1. Introduction
By now, it is not easy to find an industry where iron is not used. Pure metal is used for the manufacture of transformer cores of electric motors, electromagnets and membrane microphones, as well as in the development of new composites and intermetallic compounds, etc. Iron alloys are the main structural materials in almost all areas of modern production. Given the wide distribution in science and technology, iron, being a classic ferromagnetic, is considered one of the most studied magnetic materials. However, methods for studying the properties of materials are being improved. Therefore, the data require regular verification and clarification.

There are a lot of experimental works in the literature aimed at studying features of this metal [1–5]; including those devoted to the bulk properties of pure iron [6–13]. However, the results differ, and at a magnetic phase transition, qualitative data are not available. The values of the expansion coefficient given by the author of [14] were obtained in the temperature range of 100–700 K. As you can see, many studies on polycrystalline iron were performed as early as the 30–70s of the last century and do not reflect changes in the expansion coefficient in the second-order phase transition region.

The purpose of this work is to conduct precision measurements of the linear thermal expansion coefficient (LTEC) over the region of the magnetic transition. Unfortunately, studies of the thermal expansion of polycrystalline carbonyl iron in a wide range of temperatures, including the region of the magnetic phase transition, obtain new reliable experimental data and their approximation equations, as well as calculate critical indices of thermal expansion in the region of the Curie point.

2. Material, method and experimental equipment
The study of thermal expansion of iron was carried out on a dilatometer of the horizontal type DIL-402C (NETZSCH). The sample elongation was recorded with an inductive displacement transducer (LVDT) with a resolution of up to 0.125 nm, and the temperature was recorded with thermocouples (type S or E), one of which was in close proximity to the side surface of the sample and the second was in the furnace. The heating–cooling rate of the furnace was 0.5 or 2 K/min. Measurements were carried...
out in a helium atmosphere (99.995 vol. %); and results are given as the temperature dependence of the relative elongation of the sample \( \varepsilon \) under heating or cooling:

\[
\varepsilon(T) = \frac{(L(T) - L_{293})}{L_{293}},
\]

where \( L_{293} \) and \( L(T) \) are the sample lengths at 293.15 K and at \( T \), respectively. The LTEC \( \alpha \) is determined as follows:

\[
\alpha(T) = \frac{1}{L_{293}} \left( \frac{\partial L}{\partial T} \right)_p = \left( \frac{\partial \varepsilon}{\partial T} \right)_p,
\]

where \( p \) is the pressure. To determine the temperature dependence of the LTEC, the data for all the thermal cycles are jointly approximated, using the least squares method, by the polynomials of the following type:

\[
\alpha(T_i) = \frac{1}{2} \left( \frac{\varepsilon_{i+1} - \varepsilon_i}{T_{i+1} - T_i} + \frac{\varepsilon_i - \varepsilon_{i-1}}{T_i - T_{i-1}} \right),
\]

where \( \varepsilon_i = \varepsilon(T_i) \) is the relative elongation of the sample at the temperature \( T_i \). Such approach makes it possible to obtain directly the temperature dependence of the LTEC, and not to differentiate the approximation equation for the relative elongation. The last one introduces an additional error into \( \alpha \) associated with the ambiguity in the choice of the fitting equation for \( \varepsilon(T) \), and also does not reveal the behavior of the LTEC in the region of phase transformations.

The experimental procedure is described in detail in [15]. The unit was tested under identical conditions on samples of aluminium (99.99 wt. %) and platinum (99.93 wt. %). The analysis showed that the difference between the obtained and reference data [16, 17] is within 3%.

3. Results and Discussion

For experiments a sample of carbonyl iron \( \varnothing 6 \times 25 \) cm with a purity of 99.95 wt. % was used. The sample was obtained by melting the starting material in a corundum crucible, after which it was annealed in a high vacuum atmosphere at 1200 K for two hours. In order to achieve plane parallelism relative to each other, the samples were trimmed on an SGM-402/15 (NETZSCH) installation.

Elongation was measured in several heating–cooling cycles using fused silica and corundum holders. The temperature interval was 130–1180 K. Primary data showed good reproducibility, which made it possible to combine data from different cycles. The generalized temperature dependence of the LTEC is shown in Fig. 1.

To obtain smoothed curves, the primary measurement results were processed separately in several temperature regions. After that, the obtained data were «sewed together» at intersecting points. The temperature of the boundaries of the regions was determined from the condition of equality of the LTEC on them. Outside the temperature ranges immediately adjacent to the temperature of the magnetic phase transition, the primary data were approximated by the least square-method using polynomials:

\[
\alpha(T) = \sum_{i=0}^{k} A_i T^i,
\]
where $t = T - 273.15$ K. In the region of magnetic phase transition the treatment was performed by using scaling dependences [18]. The magnetic contribution was obtained from the values of $\alpha(T)$ and was written in the form:

$$\alpha_{\text{mag}} = A |t|^a + B,$$

where $A, B$ are constants, $a$ is the critical exponent of the LTEC, and $\tau = (T - T_C)/T_C$ is reduced temperature. Paramagnetic contribution was linear approximation of the experimental data in the temperature interval of 1060–1100 K of the paramagnetic iron state. The calculation of critical indices was reduced to the following equation:

$$\ln \left( Y_{\text{mag}} \right) = \ln(A) + a \ln \left( |\tau| \right),$$

where $a$ is the critical exponent, $A$ is the critical amplitude, and $Y_{\text{mag}} = \alpha_{\text{mag}} - \alpha_{\text{mag}}(T_C)$. A detailed description of the thermal expansion data treatment is given in [15].

![Figure 2](image.png)

**Figure 2.** Approximation results of $\ln(Y_{\text{mag}})$.
1 – experimental points; 2 – below Curie point; 3 – above Curie point.

The results of approximation (2) showed that the regions before and after the Curie point cannot be processed by one scaling equation (Fig 2, Table 1). Similar results were obtained earlier for dysprosium [15] and gadolinium [19]. The obtained approximation equations (1), (2) are summarized in Table 2.

**Table 1.** Critical exponents of iron in the region of the Curie point.

| Below Curie point | Above Curie point |
|------------------|------------------|
| $<2.5 \times 10^{-4}$ | $>2.5 \times 10^{-4}$ | $<1 \times 10^{-3}$ | $>1 \times 10^{-3}$ |
| $A$ | $\alpha$ | $A$ | $\alpha$ | $A$ | $\alpha$ | $A$ | $\alpha$ |
| 3.13 | 0.70 | 10.36 | 1.58 | 8.33 | 1.21 | 0.78 | 0.19 |
Table 2. Approximation equations of the iron LTEC.

| № of reg. | Interval, K | Equation |
|-----------|-------------|----------|
| 1         | 130–286     | \(-11.8803 + 23.1631 \times 10^{-2} T - 8.2149 \times 10^{-4} T^2 + 1.0436 \times 10^{-6} T^3\) |
| 2         | 286–580     | \(6.5156 + 20.604 \times 10^{-3} T - 1.007 \times 10^{-5} T^2\) |
| 3         | 580–776     | \(10.5544 + 7.801 \times 10^{-3} T\) |
| 4         | 776–1004    | \(89.046 - 29.067 \times 10^{-2} T + 3.827 \times 10^{-4} T^2 - 1.655 \times 10^{-7} T^3\) |
| 5         | 1004–1042.44| \(4.43 + 86.7853 \times 10^{-4} T + 22.874 \times ((1042.7 - T) / 1042.7)^{0.70}\) |
| 6         | 1042.44–1042.7| \(4.43 + 86.7853 \times 10^{-4} T + 31571.181 \times ((1042.7 - T) / 1042.7)^{1.58}\) |
| 7         | 1042.7–1043.36| \(4.43 + 86.7853 \times 10^{-4} T + 4146.418 \times ((T - 1042.7) / 1042.7)^{1.21}\) |
| 8         | 1043.36–1052| \(4.43 + 86.7853 \times 10^{-4} T + 2.181 \times ((T - 1042.7) / 1042.7)^{0.19}\) |
| 9         | 1052–1180   | \(-24.3263 + 62.408 \times 10^{-3} T - 2.4184 \times 10^{-5} T^2\) |

The temperature of the LTEC minimum was determined from scaling dependences and was taken as the Curie point:

\[ T_C = 1042.7 \text{ K}. \]

The smoothed values of the thermal coefficients of linear and volume expansion, relative elongation and density are presented in Table 3.

Figure 3 presents a comparison of the recommended LTEC curve with previously published data from other sources.

![Figure 3. Data comparison of the iron LTEC.](image)

An analysis has shown that the available data do not provide comprehensive information on the change in the coefficient of iron expansion, including the region of the Curie point. Our data agree well
with [6, 7] at low temperatures. There is a discrepancy with the works [8, 10] at high temperatures above 600 K. The difference reaches 10–15%, which is much higher than the total measurement error. Also, these works do not reveal the features of the LTEC at the Curie point. In the region of the Curie point, there is good agreement with [9]. In paper [11], on the contrary, the curve of the expansion coefficient at the Curie point has a minimum. However, the number of points is limited, which does not allow us to unequivocally talk about the character of the LTEC change in this region. We obtained the best agreement with the results of [12, 14]. The data up to 700 K actually coincided, and a small deviation was higher. Although comparable results were obtained in the region of the Curie point in [12]. Recommended values from review [13] also do not have detailed data in the region of phase transition. However, the value of the Curie point is given there and is 1043 K. This value is very close to what we have obtained.

Table 3. Smoothed values of linear and volume thermal expansion coefficients, relative elongation and density of iron.

| $T$, K | $\alpha$, $10^{-6}$ K$^{-1}$ | $\beta$, $10^{-5}$ K$^{-1}$ | $\varepsilon$, $10^{-6}$ | $\rho$, kg/m$^3$ |
|--------|-----------------|-----------------|-----------------|-----------------|
| 130    | 6.64            | 2.00            | $-$1613         | 7913            |
| 140    | 7.31            | 2.20            | $-$1543         | 7912            |
| 150    | 7.90            | 2.37            | $-$1467         | 7910            |
| 200    | 9.94            | 2.98            | $-$1015         | 7899            |
| 250    | 10.99           | 3.30            | $-$489          | 7887            |
| 293.15 | 11.69           | 3.51            | 0               | 7875            |
| 300    | 11.79           | 3.54            | 80              | 7873            |
| 400    | 13.15           | 3.94            | 1329            | 7844            |
| 500    | 14.30           | 4.28            | 2703            | 7812            |
| 600    | 15.23           | 4.55            | 4182            | 7777            |
| 700    | 16.02           | 4.78            | 5745            | 7741            |
| 800    | 16.70           | 4.97            | 7384            | 7703            |
| 900    | 16.78           | 4.99            | 9066            | 7665            |
| 1000   | 15.58           | 4.62            | 10699           | 7628            |
| 1010   | 15.32           | 4.55            | 10841           | 7625            |
| 1020   | 14.95           | 4.44            | 10975           | 7622            |
| 1030   | 14.51           | 4.31            | 11110           | 7619            |
| 1040   | 13.91           | 4.13            | 11245           | 7615            |
| 1041   | 13.82           | 4.10            | 11259           | 7615            |
| 1042   | 13.71           | 4.07            | 11272           | 7615            |
| 1042.70| 13.58           | 4.03            | 11282           | 7615            |
| 1043   | 13.80           | 4.09            | 11286           | 7615            |
| 1044   | 14.20           | 4.21            | 11300           | 7614            |
| 1045   | 14.28           | 4.24            | 11314           | 7614            |
| 1046   | 14.34           | 4.25            | 11327           | 7614            |
| 1047   | 14.38           | 4.27            | 11341           | 7613            |
| 1048   | 14.42           | 4.28            | 11354           | 7613            |
| 1049   | 14.46           | 4.29            | 11368           | 7613            |
| 1050   | 14.49           | 4.30            | 11382           | 7612            |
| 1100   | 15.06           | 4.46            | 12120           | 7596            |
| 1150   | 15.46           | 4.58            | 12884           | 7579            |
| 1180   | 15.64           | 4.63            | 13351           | 7568            |
Conclusion
According to the results of the work, new experimental data on the linear thermal expansion coefficient of polycrystalline carbonyl iron were obtained. Data were performed with high accuracy. The region of anomalous changes in the linear thermal expansion coefficient was studied in detail and the critical indices and critical amplitudes of the thermal expansion at the Curie point were calculated. The dependences below and above this temperature are described by two linear scaling equations. Tables of recommended values of the volume properties of iron using the calculated approximation equations are compiled.

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