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Influence of coil geometry on the induction heating process in crystal growth systems

M.H. Tavakoli *, A. Ojaghi, E. Mohammadi-Manesh, M. Mansour

Physics Department, Bu-Ali Sina University, Hamedan 65174, Iran

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Different shapes and orientations of the RF-coil turns in oxide Czochralski crystal growth systems are considered and corresponding results of electromagnetic field and volumetric heat generation have been computed using a finite element method. For the calculations, the eddy current in the induction coil (i.e. the self-inductance effect) has been taken into account. The calculation results show the importance of cross section shape, geometry and position of the RF-coil turns with respect to the crucible and afterheater on the heat generation distribution in a Czochralski growth system.

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1. Introduction

The principle of induction heating is widely applied to produce the required thermal power in several crystal growth systems. In a basic radiofrequency inductive heating setup such as Czochralski (CZ) furnace in [1, Fig. 1], a solid state RF-power supply sends an alternative electric current through an induction coil (inductor). The part to be heated (i.e. crucible and active afterheater) is placed inside the coil and circulating eddy currents are induced within the metallic parts. These currents flow against the electrical resistivity of the metal, generating precisely localized heat.

Coil design is one of the most important aspects of an inductive heating system [2,3]. A well-designed coil maintains the proper heating pattern and production rate, and maximizes the efficiency of the induction heating power supply. Because the heating pattern reflects the inductor geometry, coil shape is probably the most important of these factors. Induction coils are normally made of copper tubing—an extremely good conductor of heat and electricity—and can have single or multiple turns with a helical, round or square shape. RF-coils are usually cooled by circulating water, and are most often custom-made to fit the shape and size of the crucible.

Most induction heating systems have been designed based on experience and trial-and-error process. These traditional methods for induction coil and process design are time consuming and expensive due to having to manufacture and modify several inductors. These methods are also limited in what cases they can be applied to. These traditional methods do not provide the developer with a good understanding of what is going on in a given induction heating system or information on why a given induction system worked or did not work properly. Finally, this experience stays with the developer and there is no good record left behind for future process designers.

Computer simulation has none of the limitations attached to the old methods of system design. Induction heating processes can be modeled and optimized virtually without even requiring experimental verification for processes where the material response and properties are known. Computer simulation provides induction process designers with a wealth of information on the system dynamics. It also can be used to explain, demonstrate and predict the process sensitivity to changes of an induction system.

A successful growth of perfect single crystals requires a balance of energy production as well as heat and mass transport through the setup, because the quality of a grown crystal is

*Corresponding author. Tel.: +98 811 8210424; fax: +98 811 8280440.
E-mail address: mht@basu.ac.ir (M.H. Tavakoli).

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directly related to its thermal history and the transport phenomena in the furnace. The heat transfer processes in crystal growth systems are quite sensitive to the geometry of the furnace, heat generation and orientation of the coil-crucible-afterheater-insulation [4–6]. Therefore, modeling of heat generation as well as heat and mass transfer processes is necessary for achieving a complete knowledge of the growth process in order to improve the quality of the grown crystals [1,7,8].

The goal of this article is to reveal the role of RF-coil geometry on the induction heating process in an oxide Czochralski system and compare the corresponding results of electromagnetic field and heat generation distribution using a 2D FEM numerical approach. In our previous study [1], attention was paid to the effect of an active afterheater and its position with respect to the crucible on the heat generation in this system. But in the analysis presented here, the shape and location of the crucible and afterheater are fixed and different coil geometries and styles, i.e. cross section shape, radius and distance between the coil turns are considered corresponding to the real growth situations.

Our challenge is to extend the fundamental understanding of induction heating process used for crystal growth technology, because this understanding will enable the growers to optimize existing procedures, growth new crystals and design new growth methods.

2. Mathematical model

2.1. Governing equations

The mathematical model of induction heating process applied for the calculations have been described in detail elsewhere [1]. It can be summarized as follow. The assumptions are: (1) the system is axi-symmetric, (2) all materials are isotropic and non-magnetic and have no net electric charge, (3) the displacement current is neglected, (4) the distribution of electrical current (also voltage) in the RF-coil is uniform and (5) the self-inductance effect in the RF-coil is taken into account. Under these assumptions, the governing equations are

$$\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Psi_B}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{1}{r}\frac{\partial \Psi_B}{\partial z}\right) = \mu_0 J \tag{1}$$

where

$$J = \begin{cases} J_0 \cos \omega t - \dfrac{\sigma_c}{r}\dfrac{\partial \Psi_B}{\partial t} & \text{driving and eddy current in the coil} \\ -\dfrac{\sigma_c}{r}\dfrac{\partial \Psi_B}{\partial t} & \text{eddy current in the conductors} \end{cases} \tag{2}$$

with a solution of the form

$$\Psi_B(r,z,t) = C(r,z)\cos \omega t + S(r,z)\sin \omega t \tag{3}$$

and

$$q(r,z) = \begin{cases} \dfrac{\sigma_{co}\omega^2}{2r^2}\left[C^2 + \left(\dfrac{J_0 r}{\sigma_{co}\omega} - S\right)^2\right] & \text{in the RF-coil} \\ \dfrac{\sigma_c \omega^2}{2r^2}(C^2 + S^2) & \text{in the conductors} \end{cases} \tag{4}$$

where $\Psi_B(r,z,t)$ is the magnetic stream function, $C(r,z)$ and $S(r,z)$ the in-phase and out-of-phase component, respectively, $q(r,z)$ the volumetric power generation in the metallic crucible and afterheater, ω the frequency of the electrical current in the induction coil, J the charge current density, σ_c the electrical conductivity, μ_0 the magnetic permeability of free space and t the time. The driving current density in the induction coil is calculated by $J_0 = \sigma_{co}V_{coil}/(2\pi R_{co}N)$, where V_{coil} is the total voltage of the coil, R_{co} is the mean value of the coil radius and N is the number of coil turns. The boundary conditions are $\Psi_B = 0$; both in the far field $(r, z \to \infty)$ and at the axis of symmetry $(r = 0)$.

The set of fundamental equations with boundary conditions have been solved using the finite element method.

2.2. The calculation conditions

Values of electrical conductivity employed for our calculations are presented in [1] and operating parameters are listed in Table 1. The induction coil has two parts with $6+2$ hollow copper turns, respectively. In order to compare the results of electromagnetic field and heat generation distribution, we have assumed a driving electrical current with total voltage of $V_{coil} = 200\,\text{V}$ and a frequency of 10 kHz in the RF-coil (typical values) for all cases. The results based on this set of parameters will be presented now.

3. Results and discussion

We explain the results of electromagnetic field and heat generation distribution in an oxide CZ setup including crucible and active afterheater corresponding to an often used growth situation. The obtained results are presented in the following sections, starting with different cross section shapes of the coil turns and then different radii and turns' number of the RF-coil.

3.1. Cross section shapes of the coil turns

In the first section, we have considered three cross section shapes for the coil turns: rectangular, shielded rectangular and circular with unique height and wall thickness (Fig. 1). Fig. 2 shows the distribution of in-phase component (right hand side) and out-of-phase component (left hand side) of the magnetic stream function (Ψ_B) for the rectangular cross section. The maximum of in-phase component (C) is located at the lowest and top edges of the RF-coil ($C_{max} = 1.89 \times 10^{-6}$ Wb) while the minimum ($C_{min} = -8.13 \times 10^{-6}$ Wb) is located on the middle part of the crucible side wall. Variation of this component is too high in the area close to the maximum and minimum points. In other parts of the system, this component is nearly constant. For the out-of-phase component (S), the maximum is located at the outer surfaces of the induction coil turns ($S_{max} = 6.80 \times 10^{-5}$ Wb) and its intensity rapidly decreases towards the crucible and afterheater wall. The S-field distribution has a linear gradient in the space between the coil and the crucible and afterheater side wall. The intensity of S_{max} is 8 times greater than C_{min} (absolute value). The expulsion of the C-field component from the RF-coil

Table 1
Operating parameters used for calculations.

Description (units)	Symbol	Value
Crucible inner radius (mm)	r_c	50
Crucible wall thickness (mm)	l_c	2
Crucible inner height (mm)	h_c	100
Afterheater inner height (mm)	h_{af}	100
Afterheater hole (mm)	r_{af}	10
Distance between the crucible and afterheater (mm)	D_{ca}	30
Coil inner radius (mm)	r_{co}	78
Coil width (mm)	l_{co}	13
Coil wall thickness (mm)	l_{co}	1.5
Height of coil turns (mm)	h_{co}	20
Distance between coil turns (mm)	d_{co}	3
Distance between two coils (mm)	D_{co}	55

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