The Effect of Electron-pulse Modification of the Surface Layer on the Strength Properties of the Ni_3Al Intermetallic Compound

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Abstract. In this paper it was shown that pulsed electron irradiation forms in the surface layer of the Ni_3Al intermetallic compound samples a columnar crystal structure oriented perpendicular to the irradiated surface. The dimensions of the crystals of the columnar structure and the depth of the surface layer modification depend on the power density and the duration of the irradiation pulses - with power density increasing , the dispersion of the columnar structure increases, with increasing duration of irradiation pulses, the depth of the surface layer structure modification increases. Modification of the surface layer structure improves the strength properties of Ni_3Al intermetallic compound samples.

1. Introduction

The current state of research in the field of structural-phase states modification of intermetallic alloys can be estimated by the example of creating and improving the most highly loaded parts of gas turbine engines - blades of heat-resistant alloys [1-4]. The development of fourth-generation aircraft engines in the 70s-80s of the last century, connected with the need to increase the operating temperature of the coolant from 1200 to 1500-1550 ° C, required solving the problem of high-temperature protection of the blade surface. Since the 80s of the last century, intensive research has been launched to develop and create high-performance protective coatings from high-temperature gas corrosion and from the formation of thermo-fatigue defects in the form of micro- and macro-cracks in the surface layers, leading to the formation of major cracks on the surface with subsequent destruction of the blades. The solution of the first problem was achieved by creating multicomponent coatings of the type Me-Cr-Al-Y, applied by electron-beam, ion-plasma and vacuum-plasma technologies. Hardening of the surface layers towards thermal fatigue damage was achieved by modifying the structural-phase state to which the nanostructuring of the surface layer relates [5-7]. The physical meaning of this modification is to reduce the scale level of plastic deformation localization in the nanostructured surface layer, leading to a more uniform distribution of elastic stresses in a larger volume of material with external mechanical or temperature effects on the surface. As a result, the energy of nucleation of stress concentrators in the surface layer substantially increases the probability of formation in the surface layer of defects the internal structure decreases. In other words, the nanostructured surface layer exhibits damping properties in relation to the base material under shock mechanical and thermal effects, preventing premature nucleation and propagation of main cracks from the surface into the main bulk of the material. This paper presents a part of the results of the study of the pulsed electron irradiation influence in the micro- and submillisecond range of exposure time on the structural-phase state of the Ni_3Al intermetallic compound surface layer on the strength and ductility of intermetallic compound samples.

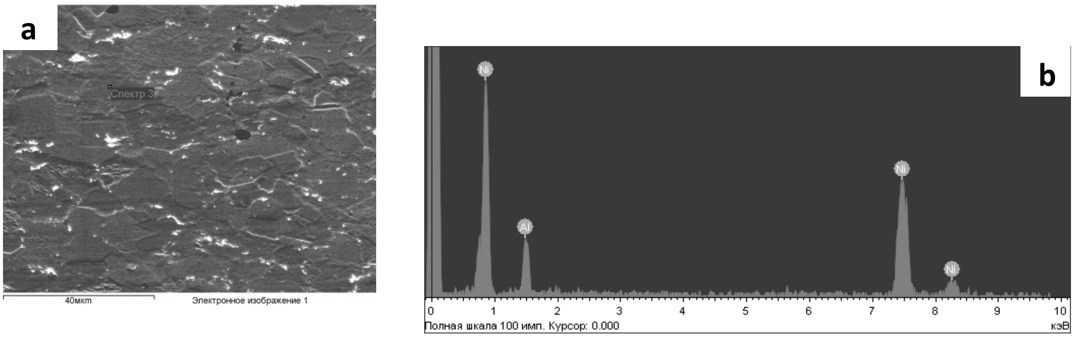
2. Material and methods

The Ni_3Al intermetallic compound was synthesized in a powder mixture of nickel (PNK-S1B, particle size 0.98 μm) and aluminum (ASD-4, particle size 1.0 μm) of stoichiometric composition (76.0 at.% Ni – 24.0 at. % Al). The high-temperature synthesis of an intermetallic compound was initiated in the thermal explosion regime of the initial powder mixture in a closed-type die mold reactor by applying pressure to a powder compact preheated to a predetermined temperature.

Intermetallic samples were irradiated in a pulsed mode by a wide-aperture (covering the entire surface of the sample) electron beam with given values of the pulse duration, the energy density per pulse and the frequency of the pulses at the facility generating irradiation pulses from 20 to 200 µs. Studies of the microstructure of the surface and surface layers of the intermetallic compound before and after pulsed electron-beam irradiation were carried out by methods of optical metallography (Neophot 32), scanning (Quanta 200 3D) electron microscopy with micro X-ray spectral analysis. The microhardness of the intermetallic compound surface was investigated on the device PMT-3. Tests of intermetallic samples before and after irradiation were carried out according to the standard scheme on an Instron-3369 machine with a loading rate of 0.2 mm/min.

3. Results and discussion

In fig. Figure 1 shows the microstructure of the Ni3Al intermetallic compound surface synthesized under pressure in the initial state, prior to electron beam irradiation. The spectrum of the characteristic radiation shows the presence in the analyzed point only nickel and aluminum in the stoichiometric ratio.



Element	%, weight	%, atomic
Ni, K_α	87.296	75.950
Al, K_α	12.704	24.050
Total	100.00	100.00

Figure 1. The microstructure of the surface (a) and the data of the grains elemental composition of the Ni_3Al intermetallic compound synthesized under pressure (b).

Typical images of the Ni_3Al intermetallic surface microstructure after pulsed electron beam irradiation are shown in Fig. 2.5.

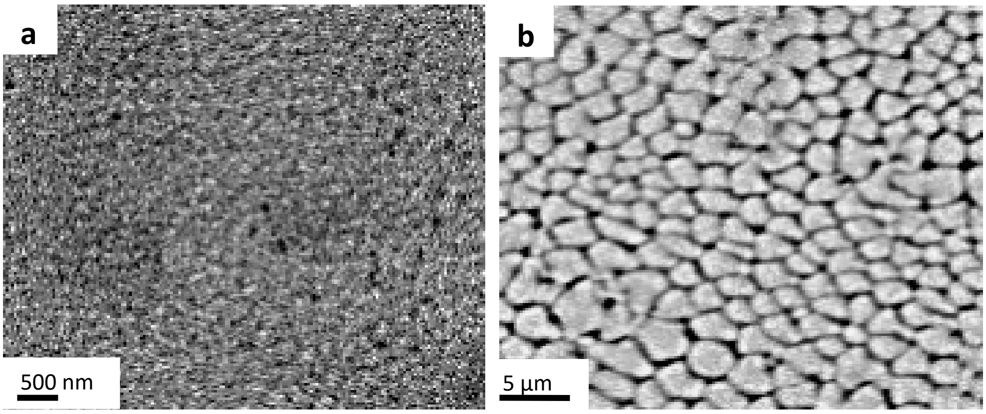


Figure 2. Microstructures of the Ni_3Al intermetallic samples surface after pulsed electron-beam irradiation at an electron beam power density of $6.0 \cdot 10^6$ W / cm^2 (a) and $0.2 \cdot 10^6$ W / cm^2 (b); the number of irradiation pulses 5

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The grain size in the modified surface layer largely depends on the parameters of pulsed electron-beam irradiation — as the electron beam power density (W_S) increases, the grain size in the surface layer decreases. If at $W_S = 6{\cdot}10^6$ W/cm^2, the average crystallite size of the surface layer does not exceed 100 nm (Fig. 2, a), then at $W_S = 0.2{\cdot}10^6$ W/ cm^2, the crystallite size varies in the range of 0.5...3.0 μm (Fig. 2, b). On the other hand, the increase in the irradiation power density associated with a decrease in the irradiation pulses duration multiply reduces the depth of modification of the surface layer structure. In fig. 3 shows the structures of the transverse fracture of the intermetallic samples surface layers after irradiation with pulses of 3 μs (a) and 50 μs (b) duration.

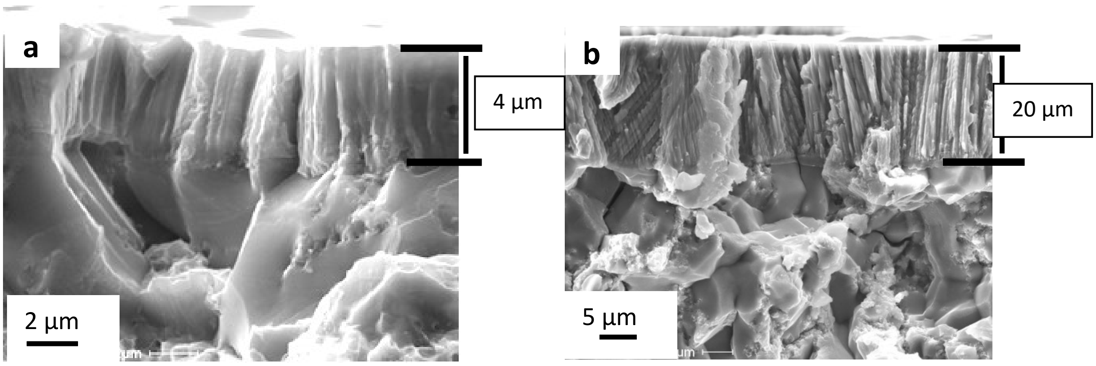

Figure 3. Fractographs of cross-sections of the intermetallic samples surfaces layers after electron irradiation with pulses of 3 μs (15 J/cm^2, 5 pulses) (a) and pulses of 50 μs (20 J/cm^2, 5 pulses) (b).

It can be stated that the cross-sectional structures of the surface layers after pulsed electron irradiation are distinguished by the columnar nature of the structure, consisting of individual needle-like crystallites oriented perpendicular to the irradiation surface. The transverse crystallite size depends on the magnitude of the irradiation power density - with an increase in the irradiation power density the transverse size of the crystallites significantly decreases. At the same time, the longitudinal size of the crystallites (the depth of modification of the surface layer structure) depends on the duration of irradiation pulses - with an increase in the duration of the pulses from 3x to 50 μs, the depth of modification of the surface layer structure increases from 4x to 20 μm.

At the same time, the longitudinal size of the crystallites (the depth of modification of the surface layer structure) depends on the duration of irradiation pulses - with an increase in the duration of the pulses from 3x to 50 μs, the depth of modification of the surface layer structure increases from 4x to 20 μm. In fig. 4 shows the load-elongation and bending stress-strain relations for the Ni_3Al intermetallic compound after pulsed electron irradiation.

Electron irradiation by pulses with a duration of 3 μs leads to a noticeable demonstration of plasticity during bending of intermetallic samples (plastic manifestation is noted in Fig. 4c and 4d). Of interest is the superposition of intermetallic samples irradiation with short and longer irradiation pulses. Figure 5 shows the microstructures of the cross-section of the Ni3Al intermetallic sample surface layer after irradiation with pulses of 50 μs duration and subsequent irradiation with pulses of 3 μs duration.

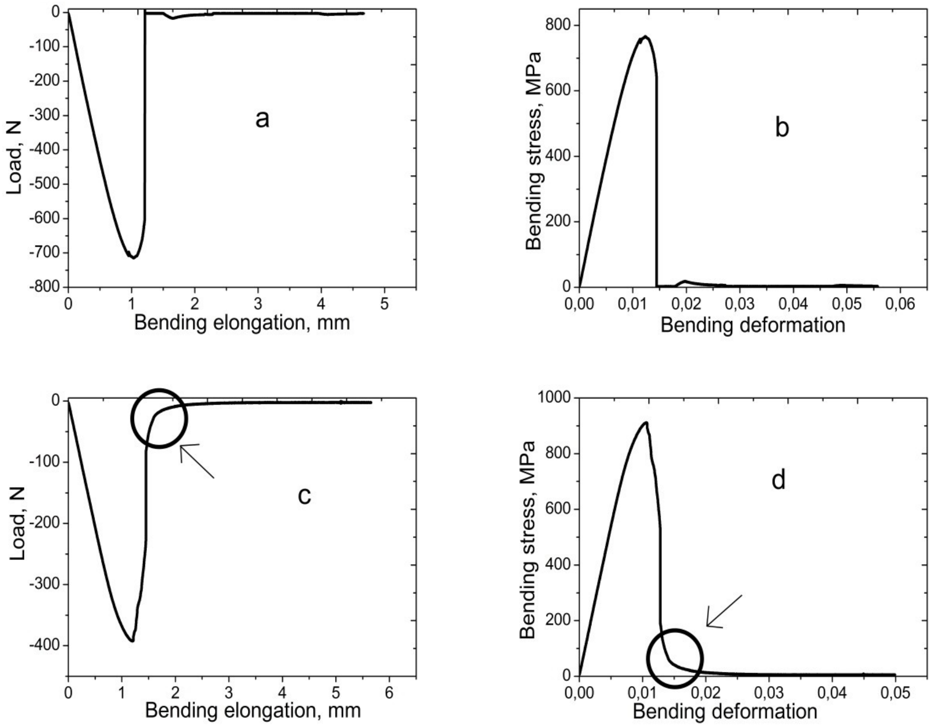

Figure 4. Dependences "load - elongation" (a, c) and "stress-strain" (b, d) during bending of Ni_3Al intermetallic samples in the initial state (a, b) and after pulsed electron irradiation according to the 5 J/cm^2 mode, 3 μs, 5 pulses, (b, d).

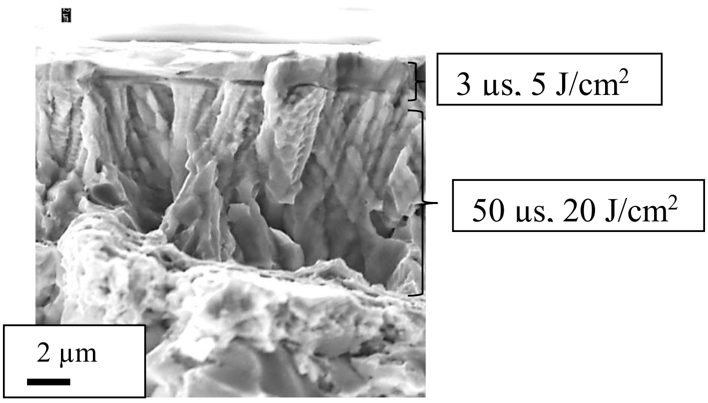

Figure 5. The microstructure of the fracture of the intermetallic sample surface layer after double pulsed electron irradiation - pulses with a duration of 50 μs + pulses with a duration of 3 μs.

The microstructure of the cross-section of the intermetallic compound surface layer after twofold irradiation consists of a thin upper layer and a more voluminous layer of the columnar structure. Tests of samples with a two-layer structure of the surface layer under tension showed a noticeable increase in the strength of the samples (Fig. 6).

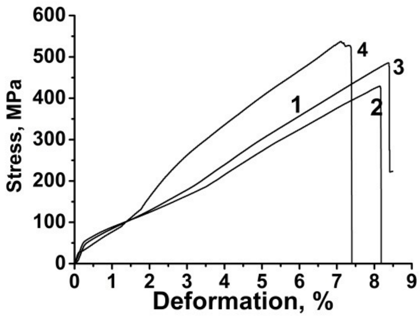

Figure 6. Extension curves of Ni_3Al intermetallic compound samples in the initial state (1), after irradiation with pulses of 50 μs (20 J / cm^2, 3 pulses) (2), pulses of 3 μs (5 J/cm^2, 5 pulses) (3) and after irradiation with pulses of 50 μs (20 J/cm2, 3 pulses) with subsequent irradiation with pulses of 3 μs (5 J/cm^2, 5 pulses) (4).

It can be stated that the formation in the surface layer of a two-layer structure with a gradient dispersion of the structure increases the ultimate strength compared with its value for samples of the intermetallic compound after single irradiation.

4. Conclusions

1. Pulsed electron irradiation drastically modifies the structure of the Ni3Al intermetallic compound samples surface layer - a directionally crystallized structure in the form of columnar intermetallic grains oriented perpendicular to the irradiation surface is formed in the surface layer.
2. With an increase in the duration of irradiation pulses, the thickness of the layer with a modified structure increases.
3. As the power density of the electron irradiation increases, the cross-sectional dimensions of the columnar structure grains decrease to nanoscale level.
4. The formation in the surface layer of a gradient fibrous structure consisting of a thin layer of highly dispersed (nanoscale) structure on a thicker layer of directionally crystallized fibrous structure, by double electron irradiation, initially with a lower power density in the electron beam, increases the ultimate strength of the intermetallic compound samples, including the number of samples after a single electron beam irradiation.

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