Applied Thermal Engineering 102 (2016) 149–157

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Inductive heating with a stepped diameter crucible

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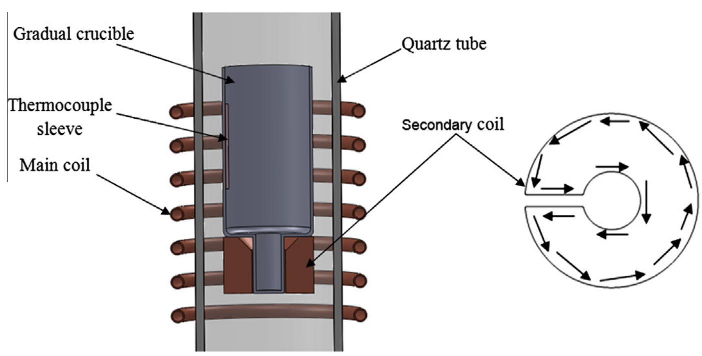
HIGHLIGHTS

- We present a novel solution for vacuum inductive heating of a gradual crucible.
- A numerical model was built to estimate the temperature gradient in the crucible.
- The method was validated with an experimental inductive furnace setup.
- The solution was shown enable to use in gradual diameter crucible.

GRAPHICAL ABSTRACT

Stepped diameter crucible with SHC. On the right, a section of the SHC is shown with current flow.



ARTICLE INFO

Article history:
Received 29 September 2015
Accepted 28 March 2016
Available online 31 March 2016

Keywords:
Inductive heating
Stepped diameter crucible
Variable diameter crucible
Secondary coil

ABSTRACT

Induced heating in a vacuum environment is the most common method for high precision and purity casting. A significant disadvantage in this process is that it is designed for heating in a crucible of uniform diameter. However, it is not suited for the heating of a crucible with stepped diameter. The use of a variable diameter crucible enables to place a larger amount of raw material into the wider diameter section of the crucible. After the material melts, the liquid fills the narrow part of the crucible and enables better control of liquid flow into the casting mold. Hence, in this research we present a novel solution for vacuum inductive heating in a stepped diameter crucible by using a secondary heating coil (SHC). In order to examine the SHC solution, numerical models were developed to describe the temperature distribution and the heat generation in the crucible. Experiments on a vacuum induction furnace were conducted to validate the numerical models of the SHC. A good match was acquired between the numerical and experimental results. The results of the simulations and experiments have shown great improvement in the capability of heating a stepped diameter crucible with an SHC.

1. Introduction

Induction heating process is widely applied in industrial operations such as thermal treatment [1], precision hardening [2] for parts with complex geometry and metal casting [3]. The dynamics of induction heating is described by Maxwell's equations. An alternating current in a coil produces a time-varying magnetic field in its surroundings with equal frequency to the coil current. This magnetic field causes eddy currents on the surface of the workpiece, located inside the coil. The resultant eddy currents are opposite in direction to the coil current, as due to the Lenz's law. The eddy currents heat the conductor according to the Joule effect.

Induction heating is a complex combination of electromagnetic and heat transfer phenomena. The design of an induction heating

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http://dx.doi.org/10.1016/j.applthermaleng.2016.03.151
1359-4311/

system has to be optimized for each application and requires a complicated analysis. Most of the analytical models were obtained for simple form [4,5]. The first of the numerical techniques to be widely used for electro-heating problems was finite difference, and the method is still used today in certain applications [6–8].

Induced heating in a vacuum environment has become more popular for high precision and purity casting. In this method a crucible is made of material with high melting temperature, such as Molybdenum and Graphite. The induced electric field generates vortex currents in the crucible and heats it to melt the alloy inside. The alloys in the casting industry come in the form of bars and plates such that the dimensions of the crucible limit the amount of raw material able to be inserted into the crucible. Therefore, there is a need to reshape the raw material to fit into the crucible (Fig. 1). The use of a stepped diameter crucible enables placing a larger amount of material into the wider region part of the crucible. After the material melts, the liquid fills the narrow part of the crucible and enables better control of liquid flow into the casting mold. A significant disadvantage of vacuum induction heating is that it is suitable for heating uniform diameter crucibles, and not stepped diameter ones. This disadvantage is most significant when the induction coil is placed outside of the heating zone. In this configuration the current flow is in the opposite direction of the coil current by Faraday's law, therefore the eddy current will be concentrated in the large diameter. Hence, the heating mechanisms of the narrow diameter are radiation and conduction from the large diameter and not by Joule effect. As a result, the temperature in the crucible's bottom is low. To prevent solidification, it is required to increase the temperature of the crucible in the large diameter [9]. Higher temperature requires an expensive crucible material and may cause increase in the amount of pollutants in the casting material.

Dhakal et al. [10] presented an induction furnace cavity for heat treatment of high purity niobium in this furnace, the niobium susceptor can is inductively heated and heat is transferred to the Niobium cavity by radiation. Another approach is to change the magnetic field density by changing the coil geometry [11]. Tudbury [12] offered the combination of two coils; in this case the current in the narrow diameter coil will be greater than in the wide diameter coil, such that the difference in magnetic flux compensates for the change in geometry. A similar idea is presented in Zinn and Semiatin [13]. It is recommended to change the density of the coil to compensate the change in the geometry of the model. These solutions are especially suitable for gradual changes in geometry and not for sharp drops in diameter as described in Fig. 1.

Another method uses a cold crucible [14–16]. A water-cooled crucible is made from copper segments. An induction coil is wrapped around the crucible. The induced currents produced in each of the sectors make the cold crucible act as SHC while the induction coil acts as primary coil. This method is effective but a leak of water into the oven can cause steam explosion, and is therefore not preferred.

A solution for heating of small parts in large induction coil by means of an "insert" is presented in [17]. The operating principle is an alternating current within the induction coil, which induces the eddy current flowing within the insert in the opposite direction. However, the slot within the insert breaks the eddy current flow, forcing it to complete a loop on the internal surface of the insert. Current flow on the inside surface of the insert creates a magnetic field of its own, which, in turn induces a current within the workpiece.

The present study uses a SHC for heating a stepped crucible, as illustrate in Fig. 1. Experimental and numerical study is conducted. The prediction of the developed model is validated with the experimental data.

2. Experimental setup

An induction furnace experimental setup was designed and built to validate the numerical model. The system shown in Fig. 2 is designed for high vacuum and a temperature of 1100 °C. A 304 L stainless steel stepped crucible with 36 g of tin in its bottom was placed in the furnace. An additional thermal insulation is obtained with an alumina cylinder surrounding the crucible. The vacuum chamber is a quartz tube sealed with a water cooled flange. Radiation shields in the top of the furnace decrease heat losses. A rotor pump is used to evacuate the inside chamber to a pressure of 10^{-3} mbar. Temperature measurements are conducted with K-type thermocouples. Accuracy of the K-type thermocouples was approximately 0.2%. One thermocouple is placed within the tin material and the second is mounted on the side of the crucible. The experiments were conducted both with and without the secondary coil. The induction power in the furnace was 1.1–1.2 kW with AC frequency of 8800 Hz. The temperature of the cooling water was 25 °C.

3. Governing equations

3.1. Electromagnetic fields

The Maxwell's equations in differential form which describe electromagnetic field is written as [18]:

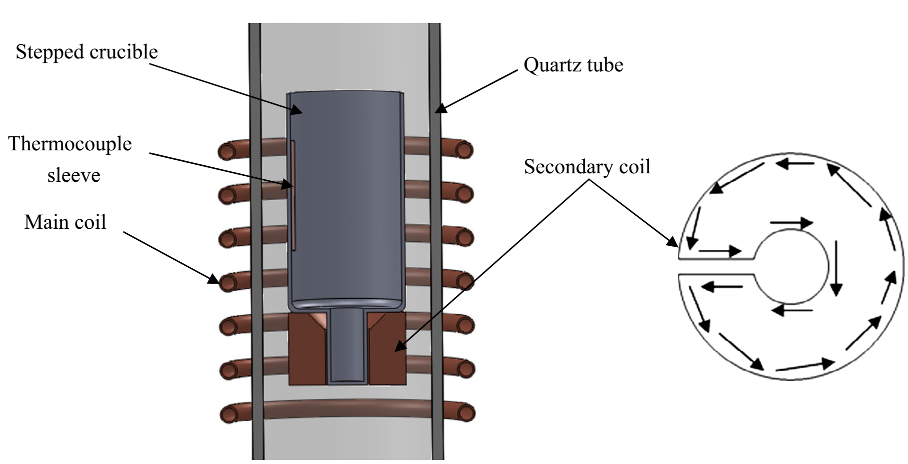

Fig. 1. Stepped diameter crucible with SHC. On the right, a section of the SHC is shown with current flow.