
FUNCTIONAL COATINGS
AND SURFACE TREATMENT

Changes in the Structure of a Thermal Protective Nickel Aluminide Coating under the Influence of a Single Thermal Laser Pulse

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Received April 2, 2021; revised April 27, 2021; accepted May 20, 2021

Abstract—The regularities of changes in the structure and phase composition of a thermal protective nickel aluminide coating (45% Ni, 14% Al, 22% Co, 18.9% Cr, 0.15% Fe, 0.14% Nb, 0.09% Y, 0.06% Ca, 0.01% Mn, 0.15% C, 0.15% Si, and 0.006% S) after exposure to short-term pulsed heat fluxes of various power created by the radiation of an LRS-150A pulse-periodic laser with a radiation wavelength $\lambda = 1.06 \mu\text{m}$ and a pulse duration $\tau = 12 \times 10^{-3} \text{ s}$ were studied. The radiation energy was $E = 5, 10, \text{ and } 15 \text{ J}$. Microstructural analysis and the elemental composition of the resulting coating were carried out as well as analysis of the phase composition. X-ray microanalysis of the coating was also carried out. In the initial state and after irradiation of the coating with a heat flux power $P = 7 \times 10^3 \text{ W/cm}^2$, light microregions are observed on the micrographs of the surface. These regions do not have clearly defined external boundaries and consist of the NiAl phase and a small amount of the Ni₃Al phase with the presence of inclusions of particles containing a solid solution of Ni–Co–Cr. After irradiation of the coating with heat fluxes of higher power ($P = 1.7 \times 10^4 \text{ W/cm}^2$ and $P = 2.2 \times 10^4 \text{ W/cm}^2$), large convex formations appeared on its surface, consisting mainly of Ni₃Al and NiAl phases. On micrographs of the surface, they appear as white areas with well-defined outer boundaries. The content of the Ni₃Al phase in them increased in comparison with the initial state and the content of the NiAl phase decreased, while the particles of inclusions of Ni, Co, and Cr disappeared. It can be assumed that an increase in the Ni₃Al content is associated with the dissolution of particles of a solid solution of Ni–Co and Cr in the melt and the subsequent diffusion of nickel into the NiAl phase. When exposed to a heat flux of power $P = 2.2 \times 10^4 \text{ W/cm}^2$, microcracks appear on the areas of the coating surface covered with aluminum oxide.

Keywords: thermal protective coating, thermal laser pulses, structural and phase changes

DOI: 10.1134/S2075113322030078

INTRODUCTION

Details and structural units of machines and power plants (gas paths, compressors, and combustion chambers [1]) are exposed to high-power continuous and pulsed heat fluxes during operation. An increase in the service life of these products is achieved through the deposition of thermal protective coatings onto their surface, which include nickel aluminide coatings [2–5]. The structure of coating is altered upon interaction with high-temperature heat fluxes, which results in the decrease in its life cycle. In addition, incidents under operation of thermal protective coatings are particularly dangerous when the system operates under short-term extremely high temperature conditions. In [6], a method for the modeling of such exposures using thermal laser pulses with a millise-

cond duration was suggested. This method was employed for the study of the principles of structural degradation of protective coatings made from tantalum [6], tantalum–tungsten [7], and titanium nitride [8] upon exposure to pulsed heat fluxes.

In this work, the results of the investigation of the changes in structure and phase composition of the coating surface after exposure to pulsed heat flux created by laser radiation to nickel aluminide coating with alloying elements are presented.

MATERIALS AND METHODS

The coating was formed through spraying onto the substrate by plasma flux in the air atmosphere on a Termoplazma instrument [9, 10]. The charge for

spraying was represented by the powder mixture with the particle size of the main fraction of $\sim 80 \mu\text{m}$, which was obtained by sintering of elements (45% Ni, 14% Al, 22% Co, 18.9% Cr, 0.15% Fe, 0.14% Nb, 0.09% Y, 0.06% Ca, 0.01% Mn, 0.15% C, 0.15% Si, and 0.006% S) and subsequent dispersion of the caked-on particles into conglomerates with the size from 10 to $90 \mu\text{m}$. Phase analysis was carried out on a Dron 3M diffractometer. Microstructural analysis and elemental composition of the coating were carried out on a TESCAN VEGA II scanning microscope. X-ray microanalysis of the coating along the scanning line was performed on an INCA Energy-250 energy-dispersive spectrometer. Ni, Al, Co, and Cr were chosen as the components added at high quantities to the charge upon analysis of the elemental distribution on the coating surface.

The heat flux exposed to the coating surface was generated by an LRS-150A pulse-periodic laser with the radiation wavelength of $\lambda = 1.06 \mu\text{m}$ and the pulse duration of $\tau = 12 \times 10^{-3} \text{ s}$. The radiation spot diameter was 4 mm. The radiation energy E_{irr} was equal to 5, 10, and 15 J. The incident heat flux power on the coating surface at the indicated radiation energy values was calculated from the following equation:

$$P = \frac{E_{\text{irr}} n}{S_1 \tau_{\text{irr}}},$$

where $n = S_2/S_1 = 2.2$ is the beam compression factor by the focusing lens, S_0 is the cross-sectional area of radiation focused on the coating surface ($S_1 = 0.13 \text{ cm}^2$), and S_2 is the cross-sectional area of the edge of active medium of laser ($S_2 = 0.28 \text{ cm}^2$). Introducing these values into the equation, we find that the heat flux power P is 7×10^{-3} , 1.7×10^4 , and $2.2 \times 10^4 \text{ W/cm}^2$ at radiation energy values E of 5, 10, and 15 J, respectively. The values of heat flux were chosen according to the results of preliminary experiments, which showed the change in surface pattern or the absence of this change.

Nickel aluminides are regarded as intermetallic compounds with the ionic-covalent bond between atoms. Therefore, it is not possible to evaluate the temperature of the surface on the basis of the power of heat fluxes generated by a laser pulse, because the existing relationships for the calculation of temperature are applicable only for the materials with a metallic bond [11].

RESULTS AND DISCUSSION

Analysis of the microstructure and distribution of the elemental composition over the coating surface after exposure to heat flux with $P = 7 \times 10^3 \text{ W/cm}^2$ did not result in significant structural changes of the initial coating. By analogy to the case before irradiation, there are dark and bright regions on the surface

(Fig. 1a). Bright regions do not possess clearly defined boundaries (some examples of these regions are indicated by arrows in Fig. 1a) and they occupy the largest area of irradiation spot. According to the results of X-ray microanalysis, dark regions are characterized by the coincidence of the signals of Al and O (Fig. 1b), which indicates that they presumably mainly consist of alumina Al_2O_3 . There are Ni and Al in bright regions and the signal intensity of Ni in relative units predominates over the signal intensity of Al (Fig. 1c). Comparison of the elemental distribution along the scanning line of the coating surface given in Figs. 1c and 1d shows that there are separate sections in bright regions that are 40 to $60 \mu\text{m}$ in size, with only Ni, Co, and Cr. Two of these sections are given in Figs. 1c and 1d by vertical columns, the width of which is nearly identical to their sizes along the scanning line. The presence of such sections is to all appearances related to the presence of the particles presumably consisting of the solid solution of these elements in the initial structure of coating.

After irradiation with the heat flux with power $P = 1.7 \times 10^4 \text{ W/cm}^2$, the appearance of the surface changed remarkably. Large bright domains with clearly defined external boundaries appeared (indicated by arrows in Fig. 2a) and were scattered along the area of irradiation. Analysis of the elemental composition showed the coincidence of the peaks of Ni and Al (Fig. 2b), as well as the presence of Co and Cr alloying elements in these phases (Fig. 2c).

Coincidence of the signals of Al and O are recorded in the dark regions, which shows the presence of oxide Al_2O_3 (Fig. 2b). The atoms of Cr are occasionally present in these regions. Comparison of Figs. 2c and 2d shows that the regions with only Ni, Co, and Cr were not identified after irradiation of the coating with the heat flux of $P = 1.7 \times 10^4 \text{ W/cm}^2$.

Figure 3a shows the image of the irradiation area after exposure of the coating to the heat flux with the power of $P = 2.2 \times 10^4 \text{ W/cm}^2$, while Fig. 3b shows its fragment at larger zoom. The coating surface out of the irradiation area represents initial structure of coating in Fig. 3a. The distribution of elements in dark and bright regions is fully analogous to their distribution after irradiation with power $P = 1.7 \times 10^4 \text{ W/cm}^2$. In contrast to irradiation with heat fluxes possessing lower power, cracks appeared in the dark region of the irradiation area (representing alumina) (Fig. 3b).

As was mentioned above, it is impossible to distinguish between the phases of Ni_3Al and NiAl through comparison of the signals of nickel and aluminum; therefore, X-ray diffraction analysis of the coating before and after irradiation with heat fluxes of 7×10^3 and $2.2 \times 10^4 \text{ W/cm}^2$ was carried out for their identification. The results of the studies are summarized in Table 1.

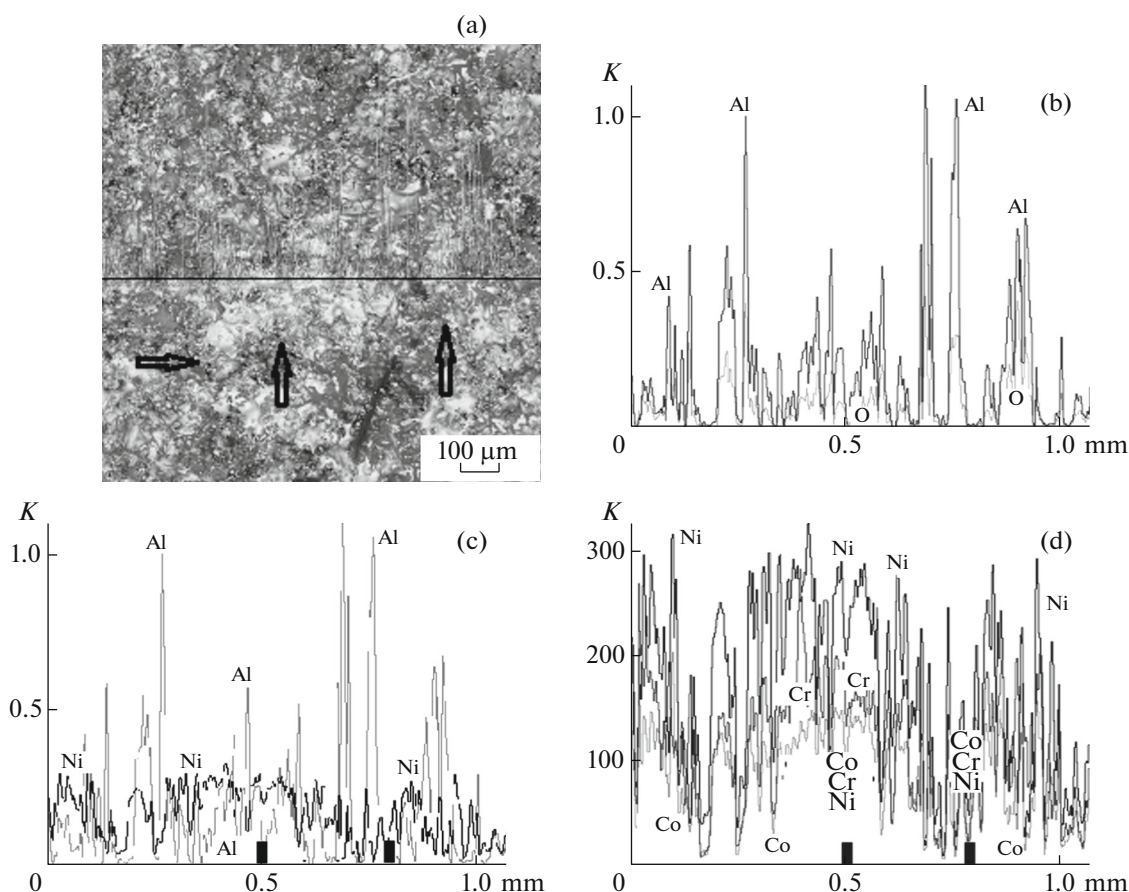


Fig. 1. (a) Fragment of the coating surface after irradiation with power of $P = 7 \times 10^3 \text{ W/cm}^2$ and (b–d) the distribution of (b) Al–O, (c) Al–Ni, and (d) Ni–Co–Cr elements on it (marked in black).

Irradiation with the heat flux of $7 \times 10^3 \text{ W/cm}^2$ did not alter the phase composition of the coating as compared to its initial state.

It can be seen from the change of the intensity of X-ray peaks that irradiation with the heat flux of $2.2 \times 10^4 \text{ W/cm}^2$ decreased the content of the NiAl phase and increased the content of the Ni_3Al phase as compared to the content of these phases in the coating in initial state and after irradiation with the heat flux with the lower power ($P = 7 \times 10^3 \text{ W/cm}^2$).

The observed principles of the change in the structure and phase composition of the coating upon exposure to laser pulses can be explained from the following considerations.

After spraying of the coating and after its irradiation with heat flux with power $P = 7 \times 10^3 \text{ W/cm}^2$, bright regions are observed on the surface (Fig. 1a). They do not possess clearly defined external boundaries and they consist of the NiAl phase and a small content of the Ni_3Al phase with the particles containing Ni–Co–Cr solid solution. After irradiation of the coating with heat fluxes of higher power (1.7×10^4 and

$2.2 \times 10^4 \text{ W/cm}^2$), large concave formations are observed on its surface, which mainly consist of the Ni_3Al and NiAl phases (Fig. 2a), which appear as white regions with clearly defined external boundaries (Figs. 2a, 3a, 3b). The content of the Ni_3Al phase increased as compared to the initial state and the content of the NiAl phase decreased; in this case, the particles of Ni–Co–Cr disappeared. The mentioned regions resemble solidified molten pools by morphology. It can be suggested that an increase in the Ni_3Al content is associated with the dissolution of the particles of Ni–Co solid solution and Cr and subsequent diffusion of nickel into the NiAl phase.

CONCLUSIONS

1. Exposure to laser thermal pulses with power of 1.7×10^4 and $2.2 \times 10^4 \text{ W/cm}^2$ results in a significant change in surface morphology, which is expressed in the appearance of large concave formations of white color crystallized from melt on its surface, which mainly consist of the Ni_3Al and NiAl phases.

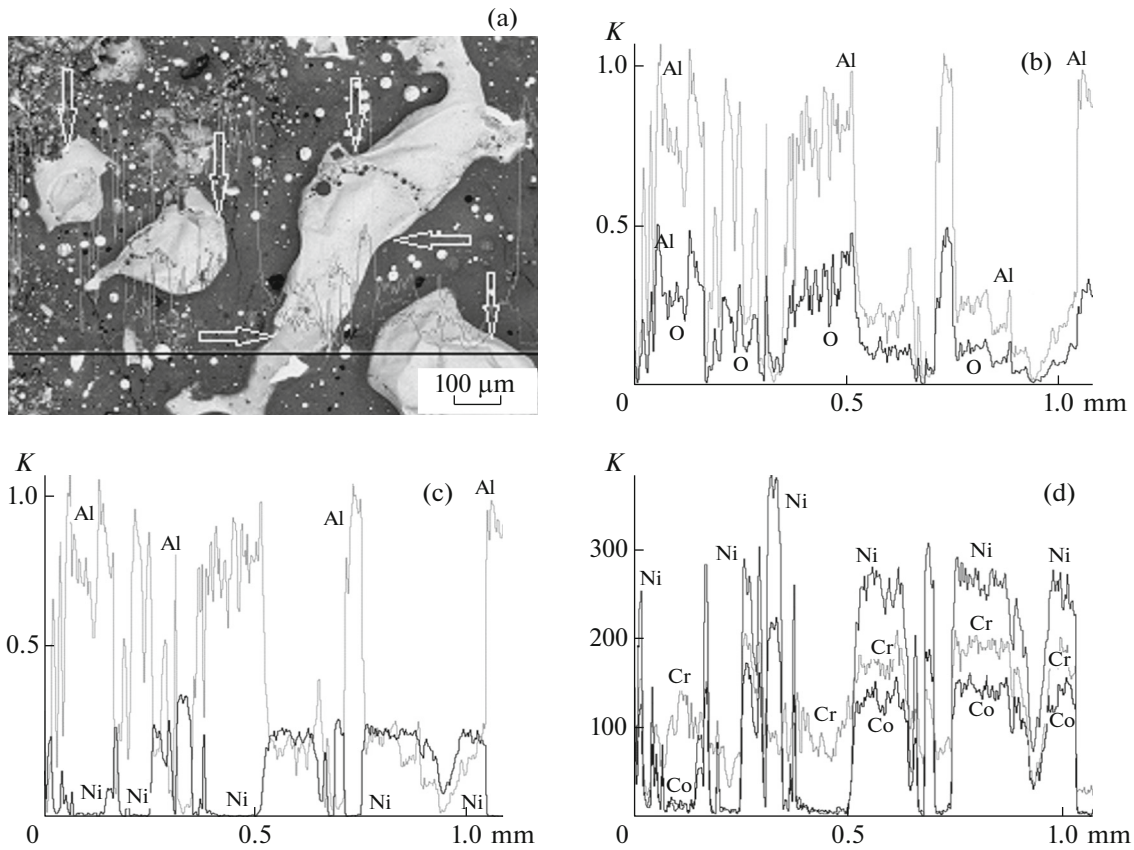


Fig. 2. (a) Fragment of the coating surface after irradiation with power of $P = 1.7 \times 10^4 \text{ W/cm}^2$ and (b–d) the distribution of (b) Al–O, (c) Al–Ni, and (d) Ni–Co–Cr elements on it (marked in black).

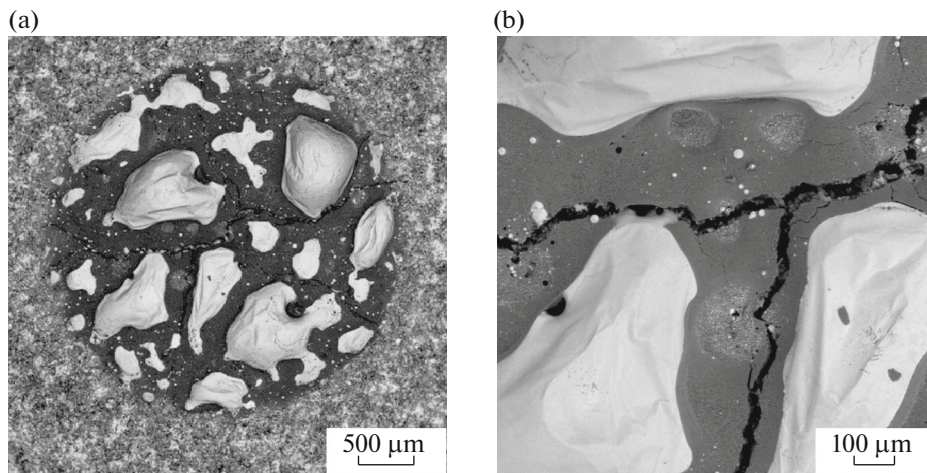


Fig. 3. (a) Area of irradiation with heat flux with power of $P = 2.2 \times 10^4 \text{ W/cm}^2$ and (b) its fragment at higher magnification.

2. Irradiation of the nickel aluminide coating with single laser thermal pulses with the duration of $12 \times 10^{-3} \text{ s}$ and power of 1.7×10^4 and $2.2 \times 10^4 \text{ W/cm}^2$

decreases the content of the NiAl phase and increases the content of the less thermally stable Ni_3Al phase as compared to the initial state.

3. An increase in the heat flux power to the value of $2.2 \times 10^4 \text{ W/cm}^2$ induces the formation of microcracks on the sections of the surface coating consisting of alumina.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

FUNDING

This work was supported by the State Assignment of the Mechanical Engineering Research Institute of the Russian Academy of Sciences on fundamental research for 2021–2023 on topic no. 0030–2021–0025.

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Translated by A. Muravev