Journal of Crystal Growth 311 (2009) 4281–4288

Contents lists available at ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/jcrysgro

Influence of crucible geometry and position on the induction heating process in crystal growth systems

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ARTICLE INFO

Article history:
Received 3 April 2009
Accepted 3 July 2009
Communicated by A.G. Ostrogorsky
Available online 15 July 2009

PACS:
02.60.Cb
02.70.Dh
41.20.−q
81.10.Fq

Keywords:
A1. Computer simulation
A1. Induction heating
A2. Czochralski method
B1. Oxides

ABSTRACT

A series of 2D finite element numerical simulations of induction heating process for an oxide Czochralski crystal growth system has been done for different shapes and locations of a metal crucible. Comparison between the computational results shows the importance of crucible shape, geometry and its position with respect to the RF-coil on the electromagnetic field and heat generation distribution in the growth setup.

1. Introduction

Radio frequency induction heating is the dominant heating method for growing refractory oxide crystals by Czochralski (CZ) method whose melting points are above 1000 °C. A CZ induction heating installation has three important parts: the electrical power source for generation of high-frequency energy, the work coil (RF-coil) and the workpiece (metallic crucible) where the final transfer of the electrical energy into required heat occurred. The RF-coil must establish suitable electromagnetic flux lines in the crucible and this field must be powerful enough to do the job, i.e. to melt the crystal material.

In crystal growth procedure, the crystal quality directly depends on its thermal history and temperature field of the furnace. Thermal history is related directly to the setup geometry such as shape and orientation of the coil–crucible–afterheater insulation [1–3]. In this aspect, the amount of power as well as its spatial distribution in the crucible and active afterheater are the major parameters to be determined. Understanding the physics of these properties is quite important when designing growth heating systems.

In the previous papers [4,5] we studied the role of active afterheater and RF-coil geometry on the induction heating process in an oxide Czochralski system. In this article, we try to investigate the effects of the crucible geometry and location on the spatial and strength of heat generation distribution in the setup. To do it, different crucible shapes and styles, i.e. without and with a baffle, with a bottom heater, thick and rounded bottom corner and also different position with respect to the induction coil are considered corresponding to the real growth situations.

2. Mathematical model

Due to the complex nature of the induction heating process we apply a mathematical model for numerical calculation which has been described in detail elsewhere [4–6]. It can be summarized as follows. The assumptions are: (1) the system is axi-symmetric, (2) all materials are isotropic, 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, (5) the self-inductance effect in the RF-coil is taken into account and (6) the currents (impressed and induced) have a steady state quality and as a result the electromagnetic field quantities are harmonically oscillating functions with a single frequency. Under these assumptions, the governing

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doi:10.1016/j.jcrysgro.2009.07.013

equations are

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

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
Baffle inner radius (mm)	r_b	35
Bottom heater height (mm)	h_{bh}	50
Height of the thick bottom (mm)	h_{tb}	10
Radius of the round bottom corner (mm)	r_{cb}	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
Current frequency of RF-coil (kHz)	f	10
Total voltage of the RF-coil (V)	V_{coil}	200

where

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

with a solution of the form

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

and

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

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 components, respectively, $q(r,z)$ the volumetric power generation in the metallic crucible, ω the frequency of the electrical current in the induction coil, J the charge current density, σ_c the electrical conductivity, μ_0 the

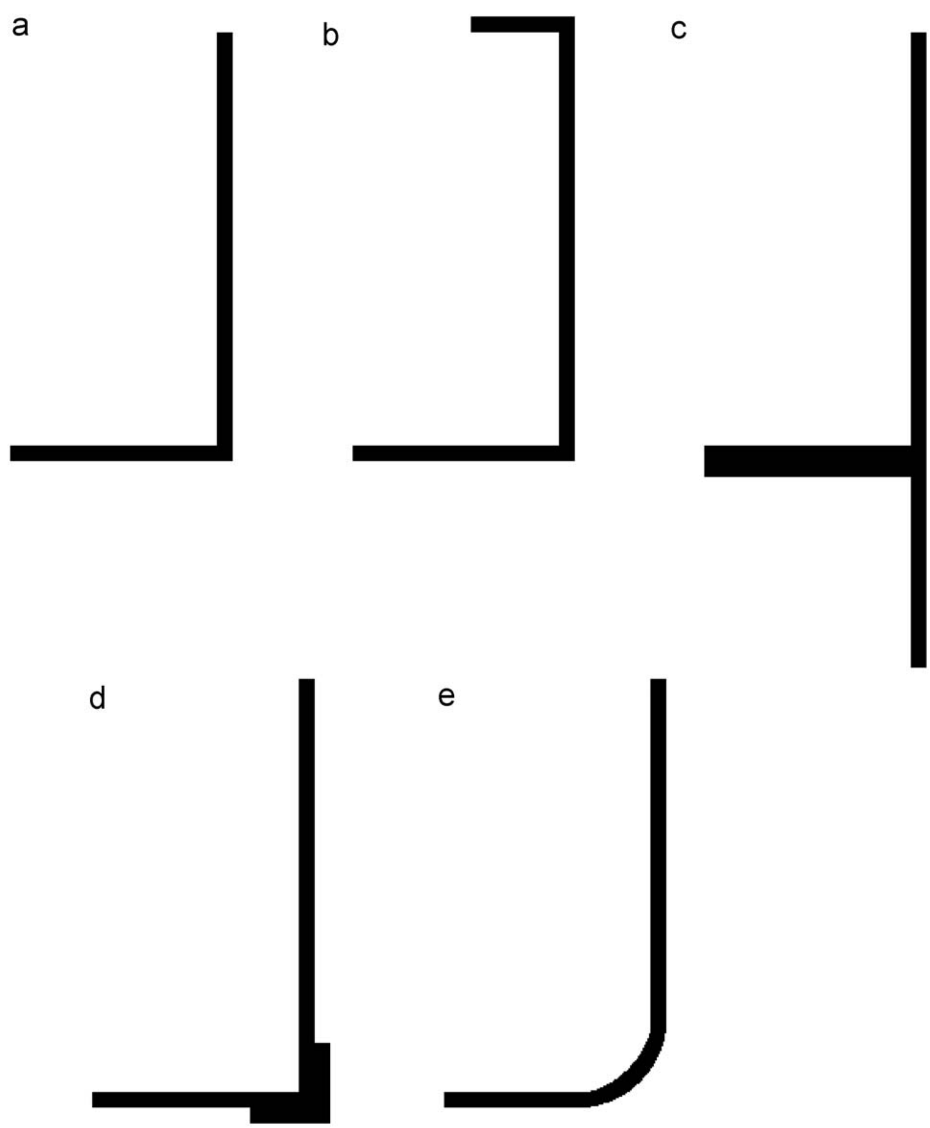

Fig. 1. Different shapes of the CZ metal crucible: (a) simple cylindrical, (b) with a baffle, (c) with a bottom heater, (d) with a thick bottom corner and (e) with a round bottom corner with unique height and thickness.