Critical indexes of the nickel thermal diffusivity

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Abstract. Using the laser flash method, the thermal diffusivity (a) of nickel was measured in the temperature range of 300–1680 K with a detailed study of the region near the Curie temperature $T_C = 628$ K. The initial experimental data in the field of magnetic phase transformation were processed by the scaling dependence, and the critical thermal diffusivity indexes ($\alpha$, $\alpha'$) were obtained below and above $T_C$: $\alpha = 0.86$ and $\alpha' = 0.26$, which in absolute value significantly exceed the critical heat capacity index. The possible reasons for this difference have been briefly discussed.

1. Introduction
The study of heat transfer processes in metals near magnetic disordering is of particular interest in solid-state physics. Magnetic phase transformations are accompanied by sharp peaks on the temperature curve of many thermophysical properties: specific heat, compressibility, thermal expansion, electrical and magnetic susceptibility, etc. Various phenomenological and microscopic approaches exist for describing critical phenomena [1–3]. However, almost all classical theories lead to results that strongly disagree with experimental data, and there are no exact solutions for model systems in the three-dimensional case [1]. Most theories of critical phenomena predict power-law dependences of the investigated properties on the reduced temperature ($\varepsilon$) in the region of magnetic phase transformations:

$$M(T) = \begin{cases} A'|\varepsilon|^\alpha, & T < T_C \\ A|\varepsilon'|^{\alpha'}, & T > T_C \end{cases}$$

(1)

where $M$ is a physical quantity, $A'$, $A$, $\alpha'$, $\alpha$ are constants, $\varepsilon$, $\varepsilon'$ are critical indexes, $\varepsilon = (T - T_C)/T_C$. In particular, the critical index $\alpha$ lies in the range of -0.08 ... -0.12 [4] for the specific heat ($c_p$) of metals. Near the critical point, an anomaly is also observed in thermal diffusivity (a), which has an inverse temperature dependence of the heat capacity [4]. Since thermal diffusivity is related to specific heat through thermal conductivity ($\lambda$) by the simple relation $\lambda = a \rho c_p$ (where $\rho$ is the density) most authors believe that the critical behavior of $a$ should be described by the same critical index as $c_p$, since the anomalous part of $\lambda$ is usually weakly expressed [4]. However, this assumption has not been discussed in detail so far.

The aim of this work was an experimental study of nickel thermal diffusivity in a wide temperature range and a determination of critical indexes of $a$ using the scaling approach (1).
2. Experimental technique

The thermal diffusivity of nickel was determined by the laser flash method [5] on an automated LFA-427 setup in the temperature range of 300–1680 K with a detailed study of the critical region 580–690 K. The measurement results are shown in figure 1. The Curie temperature was \( T_C = 628 \pm 5 \) K.

For the experiments, nickel of the N0 grade (99.99 wt. %) in the form of a disk with a diameter of 12.6 mm and a thickness of 2.8 mm was used. The experiments were carried out in an atmosphere of high-purity argon (99.992 vol. %). The principle of the laser flash method is that a flat sample in the form of a cylinder is irradiated from below with a short laser pulse (1.064 \( \mu m \)). After that, a change in the temperature of the sample upper surface is recorded by an IR detector. The thermal diffusivity of the sample is determined from the obtained heating thermogram of this surface, taking into account heat losses in the form of radiation according to the Cape and Lehman model [6] and thermal expansion, which was measured for nickel on a DIL-402C dilatometer [7]. During processing, a correction was introduced for the finite duration of the laser pulse and its real shape [8]. Measurements at a given temperature \( T \) were carried out after thermostating the sample in a series of three “shots” of the laser.

The estimated errors of the obtained data of \( a \) confirmed by experiments on reference samples were 2-4% depending on temperature, however, in the critical region, the error can significantly exceed these values due to strong change of the properties when approaching the Curie point [9]. In the classical laser flash method, it is assumed, that the thermophysical properties of the material under study are temperature independent. General heating of a sample after a laser “shot” is, as a rule, several degrees. Far from the phase transitions points, this does not lead to noticeable errors. However when irradiated with a short laser pulse, significant gradients appear in the surface layer of the sample, after which the temperature field changes with time in a complicated way. It is impossible to accurately take into account these effects, especially in the region of the sharp and nonlinear change of the properties, which is accompanied by a change in the sign of the temperature derivative. In this regard, the determination of nickel thermal diffusivity critical indexes using the laser flash method has an estimated character.

3. Results and discussion

According to the generally accepted approach [10, 11] for determining critical indices at the first stage, the magnetic component of the thermal diffusivity was determined by subtracting the paramagnetic contribution from the experimental values:

\[
a_{\text{mag}}(T) = a(T) - a_{\text{para}}(T),
\]

where \( a_{\text{para}}(T) \) is the linear approximation of the experimental data in the temperature range of the paramagnetic state, far from the Curie point (figure 1), and its extrapolation to the region of the magnetic phase transformation.

The magnetic component of the thermal diffusivity was recorded as a scaling dependence:

\[
a_{\text{mag}}(T) = A|\varepsilon|^\alpha + B,
\]

where \( A, B \) are constants. Obviously, \( B = a_{\text{mag}}(T_C) \). Then, introducing the new variable \( Y_{\text{mag}} = a_{\text{mag}} - a_{\text{mag}}(T_C) \), from (3) the following relation turns out:

\[
\ln(Y_{\text{mag}}) = \ln(A) + \alpha \ln(|\varepsilon|).
\]

As can be seen from (4), performing a linear approximation of \( \ln(Y_{\text{mag}}) \) with respect to \( \ln(|\varepsilon|) \), it is easy to obtain the values of the critical amplitude \( A \) and critical index \( \alpha \). The critical indexes \( \alpha' \) and \( \alpha \) correspond to the tangent of the inclination angle of the approximation lines for \( T < T_C \) and \( T > T_C \), respectively (figure 2).
Figure 1. Thermal diffusivity of nickel: 1 – experimental data; 2 – paramagnetic component \( a_{\text{para}}(T) \).

Figure 2. Initial data for the determination of nickel critical indices.: 1 – data for \( T < T_c \), 2 – data for \( T > T_c \), 3 – approximation lines.

The following approximation equations are obtained:

\[
a = 10.83 + 0.345\varepsilon + \begin{cases} 
15.539|\varepsilon|^{0.36}, & 580 \text{ K} < T < T_c \\
3.860|\varepsilon|^{0.26}, & T_c < T < 690 \text{ K}
\end{cases}
\]  

(5)

which show that \( a(T_c) = 10.83 \text{ mm}^2 \text{s}^{-1} \), \( a' = 0.86 \) and \( \alpha = 0.26 \). The approximation results are presented in figure 3 in comparison with the data from [9]. The authors described the behavior of the \( a(T) \) curve in [9] before \( T_c \) as a complex fractional function, and after \( T_c \) – as an exponential dependence. The values of the thermal diffusivity at the Curie point in this paper and in [9] differ by
about 8.4%, which is within the total measurement errors of these works. As can be seen from figure 3, the behavior of the curve $a(T)$ before and after the Curie point is extremely asymmetric (as in [9]), and the critical indexes $\alpha'$ and $\alpha$ differ by more than three times, which does not correspond to the classical scaling theory about the equality of critical indexes [1]. Besides, $\alpha'$ has a much higher absolute value than the classical value of 0.1 [4]. Apparently, this is due to a blurred minimum of the thermal conductivity at the Curie point [4], which, despite its small values, probably has a significant effect on the critical indices of the thermal diffusivity.

![Figure 3. Thermal diffusivity of nickel in the vicinity of the Curie point: 1 – the results of [9], 2 – our data, 3 – equations (4).](image)

**Conclusion**

New experimental data on the thermal diffusivity of nickel in a wide temperature range of 300–1680 K including the region of the magnetic phase transition were obtained. The critical indices of the thermal diffusivity have been determined by isolating the magnetic contribution and its subsequent processing by the scaling power dependence. It is shown that the critical indices before and after the Curie point differ by more than three times and have higher absolute values than the classical value of the heat capacity.

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