Thermophysical properties of Inconel 718 alloy

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Abstract. The thermal diffusivity ($a$), linear thermal expansion coefficient ($\alpha$), isobaric heat capacity ($c_p$) and phase transition enthalpy ($\Delta H$) of Inconel 718 superalloy were determined by laser flash method, dilatometric method and differential scanning calorimetry in the temperature range of 298–1375…1473 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 $(1.5–2)\times10^{-7}$ K–1 for $a$, $\lambda$, $c_p$ and $\alpha$, respectively. The approximation equations and a table of reference values for the studied properties have been obtained.

1. Introduction
The superalloy Inconel 718 based on Ni, Cr and Fe is widely applied in modern manufacturing for the aerospace and nuclear industries. In particular, the alloy is actively used to manufacture the parts of gas turbines, elements and components of rocket and aircraft engines, spacecraft and nuclear reactors. However, currently its thermophysical properties have not been studied sufficiently. For material science the data on the thermophysical properties of the alloys obtained on samples from a single initial ingot represent great value. In this case the uncertainty associated with the different composition and structure of the alloy is eliminated. Such data make it possible to trace the correlation of properties and form the basis for predicting the performance characteristics of the alloys from the minimum experimental data set. In this regard, the purpose of this work was an experimental study of the transport, caloric and thermal properties of the alloy Inconel 718 in a wide temperature range.

2. Experimental technique
To study the thermophysical properties of the alloy, samples were fabricated in the form of cylinders of various sizes from the common bar Inconel 718. Immediately before and after the experiments the mass of the samples and their geometrical dimensions were measured, from which the alloy density at room temperature ($\rho_0$) was determined: $\rho_0 = 8.17\pm0.08$ g/cm$^3$.

The thermal diffusivity coefficient ($a$) of the alloy under study was measured by a laser flash method using LFA-427 installation [1] in the atmosphere of static purified argon (99.998 vol. %) in a temperature range of 298–1375 K. A brief description of the measurement method and the experimental setup is described in [2, 3]. Thermal expansion of the sample was not taken into account. The error in determining thermal diffusivity for solid samples on LFA-427 is 2–5% depending on temperature.

The measurements of the specific heat ($c_p$) and enthalpy of phase transitions ($\Delta H$) of the Inconel 718 alloy were carried out by differential scanning calorimetry (DSC). The experiments were performed on a DSC 404 F1 unit [4] using platinum crucibles with corundum liners at heating rate of
10 K/min in a flow-through (20 ml/min) argon atmosphere. The ΔH values of phase transitions, including melting of the alloy, were found by thermal analysis of the sample weighing of 36 mg in the temperature range of 298–1673 K. The specific heat measurement of the alloy was carried out in an experiment with a sample weighing of 160 mg in the range of 298–1373 K. 12Kh18N10T stainless steel sample (also 160 mg) was used as a standard 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 the Inconel 718 alloy was investigated on horizontal dilatometer DIL-402C [5] with a holder and a pushrod made of sintered corundum. The measurements were carried out in the temperature range of 298–1473 K in a helium atmosphere (99.995 vol. %) with heating-cooling of the furnace at a rate of 2 K/min and 30 minutes isothermal holding at maximum temperature. The description of the measurement procedure and the processing of LTEC results is presented in [6] in detail. The measurement accuracy of DIL-402C confirmed by experiments with pure platinum and copper was 3% or \((1.5–2) \times 10^{-7} \text{ K}^{-1}\).

3. Results and discussion

The measurements results of \( c_p \), \( \alpha \) and \( a \) are shown in Figures 1–4, from which it can be seen that the hysteresis of the studied properties was observed in the heating-cooling cycles. Thermal analysis showed that at the temperature above 800 K two peaks on the DSC signal, indicating the solid-state phase transformation occurrence in the alloy, were observed. The temperatures and enthalpies of transitions are given in Table 1. At temperatures below 800 K and above 1200 K the change of all properties was monotonous (Figures 1–4).

As it can be seen from Figure 1, our \( c_p \) data obtained in successive thermal cycles reproduced among themselves within the estimated measurement error. On the heating curve phase transitions in the solid state are due to two peaks. The first peak is located at lower temperatures and is much smaller in amplitude than the second longer peak. In the cooling curves the reverse phase transition in the solid state manifested already in the form of one larger in amplitude and less extended peak as compared to the heating curves. In the region of the phase transitions the heat capacity takes an effective value, which reflects the heat capacity of phases and the heat of structural transformation.

| Table 1. Enthalpies and temperatures of phase transition onset |
|---------------------------------|--------------|-------------|
| Phase transitions               | \( T, K \)   | \( \Delta H, \text{J/g} \) |
| Heating: 1st peak              | 823.15       | 4.45        |
| Heating: 2nd peak              | 993.15       | 23.27       |
| Cooling                        | 1052.15      | 21.10       |
| Solid-liquid transition        | 1537.65      | 196.85      |

Figure 2 shows our recommended \( c_p \) values along with known literature data. It can be seen that our measured \( c_p \) values of the Inconel 718 alloy agree with the data of [7] within the total measurement errors excluding the region near phase transitions and they also agree well with the results of [8] in the temperature range of 298–900 K. In [9], the values obtained in a fairly narrow temperature range begin to diverge from our data above 485 K beyond the limits of total measurement errors.

The approximation of the experimental data on the specific heat gave the following equations:

\[
c_p(T) = 0.362 + 2.118 \times 10^{-4} \, T, \quad 298 \leq T \leq 800 \, \text{K}, \tag{1}
\]

\[
c_p(T) = -0.946 + 0.295 \times 10^{-2} \, T - 1.379 \times 10^{-6} \, T^2, \quad 800 \leq T \leq 900 \, \text{K}, \tag{2}
\]

\[
c_p(T) = 0.639 - 3.355 \times 10^{-6} \, T, \quad 1070 \leq T \leq 1361 \, \text{K}, \tag{3}
\]

where \( c_p \) is in J/(g K), \( T \) is in K. The root-mean-square deviations of the experimental points from (1), (2) and (3) do not exceed 0.43, 0.36 and 0.51%, respectively.
Figure 1. Specific heat of Inconel 718 alloy: 1 – 1st heating, 2 – 1st cooling, 3 – 2nd heating, 4 – 2nd cooling.

Figure 2. Comparison of the specific heat results of Inconel 718 alloy: 1 – [7], 2 – [8], 3 – [9], 4 – our recommended data.

Figure 3 shows LTEC results of two experiments, from which it can be seen that the obtained data have good reproducibility. In the region of high temperatures above 700 K the sample undergoes a phase transformation, which is accompanied by leaps in LTEC curve. The phase transition intervals were 760–1180 K during heating and 725–1075 K during cooling, within which the thermal expansion coefficient $\alpha$, like $c_p$, has no physical meaning. It can be noted that the nature of LTEC change in the phase transformation region is almost identical to the signal obtained from the DSC device (Figure 1).

The linear thermal expansion coefficient results obtained during heating were combined and least-squares processed by the following polynomials:

$$\alpha(T) = 10.747 + 0.01T - 4.2 \times 10^{-6} T^2, \quad 298 \leq T \leq 760 \text{ K},$$  \hspace{1cm} (4)

$$\alpha(T) = 13.491 + 0.007T, \quad 1180 \leq T \leq 1473 \text{ K},$$  \hspace{1cm} (5)

where $\alpha$ is in $10^{-6} \text{ K}^{-1}$. The root-mean-square deviations of the experimental points from (4) and (5) do not exceed 2.08 and 1.64%, respectively.

The results on thermal diffusivity are shown in Figure 4 in comparison with the data from [10]. As it can be seen from the figure, our data up to 700 K are consistent with the results of [10] within the measurement error. The thermal diffusivity of the Inconel 718 alloy in [10] was also measured by a laser flash method. The thermograms were processed taking into account the finite duration of the laser pulse and the heat losses in the form of radiation. As it can be seen, our results were obtained in the widest range of temperatures. The structural transformation of the alloy manifested itself as leaps and kinks in the temperature dependence $a(T)$ in the range of 980–1173 K.

The approximation of the experimental data gave the following equations:

$$a(T) = 1.901 + 0.0034 T - 4.475 \times 10^{-7} T^2, \quad 298 \leq T \leq 980 \text{ K},$$  \hspace{1cm} (6)

$$a(T) = 2.233 + 0.0021 T - 1.85 \times 10^{-8} T^2, \quad 1173 \leq T \leq 1375 \text{ K},$$  \hspace{1cm} (7)

where $a$ is in $\text{mm}^2/\text{s}$. The root-mean-square deviations of the experimental points from (6) and (7) do not exceed 0.5 and 0.4%, respectively.

Using the measured values of thermal diffusivity $a$, approximation dependencies (1), (3) for the specific heat capacity $c_p$ and the density data ($\rho$) the thermal conductivity coefficient ($\lambda$) of the alloy has been calculated by the known formula:

$$\lambda = a \rho c_p,$$  \hspace{1cm} (8)
where the density $\rho$ was found from LTEC measurement results and the density at room temperature $\rho_0$. The error in the calculation of thermal conductivity is 3–5% taking into account the errors of $a$, $\rho$ and $c_p$.

The approximation of the calculated thermal conductivity data gave the following equations for the low-temperature and high-temperature phases:

$$\lambda(T) = 5.291 + 0.0152 T + 1.382 \times 10^{-6} T^2, \quad 298 \leq T \leq 800 \text{ K},$$

$$\lambda(T) = 11.75 + 0.011 T - 9.327 \times 10^{-7} T^2, \quad 1173 \leq T \leq 1375 \text{ K},$$

where $\lambda$ is in W/(m K). The root-mean-square deviations of the calculated points from (9) and (10) do not exceed 0.5 and 0.4%, respectively.

Table 2 shows the recommended values for $a$, $\lambda$, $c_p$ and $\alpha$ of Inconel 718 alloy.

### Table 2. Recommended values of Inconel 718 alloy thermophysical properties

| $T$, K | $a$, mm$^2$/s | $\lambda$, W/(m K) | $c_p$, J/(g K) | $\alpha$, 10$^{-6}$ K$^{-1}$ |
|-------|--------------|------------------|----------------|-----------------------------|
| 298   | 2.87         | 9.94             | 0.425          | 13.36                       |
| 400   | 3.18         | 11.59            | 0.447          | 14.09                       |
| 500   | 3.48         | 13.24            | 0.468          | 14.71                       |
| 600   | 3.77         | 14.91            | 0.489          | 15.25                       |
| 700   | 4.05         | 16.61            | 0.510          | 15.71                       |
| 800   | 4.32         | 18.34            | 0.531          | —                           |
| 1100  | 4.56         | 22.72            | 0.635          | —                           |
| 1200  | 4.77         | 23.61            | 0.635          | 21.23                       |
| 1300  | 4.98         | 24.47            | 0.635          | 21.88                       |
| 1400  | 5.19         | 25.32            | 0.634          | 22.52                       |

### Conclusion

New experimental data on thermal diffusivity, thermal conductivity, heat capacity, enthalpies of phase transitions and thermal expansion of Inconel 718 alloy in the temperature range 298–1375…1473 K were obtained. For all studied properties the approximation equations were presented and a table of recommended values was developed.
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