Thermophysical properties of ML5 casting magnesium alloy

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Abstract. In the present work thermal conductivity, thermal diffusivity, heat capacity, melting enthalpy, and linear thermal expansion coefficient of ML5 casting magnesium alloy were investigated in the temperature range of 298–670…925 K. The measurements were performed using laser flash method, dilatometric method and differential scanning calorimetry on the samples made from the one initial material. Using the obtained data, the temperature dependence of the thermal conductivity was determined. For all studied properties the approximation equations were obtained which can be used for various scientific and practical applications.

1. Introduction

The ML5 magnesium alloy (American analogues are AZ81, AZ91) with good casting and high mechanical properties is widely used to manufacture the aircraft parts and the loaded parts of medium and complex configuration for operation in atmospheric conditions. However, tabular data on its thermophysical properties are fragmentary and obtained, as a rule, at room temperature with an unknown error. At the same time to optimize the manufacturing processes of various technological parts, the high-precision initial data on the thermophysical properties of structural materials are required. In this regard, the purpose of this work is an experimental study of the transport, caloric and volumetric properties of ML5 alloy in the wide temperature range.

2. Experimental technique

To study the thermophysical properties samples were fabricated in the form of cylinders of various sizes from the same rod of ML5 alloy. Table 1 shows the content of the main components in the ML5 alloy according to the Russian standard GOST 2856-79.

The thermal diffusivity (a) of the alloy was measured by a laser flash method using LFA-427 installation in the static atmosphere of purified argon (99.998 vol. %) in the temperature range of 298–677 K. A brief description of the measurement method and the experimental setup may be found in [1]. A cylinder with a diameter of 12.6 mm and a thickness of 2.3 mm was taken for experiments. The external surfaces of the sample were covered by micron layer of graphite to increase the absorption coefficient of the radiation. The thermal diffusivity measurement error for solid samples on LFA-427 was 2–5% depending on temperature.

The measurements of the specific heat (c_p) and the enthalpy of phase transition (ΔH) of the alloy were carried out by differential scanning calorimeter (DSC). The experiments were performed on the DSC 404 F1 setup using platinum crucibles with corundum inserts at a heating rate of 10 K/min in the flowing (20 ml/min) argon atmosphere. The alloy melting ΔH value was found by thermal analysis of
the sample weighing of 12 mg in the temperature range of 298–925 K. The specific heat measurement of the alloy was carried out in experiments with the sample weighing of 37 mg in the range of 320–670 K. 12Kh18N10T stainless steel sample weighing of 82 mg was used as a standard material for $c_p$. The estimated error of the obtained data confirmed by experiments with reference samples of sapphire and platinum was 2–3%.

The linear thermal expansion coefficient (LTEC, $\alpha$) of ML5 alloy was investigated on horizontal dilatometer DIL-402C with the holder and pushrod made of sintered corundum. The measurements were carried out in the temperature range of 298–673 K in a helium atmosphere (99.995 vol. %) when heating-cooling of the furnace with the rate of 2 K/min and isothermal holding for 30 minutes at maximum temperature The sample with the length of 25 mm and diameter of 6 mm was studied. The measurement procedure and the LTEC processing results were described in [2] in detail. The measurement error of DIL-402C confirmed by experiments with pure platinum and copper was 3% or $2\times10^{-7}$ K$^{-1}$.

Table 1. The content of the main components in the ML5 alloy.

| Content of elements, wt. % | Mg     | Al  | Zn  | Mn     |
|---------------------------|--------|-----|-----|--------|
|                           | 89.1–92.15 | 7.5–9.0 | 0.2–0.8 | 0.15–0.5 |

3. Results and discussion

Thermal analysis (figure 1) on the DSC calorimeter shows two peaks in the DSC curve at temperatures above 700 K. The first peak (with low amplitude) begins at $T_1 = 703$ K and, apparently, corresponds to a solid-phase transformation. The second peak (large amplitude) at $T_2 = 825$ K is due to the onset of alloy melting, i.e. $T_2$ is a solidus point. Based on area of second peak the melting enthalpy $\Delta H$ of ML5 alloy is determined to amount to 220 J g$^{-1}$. In [3], melting enthalpy $\Delta H$ and $c_p$ of AZ91 magnesium alloy (ML5 alloy analogue) were measured by DSC method on the DSC 404C Pegasus setup. The values for $\Delta H$, $T_1$ and $T_2$ were found to be 272 J g$^{-1}$, 705 and 738 K, respectively.

![DSC signal in the phase transition region of ML5 alloy.](image-url)
Figure 2. Temperature dependence of the heat capacity.

1 – data for AZ91 alloy [3], 2 – data for pure Mg, 3 – our results for ML5 alloy.

Figures 2 and 3 present our measurement results on the specific heat capacity and the thermal diffusivity of pure magnesium (purity 99.95 mass. %) and ML5 alloy in comparison with published data for AZ91 alloy [3, 4]. It can be seen that the results on the specific heat of ML5 coincide with the data for both pure Mg and AZ91 within $c_p$ measurement error; moreover, the alloys have almost identical slopes of their $c_p(T)$ curves (see figure 2).

The approximation of the experimental data on the specific heat has given the following equation:

$$c_p(T) = 0.787 + 5.626 \times 10^{-4} T, \quad 298 \leq T \leq 670 \text{ K},$$

where $c_p$ is in J (g K)$^{-1}$. The root-mean-square deviation of the experimental points from (1) does not exceed 0.3%.

The situation is different in the case of the thermal diffusivity. The results for pure Mg differ from the data for both alloys quantitatively, the differences are 50–70% (see figure 3), and qualitatively, by different signs of the temperature coefficient. As expected, the transport properties are more sensitive to the composition of the material, in contrast to the caloric properties. The thermal diffusivity in [4] was determined by the Angstroms method with the relative error of 2%. The maximum difference between our curve $a(T)$ and the data [4] does not exceed 7.6%.

The approximation of the experimental data on the thermal diffusivity has given the following equation:

$$a(T) = 9.175 + 0.0678 T - 4.091 \times 10^{-5} T^2, \quad 298 \leq T \leq 677 \text{ K},$$

where $a$ is in mm$^2$ s$^{-1}$. The root-mean-square deviation of the experimental points from (2) does not exceed 0.6%.

LTEC and relative expansion ($\varepsilon$) measurements have shown that in the region of 460 K a small kink is observed on $a(T)$ curve, which is well reproduced (figure 4). The measurement results of the linear thermal expansion coefficient, obtained during coolings, were combined. Their approximation by the least squares method has yielded the following equations:

$$a(T) = 20.51 + 2.697 \times 10^{-2} T - 2.036 \times 10^{-5} T^2, \quad 293 \leq T \leq 461 \text{ K},$$

$$a(T) = 16.66 + 2.638 \times 10^{-2} T - 9.987 \times 10^{-7} T^2, \quad 461 \leq T \leq 673 \text{ K},$$

where $a$ is in $10^{-6}$ K$^{-1}$. 
Figure 3. Temperature dependence of the thermal diffusivity.

1 – data for AZ91 alloy [4], 2 – data for pure Mg,
3 – our results for ML5 alloy, 4 – equation (2).

Recommended values for the relative expansion ε were calculated by integrating equations (3), (4) with the condition that ε equals to zero at 293.15 K (figure 4).

Figure 4. Thermal expansion of ML5 alloy: 1 – LTEC, 2 – relative expansion.

Using the measured values of the thermal diffusivity, approximation dependences (1), (3) and (4) for the specific heat capacity, relative expansion and density at room temperature ($\rho_{293 \text{K}} = 1810 \text{ kg m}^{-3}$ [5]), the thermal conductivity ($\lambda$) of the alloy was calculated using the known formula: $\lambda = a \rho c_p$. 
The error in the calculation of the thermal conductivity was 3–5% taking into account the uncertainties of \( a, \rho \) and \( c_p \). The approximation of the obtained thermal conductivity data has given the following equation:

\[
\lambda(T) = 9.153 + 0.1358 T - 5.853 \times 10^{-3} T^2, 298 \leq T \leq 677 \text{ K},
\]

where \( \lambda \) is in W (m K\(^{-1}\)). The root-mean-square deviation of the calculated points from (5) does not exceed 0.7%.

The thermal conductivity results are presented in figure 5 in comparison with \( \lambda \) data for AZ91 alloy, calculated using \( \rho, c_p \) and \( a \) values from [3, 4]. The maximum difference between our curve \( \lambda(T) \) and the \( \lambda \) data for AZ91 alloy does not exceed 10%.

![Figure 5. Temperature dependence of the thermal conductivity.](image)

1 – data for AZ91 alloy, 2 – our results for ML5, 3 – equation (5).

**Conclusion**

New experimental data on the thermal conductivity, thermal diffusivity, heat capacity, enthalpy of melting, and thermal expansion of ML5 magnesium alloy in the temperature range of 298–670...925 K have been obtained. The results have been compared with data on the properties of AZ91 alloy, which is the American analogue of ML5 alloy. Except for \( \Delta H \) the differences in thermophysical properties of these alloys do not exceed 10% in the studied temperature range. For all studied properties the approximation equations have been presented.

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**References**

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