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Numerical study of titanium melting by high frequency inductive heating

Liangliang Lu [a,b], Shaoming Zhang [a], Jun Xu [a], Huijun He [c], Xinming Zhao [a,*]

[a] General Research Institute for Non-ferrous Metals, Beijing 100088, China
[b] University of Science and Technology Beijing, Beijing 100083, China
[c] Beijing COMPO Advanced Technology Co. Ltd, Beijing 101407, China

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ABSTRACT

High frequency induction heating process of titanium wire is investigated numerically and experimentally. The electromagnetic thermal and fluid fields during high frequency induction heating process are calculated. The effects of current frequency and current value of coil on the thermal and flow fields are numerically studied. The change of the applied current has profounder influence on the melting rate than the change of current frequency did. The simulation results are verified by experiments, and good agreement with simulation. With the ability to observe temperature distribution in titanium wire during high frequency induction heating, the numerical simulation method is demonstrated to be a cost-effective tool in predicting the process of high frequency induction heating of titanium wire.

1. Introduction

High-quality titanium powders by gas atomization is applied in novel near-net shape process, such as Metal Injection Moulding (MIM), Additive Manufacturing (AM) [1–3]. The production of titanium materials is used for aerospace, biomedical, automotive and other applications [4,5]. Titanium is typically reactive and high melting metal. In order to avoiding contamination, Induction Skull Melting and Non-crucible technique are used to melt titanium alloys [6,7]. Wire induction heating gas atomization (WIGA) is a crucible free technique for powder manufacturing by gas atomization, the technique has found application in production of titanium alloy powder by gas atomization.

The induction melting titanium wire process is complex, involving electromagnetic field, temperature field and flow field. The parameter of the induction heating titanium process usually has been studied by numerical simulation and experimental method, compared with the experimental method, numerical simulation can study physics fields directly and accurately, many researchers have studied by the numerical simulation method. Bojarevics et al. [8] developed a numerical model of electrode induction melting gas atomization (EIGA) and investigated the complex interaction of the electromagnetic and thermal fields on the fluid flow with free surface. Kranjc et al. [9] used the finite element method to investigate coupled electromagnetic and thermal physical phenomena in induction heating process of steel materials. Pericleous [10] investigated the electromagnetic stirring phenomenon and temperature field during induction skull melting (ISM) process of Ti-Al alloys by the method of finite volume (FV) and spectral CFD. Cho [11] presented a coupled electromagnetic and thermal model for numerical analysis of an induction heating system including the workpieces moving relative to the inductors. Jankowski et al. [12] presented an approximate analytical solution for induction heating of non-magnetic cylinders by a cylindrical induction coil. In this paper, the process of induction heating of titanium wire was described and investigated both numerically and experimentally.

2. Numerical model description

Two-dimensional and three-dimensional axisymmetric geometries were shown in Fig. 1. The workpiece in our study was titanium wires material with given velocity, and placed in the middle of symmetric induction heating coil with three turns. The shape of the titanium wires was cylinder with 20 mm in height and 1.5 mm in radius, all the physical dimensions were given in Table 1.

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* Corresponding author.
E-mail addresses: zyfrg2008@163.com (L. Lu), xinming_zhao@126.com (X. Zhao).

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Nomenclature

H	magnetic field strength ($A\ m^{-1}$)
J	current density ($A\ m^{-2}$)
B	magnetic flux density (T)
A	magnetic potential vector ($Wb\ m^{-1}$)
E	electric field intensity ($N\ C^{-1}$)
D	electric flux density ($C\ m^{-2}$)
Q_e	heat power by eddy currents ($W\ m^{-3}$)
n	normal direction
C_p	heat capacity at constant pressure ($J\ Kg^{-1}\ K^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
L	latent heat ($KJ\ Kg^{-1}$)
q_r	energy losses by radiation (W)
T_{amb}	temperature of ambient (K)
u	velocity ($m\ s^{-1}$)
g	gravity vector ($m\ s^{-2}$)
F_{st}	surface tension (N)
t	times (s)

Greek letters

ω	angular frequency ($rad\ s^{-1}$)
ε	electric permittivity ($C^2\ N^{-1}\ m^2$)
μ	magnetic permeability ($T\ m\ A^{-1}$)
ρ	density of workpiece ($kg\ m^{-3}$)
$\boldsymbol{\mu}$	dynamic viscosity ($N\ s\ m^{-2}$)

Subscripts

e	eddy current
p	pressure
r	radiation
amb	ambient
st	surface tension

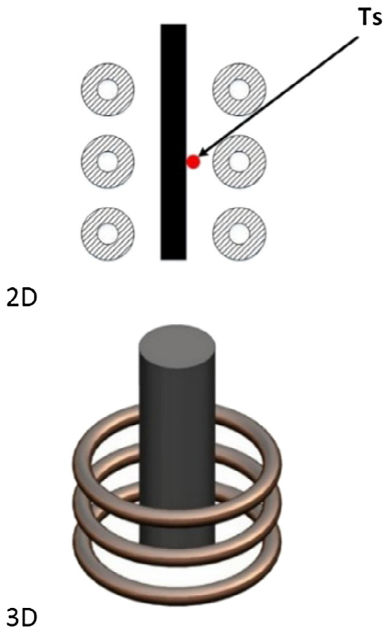

Fig. 1. Two-dimensional and three-dimensional model geometry.

Table 1
Physical dimensions.

Item	Parameter	Units
Workpiece material	Titanium	
Workpiece dimension	Wire (1.5(r) × 20(L))	mm
Workpiece shape	Cylinder	
Coil material	Copper	
Coil number of turns	3	
Coil inner radius	$r_i = 1$	mm
Coil outer radius	$r_o = 2$	mm
Coil radius	R = 16	mm
Initial temperature	$T_o = 25$	°C
Calculation domain 1	40(W) × 40(H)	mm^2
Calculation domain 2	5(W) × 15(H)	mm^2

In the paper, we consider that the thermo-physical and physical properties of the titanium materials used in this calculation, i.e. electrical resistivity, electrical conductivity, thermal conductivity, specific heat, liquid viscosity may be dependent on temperature, the properties were calculated by the JMatPro software, as illustrated in Fig. 2. Numerical calculations were performed with commercial finite element software package COMSOL Multiphysics 5.0. The mesh of the numerical model consisted of 15,493 triangular elements.

2.1. Electromagnetic field

The electromagnetic phenomena under consideration are governed by Maxwell equations [13]. The electromagnetic field is calculated by the Maxwell equations to predict the generated heat power by induction heating [14]. The Maxwell equations can be simply described by a quasi-steady state approximation as followed:

$$\nabla \times H = J \tag{1}$$

$$B = \nabla \times A \tag{2}$$

$$E = -j\omega A \tag{3}$$

$$J = \sigma E + j\omega D \tag{4}$$

where j is the complex number defined by $j^2 = -1$, Electromagnetic field constitutive equations are as followed:

$$D = \varepsilon E \tag{5}$$

$$B = \mu H \tag{6}$$

where $\varepsilon = \varepsilon_r \varepsilon_o$ is the electric permittivity ($C^2\ N^{-1}\ m^{-2}$), ε_r is the relative electric permittivity, $\varepsilon_o = 8.854 \times 10^{-12}$ ($C^2\ N^{-1}\ m^{-2}$) is the permittivity of free space, $\mu = \mu_r \mu_o$ is the magnetic permeability ($T\ m\ A^{-1}$), μ_r is the relative magnetic permeability, $\mu_o = 4\pi \times 10^{-7}$ ($T\ m\ A^{-1}$) is the permeability of free space,. From the above equations, the governing equation could be derived as followed:

$$Q_e = \frac{1}{2} R_e (J \cdot E^*) \tag{7}$$

The electromagnetic heat source Q_e is caused by the eddy currents.

The boundary conditions for electromagnetic model are shown in Fig. 3(a). The workpiece and the coil is surrounded with air enclosed in calculation domain 1 with magnetic insulation condition applied on its boundaries, which makes the normal component of the magnetic field zero, a boundary condition that sets