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Specific Heat, Electrical Resistivity, and Linear Thermal Expansion of the Magnesium Alloy AE42 Measured by Subsecond Pulse Heating[1]

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Magnesium alloy AE42 (Mg with 4% Al and 2% rare earths) is used for the production of high-temperature creep-resistant castings. Its thermophysical properties are used as input parameters for the numerical simulation of the casting process by finite methods. Measurements of specific heat capacity, electrical resistivity, and linear thermal expansion of the magnesium alloy AE42 in the temperature range from 550 to 840 K by a transient technique are presented and discussed. Tubular specimens were Joule-heated from room temperature up to melting within 500 ms by a large current pulse. The current and the voltage drop along a defined portion of the specimen were measured by a fast precision data acquisition system. Temperature measurements were made with a high-speed broad-band infrared pyrometer. Thermal expansion was measured by a polarized-beam Michelson-type interferometer.

KEY WORDS: electrical resistivity; high temperature; magnesium alloy AE42; specific heat capacity; thermal expansion.

1. INTRODUCTION

In recent years, the automotive, electronic, and aerospace industries have continued their efforts to develop new materials for light-weight components. Magnesium alloys are among these new materials having a low

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density with reasonable strength and well established process routes like high-pressure die casting. The magnesium alloy AE42 (Mg with nominally 4% Al and 2% rare earths) is a creep-resistant alloy for high temperature applications (e.g. engine blocks of lawn mowers).

Numerical simulations of industrial processes have increased tremendously in the past years. In the foundry industry, the simulation of mold filling by the melt flow and its subsequent solidification is currently state of the art [1]. However, more reliable thermophysical data are required for these techniques such as heat capacity, thermal conductivity, and density, especially for newly developed alloys and mold materials.

New opportunities for process control arise with the numerical simulation of distortion and stress during the production of castings [2]. For these calculations, precise data of thermal expansion and stress–strain relations are necessary. These data are required in the temperature range from solidification down to lower temperatures, where the alloy has gained enough strength to bear internal stresses.

Magnesium alloys are difficult to investigate at high temperatures, because specimens tend to oxidize and the vapor pressure of magnesium is very high. Subsecond measurement techniques overcome these problems due to their rapid heating periods and short measurement times.

Measurements of specific heat capacity, electrical resistivity, and linear thermal expansion of magnesium alloy AE42 in the temperature range from 550 to 840 K have been made. Tubular specimens were electrically self-heated from room temperature up to melting within 500 ms by a large current pulse. Time-resolved measurements of the current and the voltage drop along a defined portion of the specimen were performed. Temperature measurements were made with a high-speed broad-band infrared pyrometer pointing at a small sighting hole in the specimen. Thermal expansion was measured by a fast polarized-beam Michelson-type interferometer.

2. EXPERIMENTAL

The pulse-heating system uses heavy-duty batteries to supply a current of up to 4000 A. The current through the tubular specimen is determined by measuring the voltage across a standard resistor connected in series with the specimen. The voltage across the middle part of the specimen is measured between spring-loaded knife-edge probes. They are mounted on stationary clamps via a lever mechanism that allows the probes to move in the axial direction to follow the axial thermal expansion of the specimen during the experiment.

The temperature is measured by means of a high-speed broad-band infrared pyrometer targeted at a small sighting hole machined through the wall of the specimen, thereby approximating a blackbody cavity. The target size of the pyrometer is 0.2 mm; the radiation is collected by an InGaAs-PIN photodiode and converted to voltage by precision amplifiers. As the pyrometer is slightly nonlinear, it has been calibrated in steps of 25 K by comparison with a blackbody radiator. A thermocouple inserted in the blackbody has been calibrated by the Austrian Metrological Institute (BEV, Vienna).

The experimental quantities are recorded simultaneously every 0.5 ms by a data acquisition system with sample-and-hold amplifiers with full-scale resolution of 16 bit. A detailed description of the construction and operation of the pulse-heating system is given in earlier publications [3, 4].

The interferometer is a high-speed polarized-beam modified Michelson-type interferometer similar to the one described by Miiller and Cezairliyan [5]. It uses a phase-quadrature detector allowing distinguishing between expansion and contraction. The four signals of the interferometer detector are recorded simultaneously by the data acquisition system, but 10 times faster than the electrical and pyrometer signals. A detailed description of the construction and operation of the interferometer is given in an earlier publication [6].

3. MEASUREMENTS

A first series of 15 measurements of specific heat capacity and electrical resistivity was performed on five tubular specimens. The dimensions of the tubes were as follows: length, 75 mm; outside diameter, 9.0 mm; and wall thickness, 1.15 mm. For temperature measurements, a rectangular hole (0.5 mm × 1.6 mm) was machined through the wall. Material was removed on the remaining length to achieve a constant cross section over the full length.

A second series of 15 measurements to obtain thermal expansion was performed on a second set of five specimens. In addition to the blackbody hole, these specimens had two polished parallel flat surfaces that were used as end mirrors for the interferometric measurements. For this series, no voltage probe knife edges were contacted to the specimens.

All specimens were machined from primary high-purity ingots supplied by Hydro Magnesium Norway. The results of the chemical analysis by ICP spectroscopy are given in Table I. The average heating rate during the experiments was approximately $1300\,\mathrm{K}\cdot\,\mathrm{s}^{-1}$. Each specimen was preheated several times for annealing to achieve a state close to thermal equilibrium. Because of the high vapor pressure of magnesium and

Table I. Chemical Composition of the Specimens from Magnesium AE42 Alloy in mass%; Mg is the Balance

Al	Mn	Zn	Si	Fe	Ni	Cu
3.74	0.22	0.003	0.01	< 0.0005	< 0.001	0.0008
Ce	**La**	**Nd**	**Pr**	**Sm**	**Dy**	**Be**
0.87	0.43	0.26	0.08	< 0.01	< 0.01	0.0007

the problems associated with chemical reactions, all experiments were performed in an argon environment (1.5 bar).

The specific heat was computed from the time-dependent current, voltage, heating (cooling) rate, and the mass of the specimen; electrical resistivity was obtained from the current, voltage, and the geometry (length, cross section) of the specimen. Thermal expansion was computed from the phase shift of the four voltage signals of the interferometer. Details regarding the construction and operation of the measurement system, the methods of measuring experimental quantities, and other pertinent information, such as formulation of relations for properties, etc., are given in earlier publications [3, 4, 6].

4. RESULTS

The variation of the specific heat capacity as a function of temperature is shown in Fig. 1 and Table II. The reproducibility of the measurements for an individual specimen is 0.5%, and that between different specimens is 2.0%. The least-squares fit with the specific heat capacity c_P versus temperature T data, in the range $570\,\mathrm{K} < T < 840\,\mathrm{K}$, is

$$c_P = -9898.6 + 48.741T - 0.071427T^2 + 3.4820 \times 10^{-5}T^3, \qquad (1)$$

where c_P is in $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$ and T is in K.

The electrical resistivity data were first computed with room temperature specimen dimensions and in a second step – with the interferometer data – corrected for thermal expansion. All reported data of electrical resistivity are corrected for thermal expansion and relate to the true geometry of the specimen at high temperature. The variation of electrical resistivity as a function of temperature is shown in Fig. 2 and Table II. The reproducibility of the measurements for an individual specimen is 0.4%, and that between different specimens is 1.5%. The least-squares fit to the electrical resistivity ρ_{el} versus temperature T data, in the range

Table II. Experimental Results on Specific Heat Capacity, Electrical Resistivity (Corrected for Thermal Expansion), and Linear Thermal Expansion of Magnesium Alloy AE42

Temperature (K)	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Electrical resistivity ($\mu\Omega \cdot m$)	Linear thermal expansion[a] (%)
550		0.130	0.73
560		0.131	0.76
570	1126	0.133	0.79
580	1137	0.135	0.82
590	1146	0.136	0.85
600	1154	0.138	0.88
610	1159	0.140	0.92
620	1163	0.141	0.95
630	1166	0.143	0.98
640	1167	0.144	1.01
650	1168	0.146	1.05
660	1168	0.148	1.08
670	1167	0.149	1.11
680	1166	0.151	1.15
690	1165	0.153	1.18
700	1164	0.154	1.21
710	1164	0.156	1.25
720	1164	0.157	1.28
730	1165	0.159	1.32
740	1166	0.161	1.35
750	1169	0.162	1.39
760	1174	0.164	1.43
770	1180	0.166	1.46
780	1187	0.167	1.50
790	1197	0.169	1.54
800	1209	0.170	1.58
810	1223	0.172	1.61
820	1240	0.174	1.65
830	1260	0.175	1.69
840	1283	0.177	1.73
850			1.77

[a]Reference temperature = 293 K.

$550\,\mathrm{K} < T < 840\,\mathrm{K}$, is

$$\rho_{el} = 0.04046 + 1.6244 \times 10^{-4} T, \tag{2}$$

where ρ_{el} is in $\mu\Omega \cdot$ m and T is in K.

The variation of the linear thermal expansion as a function of temperature is shown in Fig. 3 and Table II. The reproducibility of the measurements for an individual specimen is 0.3% and that between different

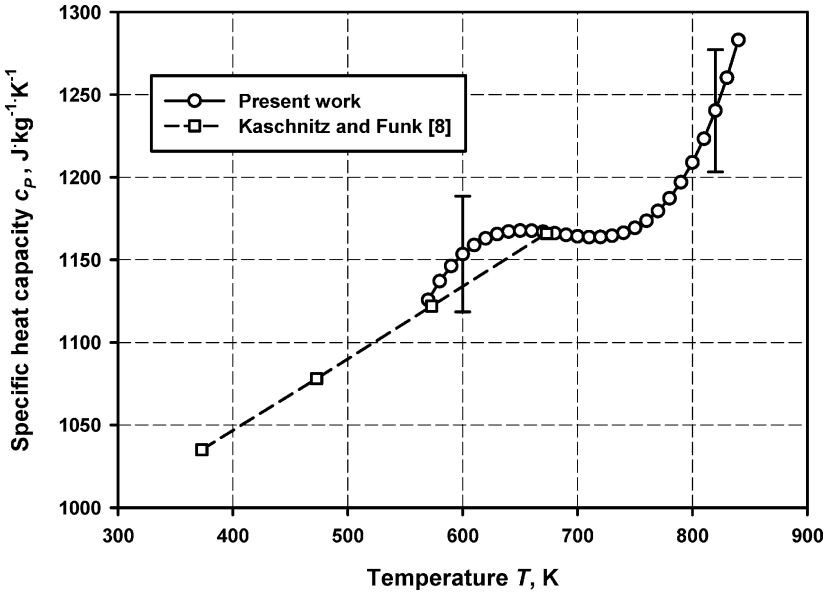

Fig. 1. Specific heat capacity c_P of the magnesium alloy AE42 as a function of temperature T.

specimens is 0.8%. The least-squares fit with the linear thermal expansion $\Delta l/l_0$ versus temperature T data, in the range $550\,\mathrm{K} < T < 850\,\mathrm{K}$, is

$$\Delta l/l_0 = 2.7249 \times 10^{-3}(T-293) + 1.3771 \times 10^{-7}(T-293)^2 + 1.2199 \times 10^{-9}(T-293)^3, \quad (3)$$

where $\Delta l/l_0$ is in %, T is in K, and reference temperature is 293 K.

5. ESTIMATE OF UNCERTAINTIES

Detailed descriptions of the estimation of the uncertainty of the specific heat capacity, electrical resistivity, and linear thermal expansion are given in earlier publications [3, 4, 6]. Additional contributions to the uncertainty budget are the increased nonlinearity of the pyrometer and a larger size-of-source effect, as the interference filter is removed to achieve a higher sensitivity of the pyrometer. The uncertainty in the measured values of specific heat capacity is calculated as recommended in EA-4/02 [7] and is estimated to be less than ±3% for the specific heat capacity, ±2% for the electrical resistivity, and ±3 to 5% for the linear thermal expansion

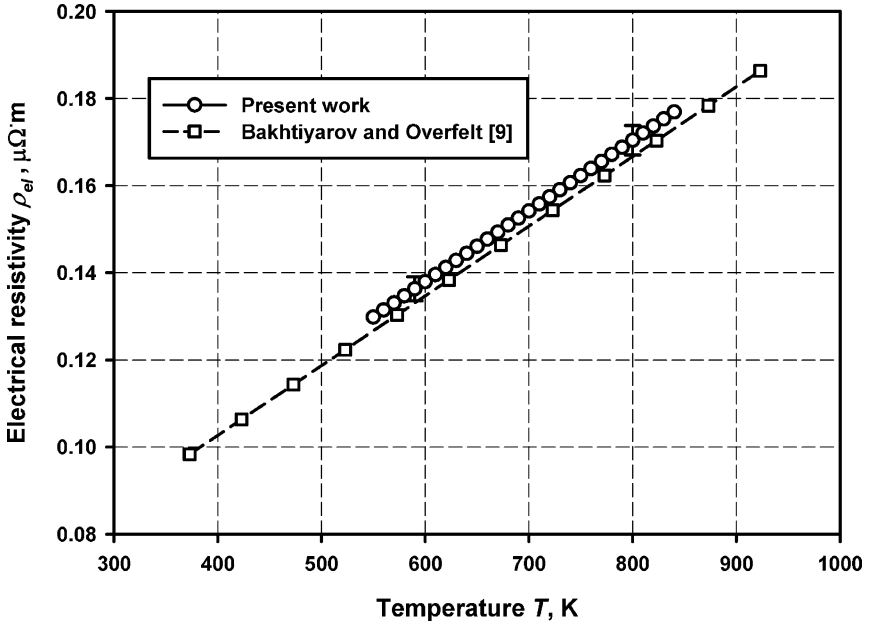

Fig. 2. Electrical resistivity ρ_{el} of the magnesium alloy AE42 as a function of tempera ture T.

in the entire temperature range. The reported uncertainties are based on the standard uncertainty multiplied by a coverage factor of 2, providing a level of confidence of approximately 95%.

6. DISCUSSION

There is very little information in the public literature on thermophysical properties of the magnesium alloy AE42. Figure 1 shows the results of the present work on specific heat capacity compared to data obtained by a differential scanning calorimeter [8], published by the same research group. The results are in agreement for the overlapping temperature range. The slight s-shape of the function may be a result of the high heating rate, where solution processes in the premelting region do not have enough time to fully develop.

Figure 2 shows the results of the present work on electrical resistivity in comparison with data obtained by a rotational inductive measurement technique [9]. These values are approximately 2% lower, but there is agreement within the respective measurement uncertainties. One has also

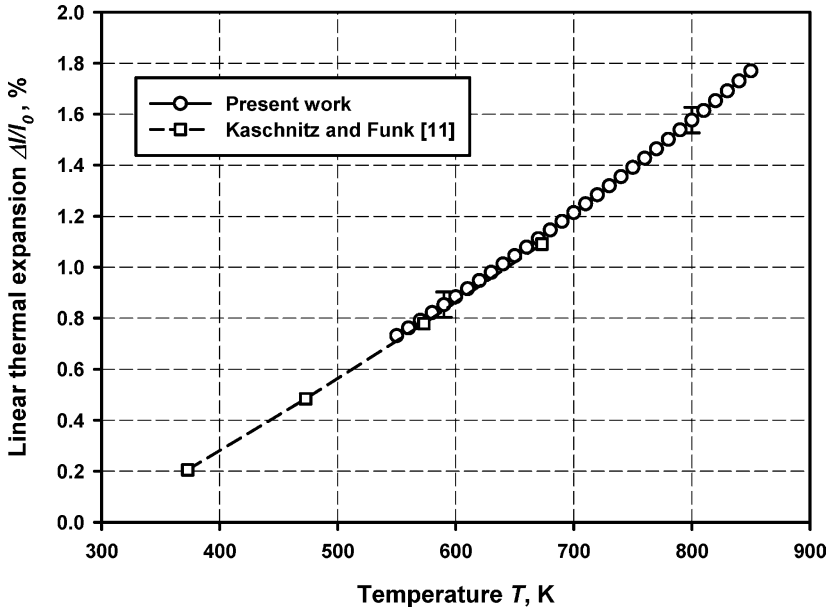

Fig. 3. Linear thermal expansion $\Delta l/l_0$ of the magnesium alloy AE42 as a function of temperature T.

to consider that the electrical resistivity as a transport property is very sensitive to the chemical composition and microstructure of the alloy, which is, of course, not exactly the same. Additional results on electrical resistivity are published in Ref. 10, which are calculated from room temperature values. Unfortunately, they are only presented in a graphical format, but they also agree within the reading limits of the graph in Ref. 10 with the results of the present work.

Figure 3 shows the results on the linear thermal expansion of the present work in comparison with data obtained by a pushrod dilatometer [11], published by the same research group. The results also agree very well in the overlapping temperature range.

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