Thermophysical properties of NP2 brand nickel

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Abstract. The heat capacity and the thermal diffusivity of NP2 brand nickel were investigated in the temperature interval 296–1000...1375 K of the solid-state, including the region of the magnetic phase transformation. Measurements were carried out on samples from one initial ingot by laser flash technique and method of differential scanning calorimetry using LFA-427 and DSC 404 F1 setups, respectively. The thermal conductivity was calculated based on the measured thermophysical properties. The estimated errors of the obtained results were 2–4%, 3–5%, and 2–3% for thermal diffusivity, thermal conductivity, and heat capacity, respectively. For investigated thermophysical properties the fitting equations and the reference table have been received.

1. Introduction
NP2 brand nickel, also known as semi-finished nickel, is a very malleable and ductile metal that is widely used in the manufacture of various semi-finished metal products, used in heavy engineering, instrumentation, electrical engineering, and radiological equipment. The metal has valuable performance characteristics (corrosion resistance, elasticity, weldability), which allow the material to be used in highly aggressive chemical environments, and to make it sealed containers and cells by argon-arc welding. The content of Ni is 99.5 wt.%, and the remaining 0.5 wt.% is mainly represented by the following impurities, namely, Cu, Fe, Mg, C, and Mn. Due to this chemical composition, the material is characterized by increased hardness, heat resistance, and toughness, which greatly expands the scope of application of this metal and its products. Nevertheless, there are practically no data in the literature on the thermophysical properties of NP2 brand nickel, and the available data were obtained at room temperature and with an unidentified error. The main attention is paid, as a rule, to the study of the thermophysical properties of pure metals, including H0 brand nickel (99.99 wt.%). However, the presence of impurities in a metal can significantly affect the thermophysical properties, which can slow down the implementation of new materials based on this metal and its alloys in different areas of industry. For materials science, data on the thermophysical properties of metals and 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 metal is eliminated. Such data 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. In this regard, the purpose of the present work was an experimental study of the thermophysical properties of NP2 brand nickel, performed on samples made of one billet.
2. Experimental technique
To measure the thermophysical properties of NP2 brand nickel, cylindrical samples of different sizes were made of one initial ingot. The density of nickel at room temperature \( \rho_0 \) was calculated from direct measurements of the sample mass and their geometric dimensions and was \( 8945 \pm 45 \text{ kg m}^{-3} \).

The experimental study of the heat capacity \( c_p \) of NP2 brand nickel was carried out by differential scanning calorimetry (DSC) using a DSC 404 F1 calorimeter [1] within the temperature interval of 300-1000 K at a heating-cooling rate of 10 K min\(^{-1}\) in the flowing-through atmosphere of high-purity argon (99.992 vol.%), whose flow rate was 20 ml min\(^{-1}\). A cylindrical nickel sample with a thickness of up to 1.5 mm and a diameter of 5 mm was made in such a way as to match the dimensions of the crucible, in which it was located during measurements of \( c_p \), and had the plane base for better thermal contact with the crucible bottom. To determine the heat capacity, a calibration sample of 12Kh18N10T stainless steel was used. The mass of nickel and calibration samples was weighed using AND GH-252 analytical balances [2] and was 174.02 mg and 141.17 mg, respectively. The analytical balances measurement error was no more than 0.3 mg. As a measuring cell for the investigated nickel specimen and calibration sample of 12Kh18N10T stainless steel, a platinum crucible with a corundum insert, which was covered with a platinum lid with a small orifice in the center for better evacuation and subsequent filling of the crucible volume with argon, was used. The setup working volume was pumped out to a vacuum of about 1 Pa and washed several times with argon before carrying out each thermal cycle. The estimated error of the received data on \( c_p \) was 2–3% depending on the temperature.

The thermal diffusivity \( a \) of the investigated sample of NP2 brand nickel was determined by the laser flash technique on an LFA-427 setup [3] with an error of 3–5% in the temperature range from 296 to 1375 K of the solid state. Measurements were carried out both in the heating and cooling cycle in a static atmosphere of high-purity argon (99.992 vol.%). Before the experiments, the installation working volume was pumped out to a vacuum of less than 1 Pa and washed several times with argon. Nickel specimen in the form of a cylinder with plane-parallel polished ends with a diameter of about 12.6 mm and a thickness of about 2.6 mm was used for experiments. A more detailed description of the thermal diffusivity measurement method for the standard cylindrical samples in a “free” state can be found in [4, 5]. According to the computational model proposed by Cape and Lehman [6] the thermal diffusivity was calculated. Corrections for the finite duration of the laser pulse and its real shape were obtained according to the procedure [7]. When determining the thermal diffusivity, the thermal expansion of nickel was taken into account, which was obtained in [8].

3. Results and discussion
The measurement results of \( c_p \) and \( a \) for NP2 brand nickel, data for pure nickel grade H0 (99.99 wt.%) obtained by us earlier, as well as recommended values of investigated properties for NP2 brand nickel are presented in figure 1, 2.

Figure 1 shows that \( c_p \) data obtained in successive thermal cycles are in very good agreement with each other and reproduce within the limits of the estimated measurement errors. It can be seen from the graph, the magnetic phase transition in the form of a sharp maximum is very clearly manifested in \( c_p(T) \) dependence. According to the DSC measurements, the Curie temperature \( T_c \) of NP2 brand nickel is 618.5 K and lies 10 degrees below \( T_c \) for H0 brand nickel (see figure 1), which is due to the high content of impurities (0.5 wt.%) in NP2 brand nickel. It is also seen from figure 1 that the results on \( c_p \) of the measured Ni coincide with the previously obtained data for pure Ni grade H0 within the measurement error.

Approximation of \( c_p \) experimental values of NP2 brand nickel by the least-squares method gave the following equations:

\[
c_p(T) = 0.6034 - 0.6139 \tau + 0.901 \tau^2 - 0.755 \tau^3, \quad 300 \leq T \leq 600 \text{ K}, \quad (1)
\]

\[
c_p(T) = 0.6175 - 1.87 \tau + 43.8 \tau^2 - 500.0 \tau^3, \quad 600 \leq T \leq 618.5 \text{ K}, \quad (2)
\]

\[
c_p(T) = 0.6282 + 4.125 \tau + 63.5 \tau^2 + 353.0 \tau^3, \quad 618.5 \leq T \leq 660 \text{ K}, \quad (3)
\]
\[
c_p(T) = 0.5794 - 1.92 \times 10^{-4} T + 1.666 \times 10^{-7} T^2, \quad 660 \leq T \leq 1000 \text{ K},
\]
where \( c_p \) is in J (g K)\(^{-1} \), \( \tau = (1 - T \cdot 618^{-1}) \), \( T \) is the temperature in K. The standard deviations of the experimental data from the fitting dependencies (1)–(4) do not exceed 0.26, 0.43, 0.32 and 0.45%, respectively.

As can be seen from figure 2, the thermal diffusivity experimental data of NP2 brand Ni obtained both during heating and cooling were well reproduced within the limits of the estimated measurement errors. It should be noted that in the \( (T) \) dependence, the magnetic phase transition was appeared in the form of a sharp minimum, in contrast to \( c_p(T) \). The results on \( a \) of NP2 brand Ni lie below the data measured by us earlier in [9] for Ni grade H0 (see figure 2). Nevertheless, the thermal diffusivity values of Ni, measured in the present article agree with the previously obtained data for pure Ni [9] within the measurement error.

The approximation of experimental points of \( a \) of the nickel under study by the least-squares method gave the expressions:

\[
a(T) = 40.311 - 1.116 \times 10^{-1} T + 1.8436 \times 10^{-4} T^2 - 1.314 \times 10^{-7} T^3, \quad 296 \leq T \leq 618.5 \text{ K},
\]

\[
a(T) = 29179.52 - 44.5032 T + 22.6364 \times 10^{-3} T^2 - 6.3726 \times 10^{-6} T^3, \quad 618.5 \leq T \leq 673 \text{ K},
\]

\[
a(T) = 8.24 + 8.78 \times 10^{-3} T - 3.39 \times 10^{-6} T^2, \quad 673 \leq T \leq 1375 \text{ K},
\]
where \( a \) is in \( 10^{-6} \text{ m}^2 \text{s}^{-1} \). The standard deviations of the experimental points from the equations (5)–(7) do not exceed 0.71, 1.06, and 0.43%, respectively.

The thermal conductivity (\( \lambda \)) of investigated NP2 brand Ni was calculated, using the known equation \( \lambda = a \rho c_p \), as well as experimental values on \( a \), approximation equations (1)-(4) for \( c_p \), and \( \rho \) data, which were calculated through the density at room temperature (\( \rho_0 \)) for NP2 brand Ni and the thermal expansion (\( e \)) for H0 brand Ni, measured using a DIL-402C dilatometer in [8], according to the equation \( \rho(T) = \rho_0 (1 + e(T))^{-3} \). It should be noted that \( c_p \) of NP2 brand Ni was extrapolated to 1350 K to calculate \( \lambda \) above 1000 K. In this case, the values of \( c_p \) for NP2 brand Ni obtained in this way above 1000 K coincide with the experimental results for H0 brand Ni obtained within a wider temperature range. The thermal conductivity error increased to 3-5% due to \( c_p \) and \( \rho \) errors. The calculated \( \lambda \) data of NP2 brand nickel were approximated by the least-squares method; the corresponding third-degree polynomials are presented below:

\[
\lambda(T) = 109.18 - 1.816 \cdot 10^{-4} T + 2.923 \cdot 10^{-4} T^2 - 2.157 \cdot 10^{-7} T^3, \quad 296 \leq T \leq 618.5 \text{ K}, \quad (8)
\]

\[
\lambda(T) = 53.07 - 5.88 \cdot 10^{-3} T + 2.535 \cdot 10^{-5} T^2 - 7.4 \cdot 10^{-9} T^3, \quad 618.5 \leq T \leq 1375 \text{ K}, \quad (9)
\]

where \( \lambda \) is in W (m K)^{-1}. The standard deviations of received thermal conductivity values from the approximations (8)-(9) do not exceed 0.68 and 1.04%, respectively. The Table presents the recommended data for \( c_p, a, \) and \( \lambda \) of investigated NP2 brand nickel, obtained using equations (1)-(9).
Table. The recommended values of NP2 brand nickel thermophysical properties.

| $T$, K | $c_p$, J (g K)$^{-1}$ | $a$, $10^{-6}$ m$^2$ s$^{-1}$ | $\lambda$, W (m K)$^{-1}$ |
|-------|---------------------|-----------------|-------------------|
| 300   | 0.423               | 19.9            | 75.2              |
| 400   | 0.466               | 16.8            | 69.5              |
| 500   | 0.514               | 14.2            | 64.5              |
| 600   | 0.586               | 11.3            | 58.9              |
| 618.5 | 0.619               | 10.7            | 57.6              |
| 700   | 0.527               | 12.7            | 58.8              |
| 800   | 0.532               | 13.1            | 60.8              |
| 900   | 0.542               | 13.4            | 62.9              |
| 1000  | 0.554               | 13.6            | 65.1              |
| 1100  | 0.570               | 13.8            | 67.4              |
| 1200  | 0.589               | 13.9            | 69.7              |
| 1300  | 0.611               | 13.9            | 72.0              |
| 1375  | 0.630               | 13.9            | 73.7              |

Conclusion
New experimental data on the heat capacity, thermal diffusivity, and thermal conductivity of NP2 brand nickel were received within the temperature range of 300-1375 K. The behavior of the temperature dependence of the investigated thermophysical properties in the region of the magnetic phase transition was studied. It was found that the presence of impurities in NP2 brand nickel does not significantly affect the thermophysical properties, however, a small shift of the Curie temperature by 10 K on the temperature dependence of the heat capacity was observed.

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