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Determination of temperature dependent thermophysical properties using an inverse method and an infrared line camera

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ABSTRACT

Temperature dependent thermal diffusivities of two alloys (Al-4 wt.% Cu and 70:30 α-brass) are determined using a one-dimensional inverse method that is based on a least-square scheme. Transient temperature histories required as input for the proposed inverse method are recorded using an infrared line camera during one-sided heating or cooling. An aerogel that is transparent for infrared radiation is used as insulation material, ensuring that heat conduction is essentially one-dimensional. Temperature profiles along the samples are obtained using up to 512 photo diodes as temperature sensors. Temperature dependent specific heat capacities of the Al–Cu alloy and brass, calculated using a thermochemical library based on the CALPHAD method, are employed to calculated thermal conductivities. The calculated thermal conductivities are in good agreement with literature values. It is shown that the combination of the numerical calculations and the heating experiments provides an efficient way to determine temperature dependent thermophysical properties of alloys.

1. Introduction

Well-known thermophysical properties of a material are an essential prerequisite for the calculation of temperature fields. The effective thermophysical property in the heat conduction equation is thermal diffusivity, which intrinsically contains density, thermal conductivity and specific heat. Over the recent decades, a considerable number of methods based on the solution of the inverse heat conduction problem (IHCP) has been proposed to determine thermal diffusivity, e.g. the laser flash method or the guarded hot plate method [1,2]. In these methods, the thermal diffusivity of a material can be expressed as an analytical solution of the linear heat conduction equation. Thus, thermal diffusivity is determined from the analytical solution and the measured temperature history. The analytical solution does not consider the temperature dependence of the thermal diffusivity, which could e.g. be obtained by measuring at a sequence of temperatures, evidently a tedious procedure. In numerous practical engineering problems, the temperature dependence of thermal conductivity and specific heat needs to be considered. The heat conduction equation appears then as a non-linear equation from which one cannot obtain an analytical solution explicitly. Therefore, those methods are limited to narrow temperature intervals, requiring the above mentioned repeated measurements at different temperature levels to retrieve the temperature dependence.

In temperature gradients extending over a larger temperature interval, the heat conduction equation is non-linear, and numerous methods have been applied for solving the IHCP to determine the time dependent or temperature dependent boundary conditions [3–9] or the temperature dependent thermophysical properties [9–23]. Huang and Yan [10] employed the conjugate gradient method with the adjoint equation for the solution of IHCP to determine the temperature dependent thermal conductivity and volumetric heat capacity. Yeung and Lam [11] used a second-order finite difference method to estimate the unknown thermal conductivity. Kim et al. [12] applied a direct integral approach to estimate the temperature dependent thermal conductivity. Char et al. [13] employed the differential quadrature method to solve the non-linear heat conduction equation; both the location dependent thermal conductivity and the temperature dependent thermal conductivity are obtained. Besides, the least-square method [14–18] was extensively implemented for the solution of the IHCP to determine the thermophysical properties. Other techniques, such as a one-step group preserving scheme [19], a genetic algorithm [20], and a neural network simulation [21] have also been adopted to determine thermal conductivities and specific heat capacities. All of the above-mentioned studies require measured temperature histories. However, some of these studies

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Nomenclature

T	temperature
x	position
T_i	calculated temperatures at the i-th site
T_i^m	measured temperatures at the i-th site
t	time
$\alpha(T)$	temperature dependent thermal diffusivity
A_0, A_1	coefficients determining $\alpha(T)$ through $\alpha(T) = A_0 + A_1 T$
A_0^0, A_1^0	estimated parameters of A_0 and A_1
$\varphi(A_0, A_1)$	square error sum between the measured and calculated temperatures
$\frac{\partial T_i(A_0,A_1)}{\partial A_0}$	sensitivity coefficient with respective to A_0 at the location of the i-th node
$\frac{\partial T_i(A_0,A_1)}{\partial A_1}$	sensitivity coefficient with respective to A_1 at the location of the i-th node
ΔA_0, ΔA_1	increments of A_0 and A_1
$\Phi(A_0, A_1)$	integration of $\varphi(A_0, A_1)$ from the starting time to the ending time
ρ	density
$c_p(T)$	temperature dependent specific heat
$\lambda(T)$	temperature dependent thermal conductivity

do not use measured temperature data as input and are thus pure methodological studies without the possibility to compare thermal diffusivities with known values [10–18]. Some authors employ several thermocouples to record the transient temperature profiles while conducting cooling [9] or heating experiments [22–24], and the thermophysical properties are deduced from the recorded transient temperature profiles by solving the IHCP. Some restrictions need to be considered when using thermocouples to measure the temperature field in a sample, which might affect the accuracy of the solution of the IHCP [25]. (i) The number of thermocouples that can be inserted in a sample is limited, which may lead to unstable solutions of the IHCP due to the ill-posed nature of the IHCP [14,22]. (ii) The temperature field might be influenced by the insertion of the thermocouple wires, inducing disturbances in the measured temperatures and consequently systematic errors in the determined thermophysical data.

In this work, an infrared line camera of 512 photo diodes is applied to measure and record the transient temperature profiles while conducting heating and cooling experiments using an Al–Cu alloy and α-brass. With the infrared line camera, a much higher density of measured temperatures along a temperature profile is recorded. The contact-free measurement excludes external disturbances of the one-dimensional heat conduction process. Using the measured temperature profiles as input data, a one-dimensional inverse method based on a least-square scheme is adopted to determine the temperature dependence of the thermal diffusivities of the Al–Cu alloy and brass. Combined with the specific heats calculated from the thermochemical software package FactSage and the SGTE 2011 database, the temperature dependent thermal conductivities of Al–Cu and brass are obtained. The thermal conductivities are in good agreement with the literature data [26].

2. Experimental

The experimental setup is shown in Fig. 1. One end of a cylindrical sample of 8 mm diameter is induction heated while the other end of the sample is exposed to air. The sample is surrounded by silica aerogel with 3 cm thickness which is transparent to infrared radiation up to a wavelength of 2.2 μm. It is an excellent thermal insulation material with a very low thermal conductivity on the order of 10^{-2} W m^{-1} K^{-1} and prevents heat dissipation from the cylinder surface. This ensures that heat conduction in the sample is essentially one-dimensional. An infrared line camera of 512 pixels collects the intensities of the infrared radiation. The optics of the infrared line camera is adjusted such that the infrared radiation is collected over a length of 34 mm. In the present study, 50 pixels out of the 512 pixels, which denote 50 temperature sensors, are situated within the measurement distance of 34 mm. One side of the cylindrical sample is ground using SiC paper (P4000) to create a plane surface of a width of about 2 mm and covered by a black stove enamel layer to generate a reproducible optical environment. The exposure time of the infrared line camera is set so that measurements are taken in the sensitive range, in the present case to 50 ms. Infrared intensities caused by temperatures ranging from 520 K to 710 K can then be measured with an accuracy of ±1 K.

For calibrating the infrared line camera, a NiCr–Ni type K thermocouple wire with 0.5 mm diameter is positioned inside the sample on the location from pixel 498 to pixel 502. The sample is slowly heated while recording the temperature and the infrared intensity simultaneously at the same position. As a result, the relationship between the temperature and the corresponding intensity is obtained. A calibration function is determined by a non-linear (logarithmic) fit to the slightly scattering temperature–intensity curve. Note that the calibration process is carried out after the relative position between the infrared line camera and the sample is fixed.

A temperature gradient is achieved by heating the higher end of sample to a given constant temperature while the lower end is air cooled. The induction furnace is turned off after a steady temperature gradient is reached, yielding decreasing temperatures at all positions along the sample. As expected, the cooling rate at the hot side of the sample was always found to be faster than at the cold side, which is tracked by the decreasing emitted infrared intensities along the sample. Finally, an almost uniform temperature along the sample is obtained. The induction furnace is turned on with high power when the temperature of the sample is dropping to the minimum temperature that the infrared line camera can detect. The higher end of the sample is heated rapidly and the intensity profiles are again recorded by the infrared line camera. Using the calibration function of the infrared line camera, temperature profiles along the measured part of the sample are obtained in time steps of 50 ms. Based on the temperature history, numerical calculations incorporating direct and inverse methods are employed to determine the temperature dependent thermal

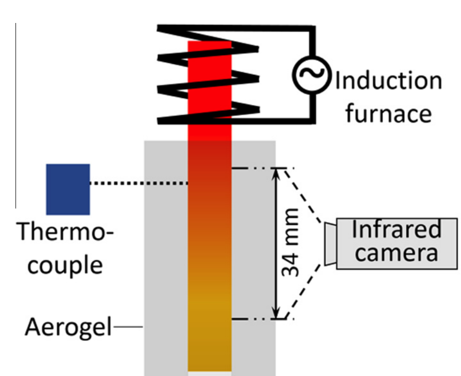

Fig. 1. Sketch of the experimental setup.