Thermal Diffusivity of the Aluminum Alloy Al–17Si–4Cu (A390) in the Solid and Liquid States

E. Kaschnitz[1,2] **and R. Ebner**[3]

The thermal diffusivity of the aluminum alloy Al–17Si–4Cu (A390) was measured in the temperature range from room temperature to 730°C using the laser-flash technique. A commercial laser-flash system (Netzsch LFA 427) was used for the measurements. A short laser pulse of $300\mu s$ was applied to heat the bottom surface of a disk-shaped specimen, resulting in a time-dependent temperature increase at the top surface. A correction for the laser pulse length as well as the surface radiation and convection was applied in order to evaluate the half time value of the temperature increase. The thermal diffusivity was calculated from the specimen thickness and the half time value. A sapphire crucible was used to contain the specimen in the mushy region and in the liquid state. As the laser is fired from below at the bottom surface of the specimen, the thickness of the melt has to be small to avoid significant buoyancy. The thermal diffusivity of the alloy above the eutectic temperature and in the liquid is drastically lower than in the solid state of the alloy.

KEY WORDS: Aluminum alloy A390; Al–17Si–4Cu; high temperature; laser-flash method; liquid metal; thermal diffusivity.

1. INTRODUCTION

The laser-flash method is presently the most straightforward and reliable method to measure the thermal diffusivity at room temperature and in the high-temperature range. A preheated flat specimen absorbs the heat of a short laser pulse at the front surface; the associated temperature rise travels through the specimen and is measured at the rear surface of the

---

[1] Österreichisches Gießerei-Institut, Parkstraße 21, 8700 Leoben, Austria.
[2] To whom correspondence should be addressed. E-mail: kaschnitz.ogi@unileoben.ac.at
[3] Materials Center Leoben, Franz-Josef Straße 13, 8700 Leoben, Austria.

specimen versus time. It was originally developed by Parker et al. [1] and has been continuously improved during the past decades. Various mathematical models have been developed to consider heat loss effects and the finite pulse length of the laser [2–5]. With the availability of sufficient computing power, sophisticated fitting of the temperature response at the rear surface of the specimen includes facial and radial heat losses, laser pulse length, and pulse shape as well as steady-state temperature drift [6–8].

Measurement of the thermal diffusivity of solid materials by the laser-flash method is an established technique today in academic and industrial research. There are several commercial manufacturers of laser-flash equipment; the measurement procedure including data processing is kept relatively simple. However, laser-flash measurements performed on liquid specimens are considerably more difficult for several reasons, e.g., possible specimen-container reactions, wetting problems, buoyancy, and convective heat loss.

Accurate thermophysical property data of solid and liquid alloys are urgently needed for the numerical simulation of casting processes. In recent years, properties of some common aluminum, magnesium, copper, and iron alloys have been measured by several research groups (e.g., Refs. [9–16]). However, there is still a lack of reliable thermophysical property data, especially for newly developed alloys and mold materials. This information (thermal diffusivity, thermal conductivity, heat capacity, latent heat of solidification, fraction solid, and density) is required to perform accurate simulations. This work presents results of thermal-diffusivity measurements of the aluminum alloy Al–17Si–4Cu (A390) in the solid and liquid states over the temperature range from room temperature to 730°C. This alloy is typically used for engine blocks and pistons for high-performance racing cars or luxury cars. The thermal diffusivity data are required for numerical simulation of castings within the industrial production process.

2. EXPERIMENTAL

All measurements were performed by a commercial laser-flash system (Model LFA 427, Netzsch Gerätebau GmbH, Selb, Germany). The system is equipped with a high-temperature furnace for the steady-state heating of the specimen, allowing measurements between room temperature and 1500°C. The sample chamber is vacuum-tight with a fused silica window at the bottom and a calcium fluoride window at the top. A turbo molecular drag pump provides a vacuum atmosphere of 10^{-5} mbar. Alternatively, the experimental chamber can be flooded with argon as an inert gas. The pulsed laser light from a commercial Nd:YAG laser system

(Model SW040, Carl Baasel Lasertechnik GmbH, Starnberg, Germany) enters the sample chamber from below and heats the bottom surface of the specimen. On top of the chamber an IR-detector is located measuring the temperature response at the top surface of the specimen. A detailed description of the laser-flash system is given by Blumm and Lemarchand [17] and Bräuer et al. [18].

The solid specimen is supported and centered by three small contacts at the bottom surface to minimize thermal contact. A cap is placed over the specimen and specimen holder which prevents scattered laser light from impinging directly on the detector. Due to thermal expansion, the specimen increases in thickness at higher temperatures. In order to compensate for thermal expansion, a correction has been applied to all solid specimens,

$$a_{\mathrm{corr}} = a_0 \left(1 + \frac{\Delta l}{l_0}\right)^2, \tag{1}$$

where a_{corr} is the true thermal diffusivity, a_0 is the measured thermal diffusivity, and $\Delta l/l_0$ is the thermal expansion.

The mushy and liquid specimens are kept in a transparent container during the measurements. This container consists of a sapphire crucible, a complex shaped sapphire lid, and two graphite support elements (Fig. 1). The sapphire lid has a circular groove and four holes working as overflows to compensate for the thermal expansion during melting.

3. MEASUREMENTS

The Al–17Si–4Cu (A390) was obtained from an aluminum foundry producing for the automotive industry (Hydro Aluminium Mandl & Berger GmbH, Linz, Austria). The specimens were cut from a cylinder head taken from the production after heat treatment. The chemical composition is given in Table I. The melting and solidification behavior of the Al–17Si–4Cu (A390) alloy was determined by differential thermal analysis (Model DSC 404, Netzsch Gerätebau GmbH, Selb, Germany). The solidus temperature was obtained at 507°C, the eutectic temperature at 562°C, and the liquidus temperature at 666°C.

All specimens used were coated with a very thin graphite layer of approximately 3μm. The coating increases the absorption coefficient of the surfaces and prevents sticking of the molten specimen in the sapphire crucible. Half of the measurements were performed in vacuum, the other half under a protective atmosphere (argon 99.999% pure). No difference in the results was observed.
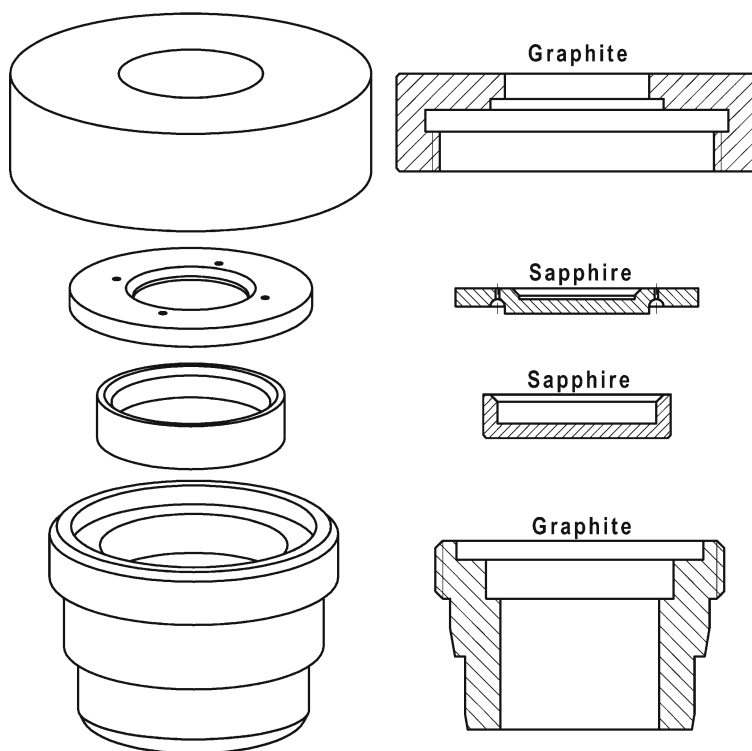
Fig. 1. Schematic drawing of the containment for the liquid specimen including sapphire cell and graphite support.

Table I. Chemical Composition (in mass%) of the Al–17Si–4Cu (A390) Aluminum Alloy

Elements											
Si	Cu	Mg	Fe	Mn	Zn	Ti	Cr	Ni	Pb	Sn	Al
17.86	4.32	0.47	0.23	0.09	0.06	0.11	<0.01	<0.01	<0.02	<0.02	bal.

For all measurements, a laser pulse length of $300 \mu s$ was applied. According to the manufacturer, an energy of approximately 3 J is provided in that time span from the laser. Considering the high absorption of the graphite layer, this leads to a temperature increase of approximately 1°C in the specimen.

A first series of measurements of the thermal diffusivity of the solid alloy was performed on six specimens in the temperature range from room temperature to 450°C. The room temperature dimensions of the cylindrical

specimens were: diameter, 12.55 mm; thickness, varying from 3 to 5 mm. Each specimen was heated in steps of 50°C and subsequently cooled to the same temperature holding points. The heating/cooling rate between the isothermal steps was 10°C·min^{-1}. At each selected temperature, five individual measurements were taken. The reproducibility of the measurements in the solid phase (except at room temperature) for an individual specimen is on the order of 0.4% (standard deviation), and between different specimens, it is between 0.3 and 0.7%. Due to a higher signal-to-noise ratio, the reproducibility at room temperature is somewhat higher (1.1%). The measured thermal-diffusivity values were corrected for thermal expansion by values given in Table II. These data were measured using a pushrod dilatometer (Model DIL 402E, Netzsch Gerätebau GmbH, Selb, Germany).

A second series of diffusivity measurements in the mushy and liquid states was made on six specimens in the temperature range from 500 to 730°C. The room temperature dimensions of the cylindrical specimens were: diameter, 10.85 mm; thickness, 1.45 mm. Each specimen was heated in steps of 10°C and subsequently cooled. During heating, in the temperature range from 500 to 530°C (in the initial melting phase), some of the measurements had distorted temperature response signals; these measurements had to be discarded. These discrepancies seem to be due to thermal stress when the specimen is not fully liquid and still has some residual strength. Measurements in the same temperature range for the cooling cycle showed no peculiarities. The reproducibility of the measurements in the mushy and liquid phases for an individual specimen is between 1 and 2% (standard deviation), and that between different specimens is 2.5% (approximately 4% in the initial melting phase). A small correction (approximately 1% at liquidus temperature) has been applied for the thermal expansion of the sapphire cell, using values from Ref. [19].

Table II. Values Used to Correct for Thermal Expansion of the Solid Specimen

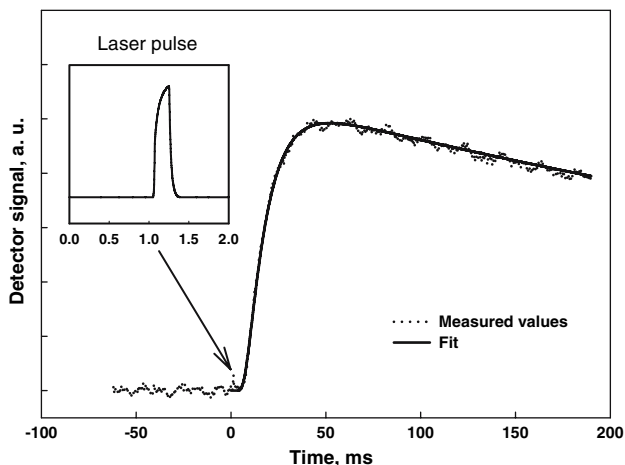| Temperature (°C)	Thermal Expansion (%)
20	0.000
50	0.055
100	0.151
150	0.249
200	0.351
250	0.457
300	0.565
350	0.676
400	0.790

Fig. 2. Example of the temperature increase at the top surface of a liquid specimen as a function of time and the shape of the laser pulse that heats the bottom surface.

Typical measurements of the temperature increase at the top surface of a specimen in the liquid state as well as the measurement of the shape of the laser beam are given in Fig. 2. The measured data of the temperature increase and the laser pulse shape was evaluated by a software package provided with the laser-flash system (LFA Analysis Version 4.7.0, Netzsch Gerätebau GmbH, Selb, Germany). This software uses a fitting procedure according to the algorithm of Cape and Lehman [3], improved by Blumm and Opfermann [8]. In order to compensate for the small baseline drift, a linear function is fitted to the baseline values prior to the laser-flash pulse and subsequently subtracted from the signal.

Tests of the measurement equipment and the measurement procedure with specimens of pure aluminum (99.999+) were carried out to check the reliability of the experiment. The obtained data for the thermal diffusivity are in good agreement with the recommended values of Mills [20].

4. RESULTS

The measured results for the thermal diffusivity of solid Al–17Si–4Cu (A390) at selected temperatures are shown in Fig. 3. The values were fitted by a third-order polynomial function using the least-squares method. It should be noted that the initial heating up to approx. 250°C yields somewhat lower values than for the cooling cycle. The material coming from the foundry was initially heat treated and changed at 300°C to "as
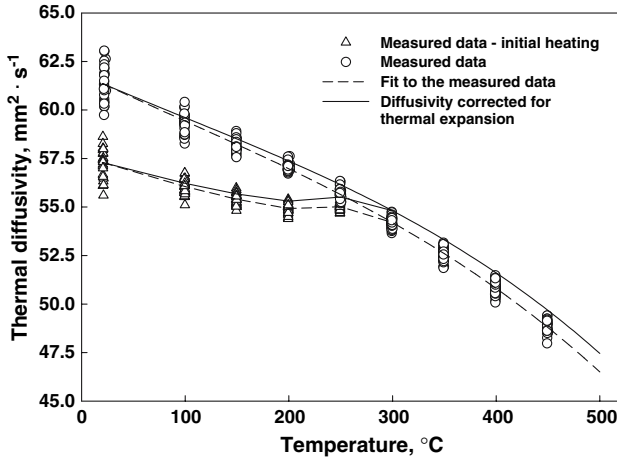
Fig. 3. Measured thermal-diffusivity values of solid Al–17Si–4Cu (A390) as a function of temperature and least-squares fits with and without correction for thermal expansion.

cast" condition during the measurement. The best fit to the measured data was then corrected for the thermal expansion of the specimen according to Eq. (1). At higher temperatures, the correction for thermal expansion increases to approximately 2%.

The variation of the thermal diffusivity as a function of temperature of liquid Al–17Si–4Cu (A390) is shown in Fig. 4. The obtained data were fitted piecewise using the least-squares method. The initial melting range up to the eutectic temperature was fitted by a third-order polynomial function; for the range between the eutectic and liquidus temperatures as well as for the liquid range, two linear functions were used.

Figure 5 and Table III show the thermal diffusivity of Al–17Si–4Cu (A390) over the entire measured temperature range. A sharp drop of the thermal diffusivity at the eutectic temperature (not at liquidus!) can be seen. In the temperature range between the eutectic and liquidus temperatures – where primary silicon crystals are growing in the melt – the values of the thermal diffusivity are similar to those of the liquid phase. No differences for heating and cooling were observed in the obtained results for the liquid and mushy states.

5. UNCERTAINTIES

The measurement uncertainty in the temperature range from room temperature to 507°C (solid state of the alloy) was calculated as recommended in Ref. [21] and according to Refs. [22] and [23]. An expanded
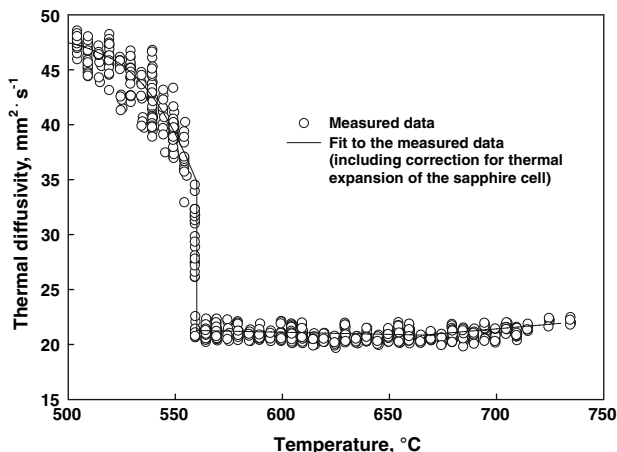
Fig. 4. Measured thermal diffusivity of Al–17Si–4Cu (A390) in the mushy and liquid states as a function of temperature and least-squares fits to the measured values.
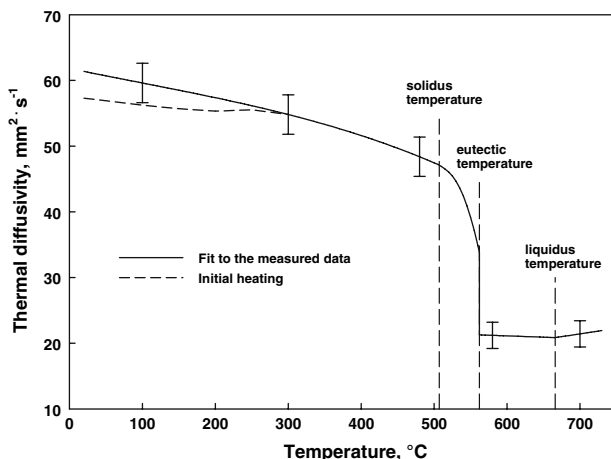

Fig. 5. Results for thermal diffusivity of solid and liquid Al–17Si–4Cu (A390) as a function of temperature.

uncertainty (with a coverage factor of 2) of $\pm$ 4% is obtained in this temperature range. A detailed analysis of the measurement uncertainties in the temperature range from 507 to 730°C (mushy and liquid states of the alloy) is given in Table IV. It follows, in principle, the work of Cusco

Table III. Experimental Results of Thermal Diffusivity of the Al–17Si–4Cu (A390) Aluminum Alloy from Room Temperature up to the Liquid State

Temperature (°C)	Thermal Diffusivity (mm$^2 \cdot$s^{-1})	Temperature (°C)	Thermal Diffusivity (mm$^2 \cdot$s^{-1})
20	61.4	562[c]	21.3
50	60.7	570	21.2
100	59.6	580	21.2
150	58.5	590	21.2
200	57.4	600	21.1
250	56.1	610	21.1
300	54.8	620	21.0
350	53.3	630	21.0
400	51.6	640	21.0
450	49.7	650	20.9
500	47.5	660	20.9
507[a]	47.1	666[d]	20.9
510	46.9	670	20.9
520	46.1	680	21.1
530	44.7	690	21.3
540	42.4	700	21.4
550	39.2	710	21.6
560	34.8	720	21.8
562[b]	33.8	730	21.9

[a] Solidus temperature.
[b] Eutectic temperature, thermal-diffusivity value extrapolated from the solid.
[c] Eutectic temperature, thermal-diffusivity value extrapolated from the liquid.
[d] Liquidus temperature.

and Monaghan [14] and yields an expanded uncertainty of approximately ± 11%.

6. DISCUSSION

Heating a melt pool with a laser from below as done in this work leads to buoyancy in the liquid. In order to estimate the order of movement in the melt, a numerical simulation using a commercial CFD-software package (Flow3D, Flow Science Inc., Santa Fe, New Mexico, U.S.A.) was carried out. With appropriate initial and boundary conditions representing the experimental conditions in this work, a negligible velocity distribution in the melt is obtained for the short period of the experiment (approximately 100 ms) and the small specimen thickness (1.5 mm).

Considering the amount of literature data on aluminum alloys, there is little information on thermophysical properties in the liquid range, and

Table IV. Sources of Uncertainty for Thermal Diffusivity in the Mushy and Liquid States

Uncertainty		Probability distribution	Divi-sor	c_i	Diffusivity uncertainty (%)
Source	(%)				
Thickness of cell	2.0	Normal	2	2	2.0
Flatness of cell	1.3	Rectangular	1.73	2	1.5
Expansion of cell	0.1	Rectangular	1.73	2	0.1
Graphite coating	1.3	Rectangular	1.73	2	1.5
Time-base DAQ	0.3	Rectangular	1.73	1	0.2
Vertical resolution DAQ	0.2	Rectangular	1.73	1	0.1
Linearity DAQ	0.2	Rectangular	1.73	1	0.1
Drift detector	1.0	Normal	2	1	0.5
Laser non-uniformity	3.0	Normal	2	1	1.5
Laser pulse energy	1.5	Normal	2	1	0.8
Finite pulse length	0.3	Normal	2	1	0.2
Heat losses, buoyancy	4.0	Rectangular	1.73	1	2.3
Quality of fitting	1.0	Normal	2	1	0.5
Temperature measurement	3.5	Normal	2	1	1.8
Measurement repeatability	2.0	Normal	1	1	2.0
Measurement reproducibility	2.5	Normal	1	1	2.5
Total combined uncertainty		Normal			5.5
Expanded uncertainty		Normal			11.1

data for Al–17Si–4Cu (A390) does not appear to be available. Published work by Szelagowski and Taylor [11] reports results of thermal-diffusivity measurements by the laser-flash method of the casting alloys LM25 (similar to Al–7Si–Mg (A356)) and LM4 (similar to Al–5Si–3Cu (A319)). Unfortunately, these data are shown as viewgraphs only and are in the range of 20–28 mm·s^{-1} for the liquid state. Other results are published by Blumm et al. [9], showing data of the aluminum alloy A356. In this viewgraph, values between 22 and 26 mm·s^{-1} can be seen for the melt. Mills [20] recommends values from 23 to 27 mm·s^{-1} for LM25, and 24 to 26 mm·s^{-1} for LM4. A paper by Overfelt and Bakhtiyarov [13] reports data on liquid A319 and A356 that are slightly higher (26–30 mm·s^{-1}) than the values of the papers mentioned above. Taylor et al. [10] published data on wrought alloys (1100, 2024, 6061, and 7075) as viewgraphs, ranging between 28 and 35 mm·s^{-1}, which are in agreement with the values recommended by Mills [20].

The comparison of published values of aluminum alloys in the liquid state with the results of this work shows a general decrease of the thermal diffusivity with a higher amount of silicon and copper. As the silicon

content of Al–17Si–4Cu (A390) is hypereutectic, the thermal-diffusivity values are considerable lower than those reported for hypoeutectic compositions. All published results on aluminum alloys as well as the results of this work show a slight increase in thermal diffusivity with temperature in the liquid state.

It should be noted that the thermal diffusivity in the range between the liquidus point and the eutectic temperature is practically as low as in the liquid state. That means that the growing primary silicon crystal network does not contribute more to the thermal diffusion than the liquid. Starting with the aluminum–silicon eutectic at the eutectic temperature, the thermal diffusivity increases rapidly to a value comparable to the solid state.

ACKNOWLEDGMENTS

REFERENCES

1. W. J. Parker, R. J. Jenkins, C. P. Butler, and G. L. Abbott, *J. Appl. Phys.* **32**:1679 (1961).
2. R. D. Cowan, *J. Appl. Phys.* **34**:926 (1963).
3. J. A. Cape and G. W. Lehman, *J. Appl. Phys.* **34**:1909 (1963).
4. T. Azumi and Y. Takahaski, *Rev. Sci. Instrum.* **52**:1411 (1981).
5. L. M. Clark III and R. E. Taylor, *J. Appl. Phys.* **46**:714 (1975).
6. A. Cezairliyan, T. Baba, and R. Taylor, *Int. J. Thermphys.* **15**:317 (1994).
7. D. Josell, J. Warren, and A. Cezairliyan, *J. Appl. Phys.* **78**:6867 (1995).
8. J. Blumm and J. Opfermann, *High Temp.-High Press.* **34**:515 (2002).
9. J. Blumm, J. B. Henderson, and L. Hagemann, *High Temp.-High Press.* **30**:153 (1998).
10. R. E. Taylor, H. Groot, T. Goerz, J. Ferrier, and D. L. Taylor, *High Temp.-High Press.* **30**:269 (1998).
11. H. Szelagowski and R. Taylor, *High Temp.-High Press.* **30**:343 (1998).
12. S. I. Bakhtiyarov, R. A. Overfelt, and S. G. Theodorescu, *J. Mater. Sci.* **36**:4643 (2001).
13. R. A. Overfelt and S. I. Bakhtiyarov, *High Temp.-High Press.* **34**:401 (2002).
14. L. Cusco and B. J. Monaghan, *High Temp.-High Press.* **34**:281 (2002).
15. H. Shibata, K. Okubo, H. Ohta, and Y. Waseda, *J. Non-Cryst. Solids* **312–314**:172 (2002).
16. T. Nishi, H. Shibata, H. Ohta, and Y. Waseda, *Metall. Mater. Trans. A* **34**:2801 (2003).
17. J. Blumm and S. Lemarchand, *High Temp.-High Press.* **34**:523 (2002).
18. G. Bräuer, L. Dusza, and B. Schulz, *Interceram.* **41**:489 (1992).
19. T. A. Hahn, *Certificate Standard Reference Material 732* (NBS, Washington, D.C., 1977).
20. K. C. Mills, *Recommended Values of Thermophysical Properties for Selected Commercial Alloys* (Woodhead Publishing Ltd., Cambridge, United Kingdom, 2002).

21. *Guide to the Expression of Uncertainy in Measurement* (International Organisation for Standardisation, Geneva, Switzerland, 1995).
22. L. Vozar and W. Hohenauer, *Int. J. Thermophys.* **26**:1899 (2005).
23. B. Hay, J. R. Filtz, J. Hameury, and L. Rongione, *Int. J. Thermophys.* **26**:1883 (2005).