Experimental Thermal and Fluid Science 44 (2013) 673–679

Contents lists available at SciVerse ScienceDirect

Experimental Thermal and Fluid Science

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

On the exploitation of thermoelectric coupling for characterization of elliptical inclusions in metals

Hector Carreon *

Insituto de Investigaciones Metalurgicas, Edif. "U" Ciudad Universitaria, Morelia, Mich. 58000-888, Mexico

ARTICLE INFO

Article history:
Received 26 June 2012
Received in revised form 21 August 2012
Accepted 9 September 2012
Available online 17 September 2012

Keywords:
Thermoelectric measurements
Magnetic field distribution
Elliptical inclusions
Fluxgate sensors

ABSTRACT

A comparison between reported analytical results with experimental data of the magnetic flux density on cylindrical tin inclusions of elliptical cross-section embedded in a copper matrix under external thermal excitation is presented. By changing the aspect ratios b/a designated by e of the elliptical inclusions, a wide range of real situation such as slender inclusions can be simulated. The aspect ratio of the elliptical cylindrical inclusions varied from 0.50 to 3.250. A fairly modest 2.3 °C/cm temperature gradient in the specimen produced magnetic flux densities ranging from 2 to 100 μT at 2 mm lift-off distance between the tip of the magnetometer probe and the specimen. The experimental magnetic field distribution illustrated the potential for the non contacting thermoelectric technique to detect and characterize metallic inclusions of different geometries based on their magnetic signature. Preliminary results on a cylindrical hard alpha (TiN) inclusion embedded in Ti–6Al–4V matrix is also presented to demonstrate that the proposed method might be applicable to a wide range of alloys including high-strength, high-temperature engine materials.

© 2012 Elsevier Inc. All rights reserved.

1. Introduction

Most metallic materials contain inclusions which can be either metallic or non-metallic. Inherent to elaboration process, they are distributed inside the materials. These inclusions have generally a higher melting point than the host metals. Such inclusions in alloys reduce mechanical properties, are detrimental to surface finish and increase porosity, as well as having a tendency to increase corrosion. Furthermore, they act as stress raisers and can cause premature failure of in-service components. There are many established methods of traditional NDE that are employed today to analyze the quality of new and in-service materials. The detection of inclusions is their prior task. From all of these, one can retain ultrasound, X-ray, eddy current or electrostatic conductivity [1]. Each of them has advantages and disadvantages. Successful results have been obtained using the previous mentioned techniques for non-metallic inclusions. However, metallic inclusions are a little bit more complex to detect due to the very similar physical properties they could have with the host metal. In this work, we consider an alternative detection technique, which potentially has the possibility to detect surface and subsurface metallic inclusions, i.e. the non-contacting thermoelectric power measurements.

It has been demonstrated that the thermoelectric coupling in metallic materials can be exploited as a viable means of characterizing all types of imperfections and material defects such as inclusions, inhomogeneity, residual stresses, texture, fretting and segregations [2–7]. This nondestructive detection is carried out in an entirely non-contact way by using various types of magnetometers to sense the weak thermoelectric currents around the affected region when the specimen is subjected to an external temperature gradient. A schematic diagram of the thermoelectric measurement process in the presence of material imperfections is shown in Fig. 1. For this case, an external heating or cooling is applied to the specimen to produce a temperature gradient in the region to be tested. This creates a situation in which different points of the boundary between the host material and the imperfection are at different temperatures, therefore also at different thermoelectric potentials. This will produce opposite thermoelectric currents inside and outside the imperfection. The thermoelectric currents form local loops that run in opposite directions on the opposite sides of the imperfection relative to the prevailing heat flux. When the specimen is scanned with a highly sensitive magnetometer, the magnetic field of these thermoelectric currents can be detected even when the imperfection is buried below the surface few milimeters and the sensor is as far as a couple of centimeters from the specimen [8,9].

Several authors have developed analytical models to predict the magnetic field produced by thermoelectric currents around inclusions of specific geometries such as a cylinder and a sphere respectively in a homogeneous host material under external thermal excitation [10,11]. In subsequent publications, some of these

* Tel.: +52 443 316 7414.
E-mail address: hcarreon@umich.mx

0894-1777/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.expthermflusci.2012.09.007

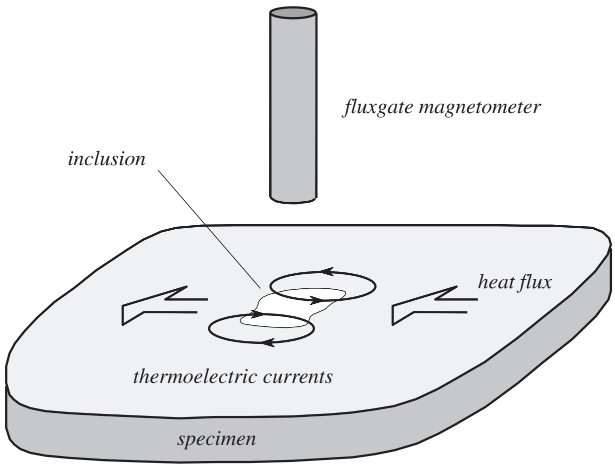

Fig. 1. Schematic diagram of noncontacting thermoelectric detection of material imperfections by magnetic sensing.

theoretical models were verified by experimental results [5,8]. This research work have provided a better understanding of the phenomenon and helped lay down the foundations for the development of this emerging NDE technique. However, real applications involve more complicated-geometry inclusions. Achieving this ambitious goal will require closely related theoretical and experimental efforts, the development of new, predictive analytical models, more sensitive experimental procedures, and, ultimately, increased probability of detection for small inclusions and weak material imperfections.

In a recent article, Faidi and Nayfeh demonstrated the existence of the underlying physical phenomena by presenting a theoretical model capable of predicting the magnetic field produced by thermoelectric currents around cylindrical inclusions of elliptical cross-section under external excitation [12]. They investigated the shape and magnitude of the resulting thermoelectric signal with respect to the inclusion geometry. The effect of the orientation of the elliptical inclusion on the signal magnitude was also reported. Although the best experimental tool for such studies is undoubtedly a superconducting quantum interference device (SQUID)-based magnetometer, we managed to use a fluxgate magnetometer to provide experimental evidence of the theoretical predictions through the example of elliptical cylindrical tin inclusions by varying the aspect ratio e of the elliptical inclusions in a copper matrix at 2 mm lift-off distance between the sensor and the surface specimen. First, we are going to present a brief review of the analytical model of Refs [12,13], and then we will proceed by describing the experimental procedure and finally, discuss the experimental results and compare them to the analytical predictions.

2. Review of the theoretical model

Thermoelectric behavior in metals is a result of intrinsically coupled transport of electricity and heat. The electric current density $\mathbf{j}$ and thermal heat flux $\mathbf{h}$ are related to a given combination of electric potential Φ and temperature T distributions in accordance to [14]

$$\begin{bmatrix} \mathbf{j} \\ \mathbf{h} \end{bmatrix} = \begin{bmatrix} \sigma & \varepsilon \\ \bar{\varepsilon} & \kappa \end{bmatrix} \begin{bmatrix} -\nabla\Phi \\ -\nabla T \end{bmatrix} \tag{1}$$

where σ denotes the electrical conductivity measured at uniform temperature, κ is the thermal conductivity of zero electric field, and ε and $\bar{\varepsilon}$ are thermoelectric coupling coefficients. These equations are supplemented with [10]

$$\nabla\cdot\mathbf{h} = 0, \quad \nabla\cdot\mathbf{j} = 0 \tag{2}$$

Imposing the requirements of Eq. (2) in Eq. (1) and noting that $\sigma\kappa - \varepsilon\bar{\varepsilon} \neq 0$ dictates that the Laplacian of T and Φ vanish individually, namely.

$$\nabla^2 T = 0, \quad \nabla^2\Phi = 0 \tag{3}$$

Consider an infinite, homogeneous and isotropic medium containing an elliptical cross-section cylindrical inclusion aligned along the z-direction of a given Cartesian coordinate system (x,y,z) as illustrated in Fig. 2. The cross-section is of 2a major axis along the x-direction and 2b minor axis along the y-direction. To differentiate between the properties of the two media, we designate those of the inclusion with a prime. The system is subjected to a uniform thermal heat flux h_0 far away from the inclusion and directed along the x-direction.

Both the temperature T and the electric potential Φ in the host and the inclusion domains should satisfy the Laplace's Eq. (3). This equation is an important equation that represents several physical problems encountered in steady state situations such as heat conduction [15,16], electricity [17,18] and hydrodynamics [19].

In general, the steady linear flow of heat will be disturbed around the inclusion in a way that depends on the shape of the inclusion. Nevertheless, solutions of Eq. (3) Far away from the inclusion will not be affected by the inclusion geometry. These unaffected solutions provide the necessary conditions at infinity (far away from the inclusion) and can be obtained by solving Eq. (1) for T and Φ as

$$T = T_0 = -\frac{h_0}{\kappa}x \quad \Phi = \Phi_0 = \frac{\varepsilon h_0}{\kappa\sigma}x \tag{4}$$

Here, it is considered that the thermoelectric coupling constants ε and $\bar{\varepsilon}$ are very small comparing to the thermal and electrical conductivity constants κ and σ, and so the product $\varepsilon.\ \bar{\varepsilon}$ can be neglected, as argued in [10]. Since x satisfies Laplace's equation, formal solution of Eq. (3) for both the host and the inclusion, respectively, can be obtained using superposition as

$$T = Ax + BA_0x \quad T' = Dx \tag{5a}$$

$$\Phi = A^*x + B^*A_0x \quad \Phi' = D^*x \tag{5b}$$

Here the boundedness of the solutions inside the inclusion has been satisfied as reflected in the elementary form of the expression T' and Φ'. Furthermore, A, B, D, A^*, B^* and D^* are currently unknown constants that need to be determined from the appropriate boundary and interface conditions. At the interface between the host and the inclusion, the continuity conditions require that the temperature, the electric potential and the normal components of both the electric current density and thermal heat flux to be continuous, namely,

$$T = T', \quad \Phi = \Phi', \quad h = h'_n, \quad j = j'_n \tag{6}$$

The unknown constants A, B, D, A^*, B^* *and* D^* can now be determined by imposing these conditions in Eq. (5). After some algebraic reductions and manipulations, we obtain

$$A = -\frac{h_0}{\kappa}, \quad A^* = \frac{\varepsilon h_0}{\kappa\sigma} \tag{7}$$

$$D = \frac{-h_0}{\kappa + (\kappa' - \kappa)A_0}, \quad D^* = \frac{-h_0[\varepsilon + (\varepsilon' - \varepsilon)A_0]}{[\sigma + (\sigma' - \sigma)A_0][\kappa + (\kappa' - \kappa)A_0]} \tag{8}$$

and

متن کامل مقاله ← دریافت فوری

ISIArticles
مرجع مقالات تخصصی ایران

- ✓ امکان دانلود نسخه تمام متن مقالات انگلیسی
- ✓ امکان دانلود نسخه ترجمه شده مقالات
- ✓ پذیرش سفارش ترجمه تخصصی
- ✓ امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
- ✓ امکان دانلود رایگان ۲ صفحه اول هر مقاله
- ✓ امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
- ✓ دانلود فوری مقاله پس از پرداخت آنلاین
- ✓ پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات