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Thermophysical properties of Alloy 709

D.S. Smith [1], N.J. Lybeck, J.K. Wright, R.N. Wright *

Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415, USA

HIGHLIGHTS

- Thermal diffusivity, specific heat capacity and thermal expansion were measured.
- Previously unknown thermophysical properties for Alloy 709 are presented.
- Properties do not vary significantly for the three heats of Alloy 709 tested.
- Results compare well with those of similar austenitic stainless steels.

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ABSTRACT

Alloy 709 (UNS S31025) has shown enhanced performance, particularly in creep strength, over current generation high temperature structural materials, specifically Type 316 stainless steel and Grade 91. Accurate knowledge of the thermal properties of the material is important to design efficient systems and to allow calculation of thermally induced stresses and stress gradients. Thermal diffusivity, thermal conductivity, specific heat capacity, and coefficients of thermal expansion have been determined for Alloy 709 as a function of temperature in the range of 20–850 °C. The results do not vary significantly for the three heats of Alloy 709 tested, and compare well with those reported for other high Cr, high Ni austenitic stainless steels. Deviations from monotonic behavior have been observed for the specific heat capacity and to a lesser degree for the thermal conductivity, while the thermal expansion and thermal diffusivity increase nearly linearly with increasing temperature.

1. Introduction

Improved structural material performance is one of the key pathways to improving the economics of modern fast reactors. Advanced materials have the potential to allow higher operating temperatures enabling higher thermal efficiency and power output, longer component lifetimes, and improved material reliability. Improved properties may also permit thinner sections and reduced thermal gradients in components. Advanced materials development efforts during the past several years have led to the downselection of an advanced austenitic stainless steel, Alloy 709, for structural applications (Yamamoto et al., 2012). Alloy 709 (UNS S31025) is a niobium-strengthened austenitic stainless steel alloy strengthened by nanoscale carbides and based on a Fe-20Cr-25Ni alloy composition (Staubli et al., 2003; Kikuchi et al., 1987; Takahashi et al., 1988; Quality et al., 1996). These advanced structural alloys have shown enhanced performance, particularly in creep strength, over current generation high temperature structural materials, specifically Type 316 stainless steel and Grade 91 (Yamamoto et al., 2012). This alloy is currently covered by an ASTM standard (A213/A213M-17, 2017) and an ASME Boiler and Pressure Vessel (B&PV) Code Case ASME Boiler and Pressure Vessel Code Case 2581 (2017) for use in steam generator tubes. The plate product form is currently being characterized for potential use in other nuclear components.

Accurate knowledge of the thermal properties of the material is important to design efficient systems and to allow calculation of thermally induced stresses and stress gradients that can determine service life. A series of experiments will be reported here to determine the thermal diffusivity, thermal expansion behavior and specific heat capacity of three different heats of Alloy 709 plate at temperatures ranging from 25 °C to 850 °C. These measured values allow calculation of the thermal conductivity for the three heats of material.

* Corresponding author.
E-mail address: Jill.Wright@inl.gov (R.N. Wright).
[1] Present address: Colorado School of Mines, Golden, CO 80403, USA.

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2. Experimental procedure

2.1. Materials

Three heats of Alloy 709 produced by Carpenter Technologies were tested. The material was in plate form and chemistry of the three heats is shown in Table 1, along with the chemistry ranges of the alloy specification for TP310MoCbN (UNS S31025) in A213/A213M-17 (2017).

2.2. Measurement methods

Thermal diffusivity was measured at room temperature and at 50 °C intervals over a temperature range from 50 °C to 850 °C using a Netzsch Model LFA457 laser flash system following the procedures of ASTM E2585-09 (2015). Specimens nominally 12.75 mm in diameter and 3 mm thick were heated in a SiC holder with a measurement thermocouple attached to the holder adjacent to the specimen. The temperature ramp rate was 5 °C/min and the temperature of the specimen was equilibrated to a constant value of ±1 °C from the measurement temperature prior to firing the laser pulse. Three measurements were made at each temperature for each specimen. The measurement uncertainty is estimated to be ±3%.

The specific heat capacity was measured following ASTM E1269-11 (2011). This method compares the heat flow for a standard sample of sapphire to heat flow into the sample of interest at a constant heating rate. A Netzsch Model DSC 404 differential scanning calorimeter was used over the temperature range of 30 °C to 850 °C at a constant heating rate of 10 °C/min in helium; data was recorded at 1 °C intervals. The measurement uncertainty for this method is estimated to be ±5%.

Cylindrical specimens measuring nominally 6 mm in diameter and 12.5 mm in length were measured and massed to determine room temperature density. Measurements were repeated four times, allowing average and standard deviation values to be calculated. The same specimens were then used for linear thermal expansion measurements.

Linear thermal expansion measurements ($\Delta L/L_0$) were carried out using a Netzsch Model DIL 402 dilatometer over the range of 30–850 °C and data was recorded at 1 °C intervals. Measurements were performed according to ASTM E228-11 (2011) at a heating rate of 3 °C/minute. The uncertainty of measurements is estimated to be ±5% below 500 °C and ±3% above 500 °C.

3. Results and discussion

3.1. Thermal diffusivity

The thermal diffusivity measured using the laser flash method is shown as a function of temperature in Fig. 1. The general trend is a monotonic increase in diffusivity with temperature, although there is some variation among the different specimens. A second order polynomial was fit to the data and used to calculate the average diffusivity at 25 °C intervals listed in Table 2. The behavior of Alloy 709 is similar to that reported for other austenitic stainless steels reported in the ASME B&PV Code, Division II, Part D (ASME Boiler and Pressure Vessel Code, 2017), as shown in Fig. 2.

3.2. Specific heat capacity

The specific heat capacity of the three heats of Alloy 709, as well as the average values, are shown as a function of temperature in Fig. 3. Values below the minimum measurement temperature of 30 °C were estimated by fitting a 6th order polynomial to all the data in the temperature range of 30–180 °C, and extrapolating to 20 °C (also in Fig. 3). The 30–180 °C temperature range provides sufficient information to accurately extrapolate the data trend. The extrapolated and average values are given at 25 °C intervals in Table 2.

The specific heat capacity increases rapidly at low temperatures, then more gradually between about 100 and 550 °C, at which point it increases dramatically over a range of about 100 °C. Above about 625 °C, the data is not monotonic, but is roughly constant with temperature. Two of the heats are very similar, but the third appears notably higher; however, variations are less than the "within laboratory" mean repeatability given in ASTM E1269-11 (2011). An anomaly at about 600 °C has been reported in some studies for austenitic stainless steels (Hanitzsch, 1987; Dobrosavljević and Maglić, 1992; Dimitrov et al., 1981) and other Ni-Cr-Fe alloys (Rabin et al., 2013; Richter, 1991, 1986) and is attributed to very short-range (~10Å) ordering of Ni_3Cr or Ni_3Fe (Rabin et al., 2013; Richter, 1986, 1988).

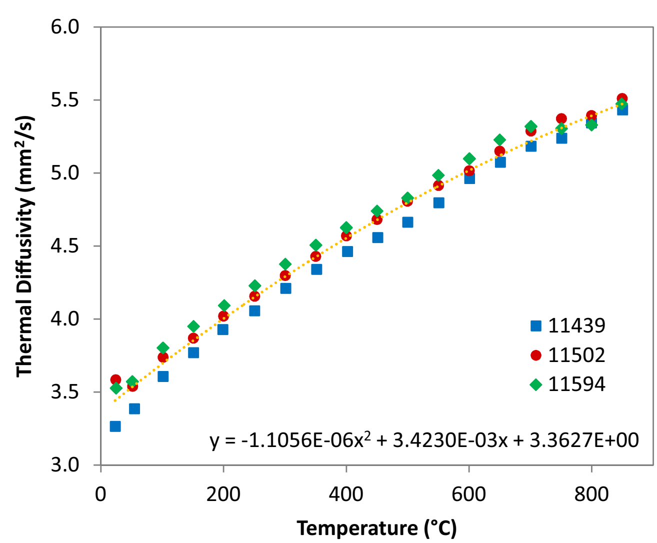

Fig. 1. Thermal diffusivity as a function of temperature with the second order polynomial fit to the combined data set.

Table 1
Chemical Composition of Alloy 709 (Weight Percent).

	Source	Ni	Cr	Mo	Mn	Ti	Nb	Si	C	S	N	P	B
min	ASTM 213	23.0	19.5	1.0	–	–	0.10	–	–	–	0.10	–	0.002
max		26.0	23.0	2.0	1.5	0.2	0.40	1.00	0.10	0.030	0.25	0.030	0.010
11439		25.03	19.99	1.50	0.89	0.01	0.26	0.40	0.068	<0.001	0.16	<0.005	0.0040
11502		25.09	19.80	1.50	0.90	<0.01	0.26	0.40	0.067	<0.001	0.15	<0.005	0.0043
11594		25.01	19.89	1.51	0.90	<0.01	0.25	0.39	0.078	0.0006	0.14	<0.005	0.0037