Thermal diffusivity of corrosion-resistant coating SDP-1

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Abstract. In the present work, the thermal diffusivity of the SDP-1 grade nickel alloy was investigated in the wide temperature range of 300-1476 K. The SDP-1 alloy (Ni-Co-Cr-Al-Y) is the heat-resistant coating for blades of gas turbine plants, providing protection against sulfide-oxide corrosion in the temperature range of 1070-1220 K. The measurements were performed by laser flash method using LFA-427 apparatus. The estimated errors of the obtained data were 2-5% depending on temperature. The thermal diffusivity approximation equations and a table of reference values for various scientific and practical applications were obtained.

1. Introduction
At present, due to an increase in operating temperatures (from 1100 to 1800 K and above), the possibility of using aircraft engines that have exhausted their flight life is being considered in industrial gas turbine units (GTU). In addition to the industry's need for more heat-resistant materials used in turbine blades manufacture, it should also be taken into account that, unlike aircraft engines, industrial turbines use fuel, containing certain impurities, that form aggressive compounds based on sulfur and chlorine (molten salts of sulfites, sulfates, and chlorides) on the surfaces of parts of the hot path, which results in corrosive destruction of the turbine blades made of heat-resistant nickel alloys. The combined impact of oxygen, sulfur, and chlorine on the surface of the blade causes sulfide oxide corrosion. To protect the upper layer of GTU turbine blades from sulfide oxide corrosion, an ion-plasma coating of Ni-Co-Cr-Al-Y alloys is used, among which the SDP-1 alloy is actively employed in the industry. Table 1 shows the SDP-1 alloy chemical composition. In the literature, as a rule, the results for corrosion resistance testing of the coating made of SDP-1 [1–3] are given, however, there is no information on its heat transfer coefficients. The availability of reliable data on the thermal diffusivity of protective coatings in a wide range is very relevant if it is required to carry out high-precision thermal engineering calculations for various operating modes of the gas turbine unit.

In this way, an experimental study of the thermal diffusivity of the SDP-1 nickel alloy in a wide temperature range was the main task of the present article.

2. Experimental technique and description
The thermal diffusivity (α) of the SDP-1 alloy was measured by the laser flash method [4, 5] on an automated experimental setup LFA 427 from NETZSCH. In this technique, a short laser pulse (of about 1 ms) from an IR detector heats the plane-parallel sample bottom side; then the sample’s opposite surface temperature is recorded. The thermal diffusivity α is determined from the time course
of this temperature. The laser flash method (flash method) was proposed by W.J. Parker et al. in 1961 [5] for the first time. For the adiabatic case, a simple calculation formula was obtained:

\[ a = \frac{1.38h^2}{\pi^2t_{1/2}^2}, \]  

(1)

where \( t_{1/2} \) is the time to heat the sample upper surface to half of its maximum temperature \( T_{\text{max}} \), \( h \) is the sample thickness (Figure 1). It should be noted that in the derivation of formula (1), several assumptions were taken, namely, the specimen was homogeneous, the properties were independent of temperature, there was no heat loss from the surface of the sample, the heat pulse was infinitely short, and the heat flux into the sample was considered one-dimensional. The model described in this way (also known as the adiabatic model) works well for room temperatures, but at temperatures exceeding room temperature, it does not provide accurate data, since it does not take into account the sample heat loss to the environment. With allowance to the two-dimensional radiation model proposed by Cape and Lehman [6], the heat losses of the sample were taken into account in the present work. This approach assumes the following resolutions, namely, the sample is homogeneous, the radiation is absorbed instantly by a thin surface layer, and heat losses are due to external surfaces radiation. The method [7] takes into account the laser pulse corrections for the finite duration and its real shape. The typical shape of the laser pulse in the LFA 427 experiment and its approximation by the method [7] are shown in Figure 2.

### Table 1. Chemical composition of the SDP-1 alloy [1].

| The element’s content, wt.% | Ni   | Cr  | Co  | Al  | Y    |
|-----------------------------|------|-----|-----|-----|------|
|                             | 42–53| 18–22| 18–22| 11–13| 0.2–0.6 |

**Figure 1.** The sample rear surface thermogram in the flash method.

**Figure 2.** The laser pulse amplitude time dependence. 1 — original signal, 2 — approximation [7].

In the present work, a sample SDP-1 in the form of a cylinder of about 1.8 mm thick and 10 mm in diameter with plane-parallel polished ends was investigated. Before placing the sample in the LFA 427, its weight and geometric dimensions were measured. The sample thickness \( h \) was measured with a Tesa Digico 10 electronic length gauge, additionally calibrated by end measures, at five points (with one point in the center of the specimen and four points equidistant from the center at a distance of 3 mm); the measurement error of the thickness did not exceed 10 \( \mu \)m. High-precision measurement
of the thickness of the test sample is of fundamental importance for the flash method, since the thickness \( h \) is squared in the calculation formula (1) for \( a \). After installing the samples in LFA 427, the working volume was evacuated to 1 Pa. Thereafter it was filled with argon, whose purity was 99.992 vol.\%, and the main impurities were: \( \text{N}_2 - 0.0005\% \); \( \text{H}_2\text{O} - 0.0004\% \); \( \text{O}_2 - 0.0001\% \); \( \text{H}_2 - 0.0001\% \); \( \text{CH}_4 - 0.0001\% \); and \( \text{CO}_2 - 0.00002\% \). During the measurement, the sample’s lower surface was irradiated with a short laser pulse (1.064 \( \mu \)m) from an Nd:YAG laser with an energy of up to 10 J and a duration of 0.8 ms. The upper surface temperature change was registered by an IR detector, cooled with liquid nitrogen, based on indium antimonide. The thermal diffusivity was calculated immediately after each laser shot, which made it possible to quickly monitor the results obtained. The alloy thermal expansion was not taken into account. After thermostating the sample at a given temperature, measurements were carried out in a series of three laser shots. A three-minute interval was maintained between shots. The total error in determining \( a \) was 2\% at 300 K and 5\% at 1500 K, which was established from the results of measurements with standard solid samples of copper and molybdenum.

3. Results
The primary measurement results of \( a \) for SDP-1 are shown in figure 3. The data on the graph were obtained in several heating cycles in the temperature range of 300-1476 K. The approximation of the obtained results by the least-squares method gave the following equations:

\[
\begin{align*}
  a(T) &= 2.71 + 7.714 \times 10^{-5} T + 6.98 \times 10^{-6} T^2 - 4 \times 10^{-9} T^3, \quad 300 < T < 995 \text{ K}, \\
  a(T) &= 14.11 - 0.0183 T + 1.287 \times 10^{-5} T^2 - 3 \times 10^{-9} T^3, \quad 995 < T < 1476 \text{ K},
\end{align*}
\]

where \( a \) is the thermal diffusivity in \( \text{mm}^2/\text{s} \). The root-mean-square deviations of the experimental points from (2) and (3) are 0.4 and 0.3\%, respectively.

![Figure 3. Thermal diffusivity of SDP-1 alloy. 1 – experimental data, 2 – equations (2) and (3).](image-url)
As is seen from the graph, the temperature dependence $a(T)$ increases from room temperature and has a bend near 995 K, which is due to the structural phase transformation in the alloy, after which the $a(T)$ curve radically changes the behavior and decreases already weakly nonlinearly to 1476 K.

Table 2 shows the recommended values for $a$ of the studied alloy, obtained based on equations (2) and (3).

| $T$, K  | $a$, mm$^2$/s |
|---------|---------------|
| 300     | 3.25          |
| 400     | 3.59          |
| 500     | 3.97          |
| 600     | 4.37          |
| 700     | 4.75          |
| 800     | 5.10          |
| 900     | 5.39          |
| 1000    | 5.60          |
| 1100    | 5.46          |
| 1200    | 5.37          |
| 1300    | 5.32          |
| 1400    | 5.28          |
| 1476    | 5.26          |

4. Conclusion

New experimental data on the thermal diffusivity of the SDP-1 grade alloy (Ni-Co-Cr-Al-Y) were obtained with the estimated errors of 2-5%. The approximation equations and a table of reference values for the studied property have been developed which can be used for various scientific and practical applications.

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