DOI: http://dx.doi.org/10.15407/tpwj2019.06.03

REPAIR SURFACING OF GAS TURBINE ENGINE BLADES FROM HIGH-TEMPERATURE NICKEL ALLOYS WITH SURFACE DEFECTS AND DAMAGE

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The main types of defects and damage were determined based on studying full-scale gas turbine blades after manufacture and operation. Most of the defects are located on the surface. The possibility is shown for performance of operations on their elimination by electron beam surfacing with filler of the same composition as that of the blade. Relationship temperature-time of parameters of formation of repair welds, their dimensions and geometry was established. The technological schemes were determined for providing the temperature-time and crystallographic orientation conditions of preservation of single-crystal structure in repair of high-temperature nickel alloy blades. The peculiarities of formation of welds, and their structure, depending on technological parameters of the process of electron beam surfacing were investigated. The methods of practical realization of the obtained results in repair of blade areas of various crystallographic orientation were developed and tested. Examples of repair of blades with structural defects of airfoil surface and damage of edges are given, when restoration of initial geometry, crystallographic orientation and single-crystal structure is provided. 26 Ref., 9 Figures.

Keywords: *electron beam surfacing, gas turbines, blades, high-temperature nickel alloys, defects and damage restoration, single-crystal structure*

Blades of aviation gas turbine are the most loaded elements of the hot section, responsible for operating characteristics, service life and reliability of the power unit as a whole [1, 2]. This results in high requirements to materials, from which they are made, to their composition and quality of the structure. At present high nickel alloys with single-crystal structure meet these requirements to the most. However, extreme conditions of blade operation cause a considerable extent of erosion damage that significantly lowers the power, cost and other characteristics of the engine, including the safety and reliability of its operation. Highly critical in this respect are also the structural defects, which may arise during growing the single-crystal blades, as a result of disturbance of directed crystallization conditions.

Analysis of statistical data on manufacturing and operational damage of single-crystal blades shows [2–5] that the greater part of them is on the surface. Operational defects include mechanical damage and erosion, surface cracks due to thermal fatigue of airfoil edges, shroud flange seals; manufacturing defects are blisters and grains 150–500 μm deep on airfoil surface, freckle-type liquation, and carbide precipitation. A common feature of the defects is their surface location and depth down to 500 μm.

The urgency of repair becomes obvious, considering the increasing volume of production and application of blades with directional and single-crystal structure from high-temperature nickel alloys (HTNA) in modern gas turbines, high cost, considerable percentage of rejects (up to 30–70 %) during their manufacture and damage in operation, as well as the need for extension of service life of engines.

The main question, in addition to restoration of surface geometry, is providing the single-crystal structure and initial crystallographic orientation of weld metal in the repaired area. Application of fusion welding in repair of blades with a polycrystalline structure [6–10] allows solving the respective tasks of a number of aircraft-repair plants. At the same time, its application for repair of single-crystal blades is restrained, in view of the structural features and operational requirements.

Analysis of the conditions of formation of single-crystal structure in HTNA welds [11–15], showed that ensuring the high temperature gradient on the growth front and flat macrofront at crystallization are the most essential elements in blade repair. The design and geometrical features of the blade and thickness of metal cross-section in the repaired area impose certain difficulties. This raises the questions not only of selection of the welding process and modes, kind of filler material and method of its feeding into the weld pool, but also providing controllable heat input.

Welding process for repair performance. Such processes of welding with filler, as argon-arc, microplasma, laser, electron beam are used for repair of

HTNA blades with a polycrystalline structure [6–10]. Each of them has its features, which determine the limitations of their application in repair of blades with single-crystal structure.

Argon-arc and microplasma methods are limited by the complexity of precision control of the thermal cycles, limitation of overheating of the base and deposited metal at formation of a single-crystal structure. In addition, the main alloying elements of HTNA, particularly γ'-forming ones — aluminium and titanium, increase the probability of formation of hot cracks in fusion welding [15–20]. Insufficient protection of the pool melt leads to oxidation and formation of refractory oxides [20, 21]. The latter not only hinder formation of single-crystal structure of the deposit, but can also be the crystallization centers of randomly oriented grains (ROG) that is an indication for rejection [13, 22, 23]. Particularly inacceptable is oxygen enrichment of the weld pool because of:

- weld pool surface oxidation;
- presence of impurities in filler material;
- presence of residual oxygen in shielding gas atmosphere, in particular, at disturbance of laminarity of shielding gas outflow.

Application of electron beam welding (EBW) in the high vacuum environment of the work chamber (10^{-4}–10^{-5} mm Hg) eliminates these problems. Selection of the welding process was based on the possibility of preservation of crystallographic orientation [12–15], temperature-time [11] and temperature-space conditions of directed crystallization at surfacing. It was taken into account that in the general case the nonequilibrium and nonuniformity of these conditions both in time and across the welded joint section are in place in welding, which are enhanced by complex, variable geometry, thickness and crystallography of the repaired section. Therefore, the main attention was given to energy and technological characteristics of the welding process, which allowed limiting the negative influence of the above factors.

EBW process allows controlling in a broad range the main structure-determining parameters of weld pool crystallization:

- temperature and time of melt existence;
- geometry of solidification macrofront;
- temperature-time parameters at the crystallization front.

This allowed achieving refinement of the dendrites, as well as γ'-phase, carbides, optimizing their morphology, and reducing dendrite liquation. Such a structure promotes improvement of both the mechanical properties, and operational characteristics at preservation of crystallographic orientation of single crystals.

Surfacing material. In order to provide the mechanical properties and operational characteristics of products at repair operations, matching of chemical composition of the deposited and base metal is required, alongside ensuring the temperature-time and orientational conditions of formation of single-crystal structure of the deposits. In connection with the fact that manufacturing filler wire materials from HTNA with more than 60 % content of strengthening γ'-phase is problematic, because of the high strength and low ductility, the possibility of application of powder and rod materials was considered.

«Selective laser sintering» scheme can be used as one of the best variants of powder feeding into the surfacing zone [24]. With this technique a layer of powder material of a certain thickness is formed at the first stage, then the powder section is selectively surface melted, followed by formation of a new layer of dispersed material, and this process is repeated until the required height of the deposit has been achieved. Application of such a scheme at EBW can have a number of advantages, one of which is absence of gas transporting the powder that is essential under the high vacuum conditions. However, application of dispersed materials at EBW can be limited as a result of:

- complexity of equipment adaptation and precision metering of powder under the conditions of a vacuum chamber;
- powder spraying under the impact of the electron beam;
- weld metal contamination by oxygen and other impurities, in connection with the developed surface of powder components;
- high probability of ROG formation at crystallization;
- high requirements to uniformity of granulometric and chemical composition, flowability, conditions of powder manufacturing and storage.

In order to limit the above disadvantages of filler materials, it was proposed to use at EBW the standardized rods cut out of HTNA single-crystal billets. Their trials at surfacing 2 mm samples from ZhS26 alloy showed a positive result — sound formation of deposits of specified dimensions and structural composition is achieved.

Features of formation of the deposits, their structure and crystallographic characteristics. Complex alloying of HTNA single-crystals, high content of the strengthening γ'-phase, absence of high-angle grain boundaries — factors, ensuring the complex of mechanical properties and maximum operational life, impair their weldability at the same time. This is manifested in proneness to formation of cracks, structural defects, ROG appearance, deviation of crystallographic orientation from the initial one, that, eventually, lowers the technological and operational strength [11–15, 23]. The objective is to produce sound deposits and welded joints of HTNA single-crystals, taking into account formation of the specified structural state and crystallographic characteristics of weld metal. Complex of performed research showed that [11–15] the optimal parameters of structural perfection of the weld are achieved when ensuring certain temperature-time and orientation conditions of welding, which are defined by the value and direction of temperature gradient **G** at weld pool crystallization front, solidification rate **R**, their ratio **G/R,** crystallographic orientation of the edges being joined and welding direction. A relationship between the above crystallization parameters and technological factors was established [11]. The possibility is shown of producing single-crystal welds even at unfavourable crystallographic conditions, at the expense of controlling the temperature-time parameters of weld pool crystallization. This is particularly important in welding or surfacing of blades of a complex spatial shape. It is important to take into account different orientational characteristics of potential repair sections (Figure 1). Some of these areas match [001] orientational that corresponds to symmetrical conditions of crystallization (leading and trailing edge), and some of them do not coincide with [001]. Such combinations of the conditions strongly hinder ensuring directed crystallization and formation of a single-crystal structure of the required perfection.

We assume that the expression «perfection of structure» means orientational uniformity of weld metal, heat-affected zone and base metal at maximum admissible deviation up to 5–8°, absence of grains of other orientation; uniformity of dislocation distribution.

Possibility of ensuring directed crystallization at weld pool solidification front, formation of single-crystal structure of the weld under asymmetrical conditions was the key task, the solution of which allowed establishing the main principles of basic technologies of repair. The dimensional-orientational features of repair sections should be taken into account, and physical conditions of directed crystallization of weld metal should be provided. Therefore, the main part of the work is aimed at investigation of the effect of technological factors on temperature-time and orientation parameters of the surfacing process, and, therefore, on improvement of weld metal structure.

Technique of electron beam surfacing. Surfacing of blade airfoil surface. Part of the studies was performed on flat samples and blades. Samples were cut out by electric-spark method from 80×60×8 mm billets of ZhS26 alloy. Sample thickness of 1.5 to 2.0 mm was chosen, proceeding from mid-thickness of the section of blade airfoil flanges. Initial crystallographic orientation of the deposit surface was selected in keeping with the sections of possible blade repair and corresponded both to symmetrical and asymmetrical (*hkl*) > 20° of (100)) crystallographic conditions.

We proceeded from the statement of [25] that the rate of weld metal cooling and, consequently, of other temperature-time parameters of welding, is deter-

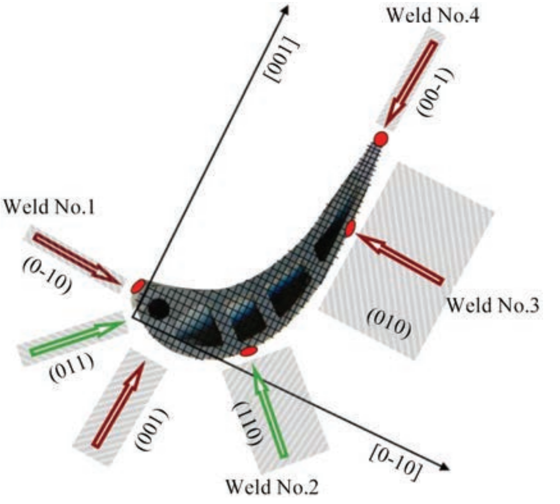

Figure 1. Scheme of location of crystallographic zones and possible repair sections of the blade

mined by the ratio of the mass (volume) of weld pool melt to base metal. Temperature-time conditions of crystallization are established proceeding from the dimensions of the deposit (total height h and width B). Use of EBW process allows controlling these parameters in a broad range.

Results of metallographic examination showed that at geometrical parameters of the deposit (Figure 2) $h \leq 0.6$ mm and $h/B \leq 0.2$, made in one pass, increase of the stability of directed crystallization zone, formation of finely-dispersed ($\lambda = 1.5$–2.0 μm) cellular-dendritic structure are ensured, that limits formation of randomly-oriented grains (Figures 2, 3). Characteristics of dislocation structure correspond to uniform distribution (Figure 4), which is indicated by the shape of closed smooth regular iso-intensive lines $I_{q\perp}$ of X-ray reflections. On the whole, the structure of deposit zones corresponds to typical requirements of HTNA single-crystals.

Increase of deposit height to 0.8 mm and ratio $h/B = 0.25$ leads to formation of isolated ROG. Further change of geometrical parameters of the deposited layer leads to increase of ROG number and cracking (Figures 3, 5).

It should be noted that the results of calculations made by the procedure, described in [11], using the

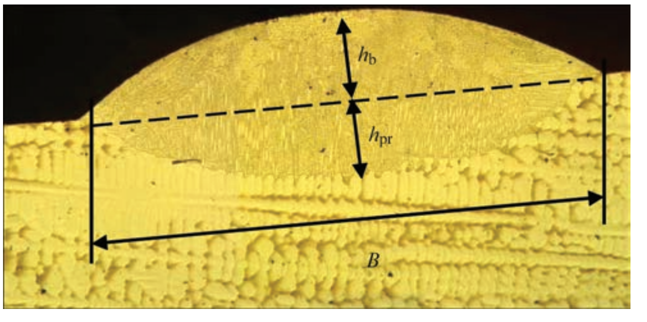

Figure 2. Parameters of geometrical characteristics of the deposit: B — deposit width; $h = h_b + h_{pr}$ — total deposit height; where h_b is the bead height; h_{pr} is the base metal penetration depth (×50)

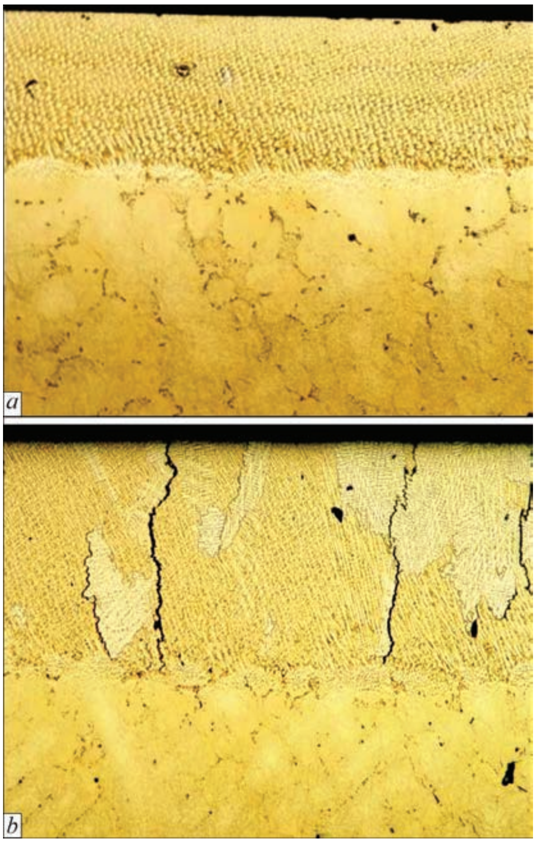

Figure 3. Microstructure (×100) of the deposit from single-crystal alloy Zhs26 2 mm thick under asymmetrical crystallographic orientation conditions at the ratio of weld geometrical parameters: *a* — *h*/*B* = 0.2 and deposit height *h* = 0.6 mm; *b* — *h*/*B* = 0.3, *h* = = 0.9 mm

known Brody-Fleming relationship, showed that temperature-time characteristics of deposit crystallization (ratio **G/R** > 10^4 s/·°C/mm^2), made in asymmetrical orientation at $h/B \le 0.2$, correspond to the conditions of formation of single-crystal structure.

Surfacing of blade edge. During GTE operation, the leading attack edge [1] of approximately 3–4 mm width and thinner trailing edge of about 2–5 mm are most often damaged. Testing of edge surfacing technique was conducted on the end faces of single-crystal plates from ZhS26 alloy 2–3 mm thick. The effect of temperature-time characteristics of the process on the change of the structure was evaluated using wedge-shaped plates 4–8 mm thick, which determined the variable width of the substrate, which was surfaced in a constant mode. Crystallographic orientation of the plates corresponded to [001] with deviation of up to 15°. The correspondence of physical conditions **G/R** to formation of single-crystal structure was assessed by deposit dimensions (*h*, *B*) and value of their ratio, as in surfacing on the plane.

During investigations a relationship was established between geometrical ratio *h*/*B* of the deposit on the edge and its formation quality, preservation of single-crystal structure, formation of ROG and cracks (Figure 6). Differences are observed at geometrical ratio of single-pass deposit — $h/B \ge 0.8$ (Figures 4, 6, 7). Disorientation of block-type dendrite structure does not exceed 5 – 8°. The optimum variant are parameters of geometrical ratio $h/B \le 0.4$ (Figures 5;

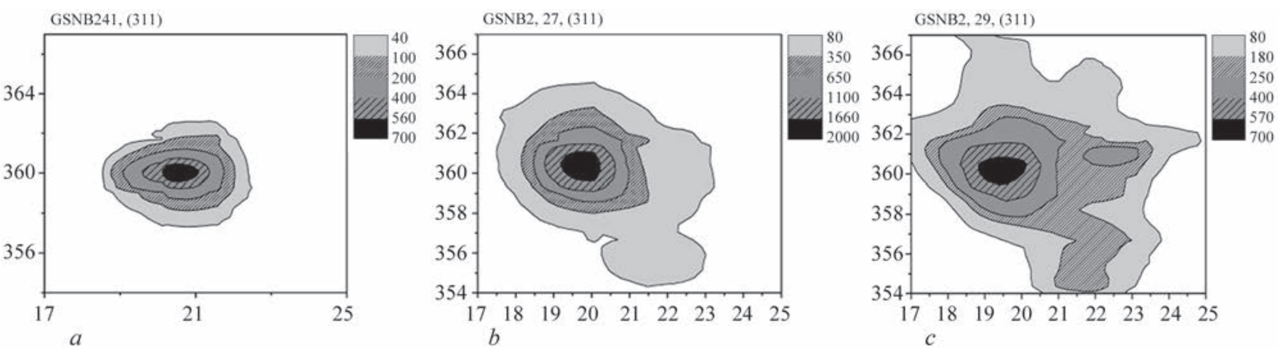

Figure 4. Iso-intensive lines of distribution $I_{q\perp}$ of (311) reflection in base metal (*a*), HAZ (*b*) and in the weld (*c*) for deposits with ratio *h*/*B* = 0.8

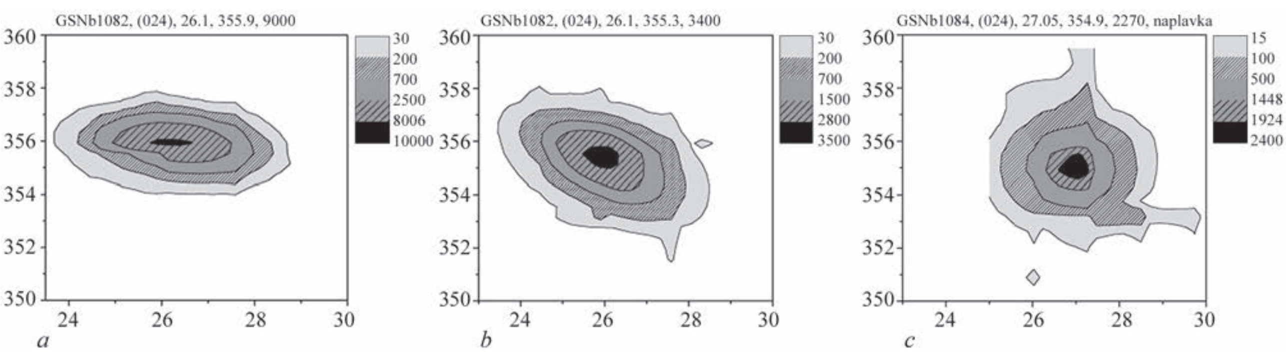

Figure 5. Iso-intensive lines of distribution $I_{q\perp}$ of (311) reflection in base metal (*a*), HAZ (*b*) and in the weld (*c*) for deposits with ratio *h*/*B* = 0.4

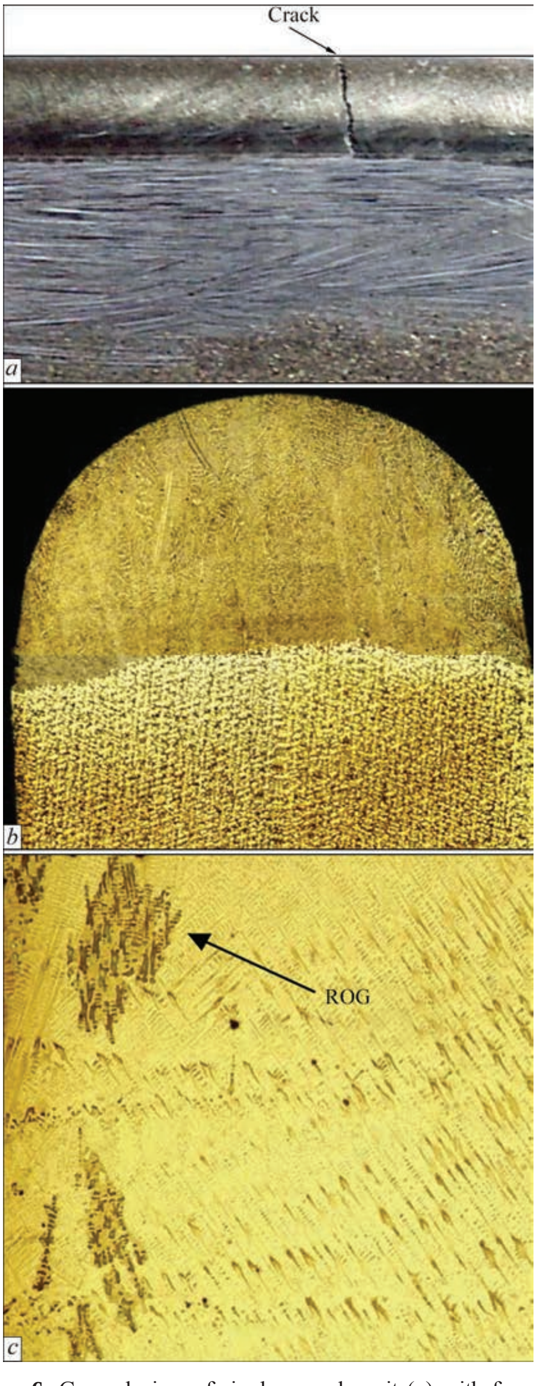

Figure 6. General view of single-pass deposit (*a*) with formation defects, cracks and ROG (*a-c*), macro- and microstructure (*b*, *c*). Geometrical parameter of the deposit $h/B = 0.8$ (*b* — ×25; *c* — ×100)

7, *b*; 8). Maximum deviation of structural component orientation $\Delta\alpha$ from the crystallographic orientation of initial metal does not exceed 1.5°. Characteristics of dislocation structure correspond to their uniform distribution (Figure 5). On the whole, the deposit zone structure meets typical requirements to the growth structure of single-crystal blades from HTNA.

Increase of the deposit height enhances the probability of ROG and crack formation, in connection with accumulation of structural defects and stresses. Nonetheless, the single-crystal deposit height was brought to 10 mm, by successive deposition of layers

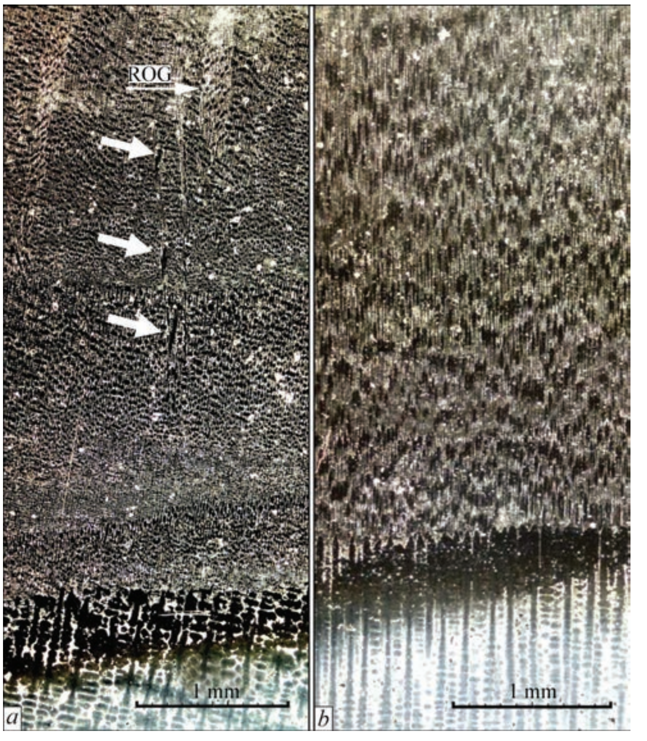

Figure 7. Longitudinal microsections (×50) (dark field) of surfaced samples: *a* — $h/B \geq 0.8$ (arrows show microcracks and ROG); *b* — $h/B = 0.4$

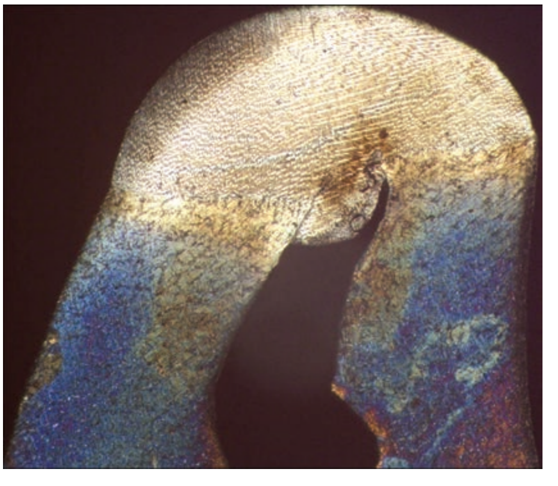

Figure 8. Restored leading edge of a single-crystal blade from ZhS26 alloy of aviation GTE at electron beam surfacing with deposit ratio $h/B = 0.4$ (×50)

made to the respective technological requirements, at initial edge width of 5–7 mm.

Results of the performed studies and test deposits allow recommending repair of sections of different crystallographic orientation of single-crystal blades from HTNA with surface defects (Figure 1) by successive deposition of layers by EBW. The proposed technology was tried out in repair of blades (Figures 8, 9) from ZhS26, ZhS32 alloys [26].

Conclusions

1. The main objectives of repair of single-crystal blades from HTNA with manufacturing defects and

Figure 9. Appearance of single-crystal blades from ZhS32 alloy with repair welds

operational damage is restoration of initial geometry, physical continuity and crystallographic uniformity of near-surface regions of the airfoil and edges.

2. Realization of physical conditions of formation of single-crystal structure of repair welds is achieved by technological means of EBW, by limiting the value of the ratio of deposit geometrical parameters *h*/*B*, with application of standardized rod filler material in keeping with study results. The technology was tried out both for single-pass and multipass surfacing of single-crystal elements of GTE hot section.

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Received 15.04.2019