Experimental study of the thermophysical properties for aluminum-magnesium alloy AMg3

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Abstract. The thermal diffusivity ($\alpha$), the thermal coefficient of linear expansion ($\alpha$), the isobaric heat capacity ($c_p$) and the fusion enthalpy ($\Delta H$) of aluminum-magnesium alloy AMg3 were investigated by laser flash method, dilatometric method and method of differential scanning calorimetry in the temperature range of 300–773…1000 K. The thermal conductivity ($\lambda$) has been calculated from the measurement results. The estimated errors of the obtained data were 2–5%, 3–5%, 2–3% and $(1.5–2.0)\cdot10^{-7}$ K$^{-1}$ for $\alpha$, $\lambda$, $c_p$ and $\alpha$, respectively. Approximation equations and a table of reference values for the temperature dependence of the studied properties have been obtained.

1. Introduction

Alloys of aluminum with magnesium AMg, called magnalium, weld well, have high corrosion resistance and toughness, and the highest fatigue limit of all aluminum alloys. A magnalium AMg3 is used in various areas of industrial and economic activities for the manufacture of welded and riveted structures resistant to corrosion. In particular, it is used in nuclear power engineering as a cladding material for fuel rods for research water-cooled reactors. Foreign analogues of the alloy: AlMg3 (Sweden), A95154 (USA), AlMg2 (Germany). The operational mechanical properties of AMg aluminum alloys are well known in the literature, however, there are practically no data on their thermophysical properties [1]. The existing data are fragmentary, obtained in limited temperature ranges and with an unknown error. From a fundamental point of view, the results on the thermophysical properties of alloys obtained on samples from one initial ingot are of great value. In this case, the uncertainty associated with the different composition and structure of the alloy is eliminated. Such values make it possible to trace the correlation of properties and create a basis for predicting the performance characteristics of alloys using a minimum set of experimental data.

The aim of this work was to obtain reliable experimental data on thermal conductivity, thermal diffusivity, specific heat, enthalpy of melting and thermal expansion of the AMg3 alloy in a wide temperature range.

2. Experimental technique and description

The composition of the alloy [1] is given in Table 1. Samples for experiments have been cut from a one common ingot. The density at room temperature ($\rho_0$) was determined by direct measurements of geometric dimensions and mass and it amounted to 2.64±0.03 g/cm$^3$.

Thermal diffusivity ($\alpha$) AMg3 was determined by the method of laser flash on an automated device LFA-427 [2] from NETZSCH (Germany) in an atmosphere of static additional purified argon.
(Ar 99.992 vol. %) in the temperature range 300–773 K. A brief description of the measurement method is presented in works [3, 4]. The computational model proposed by Cape and Lehman [5], taking into account radiation heat losses, was used. A correction was introduced for the finite duration of the laser pulse and its real shape [6]. For the experiments, two samples were taken in the form of cylinders with diameter of 12.6 mm and thicknesses of 2.5 and 3.0 mm. To improve the emissivity, a micron layer of graphite was applied to the end surfaces of the samples. The estimated error in measuring the thermal diffusivity for solid samples on the LFA-427, confirmed by measurements on the reference materials inconel and pyroceram, is 2–4% depending on the temperature.

The experimental study of the specific heat capacity (c_p) of AMg3 was carried out by the differential scanning calorimetry (DSC). The measurements were carried out on a DSC 404 F1 [7] device manufactured by NETZSCH using platinum crucibles with corundum inserts in the temperature range of 300–823 K at a heating rate of 10 K/min in a flowing argon atmosphere (20 ml/min), the purity of which was 99.992 vol.%. A preliminary thermal analysis of the alloy under study was carried out: a sample with a mass of 10.75 mg was heated from room temperature to 1000 K, after which the value of the melting enthalpy (ΔH) was determined. To measure the specific heat, a sample weighing 54.85 mg was used. Stainless steel 12Kh18N10T with a mass of 98.64 mg was taken as a calibration sample. The estimated error of the obtained data on c_p, confirmed by experiments with reference sapphire and platinum samples, is 2–3%.

Thermal coefficient of linear expansion of the alloy α(T) = 1/\(L_o \left( \frac{\partial L}{\partial T} \right)_p \), where L is the length of the sample at temperature T, \(L_o\) is the length at 293.15 K, was investigated on a horizontal dilatometer DIL-402C [8] manufactured by NETZSCH. Sample AMg3 was made in the form of a cylinder Ø6×25 mm. The measurements were carried out in a static helium atmosphere (He 99.995 vol.%) in the range of 300–773 K in the heating–cooling mode at a rate of 2 K/min and isothermal holding for 30 min at the maximum temperature. The description of the measurement technique and the processing of the results is described in detail in [9, 10]. Comparison of the measurement results for pure Pt and Cu with the most reliable literature data from [11, 12] showed that the difference in the α values did not exceed 2% or (1.5–2.0)×10^{-7} K^{-1}.

### Table 1. Chemical composition (wt. %) of the AMg3 alloy [1].

| Element | Fe | Si | Mn | Ti | Al | Cu | Mg | Zn | Impurities |
|---------|----|----|----|----|----|----|----|----|------------|
|         | < 0.5 | 0.5–0.8 | 0.3–0.6 | < 0.1 | 93.8–96.0 | < 0.1 | 3.2–3.8 | < 0.2 | 0.1 |

The results of the specific heat of the AMg3 alloy were approximated in terms of the specific heat of pure metals, taking into account the content of impurities. The computational model proposed by Cape and Lehman [5], taking into account radiation heat losses, was used. A correction was introduced for the finite duration of the laser pulse and its real shape [6]. For the experiments, two samples were taken in the form of cylinders with diameter of 12.6 mm and thicknesses of 2.5 and 3.0 mm. To improve the emissivity, a micron layer of graphite was applied to the end surfaces of the samples. The estimated error in measuring the thermal diffusivity for solid samples on the LFA-427, confirmed by measurements on the reference materials inconel and pyroceram, is 2–4% depending on the temperature.

### 3. Results and discussion

Thermal analysis of the AMg3 alloy by the DSC method showed that at temperatures above 850 K two peaks were observed on the DSC-signal, indicating the occurrence of phase transformations of the first kind in the alloy (Figure 1). The alloy melted in the temperature range of 850–940 K. The temperatures and enthalpies of transitions are given in Table 2. \(T_1\) and \(T_2\) are the temperatures of the phase transition onset determined from the first and second peaks, respectively, \(ΔH_1\) is the phase transition enthalpy due to the first peak, \(ΔH\) is the integral enthalpy of phase transitions (based on the total area of two peaks). The latter value is the enthalpy of melting of the AMg3 alloy.

Figure 2 shows the measurement results of the specific heat obtained with three successive heating in the range of 300–823 K. As can be seen from the graph, our data on c_p at the second and third heating were reproduced among themselves within the measurement error. The results for the first heating differed from the subsequent two heating. This is due to the fact that during the first heating, the studied alloy was annealed with the removal of absorbed substances from the surfaces and the stress relief.

The experimental data approximation of the second and third heating in terms of the specific heat of the AMg3 alloy gave the following equation:
where \( c_p \) in J/(g K), the root-mean-square deviation of the experimental points from (1) is 0.67%.

**Table 2.** Temperatures and enthalpies of phase transformations in the AMg3 alloy.

| Heating | \( T_1 \), K | \( \Delta H_1 \), J/g | \( T_2 \), K | \( \Delta H \), J/g |
|---------|-------------|-----------------|-------------|-----------------|
| 1-st    | 858.8       | 4.89            | 894.6       | 390.7           |
| 2-nd    | 858.8       | 11.89           | 889.6       | 386.1           |
| 3-rd    | 858.8       | 12.09           | 889.1       | 388.1           |

Figure 3 shows the measurement results of the thermal diffusivity temperature dependence for two AMg3 samples. The data were obtained with heating in the range of 300–773 K. It can be seen from the figure that the results for both samples were reproduced among themselves within the measurement error, and there was a gentle maximum on the \( a(T) \) curve near a temperature of 630 K. The approximation of the experimental data gave the following equation:

\[
a(T) = 37.493 + 0.0773 T - 6.129 \cdot 10^{-5} T^2,
\]  

where \( a \) is in mm\(^2\)/s, \( T \) is in K. The root-mean-square deviation of the experimental points from (2) does not exceed 0.65%.

Thermal expansion measurements were carried out in the temperature range 300–773 K. By approximating the \( \alpha \) data for three heating-cooling cycles, the following equation was obtained:

\[
\alpha(T) = 18.3101 + 4.036 \cdot 10^{-2} T - 6.489 \cdot 10^{-5} T^2 + 4.96 \cdot 10^{-8} T^3,
\]  

where \( \alpha \) is in 10\(^{-6}\) K\(^{-1}\). The recommended values for the relative elongation \( \varepsilon \) were calculated by integrating equation (3) with the condition that the value of \( \varepsilon(T) \) is equal to zero at room temperature and the following equation was obtained:

\[
\varepsilon(T) = \left[ -6648.428 + 18.31 T + 2.018 \cdot 10^{-2} T^2 - 2.16 \cdot 10^{-5} T^3 + 1.2 \cdot 10^{-8} T^4 \right] \cdot 10^{-6}.
\]  

The obtained curves \( \alpha(T) \) and \( \varepsilon(T) \) are shown in Figure 4.

Thus, experiments have shown that at temperatures below 800 K, the change in all properties is monotonic, without jumps or kinks (Figures 2–4), and results are also well reproduced in heating-cooling cycles. This indicates the invariability of the phase state and structure of this magnalium.

Using the primary values of thermal diffusivity, \( a \), approximation dependence (1) for the specific heat \( c_p \) and data on density (\( \rho \)), the thermal conductivity (\( \lambda \)) of AMg3 was calculated using the well-
known formula $\lambda = a \rho c_p$. The density $\rho$ was found from the relative elongation measurement results $\varepsilon(T)$ and the density at room temperature $\rho_0$. The thermal conductivity calculation results are shown in Figure 5. The error in calculating the thermal conductivity is 3–5%, taking into account the errors of the values $a$, $\rho$ and $c_p$.

An approximation of the thermal conductivity calculated data gave the following equation:

$$\lambda(T) = 77.986 + 0.1991 T - 9.011 \cdot 10^{-5} T^2,$$

where $\lambda$ is in W/(m K). The root-mean-square deviation of the calculated points from (5) is 0.61%.

For all investigated properties, a table of recommended values in the temperature range of 300–773 K was compiled using approximation equations (1)–(5) (Table 3).
Table 3. Smoothed values of the measured thermophysical properties of the AMg3 alloy

| T, K | α, mm²/s | λ, W/(m K) | c_p, J/(g K) | α, 10⁻⁶ K⁻¹ | ε, 10⁻⁶ |
|------|----------|------------|-------------|-------------|---------|
| 300  | 55.15    | 129.60     | 0.898       | 25.92       | 177.18  |
| 400  | 58.59    | 143.20     | 0.939       | 27.25       | 2837.40 |
| 500  | 60.79    | 155.00     | 0.989       | 28.47       | 5622.60 |
| 600  | 61.78    | 165.00     | 1.047       | 29.88       | 8536.87 |
| 700  | 61.53    | 173.19     | 1.113       | 31.77       | 11614.09|
| 773  | 60.58    | 178.04     | 1.167       | 33.64       | 13998.74|

Conclusions

New experimental data have been obtained on thermal diffusivity, thermal conductivity, heat capacity, enthalpy of melting and thermal expansion of the AMg3 alloy in the temperature range 300–773...1000 K. Based on the measurement results, a table of the recommended dependences of the thermophysical properties of the AMg3 alloy on temperature has been developed.

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