Pulsed micro-melting method for single-cristal turbine blade reduction technology

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Abstract. The paper is devoted to the study of the composition, microstructure and mechanical properties of heat-resistant single crystalline intermetallic alloy. In order to develop a resource-saving technology, the method of pulsed micro-surfacing has been tested, designed to restore the geometric dimensions of cooled gas turbine blades.

1. Introduction
Erosion wear and destruction of the flange in the upper part of the blade feather occurs during long-term operation, which leads to a decrease in the efficiency of the engine. Therefore, properly conducted surfacing work to restore the geometric parameters of the flange and damaged areas of the blade will ensure the recovery of not only the blades, but also the turbine as a whole [1]. It is known that in the process of surfacing it is necessary to strive for minimal manifestations of the effects of melting the base material and creating minimal residual stresses in the part. This is especially important for monocristalline alloys, since it is necessary to preserve the invariance of the structure of the material in important zones of parts.

This work is devoted to the study of the composition, structure and mechanical properties of a single-crystal intermetallic alloy in the initial state and after surfacing in various ways. The results will be useful in the development of recovery technology of single-crystal gas turbine blades.

2. Research methodology and discussion of results

Research methods
The object of the study was a sample (size 30x25x5 mm) (figure 1a) of a heat-resistant single-crystal intermetallic alloy produced by the method of gradient directed crystallization and intended for the manufacture of turbine blades [2]. The surfacing of the samples was carried out using pulsed argon-arc micro-welding with “WeldPro SW-V01” apparatus (arc current I = 80 A, pulse duty ratio 0.8 s) and manual argon-arc welding with “Campy” apparatus (arc current 120 A). As an surfacing material, EP648 heat-resistant nickel alloy wire was used (the elemental composition: Ni – base, W-9.87%, Co-9.38%, Al-6.09%, Cr-4.58%, Mo-1.09%, Re-4.25%, Ta-3.44%, Nb-1.08%) [3].

Elemental analysis of the alloy was investigated on a “Niton XL2 Analyzer”. The phase composition was determined on different faces of the sample by X-ray diffraction (Bragg-Brentano diffractometer, Cu-Kα radiation). The microstructural analysis was carried out with an microscope “Microcon” and an electron microscope “TESCAN VEGA II”.

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The microhardness of the alloy was measured on PMT-3 microhardness tester (with a load of 1 N). To determine the microplasticity limit $\sigma_0$ and the yield strength $\sigma_T$ of the material, a multi-stage compression method with increasing load on the relaxometer was used.

**Research results**

**Initial state**

The single-crystal intermetallic alloy has the elemental composition: Ni – base, W - 9.87%; Co - 9.38%; Al - 6.09%; Cr - 4.58%; Mo - 1.09%; Re - 4.25%; Ta - 3.44%; Nb - 1.08%. The base phase of the alloy is $\gamma'$-Ni$_3$Me intermetallic (figure 2, table 1). On the diffractogram obtained for the “A” face of the sample, there is one high-intensity reflex corresponding to the crystallographic plane with the (100) orientation (figure 2a). In this case, the microstructure has the form of oriented dendrites with a branch size of 420 x 330 $\mu$m (figure 1b).

**Figure 1.** The appearance of the sample of the single-crystal intermetallic alloy (a), the dendritic microstructure of the material for the face "A" (b).

The phase composition obtained for the faces “B” and “C” of the sample is a set of reflexes of $\gamma'$-phase and carbides (figure 2b, table 1). The microstructure of the material for these faces has a fragmentary structure: the fragments are elongated along the direction of crystallization and consist of finely-divided blocks (figure 3a). Between them there are areas with fine carbide inclusions (figure 3b).

**Figure 2.** Diffractograms of the alloy obtained for different faces of the sample: a - "A", b - "B" and "C".

Local elemental analysis showed that the alloying elements in the alloy have a non-uniform distribution. The elements W, Co, Al, Mo participate in the formation of the intermetallic phase of the $\gamma'$-Ni$_3$Me complex composition (figure 4a, spectra 13-15). Rare-earth elements form clusters of fine particles (figure 4b, spectra 17-19).
Table 1. The results of x-ray phase analysis of single-crystal intermetallic alloy.

| Face | 2θ (grad) | D (nm) | I (%) | Phase             |
|------|-----------|--------|-------|-------------------|
| A    | 50.800    | 0.2215 | 100   | γ′-Ni<sub>3</sub>Me |
|      | 40.750    | 0.1797 | 3     | Cr<sub>7</sub>C<sub>3</sub> |
|      | 34.373    | 0.2613 | 25    | γ′-Ni<sub>3</sub>Me |
|      | 39.984    | 0.2254 | 26    | Cr<sub>7</sub>C<sub>3</sub> |
|      | 43.211    | 0.2095 | 100   | γ′-Ni<sub>3</sub>Me |
| B    | 50.226    | 0.1818 | 20    | γ′-Ni<sub>3</sub>Me |
|      | 58.223    | 0.1586 | 13    | γ′-Ni<sub>3</sub>Me |
|      | 69.447    | 0.1352 | 9     | Ni<sub>6</sub>C |
|      | 74.217    | 0.1278 | 31    | γ′-Ni<sub>3</sub>Me |
|      | 34.373    | 0.2613 | 49    | γ′-Ni<sub>3</sub>Me |
|      | 39.984    | 0.2254 | 21    | Cr<sub>7</sub>C<sub>3</sub> |
|      | 43.352    | 0.2085 | 63    | γ′-Ni<sub>3</sub>Me |
| C    | 50.226    | 0.1818 | 100   | γ′-Ni<sub>3</sub>Me |
|      | 58.223    | 0.1586 | 25    | γ′-Ni<sub>3</sub>Me |
|      | 69.449    | 0.1352 | 21    | Ni<sub>6</sub>C |
|      | 74.357    | 0.1276 | 37    | γ′-Ni<sub>3</sub>Me |

The anisotropy of the phase composition and microstructure present in the material has led to non-uniformity of mechanical properties. Microhardness measurements showed that:

(for the “A” face) in the interdendritic space, the microhardness value is HV = 5.0 GPa, in the region of dendrites HV = 6.75 GPa, in the zones of fine carbide inclusions HV = 6.5 GPa.

(for faces “B” and “C”) the microhardness of the matrix is in the range HV = 4.5 - 5.65 GPa (figure 3a, b). In the zones of dendrites and carbide particles, it is significantly higher and amounts to HV = 6.2 - 6.55 GPa (figure 3b).

![Figure 3](image-url)

**Figure 3.** The microstructure of the alloy obtained for the faces "B" and "C": a – fragmented structure, b – areas with carbide inclusions.
The relaxation tests carried out on the samples showed that the mechanical properties of the material depend on the direction of crystallization. Samples cut along the direction of crystallization have higher values of microplasticity and yield strength compared with samples cut in the transverse direction.

After surfacing
Using a pulsed micro-surfacing, a layer ~ 500 μm thick was built up onto the sample face (“A”) (figure 4a). Metallographic studies have shown that this layer has a uniform microstructure with a columnar grain shape (figure 4c). The interface between the base and weld metal has no holes, pores, microcracks, and also has high adhesive properties (figure 4b). Near the weld area is not observed pronounced heat-affected zone. At the same time, the structure of the base material has not changed. On the “A”, “B” face (under the layer of the deposited material) a dendritic microstructure remained, and on the «C» face, there is a fragmented microstructure of the alloy (figure 5). Measurements of microhardness showed that the weld metal has a microhardness of HV = 4.1 GPa. The hardness of the base material directly near the interface is in the range HV = 4.3 - 4.6 GPa, at a distance (> 10 mm) from the area of the weld - HV = 4.3 - 4.9 GPa and corresponds to the initial values (before surfacing). Thus, the pulsed micro-surfacing does not have a significant effect on the mechanical properties and the structure of the base material.

![Figure 4](image_url)  
**Figure 4.** Appearance (a) and microstructure of the sample cross-section (b), the microstructure of the weld metal (c) after pulsed micro-melting: 1 – weld metal, 2 – main material.

![Figure 5](image_url)  
**Figure 5.** The microstructure of the base material obtained for the faces "A" (a), "B" (b) and «C» (c) near the zone of pulsed micro-melting.

Comparative analysis of methods of surfacing
For comparison of the methods of surfacing on a single-crystal sample, argon-arc surfacing (figure 6a) was carried out (wire and sample are the same as in the first study). The thickness of the weld layer was ~ 1 mm. The grains of the weld metal have a dendritic structure (figure 6b) with different orientation of the dendrites (figure 6c). Microhardness of the layer HV = 5.7 GPa. The interface is a...
zone of strong etching, which indicates a weak connection with the main material. Along the interface there are areas of discontinuities. A zone of thermal influence is observed near the interface. This zone consists of two parts: the first light non-etching layer having a thickness of 100-250 µm and a hardness of HV= 5.4 GPA (layer 3 in figure 6b); the second layer having a thickness of ~ 0.7 mm and a hardness of HV=5.2 GPa (layer 4 on figure 6b). The material with the initial structure and hardness HV=4.9 GPa is observed behind the zone of thermal influence. Micro-indentation tests showed low adhesion strength to the base material, as evidenced by the delamination of the interface observed after the test.

Figure 6. Appearance (a) and microstructure (b) of the sample cross-section, the microstructure of the surfacing metal after argon-arc surfacing: 1 - weld metal, 2 - interface, (3 + 4) - heat-affected zone, 5 - the main material.

The results of the comparative analysis showed that the pulsed micro-surfacing has advantages in comparison with the traditional argon-arc surfacing, in which a pronounced zone of thermal influence is formed. The method of pulsed micro-surfacing was tested when restoring blades of the 1st stage of the Siemens SGT-800 turbine (figure 7) [4].

Figure 7. Turbine blade of the 1st stage of SGT-800 Siemens after operation (a) and restoration by the method of pulsed micro-surfacing (b).

3. Conclusions
Studies have shown that in heat-resistant monocrystalline alloys mechanical characteristics depend significantly on the direction of crystallization. When developing resource-saving technologies for turbine blades, it is necessary to take into account the features of the crystal structure of single-crystal alloys and the anisotropy of mechanical properties. It is established that the method of pulsed micro-melting does not have a temperature effect on the structure and mechanical characteristics of the base material, which is important in terms of preserving the heat-resistant and mechanical properties of the single-crystal alloy. This method of surfacing is recommended for use as part of repair and restoration technologies to extend the life of turbine blades not only imported but also domestic gas turbine engines.
Acknowledgments
Work is performed within the framework of the State job of IAP RAS to conduct fundamental research on 2013-2020 Gg. on the topic of № 0035-2014-0401 (registration No. 01201458049).

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