Heat capacity of Inconel 617 alloy

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Abstract. In the present article, the heat capacity of Inconel 617, one of the most promising superalloys, was investigated. The measurements were carried out in the temperature range from 300 to 1270 K of the solid state. The method of differential scanning calorimetry was applied using DSC 404 F1 Pegasus calorimeter. The estimated error of the received data was 2-4% depending on the temperature. The fitting equations for the temperature dependences of the heat capacity and the reference table of recommended values have been received for use in various engineering and scientific tasks.

1. Introduction
In recent years, the development of nickel-based superalloys has received specific attention due to their properties required for use at high temperatures above 1000 K. One of the most promising candidates in this context is Inconel 617 alloy, which has excellent characteristics, especially high resistance to oxidative processes at high temperatures, strength, and resistance to corrosion formations. The alloy is neutral to the exposure of a large number of chemicals; it lends itself well to processing and welding. In this connection, Inconel 617 has a very wide range of applications, namely, it is used as elements of combustion chambers of gas turbines, liners and adapters, pipes and fittings for pipelines that transport aggressive liquids and gases, units of installations for acid processing, air heaters, as well as helium heat exchangers in high-temperature nuclear reactors.

To date, the thermophysical properties of Inconel 617 alloy, in particular, the heat capacity, have been studied in a limited number of works. The heat capacity investigation of Inconel 617 was carried out only in works [1-4], however, measurements were performed by the authors of these articles on samples previously subjected to water quenching [1], annealing at high temperatures [1, 3, 4] including in air [2], thermal fatigue testing [2], and aging treatment [3]. However, the thermophysical and thermomechanical properties of alloys at high temperatures decisively depend on the initial microstructure and composition of the alloy, on the thermal stability of various precipitated phases that are formed during alloy production and operating conditions. Thus, this article aimed to experimentally study the heat capacity of Inconel 617 alloy in a wide range of temperatures of the solid state, including the phase transitions region.

2. Experimental technique
The heat capacity \( (c_p) \) of Inconel 617 superalloy was measured within the temperature range of 300-1270 K by the method of differential scanning calorimetry (DSC). The measurements were carried out using a DSC 404 F1 Pegasus calorimeter [5] at a heating rate of 10 K/min in the flow-through argon atmosphere (Ar flow rate was 20 ml/min). The sample of the alloy under study had a cylindrical shape...
up to 1.5 mm thick and 5 mm in diameter with a flat base for better thermal contact with the crucible bottom, in which it was placed during the experiment. The mass of the sample was weighed on AND GH-252 analytical balances [6] with an error of no more than 0.3 mg and equaled to 189.05 mg. The 12Kh18N10T stainless steel with a mass of 141.17 mg was used as a calibration sample for \( c_p \) calculation. The investigated specimen of Inconel 617 and calibration sample were placed in platinum crucible with corundum insert and covered with a platinum lid with a small orifice for argon access inside the crucible. Before carrying out each thermal cycle, the working volume of the installation was pumped out to a vacuum of about 1 Pa and washed several times with argon, whose purity was 99.992 vol.%. The main impurities were: \( O_2 - 0.0001\% \); \( N_2 - 0.0005\% \); \( H_2O - 0.0004\% \); \( CO_2 - 0.00002\% \); \( CH_4 - 0.0001\% \); and \( H_2 - 0.0001\% \). The measurement error of \( c_p \) for DSC 404 F1 setup is estimated at 2-4\% depending on the temperature, which was confirmed by experiments with reference samples of high-purity platinum and sapphire.

3. Results and discussion

The heat capacity measurement results of Inconel 617 alloy are presented in figure 1. It can be seen from the graph that the data obtained in successive heating-cooling thermal cycles are in very good agreement with each other, and reproduce within the limits of the estimated measurement errors.

![Graph](image_url)

**Figure 1.** The measured data of Inconel 617 heat capacity.

1 – 1-st heating; 2 – 2-nd heating; 3 – 1-st cooling; 4 – 2-nd cooling.

The thermophysical properties of Inconel 617 alloy at high temperatures decisively depend on the initial microstructure and composition of the alloy, on the thermal stability of various precipitates that are formed during alloy production, and operating conditions. In [4], devoted to the study of the thermophysical properties of the Inconel 617 alloy, based on the data of X-ray diffraction analysis (XRD), the presence of four different phases in the alloy was confirmed, namely solid solution \( \gamma \) (FCC, face-centered cubic lattice), ordered phase Ni3(Al, Ti) known as \( \gamma' \) phase (FCC), and also carbides of the types of MC \{ Nb, Ti)C \} and M23C6 (M = Cr, Fe, Mo). Figure 1 shows that in the
temperature range of ~770-935 K, a phase transformation occurs in the alloy under study, which is accompanied by a jump of \(c_p(T)\), while a small hysteresis of \(c_p\) is observed in the heating-cooling cycles. It follows from [4] that this feature is associated with the precipitation of \(\text{M}_{23}\text{C}_6\) carbide, in which the transition onset temperature was ~750 K, and the transition end temperature was ~940 K, which was established based on the DSC heating thermogram. Also in [4], it was revealed the presence of phase transformations occurring in the ranges of ~1053-1230 K and ~1250-1450 K, which relate to the dissolution of the \(\text{M}_{23}\text{C}_6\) and \(\gamma'\) phases, respectively. In our case, as can be seen from figure 1, no anomalies were detected in the temperature range of 935-1270 K, and \(c_p(T)\) dependence has a linear character. The heat capacity has not been determined in the temperature range of 790-900 K, since it represents the intrinsic heat capacity of the phase and the heat of the phase transformation.

Approximation of \(c_p\) experimental points of Inconel 617 alloy by the least-squares method gave the equations:

\[
c_p(T) = 0.3544 + 2.282 \times 10^{-4} T, \quad 300 \leq T \leq 790 \text{ K}, \quad (1)
\]

\[
c_p(T) = 0.5415 + 8.820 \times 10^{-5} T, \quad 900 \leq T \leq 1270 \text{ K}, \quad (2)
\]

where \(T\) is the temperature in K, \(c_p\) is heat capacity in J (g K)\(^{-1}\). The standard deviations of the experimental values from the approximation dependences (1) and (2) do not exceed 0.48% and 0.55%, respectively. Recommended data for \(c_p\) of investigated superalloy, obtained using equations (1) and (2), are presented in the table.

A comparison of experimental results on \(c_p\) of Inconel 617 alloy obtained in the present work with previously received literature data [1–4] is shown in figure 2.

![Figure 2. Comparison of the experimental results on heat capacity for Inconel 617 alloy.](image)

1 – [1]; 2 – [2]; 3, 4, 5, 6 – 1-st, 2-nd, 3-rd, 4-th heatings in [3], respectively; 7 – [4]; 8 – our recommended values.
Figure 3 shows that our data on $c_p$ of Inconel 617 practically coincide with the results of [1] in the range of 300-800 K before the onset of the phase transition, and within the total measurement error agree with them in the range of 970-1270 K after the phase transformation, and have a sharper character of change in $c_p(T)$. It should be noted that no phase transitions on $c_p(T)$ were noted in [1], even though the heat capacity in this work was measured by the DSC method; however, the sample of Inconel 617 was preliminarily annealed at 1400 K for 30 min and was subjected to water quenching before the main measurements. Therefore, the initial microstructure of the alloy, used to measure $c_p$ in [1], apparently, differs from the microstructure of the alloy studied in the present work. In our experiments, the investigated sample was annealed to 1273 K directly during the first heating of the DSC measurements in an argon atmosphere, after which the sample was kept isothermally at this temperature for 30 min, following by a segment of cooling to room temperature.

Starting from 400 K, the results of [2] are higher than our recommended values, and in the temperature range of 300-773 K, they coincide within the total measurement errors, however, above the phase transition temperature they go beyond the total measurement errors. This difference is because in [2] the sample was preliminarily annealed at 1450 K in air, slowly cooled to room temperature, and subjected to thermal fatigue testing, which included cyclic heating and cooling of the sample, as well as imitation of thixoforming of steels. The heat capacity measurements in [2] were carried out in a flowing nitrogen atmosphere. Thus, the strong oxidation of the Inconel 617 sample in [2] and the change in its initial microstructure due to the above procedures caused such a difference between the results of [2] and our measured values of $c_p$.

The data of [3] on $c_p$, obtained in four different heating cycles (see figure 2), are in good agreement with our data and coincide within the total measurement errors. The phase transformation in [3] occurs in the range of ~820-925 K, while in our case as well as imitation of thixoforming of steels – in the range of ~770-935 K. Even though in [3] and in our $c_p(T)$ curve, the regions of phase transitions are slightly shifted relative to each other, which can be explained by even an insignificant difference between the main components and the content of impurities in the alloys under study, the magnitude of the jumps in $c_p$ during the polymorphic transformation practically coincides. The maximum differences observed between the four different heating cycles in [3] are within a measurement error of ±5%. It was also established in [3] that the aging treatment of an alloy sample, which was held for up to 2000 h at 1023 K, did not have a significant effect on its thermophysical properties.

The results of [4] are below our recommended values and coincide within the total measurement errors in the temperature intervals of 300-800 K and 1050-1270 K. The data of [4] on $c_p$ were obtained by differentiating the approximation equations for the enthalpy increment ($\Delta H = H_f - H_{298}$) of the studied alloy. The value of $\Delta H$ was measured by drop calorimetry. It can be seen from figure 2 that in [4] $c_p(T)$ has two phase transformations at temperatures of ~1050 K and ~1150 K, which correspond to the dissolution of the $\text{M}_{23}\text{C}_6$ and $\gamma'$ phases. Also, in [4], there is no phase transition on $c_p(T)$, associated with the precipitation of $\text{M}_{23}\text{C}_6$ carbide, since it was impossible to find it based on the data on drop calorimetry, in contrast to DSC measurements. As stated in [4], this may be because this phase transition involves very small heat content.

| $T$, K  | $c_p$, J (g K)$^{-1}$ | $T$, K  | $c_p$, J (g K)$^{-1}$ |
|--------|----------------------|--------|----------------------|
| 300    | 0.423                | 900    | 0.621                |
| 400    | 0.446                | 1000   | 0.630                |
| 500    | 0.468                | 1100   | 0.639                |
| 600    | 0.491                | 1200   | 0.647                |
| 700    | 0.514                | 1270   | 0.654                |
| 790    | 0.535                | —      | —                    |

Table. The recommended values of the heat capacity of Inconel 617 alloy.
Conclusion
New experimental data on the heat capacity of Inconel 617 superalloy were obtained in the temperature interval 300-1270 K of the solid state. It was found that the alloy undergoes a phase transformation in the temperature range of 770-935 K, which is accompanied by a jump in the temperature dependence of the heat capacity, and a slight hysteresis in the heating-cooling cycles. The obtained experimental results were compared with the data, available in the literature.

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