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Development and application of online Stelmor Controlled Cooling System

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ABSTRACT

An online Stelmor Controlled Cooling System (SCCS) has been developed successfully for the Stelmor production line, which can communicate with the material flow management system and Program Logic Control System (PLCs) automatically through local network. This online model adopts Implicit Finite Difference Time Domain (FDTD) method to calculate temperature evolution and phase transformation during the production process and predicts final properties. As Continuous Cooling Temperature (CCT) curves of various steels can be coupled in the model, it can predict the latent heat rise and range of phase transformation for various steels, which can provide direct guidance for new steel development and optimization of present Stelmor cooling process. This unique online system has been installed in three Stelmor production lines at present with good results.

1. Introduction

With increasing tough competition in the steel industry, how to develop new steel products and stabilize quality of present products becomes the major concern for steel producers. Pushing the mechanical properties of rod wire closer to its technical limits, the demand on more reliable predictive control technique for the cooling process in Stelmor production line increases continuously.

Stelmor is the most popular controlled cooling process to produce the steel wire due to its fast production speed and homogeneous mechanical properties along the length of wire coil. In Stelmor process as shown in Fig. 1, a rod wire with temperature above 1000 °C coming from the finishing mill quickly passes through several water tanks to the laying head at a specific temperature to form into loops, depositing on to a conveyor in an overlapping pattern, the specific cooling rate is achieved by opening of a series of fans below.

The final mechanical properties depend mainly on the chemical composition and the cooling rate before the phase transformation for high carbon steel [1,2,6]. As the cooling rate and phase transformation cannot be observed directly during production, it is urgently required to develop an online model to predict the final mechanical properties and phase transformation. Although there are several research reports in this field [3–6], the online quality prediction model for Stelmor process has not found reported yet. Adopting Implicit Finite Difference Time Domain (FDTD) method, an online controlled cooling model was developed and installed to monitor the real production process. This paper focuses on introduction of its basic theory and control method of the online system, which is helpful for stabilization of the product quality. At present, this online model SCCS has been installed in three Stelmor production lines with satisfactory performance.

2. Mathematical model

2.1. Thermal model

In the Stelmor production line, axial heat conduction can be ignored because of an infinitely long steel rod moving at high speed, the model can be formulated to solve 1D heat conduction based on following assumptions: (1) radial symmetry; (2) uniform circular cross-section; and (3) uniform initial temperature, which is briefly close to reality.

Basic equation to solve the heat flow within the rod is following:

$$\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right)+\frac{k}{r}\frac{\partial T}{\partial r}+g(T)=\rho C_p\frac{\partial T}{\partial t} \tag{1}$$

Note that $g(T)$ is the volumetric rate of heat generation within the rod due to phase transformation, ρ material density, C_p the heat capacity and k the thermal conductivity.

In order to reduce loss of material message during calculation, real experimental data ρ, k, and C_p can be input directly in the interface of model as shown in Figs. 2 and 3, compared with traditional regression method.

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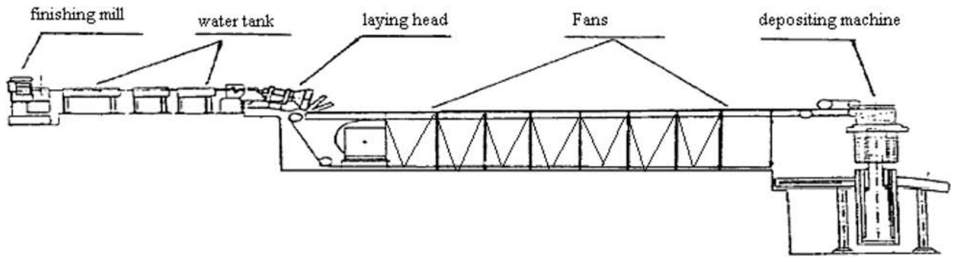

Fig. 1. Layout of Stelmor machine.

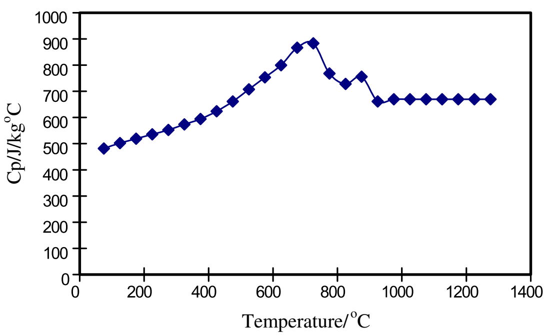

Fig. 2. The steel's specific heat change with temperature.

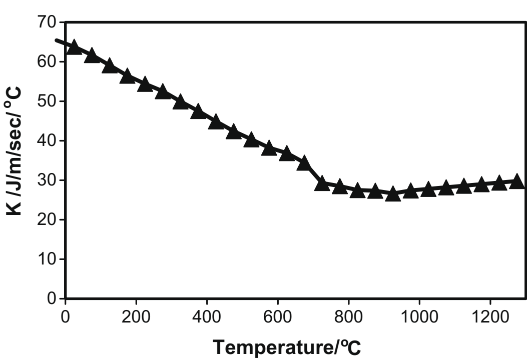

Fig. 3. The steel's thermal conductivity change with temperature.

The FDTD Crank–Nicolson method has been adopted to solve above equation as it is fast and unconditionally stable, which can meet the requirement of online modeling.

In order to maintain balance between speed and accuracy of the model, 20 nodes has been selected along radial direction after trial and error. In general, large number of nodes is helpful to guarantee accuracy of the model, but it will cause the slow speed of the model, which is unacceptable for the online model, as in real production, one rod wire can pass the laying head in no more than 2 s.

The following boundary conditions have been applied:

- At the centerline

$$t > 0, \quad r = 0, \quad -k\frac{\partial T}{\partial r} = 0 \tag{2}$$

- At the rod surface

$$t > 0, \quad r = r_0, \quad -k\frac{\partial T}{\partial r} = h(T_{r_0} - T_a) \tag{3}$$

where the initial condition is:

$$t = 0, \quad 0 \leqslant r \leqslant r_0, \quad T = T_{in}$$

where t is time in second, r_0 the radius of rod wire, h the heat transfer coefficient. T_{r_0} rod surface temperature, T_a air or water temperature surround.

When the online model is running, T_{in} is the measured temperature coming from the pyrometer installed after the finishing mill.

The model divides the Stelmor line into several stages, each with its constant heat transfer coefficient h value, which can be self-adapted to match real measurements from several pyrometers installed in the production line. In one Stelmor production line in Sha-Steel company, there are 14 fan machines put below in sequence to control the cooling rate of steel rod by opening its fan volume. A constant h is assigned to each fan machine controlled stage, which can be self-adapted according to the following self-developed equation:

$$h_{new} = h_{old} \times (T_C - T_{air})/(T_M - T_{air}) \tag{4}$$

where h_{old} is the original heat transfer coefficient, T_C the model predicted temperature at one pyrometer position on the fan cooling production, T_M the measured temperature from the specified pyrometer, and T_{air} the air temperature.

The computer model was checked by comparison between the FDTD model and commercial FEM model FEMLAB under the exact same conditions, Fig. 4 shows the exact same results from both models at different condition and proves the accuracy of the FDTD model.

As an online model, the SCCS model needs to communicate with the material flow management system and PLC automatically through local network continuously. The model needs to input two groups of data: one is the real temperature from online pyrometers, another is the basic wire rod information. Eight pyrometers have been installed in the production line to provide real temperature data for the model to calculate and compare.

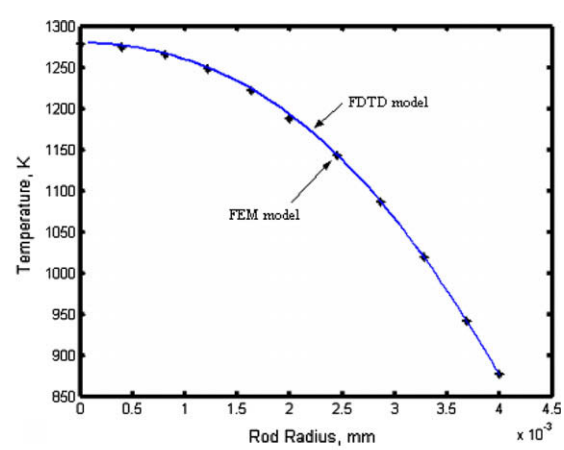

Fig. 4. Comparison of FDTD and FEM modeling result.