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Thermophysical properties of the Ni-based alloy Nimonic 80A up to 2400 K, II

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Abstract

Numerical simulation of fluid flow, heat transfer, solidification or thermal induced stresses have gained a tremendous significance in steel working industry branches. With the advent of adequate computing power, full three-dimensional calculation of the determining physical equations have become possible. A major drawback of these simulation techniques is the lack of accurate thermophysical properties. By the means of a fast pulse heating technique thermophysical data for the solid and liquid material required for the simulations can be measured. Important input parameters for the heat transfer equation are heat capacity, heat of fusion, density and thermal conductivity. Since direct measurements of thermal conductivity of alloys in the liquid state are almost impossible, its estimation from the electrical conductivity using the Wiedemann–Franz law is very useful.

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Keywords: High temperature alloys; Enthalpy; Heat capacity; Heat conduction; Thermodynamic properties

1. Introduction

Nimonic 80A is a nickel–chromium alloy which is strengthened by additions of titanium and aluminum. The alloy with excellent oxidation resistance is used for high temperature, high strength applications, such as gas turbine hot section components, for hot work tools, forging hammers, swaging dies, shear blades and also bolts and nuts. Within this paper further measured data of Nimonic 80A are discussed (see Ref. [1]) to complete the set of data. Table 1 gives an overview of composition, the solidus–liquidus temperatures and the density at room temperature as specified by Böhler Edelstahl GmbH, Mariazellerstrasse 25, 8605 Kapfenberg, Austria.

2. Experimental setup

Wire shaped Nimonic 80A samples with 0.6 mm diameter and 70 mm length supplied by Böhler Edelstahl GmbH, are resistively volume heated as part of a fast capacitor discharge circuit (500 μF charged up to 5.5 kV). This technique is also commonly known as a fast ohmic pulse heating technique, and has been described in detail, e.g. in Ref. [2,3]. Time resolved measurements with sub-μs resolution of current through the specimen are performed with a Pearson probe, the voltage drop across the specimen is measured with knife-edge contacts (active length of 30–40 mm) and ohmic voltage dividers, radiance temperature of the sample at 1570 nm with an optical pyrometer (FWHM of interference filter 84 nm) and volume expansion of the wire by means of a fast acting CCD-camera. These measurements allow one to determine heat of fusion as well as heat capacity and electrical resistivity of Nimonic 80A as a function of temperature in the solid and in the liquid phase up to 2400 K. Thermal conductivity and thermal diffusivity is estimated via the Wiedemann–Franz law [4].

3. Results and discussion

Within this work all thermophysical properties were reported as function of true temperature. Due to the unknown emissivity, the radiance intensity of the pyrometer at the melting temperature (arithmetic mean value of solidus and liquidus temperature) of the investigated material was used for calibration. The temperature covered by the pyrometer at 1570 nm was approximately from 1100 up to 2400 K.

The used units for the given fits are: density: $[d] = \mathrm{kg\,m^{-3}}$; temperature: $[T] = \mathrm{K}$; resistivity: $[\rho] = \mu\Omega\,\mathrm{m}$; specific enthalpy: $[H_s] = \mathrm{kJ\,kg^{-1}}$; thermal conductivity: $[\lambda] = \mathrm{W\,K^{-1}\,m^{-1}}$; thermal diffusivity: $[a] = 10^{-6}\,\mathrm{m^2\,s^{-1}}$.

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Table 1
Material properties of Nimonic 80A

Composition (%)					Density (293 K) ($kg\,m^{-3}$)	T_{solid} (K)	T_{liquid} (K)
Ni	Cr	Ti	Al	Fe			
Balance	19.5	2.5	1.7	Max. 1.5	8152	1593	1638

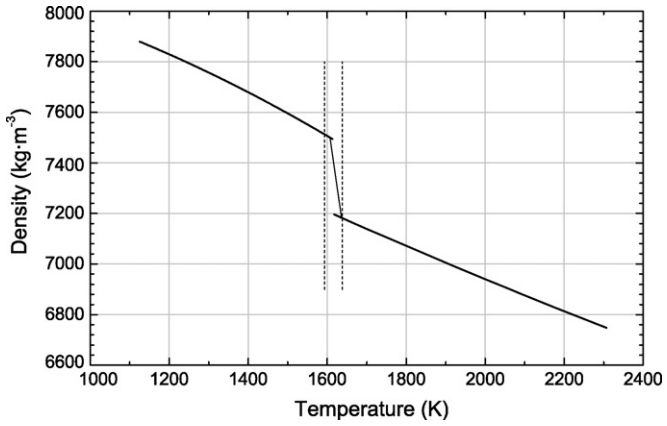

Fig. 1. Density in the solid and liquid state. Vertical dotted lines: solidus and liquidus temperature; bold lines: fit (1) for solid phase and fit (2) for liquid phase.

In Fig. 1, the density as a function of temperature is plotted for the solid and the liquid phase. In the temperature range $1100\,K < T < 1593\,K$ the following fit is obtained from pulse-heating measurements:

$$d(T) = 8251.0 + 0.0101T - 2.845 \times 10^{-4}T^2 \quad (1)$$

During melting the density decreases from 7545 to 7182 $kg\,m^{-3}$. The polynomial fit for the liquid phase ($1638\,K < T < 2300\,K$) is:

$$d(T) = 8475.5 - 0.8897T + 6.10 \times 10^{-5}T^2 \quad (2)$$

In Fig. 2, the mean value of the specific electrical resistivity with and without correction for volume expansion in the solid and liquid state is shown. The resistivity increases nearly linearly and can be calculated with the polynomial Eq. (3) in the temperature range $1200\,K < T < 1593\,K$ and with (4) for $1638\,K < T < 2400\,K$. At melting the resistivity with correction for volume expansion increases from 1.35 to 1.46 μΩ m.

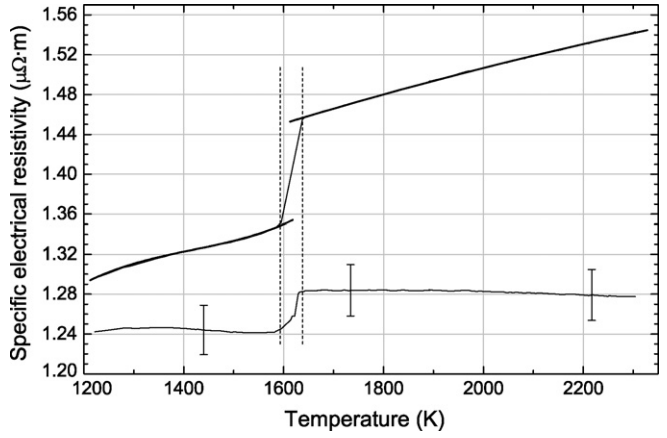

Fig. 2. Specific electrical resistivity with and without correction for volume expansion in the solid and liquid state. Vertical dotted lines: solidus and liquidus temperature; bold lines: fit (3) for solid phase and fit (4) for liquid phase.

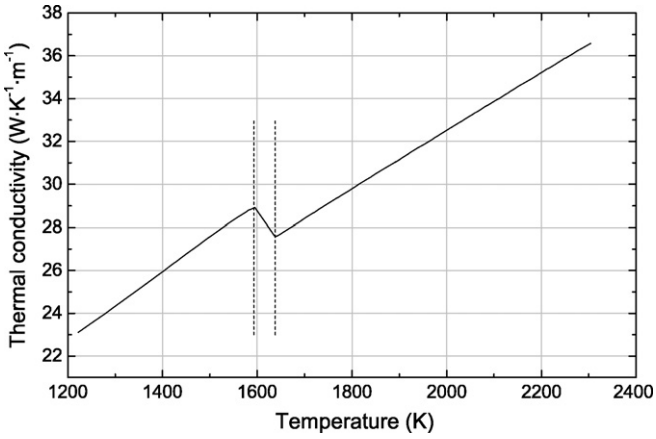

Fig. 3. Thermal conductivity in the solid and liquid state. Vertical dotted lines: solidus and liquidus temperature.

$$\rho(T)_{corr} = -1.942 + 6.71 \times 10^{-3}T - 4.663 \times 10^{-6}T^2 + 1.097 \times 10^{-9}T^3 \quad (3)$$

$$\rho(T)_{corr} = 1.125 + 2.55 \times 10^{-4}T - 3.2 \times 10^{-8}T^2 \quad (4)$$

The figure of specific enthalpy as a function of temperature is already given in paper [1]. For completeness the linear fits are summarized with (5) for the range $1200\,K < T < 1593\,K$ and (6) for the range $1638\,K < T < 2400\,K$.

$$H_s(T) = -382.0 + 0.7137T \quad (5)$$

$$H_s(T) = -322.6 + 0.8466T \quad (6)$$

The thermal conductivity λ was calculated using the correlation of Wiedemann–Franz (7).

$$\lambda = \frac{L\,T}{\rho_{corr}} \quad (7)$$

The literature value for the Lorenz–number L differs with the author. For all calculations in this article a literature value of $L = 2.45 \times 10^{-8}\,V^2/K^2$was used; if theoretical models give a better matching value of L for this material one has to adapt the given fits to it. For the solid phase, the linear Eq. (8) describes thermal conductivity in the temperature range $1200\,K < T < 1593\,K$ and in the liquid phase one has to calculate with Eq. (9) in the range $1638\,K < T < 2300\,K$ (Fig. 3).

$$\lambda(T) = 3.71 + 0.0159T \quad (8)$$

$$\lambda(T) = 5.33 + 0.0136T \quad (9)$$

The slope from the linear fit of $H(T)$ can be read as specific heat capacity c_p and was used to calculate the thermal diffusivity a. The corresponding fits (10) for $1200\,K < T < 1593\,K$ and

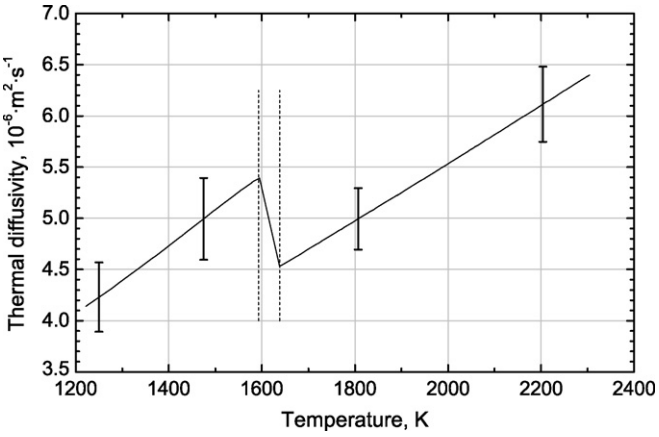

Fig. 4. Thermal diffusivity in the solid and liquid state. Vertical dotted lines: solidus and liquidus temperature.

Table 2
Uncertainties for the measured data

Measured data	Uncertainty ($k = 2$)/%
Specific enthalpy in the solid phase H_s	±5
Specific enthalpy in the liquid phase H_s	±4
Specific electrical resistivity with initial geometry $\rho_{ig}(T)$	±2
Specific heat capacity c_p in the solid phase	±6
Specific heat capacity c_p in the liquid phase	±4
Thermal diffusivity a in the solid phase a	±8
Thermal diffusivity a in the liquid phase a	±6

(11) for 1638 K $< T <$ 2300 K describe the curves in Fig. 4.

$$a(T) = -0.06 + 3.43 \times 10^{-3} T \quad (10)$$

$$a(T) = -0.08 + 2.81 \times 10^{-3} T \quad (11)$$

All given uncertainties are values for a single experiment calculated with quantities of type B using Guide to the Expression of Uncertainty in Measurement (GUM), [5]. The fact, that the given mean values are derived from seven experiments is not taken into account for this budget and can lead to lower values of uncertainty for the mean values.

The calculation for the uncertainty of the specific heat capacity is now based on an article of Matus [6] and this is the reason for the lower values concerning previous published data for this material. For the density measurement with the fast CCD-camera, no GUM conform uncertainty budget is calculated until now. Consequently, there are also no error bars for the calculated properties electrical resistivity with correction for volume expansion and thermal conductivity.

The uncertainties reported in this paper are assigned expanded uncertainties with a coverage factor of $k = 2$ and correspond to a coverage probability of approximately 95% (Table 2).

4. Conclusion

This paper adds to data reported in a previous work on thermophysical properties of solid and liquid Nimonic 80A at high temperatures. The properties density, specific electrical resistivity corrected for expansion, thermal conductivity and thermal diffusivity in the investigated temperature range are reported for temperatures between 1100 and 2400 K. A detailed uncertainty budget based on the guide to the expression of uncertainty in measurements has been calculated.

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