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Temperature Rise Of Hot Bar In Induction Heating Process

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Abstract

A contact-free temperature increase in hot barcan be achieved within a short time by induction heating.A Numerical code was developed to obtain the temperature distribution of the hot bar. Most of the parameters included in hot mill process are bar heater (frequency, power), edge heater and speed of bar. Numerical simulation has been performed to investigate the temperature distribution of the slab in hot mill process. The effect of several parameters on the junction temperature was examined to confirm the thermal efficiency of the model developed in this study. The results from our thermal model showed fairly good agreement with experimental results by applying the correction coefficient for the amount of the cooling, setting power efficiency of the induction heater and heating efficiency.

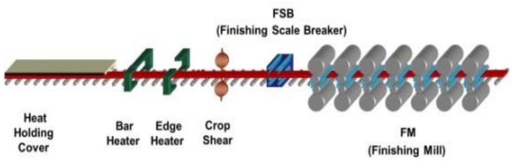
Keywords:induction heating, hot bar, bar heater, skin depth, transverse direction, numerical method.

1 Introduction

The magnetic flux induces an eddy current in a steel bar which generates heat in the work piece due to the resistance of the material. Rudnev[1] reported a comprehensive study of induction heating prior to hot working. The basic electromagnetic phenomena in induction heating are applied to investigate the advantage of heating by induction.Nemkov and Goldstein [2] presented several examples that show the results of computer simulation.Bose *et al.*[3] simulated an induction heating using the finite element procedure, utilizing the commercial program of Abaqus/Standard. The mechanism of the energy transformation in induction heating with magnetic flux concentrator is carried out in [4]. Bay *et al.* [5] presented a solving procedure for the electromagnetic problem to consider the case of non-linear magnetic materials.Rudnev and Loveless [6] investigated some parameters related to edge/end and illustrated the temperature profiles along the bar's length/width. Fukushima *et al.* [7]developed an induction heater for hot bar mill that sufficiently heated the edge portion of a transfer bar. In this study, a numerical code was developed to obtain the temperature distribution of the hot bar. Most of the parameters included in hot mill processare bar heater (frequency, power), edge heater and speed of bar.

2 Physical model

Figure 1 shows the layout of a typical hot bar finishing mill process [8]. Two induction heaters (bar heater) are installed between the rough unit and finishing mill to raise the temperature of steel bars to proper temperature for next process.The inlet temperature of bar heater of 1020℃ increases through the bar heater from 0℃ to 40℃ with heater setting power. The setting power varies from 0 to 15250 kW with 1.4 kHz frequency depend upon the required raising temperature. The edge area of the slab loses a lot of heat and, consequently its temperature drop. This temperature drop at the edge area was controlled by edge heaters.



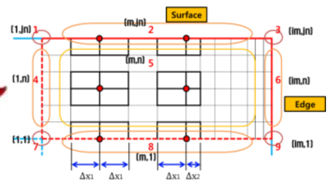


Fig.1.Layout of typical finishingmillFig.2. Computational domain of the bar

3Two dimensional thermal modeling

The heating process of hot strip by induction heater can be modeled as a two dimensional unsteady heat conduction equation written in the following form:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

Where kis the thermal conductivity, T is the temperature, $\alpha = k/\rho C_p$ is the thermal diffusivity and $\dot{q}$ is the heat generation rate per unit volume by induced current. The heat generation rate can be calculated using total input power (Q) as follows:

$$\dot{q}(x) = f(Q, \sigma, H, w) \cdot J(x)^2$$

$$= \eta \frac{Q}{H \cdot w \cdot v \cdot t_{IH}} \cdot \frac{e^{\frac{-2x}{\delta}} - 2e^{\frac{-H}{\delta}} + e^{\frac{2(x-H)}{\delta}}}{\delta - 2H \cdot e^{\frac{-H}{\delta}} - \delta \cdot e^{\frac{-2H}{\delta}}} \quad (2)$$

Where η is induction heater efficiency, H is slab thickness and δ is skin depth.*w*is width of the slab, *v* is velocity, t_{IH} is the elapsed time of heating power. Skin depth can be calculated by following equation:

$$\delta = \frac{1}{\sqrt{\pi \sigma_{IH} \mu f}} = 503.3\sqrt{\frac{\rho_{IH}}{\mu_r f}}$$

Relative magnetic permeability (μ_r) is a ratio of magnetic permeability to that of vacuum. If the heated material is nonmagnetic is 1. F is frequency, ρ is electrical resistivity of induction heater.

(Initial condition)

The temperature measured behind rough mill (RDT) considered as an initial temperature of the transient heat transfer problem. $T(0) = T_{RDT}$.

(Boundary condition)

Boundary conditions at the external surfaces of the strip are convection and radiation boundary conditions written in the following form:

$$q_{surface} = h_{surface}[(T_{surface} - T_{surr}) + \varepsilon\sigma\{(T_{surface}^4 - T_{surr}^4)] \quad (3)$$

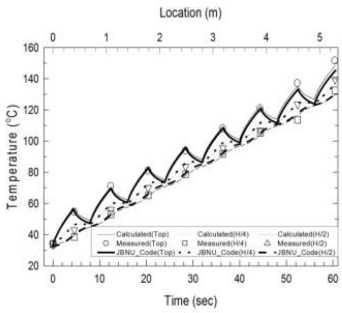
(Numerical method)

The finite difference formulation for the governing equation of (1) and boundary conditions has been carried out by the control volume approach [9]. Figure2 shows computational domain of the cross section of strip. The numerical calculation has been performed to calculate the time dependent temperature distribution of the strip. The unknown temperature at time level n+1 can be obtained by numerical calculation of algebraic equation for the discretization equation for internal control volumes and representative external surfaces.

4 Results and discussion

Figure 3 illustrates the comparison of results obtained in this study and that of experiments in literature [9]. It can be seen that the maximum deviation between each method is less than 4.6%. The results confirm the availability of the parameters such as efficiency, total input power, skin depth and moving speed in equation (2).Figure 4 shows the temperature variations of the stainless steel passing through the bar heater. It can be seen that the surface temperature increases immediately with induction heating, while the response retarded as the thickness of the bar increased. The predicted temperature agrees fairy well with experimental results except initial state of rapid heating

Figure 5 shows the thermal image of the hot bar taken by the IR camera (FLIR SC2500, FLIR). The image illustrates the surface temperature of the hot bar moving through the actual hot rolling process. The tested temperature profiles along the three different radial directions are shown in Fig. 5(b). The thermo-graphic data are analyzed using the software FLIR Altair. The temperature was measured at three different case settingΔT = 0℃, 20℃ and 40℃ (case 1 – case3).The inlet temperature about 1050^{o}C increases according to the required temperature. It can be seen that the temperature keeps uniform through the length of the bar except edge area due to the edge effect.



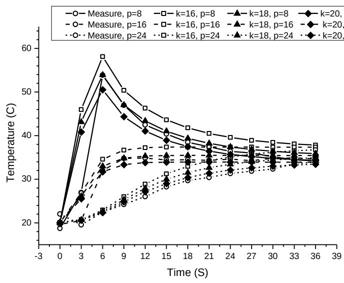
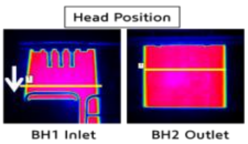


Fig.3. Comparison of temperatureFig.4. Temperature variations with time



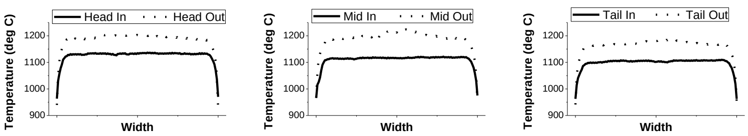
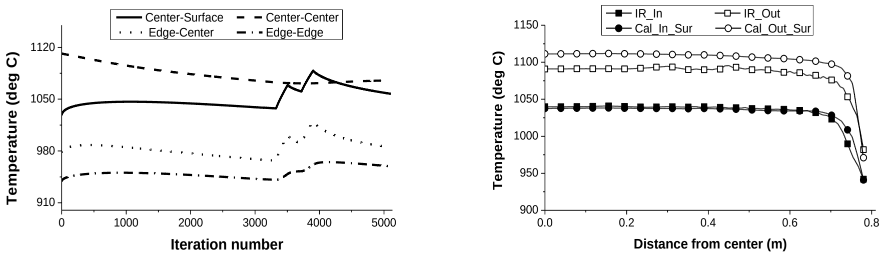


Fig.5(a) Thermal image of surface   Fig.5(b) Temperature profile in case 1,2,3

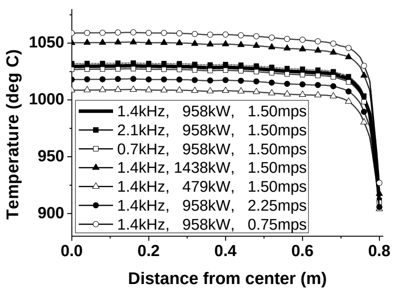
Figure6shows the temperature variations of barpassing through the bar heater. The hot bar at temperature of 1000^{o}C is to be heated to 40^{o}Ctemperature rise by two 15,250 kW bar heaters. The barat temperature of 1055^{o}C enters the heater set with 1 m/s velocity. Three surface temperatures are decreased gradually by convection and radiation heat transfer and heated up twice while passing through the two heaters. It can be seen also that temperature at the mid-plane decreases during the entire elapsed time. That is because that thickness is longer than the skin depth, where the induction heating is no more effective



(a) Temperaturevariations with time **(b) Temperature profile across the width**

Fig 6Shows the temperature variations of barpassing through the bar heater

The effect of power, frequency of the induction heater and bar velocity on the surface temperature is shown Figure 7. The temperature rise increases from to 20°C to 60°Cas the power varies from 4.79x10^5 W to1.44x10^6 W. Furthermore, the temperature dropped significantly when thebarvelocity increased because of the reduced thermal energy supplied to bar. It can be noted that the frequency does not have a great effect on the temperature distribution at fixed power of 9.584.79x10^5 W. However, it was found that the skin depth changes significantly with frequency variations.



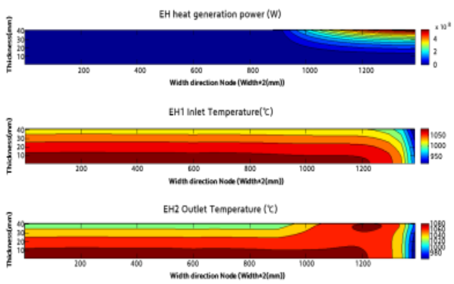


Fig.7.Effect of power, frequency andFig.8Contours of heating power, inlet and bar velocity on surface temperatureexit temperature of edge heater

Figure8illustrates the contours of inlet temperature, edge heater setting power to be used as input conditions and predicted temperature due to the induction heating near edge area. It can be seen that the heating power of the edge heater is concentrated in corner area. This area is determined by considering the information of heater characteristics provided by the manufacturer.

5. Conclusion

Numerical simulation has been performed to investigate the temperature distribution of the slab in hot mill process. The effect of several parameters on the junction temperature was examined to confirm the thermal efficiency of the model developed in this study. The results from our thermal model showed fairly good agreement with experimental results by applying the correction coefficient for the amount of the cooling, setting power efficiency of the induction heater and heating efficiency. The effect of bar heater is also considered to investigate the transverse temperature distribution of the hot bar. It is found that the temperatureincreases uniformly across the width directionexcept the edge area where edge effect occurs at 13% length of the width. The temperature drop at the edge area can be controlled with two edge heaters. Temperature drop decreases with heating power, while the maximum temperature near edge increases, which results in the non-uniform temperature distribution across the width.

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