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Numerical Simulation of Induction Heating of Aluminum Alloy Billets

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Abstract. In this work, a numerical model for induction heating is proposed. The heating process considers only interaction of electromagnetic effects and heat transfer, and is represented by an unsteady heat diffusion equation. The numerical simulation of the process is performed using a finite volume method in which the induction heating is represented by a volumetric heat source term. The heat source term is evaluated analytically using principles based on Faraday's and Biot-Savart laws. The technique is applied to the case of induction heating of a cylindrical A356 aluminum alloy billet. The model predicts magnetic flux density and temperature distribution during the heating process. The effects of process parameters, such as frequency and current density, on the temperature distribution are also studied. The results show that nearly uniform distribution of temperature can be achieved when the billet is heated slowly with low frequency and low supply current density.

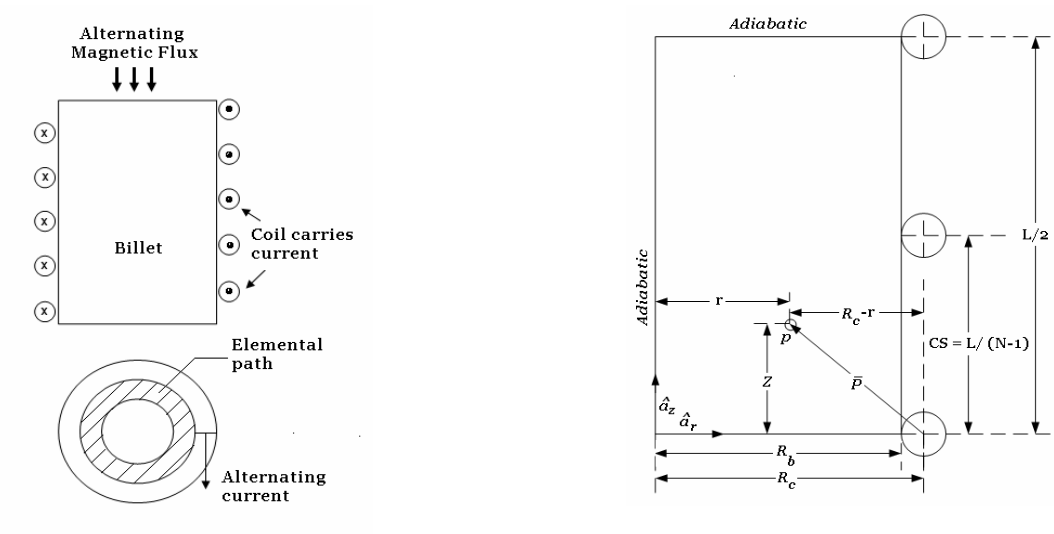
Introduction

In semisolid forming, a billet with non-dendritic microstructure is reheated to a desired temperature such that liquid and solid phases coexist. Induction heating is generally used to reheat the billets in semisolid state [1-4], in which a major objective is to minimize non-uniformity in temperature distribution. In this context, Hirt *et al*. [1,2] and Kang *et al*. [4] predicted temperature distribution of aluminium alloy billets using a finite difference method where Bessel functions were used to describe the electromagnetic fields. Ko *et al*. [5] and Kawaguchi *et al*. [6] predicted the temperature distribution during induction heating based on a finite element method. Choi *et al*. [7] calculated the temperature distribution analytically considering induction heating and compared their results with experiments. They found a good agreement between experimental and calculated results.

The above formulations are based on uniform distribution of magnetic fields in the axial direction. But, for a single conductive wire (each turn of induction heating coil), the current field distributes itself equally over surface of the wire. When a second conductive wire is placed in the vicinity of the first one, the electric fields of the two currents interfere with each other and the field distribution becomes asymmetric. This induces a change in the associated magnetic field. In reality, however, an induction heating system has coils with many conductive wires or turns, and therefore, the existing numerical models assuming uniform distribution of magnetic field are not suitable. In the present work, a numerical model is proposed to investigate temperature distribution during induction heating of a cylindrical A356 aluminum alloy billet using finite volume method which considers the effect of each conductive wires as well as their spacing. The basic principles of the model are based on Faraday's and Biot-Savart laws [8, 9]. These general laws of physics demonstrate that when a conducting material is situated in a varying magnetic field, it experiences an eddy current circulating within the mass of conducting material. The eddy current then produces heat by Joule effect. In the present work, in order to simulate the process, an unsteady energy conservation equation is solved based on a finite-volume method in which the induction heating is represented by a volumetric heat source term. The model predicts magnetic flux density and temperature distribution during the heating process. The model is first validated against experimental and analytical results available in literature. The effects of process parameters, such as frequency and current density, on the temperature distribution are also studied.

Description of physical problem

A schematic diagram of a typical induction heating system is shown in fig.1. The system contains a coil of *N* turns that placed around a cylindrical billet of A356 alloy. The billet axis is in z-direction. Because of the nature of heating, an axisymmetric computational domain is considered, as shown in fig.1b. The thermo-physical properties of the billet used in simulation are summarized in Table 1[5, 8 and 10].



(a) (b)

Figure 1: (a) Schematic diagram of induction heating system, (b) Computational domain

Properties	*Value*
Density (ρ)	2700 [Kg/m^3]
Specific heat (C)	900 [W/m^2-°C]
Thermal conductivity (k)	120 [W/m-K]
Relative permeability (μ_R)	1
Specific resistance (α)	2.62×10^{-8}[Ω-m]
System data	
Billet radius (R_b)	45 [mm]
Billet length (L)	50 [mm]
Heating coil diameter(d)	5, 10 [mm]
Heat transfer coefficient (h)	25 [W/m^2-K]
Surface emissivity (ε)	0.2

Table1: Thermophysical properties and system data

Mathematical formulation

The induction heating process involves interaction of heat transfer and electromagnetic effects, and is governed by an unsteady heat diffusion equation [4] given as

$$\rho C\frac{\partial T}{\partial t} = k\nabla^2 T + Q \quad (1)$$

It is noted here that the model does not consider the phase change process during heating. In equation (1), Q is volumetric heat source term due to induced eddy currents. This equation is solved using a finite volume method and TDMA solver.

Volumetric heat source term

Considering a current I flowing in a differential vector of length $d\overline{L}$, the induced differential magnetic flux density [8], based on Biot-Savart law, at any point p as shown in fig.2a is given as

$$d\overline{B} = \frac{\mu I \, d\overline{L} \times \hat{a}_P}{4\pi \left|\overline{P}\right|^2} \tag{2}$$

where $\mu = \mu_R \mu_0$, μ_R being the relative permeability of medium and μ_0 the free space permeability($4\pi \times 10^{-7}$ Henry/m^2). In eqn. 2, $\hat{a}_P$ is unit vector to specify direction of vector distance $\overline{P}$.

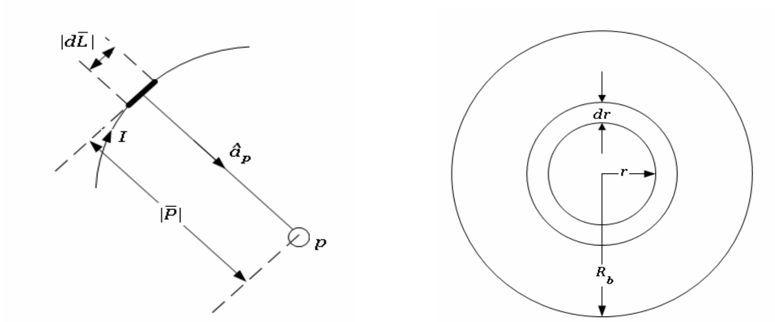


Figure 2: (a) Current (I) passing through a wire, (b) billet cross section

In modelling billet heating, the billet is assumed to be made of a large number of closed conducting paths as shown in fig. 2b. Since alternating current in the coil induces an alternating magnetic field within the billet, it produces eddy currents in each closed conducting path and correspondingly heats by Joule effects. The magnetic flux density on an elemental closed conducting path of length 2πr, using Biot-Savart law, for a single coil turn [8, 9] is given as

$$B_n = B_{\max} \sin \omega t \tag{3}$$

where B_n is magnetic flux density for the *nth* turn of the coil

and $B_{\max} = \dfrac{\mu I_{eff} \, R_c \left(R_c - r\right)}{\sqrt{2}\left[\left\{(n-1)CS - z\right\}^2 + \left(R_c - r\right)^2\right]^{\frac{3}{2}}}$. The total flux density for N turns of the coil is given as

$$B_{total} = \sum_{1}^{N} B_n \tag{4}$$

In equation (3), $CS = L/(N-1)$, R_c is coil distance from billet center, $\omega = 2\pi f$ where f is frequency, I_{eff} is the amplitude of the supply current and t is the time. This alternating magnetic field is parallel to axis of the billet. The magnetic flux [9] enclosed by the elemental circular path of radius r, radial width dr and height dz (as shown in fig. 2b) at any instant is $\pi r^2 B_{total}$ .Thus, the emf induced in the elemental path [9], based on Faraday's Law, is given as

$$e = \frac{d}{dt}\left(\pi r^2 B_{total}\right) = 2\pi^2 r^2 f \sum_{1}^{N} B_{\max} \cos \omega t \tag{5}$$

and the corresponding root mean square value, e_{rms}, is $\sqrt{2}\pi^2 r^2 f \sum_{1}^{N} B_{\max}$.

The resistance of the elemental closed path is $R_r = \alpha \dfrac{2\pi r}{dr\,dz}$. Hence, the root mean square value of eddy current in the elemental path is

$$I_r = k_i \frac{\pi r f \sum_{1}^{N} B_{\max}\, dr\,dz}{\sqrt{2}\alpha} \tag{6}$$

where k_i is correction factor and α is specific resistance of the billet. The calculated I_r is compared with the works of Kang *et al*. [4] and Milind *et al*. [10], which gives k_i = 0.551. Therefore, the volumetric eddy current loss equivalent to volumetric heat generation (Q) is given as

$$Q = \frac{I_r^2 R_r}{2\pi\, r dr dz} = k_i^2 \frac{\pi^2 r^2 f^2 \left[\sum_{1}^{N} B_{\max}\right]^2}{2\alpha} \tag{7}$$

Boundary conditions

At the left face, an axisymmetric condition is used. At the right, top and bottom faces, convective and radiative boundary conditions are applied.

Results and discussion

The present model is validated with experimental and analytical work by Choi *et al*. [7] where a cylindrical A356 alloy billet of 75 mm diameter and 50 mm length was considered. The predicted temperature variation with time at middle of outer surface is plotted in fig. 3a. The figure shows that the present prediction agrees well with the analytical and experimental results. In the present model, however, phase change during heating is not considered. Thereafter, the model is used to study temperature distribution during heating of A356 cylindrical billet of 90 mm diameter. Fig. 4a shows temperature distribution in the computational domain after 1100s of induction heating with 200A supply current at 5 kHz frequency. Here, the heating coil is considered to have six equally spaced turns (d=10mm). As magnetic flux density on the area near the coil is higher than the inside area (see fig. 4b), heating effect is more near the outer surface, resulting in higher temperature at the periphery of the billet, compared to the center. Fig.4a also shows that temperature is less at the top and bottom surfaces, because of convection and radiation heat loss. During heating, the temperature evolution at the surface and at the center of the billet is shown in fig.3b. The difference in temperature between the center and outer surfaces can be attributed to non-uniformity of magnetic flux density distribution, as reported in Choi *et al*. [7].

The induced magnetic flux density depends mainly on frequency and density of supply currents. The effect of frequency on temperature evolution during heating is shown in fig. 5a. The simulation is performed for 200A power supply and variable frequency, with six equally spaced turns of the coil. The average temperature of the domain increases significantly with increasing frequency. During processing, to reach a temperature in the semisolid range, it takes longer time when billet is heated at low frequency. As an example, the billet reaches a temperature of 600°C at 1085s (t_2) when it is heated at 5 kHz frequency whereas it takes 490s (t_1) when the billet is heated at 6 kHz frequency. The heating process also depends on current density; correspondingly computation is performed for various current densities (for f =3 kHz). The current density is changed by increasing the amplitude of current. Fig. 5b shows the variation of average temperature evolution with heating time at various amplitude of supply current (d=10mm). The billet is heated faster with increasing current density. The billet reaches a temperature of 600°C at 720s (t_2) when it is heated at 400A supply current whereas it takes 300s (t_1) when the billet is heated at 500A supply current.

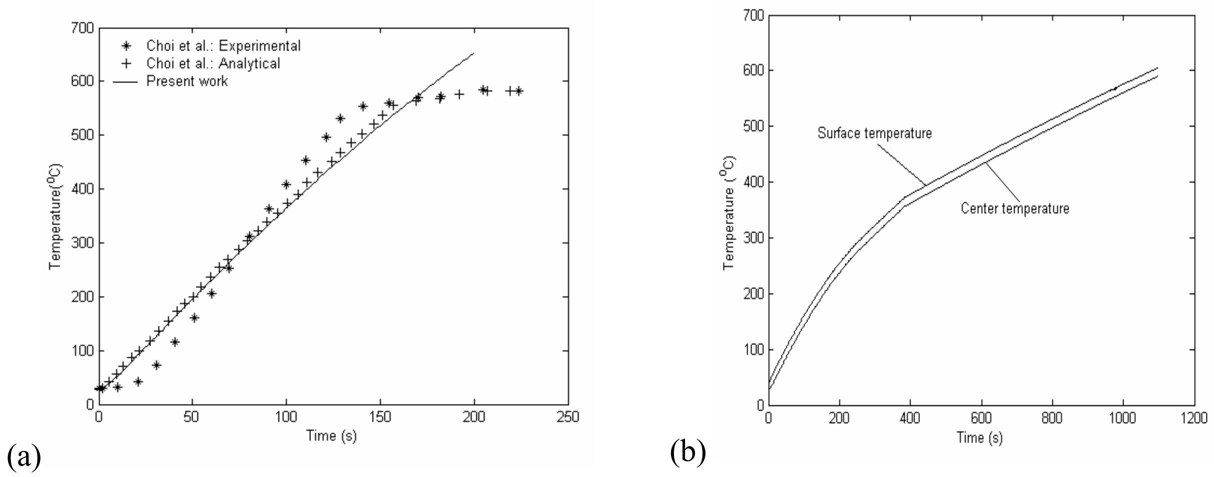


Figure 3: (a) Temperature rise with time on outer surface of billet, (b) Variation of temperature with heating time at center and outer surface of billet for *f = 5 kHz* and *I=200 A*, *N= 6*

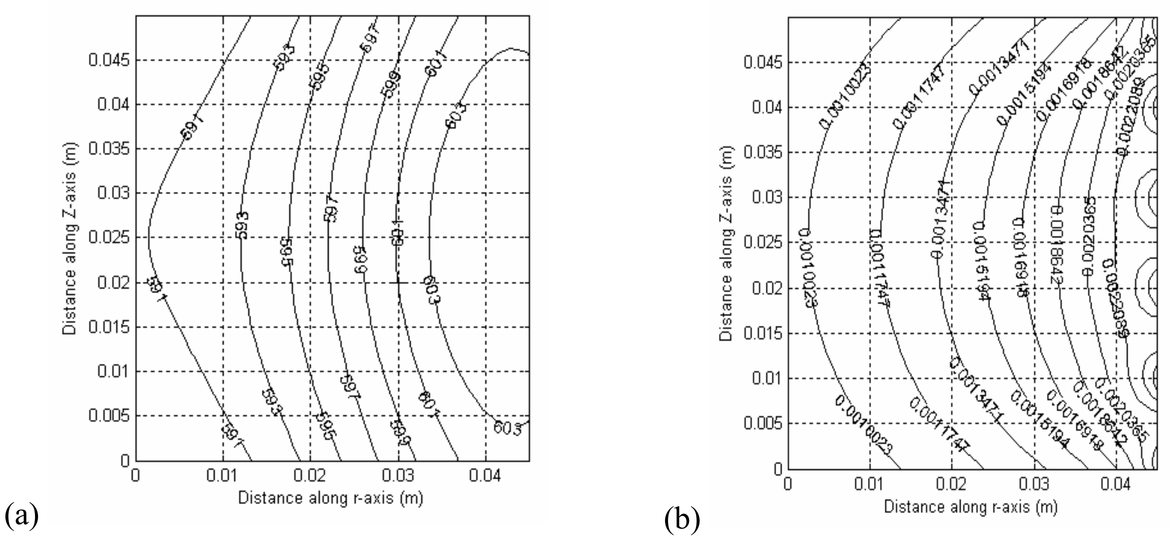


Figure 4: (a) Temperature distribution for *f = 5 kHz* and *I=200 A*, *N= 6* at *t = 1100 s*, (b) corresponding magnetic flux density distribution

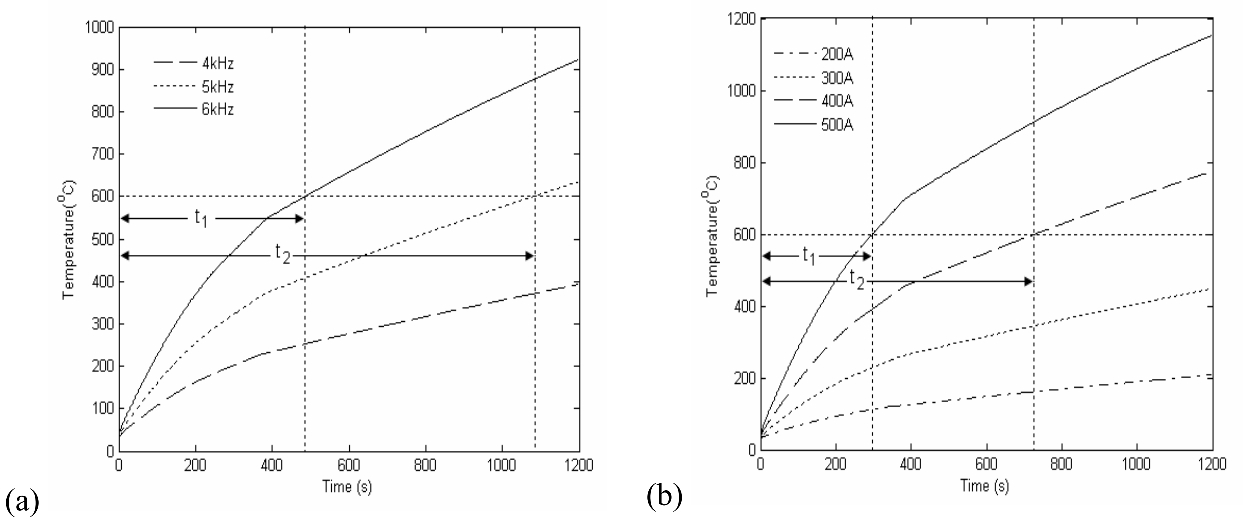
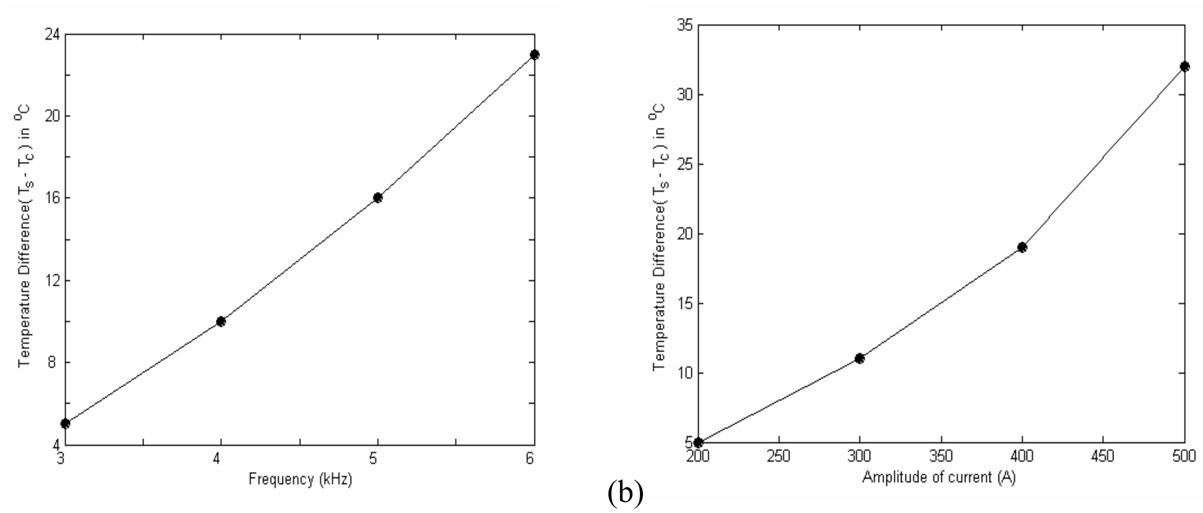


Figure 5: Variation of temperature with time (a) for various frequency of supply current (200A), (b) for various amplitude of supply current (f=3kHz)

In Fig.6, temperature difference between surface and center of the billet is shown. The difference in temperature increases with frequency as well as density of supply current. Hence, uniform temperature distribution can be achieved at low frequency as well as low magnitude of supply current.



(a) (b)

Figure 6: Temperature difference between surface and center of billet at t = 700 s (a) for various frequency of supply current, (b) for various amplitude of supply current

Conclusions

The present work predicts numerically magnetic flux density and temperature distribution during induction heating of a cylindrical A356 alloy billet. It is found that the temperature slope increases significantly with frequency as well as supply current density. It is also concluded that nearly uniform distribution of temperature can be achieved when the billet is heated slowly with low frequency and low supply current density.

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