the correctness of meshes is checked by controlling the number of node thus to control the number of elements. In general, the smaller the mesh size, the higher the calculation accuracy, but the higher the calculation cost. The models studied in this paper mostly have simple structures, e.g., cylindrical shape. In these models, plane mesh generation is mainly conducted first, and then volumetric mesh generation is conducted; afterwards, mesh accuracy correction is performed using the mesh quality control procedure self-contained in the application software, and the mesh quality is checked as follows:

Min Side Length: No problems found (with value <0.5)
Max Aspect Ratio: No problems found (with value >6)
Min Tria Internal Angle: No problems found (with angle <6 degree)

Table 2
Model data.

Parameter	Value
Size of casting blank (mm)	ϕ90xϕ25
Size of crystallizer (mm)	ϕ120x400
Size of liquid inlet (mm)	5xϕ8
Size of copper sleeve (mm)	ϕ140x180