XXI Symposium
Electromagnetic Phenomena in Nonlinear Circuits
June 29 - July 2, 2010, Dortmund and Essen, Germany

Investigation of the Skull Melting Method for the Generation of Particulate Material of Inorganic Compounds

Björn Riemer, Enno Lange, Kay Hameyer

RWTH Aachen University, Institute of Electrical Machines
Schinkelstraße 4, 52056 Aachen, Germany, e-mail: bjoern.riemer@iem.rwth-aachen.de

Abstract - **The Skull melting method is an inductive heating process, which can exceed temperatures of 3000 K within a pure melt. This paper presents the application of the Skull melting method to inorganic compounds for the generation of particulate material. The induced power inside the heating material is calculated by an one dimensional model. Thermal losses are analyzed with respect to the crucible radius. Finally, a method for a coupled electromagnetic thermal field calculation is presented.**

I. INTRODUCTION

For a safety-related evaluation of atomic reactor perturbations, the behavior of resulting particulate material is of special importance. For an artificial generation of this particulate material the application of the Skull melting method to different inorganic target material compounds like CsOH, NaOH, SnO_2 and UO_2 has to be investigated.

Skull melting is a quasi crucible free inductive heating method where the heating material is charged inside a cylindrical water cooled copper crucible, which is surrounded by a water cooled high frequency coil [1]. The coil is driven by current up to a frequency of about 2 MHz. Due to the resulting magnetic field, eddy currents are induced within the target material. As a result of the eddy currents, the heating process is activated due to ohmic losses. An increasing electrical conductivity of the target material with increasing temperature is essential for a successful Skull melting process. During the heating process a sinter crust is generated at the cool crucible wall and on top of the melt. This sinter crust insolates the crucible to the high temperature of the melt and shields the melt from a contamination by possible impurities of the crucible.

The advantages of the Skull melting method are the purity of the melt and the possibility to heat materials up to temperatures above 3000 K.

To investigate the applicability of the Skull melting method to the materials mentioned above, the process is analyzed analytically. Based on the specification of the material parameters, the electromagnetic induced power inside the heating material is calculated. Thermal losses due to radiation and convection are analyzed with respect to the crucible radius. Finally, a method for the coupling of the electromagnetic and thermal field calculation is presented.

II. ANALYSIS OF A SKULL MELTING PROCESS

A. Material properties

The electromagnetic field calculation of the Skull melting process requires the knowledge of the relative permeability $\mu_r(\vartheta)$ and the electrical conductivity $\sigma(\vartheta)$ over the whole temperature range up to the boiling point. As the materials under consideration do not contain any ferromagnetic components, the relative permeability is assumed to be $\mu_r=1$. The electrical conductivity is partially known from the literature [2]. A continuous characteristic for a temperature range up to the boiling point can be approximated by the Arrhenius equation:

$$\sigma(\vartheta) = A \cdot e^{-\frac{E_A}{k_B \cdot \vartheta}}, \tag{1}$$

with the pre-exponential parameter A, the Boltzmann constant k_B, the activation energy E_A and the temperature ϑ.

The characteristic of the electrical conductivity of UO_2 is shown in Figure 1. It is approximated by two different Arrhenius functions due to a transition from p-type conduction to n-type conduction around 1400 K.

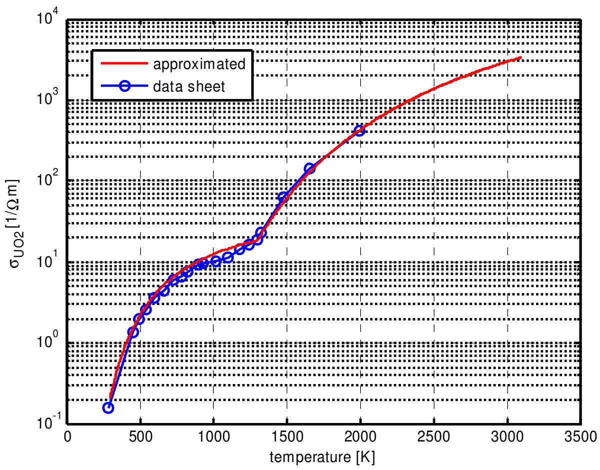

Fig.1. Electrical conductivity of UO_2: Measured data and Arrhenius approximation [2].

B. Electromagnetic field calculation

Due to the symmetrical design of the crucible the electromagnetic field calculation can be reduced to a one dimensional problem. The induced eddy current density of the harmonic electromagnetic field problem

$$\Delta \mathbf{H} - j\omega\mu\sigma\mathbf{H} = 0, \tag{2}$$

with

$$\frac{\partial \mathbf{H}}{\partial \varphi} = 0 \text{ and } \frac{\partial \mathbf{H}}{\partial z} = 0,$$

is calculated by:

$$\mathbf{J}(r,t)=\frac{p\cdot N\cdot I}{J_0(p\cdot r_{me})}\cdot J_1(p\cdot r)\cdot e^{j\omega t}\mathbf{e}_\varphi \quad (3)$$

with the Laplace operator Δ, the magnetic field strength **H**, the angular frequency ω, the eddy current density **J**, the coil current I, the number of windings related to height N, the melt radius r_{me}, the Bessel function of n-th order J_n and:

$$p=\sqrt{-j\omega\mu\sigma}=(-1+j)^2\cdot\frac{1}{\delta}, \quad (4)$$

with the skin depth δ.

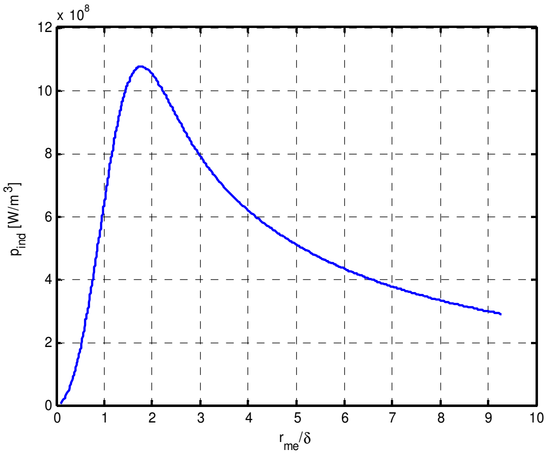

Fig.2. Induced power density into a cylindrical billet as a function of the ratio of melting radius and skin depth.

Consequentially the induced power density p_{ind} as a function of the electrical conductivity, which depends on the temperature, is calculated by:

$$p_{ind}(\sigma(\vartheta))=\frac{2}{r_{me}}\cdot\left|\int_{r_{me}}\frac{\mathbf{J}(r,\sigma)\cdot\mathbf{J}^*(r,\sigma)}{2\sigma}\mathrm{d}r\right|. \quad (5)$$

Figure 2 depicts the characteristic of the induced power density as a function of the ratio of the melt radius r_{me} and the skin depth δ. To induce the maximum power inside the target material, the crucible radius r_{cr} can be adjusted with respect to the skin depth of each target material for a given starting temperature.

C. Thermal losses

The main parts of the thermal outgoing losses occur due to thermal radiation above the melt, as well as by heat convection from the melt through the sinter crust to the crucible. The convection losses in radial direction from the melt to the crucible are estimated by [3]:

$$P_{con}=\frac{2\pi\cdot\lambda_{sc}\cdot h_{me}\cdot(T_{me}-T_{cw})}{\ln\left(\frac{r_{cr}}{r_{me}}\right)}. \quad (6)$$

The thermal radiation above the melt can be determined by:

$$P_{rad}=\varepsilon\cdot\sigma_{SB}\cdot\pi\cdot r_{me}^2\cdot\left(T_{me}^4-T_{amb}^4\right), \quad (7)$$

with the thermal conductivity of the sinter crust λ_{sc}, the height of the melt h_{me}, the melt, crucible wall and ambient temperature $T_{me,cw,amb}$, the emissivity ε and the Stefan Boltzmann constant σ_{SB}.

By increasing the crucible radius to increase the induced power inside the target material the thermal losses will also increase, as can be seen in (6) and (7). Especially the radiation losses increase quadratically with the melt radius.

D. Electromagnetic thermal field coupling

To calculate the temperature distribution inside the target material and to determine the thermal outgoing losses of the melt, a coupled thermal and electromagnetic calculation has to be performed. The procedure of this coupled calculation is depicted in Figure 3. A detailed analysis of the thermal calculation will be presented in the full paper.

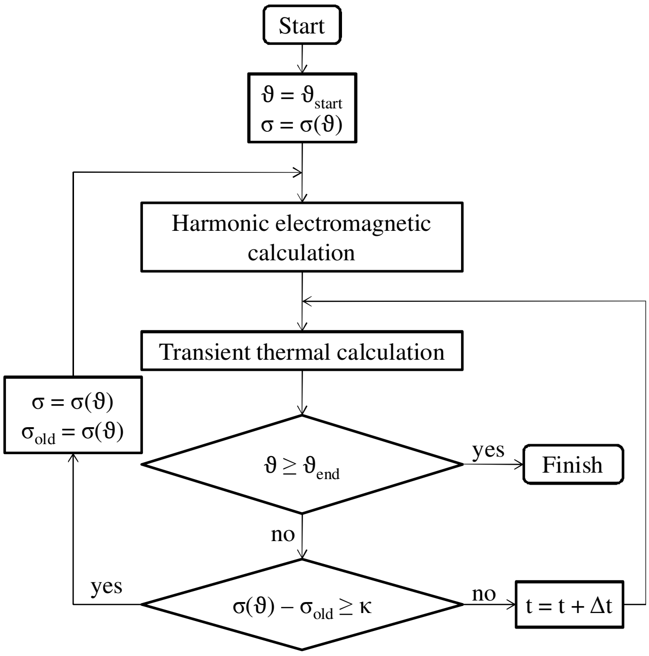

Fig.3. Flowchart of the coupled electromagnetic and thermal field calculation.

III. CONCLUSION

This paper presents the electromagnetic calculation of the Skull melting method for inorganic compounds. The thermal losses of the Skull melting process are analyzed with respect to the crucible radius. Finally, a coupled electromagnetic thermal method is presented. The calculation of the temperature distribution is analyzed and results will be presented in the full paper.

REFERENCES

[1] J.F. Wenckus, M.L. Cohen, A.G. Emslie, W.P. Menashi, P.F. Strong, “Study, design and fabricate a cold crucible system”, Air Force Cambridge Research Laboratories, Technical Report 75-0213, 1975.

[2] D. Kaczorowski, R. Troc, “Magnetic Properties of Non-Metallic Inorganic Compounds Based on Transition Elements: Binary Actinide Oxides”, *Landolt Börnstein New Series,* vol. III/27C2, p. 111, Springer Verlag Berlin Heidelberg, 1999.

[3] C. Gross, W. Assmuss, A. Muiznieks, G. Rahming, A. Mühlbauer, C. Stenzel, "Power Consumption of Skull melting, Part I: Analytical aspects and experiments", *Cryst. Res. Technology 34, 3,* pp. 319-328, 1999.