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CRYSTALLOGRAPHIC AND DIMENSIONAL CHARACTERISTICS OF STRUCTURE ELEMENTS IN WELDS OF HIGH-TEMPERATURE NICKEL ALLOY SINGLE CRYSTALS

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ABSTRACT

Crystallographic-orientational and dimensional-morphological features of microstructure in welded joints of high-temperature nickel alloy single crystals are considered, depending on the initial crystallographic orientation and its change over the weld solidification macrofront. EBSD analysis and optical metallography methods were used to study the structural features of individual zones of welded joints of high-temperature nickel alloy single crystals. Their dependence on the initial crystallographic orientation of the welded joint and its change over the weld pool solidification macrofront is established. It is shown that alongside the predominant inheritance of base metal crystallographic orientation by the weld metal, formation of a grain structure of different crystallographic orientation, morphology, dimensions and nature, namely solidification and deformation-induced, can be in place. The mechanisms of formation of grains of the specified nature are considered. Boundaries of solidification type grains are the junction of dendrite blocks with different crystallographic orientation. Deformation type grains are the result of relaxation of microstresses at the stage of welded joint cooling, and they form in areas where the direction of acting stresses is the closest to the crystallographic orientation of easy slip. It was also found that deformation type grains can form both in the weld metal, and in the HAZ. At the same temperature conditions of making the welded joints, the quantitative and dimensional-orientational parameters of deformation structure of the HAZ metal correlate with similar parameters of weld structure elements. The possibility to produce welds without cracks with perfect single crystal structure is indicated.

KEYWORDS: single crystals, high-temperature nickel alloys, welded joints, EBSD-analysis, crystallographic orientation, structure parameters, grain nature, weld pool, solidification macrofront

INTRODUCTION

The work is related to constantly growing demand for improvement of tactical and technical, service, production and ecological characteristics of gas turbine engines (GTE), and power units (GTU) of both military and civil applications [1–3]. As is known, improvement of thermodynamic characteristics of GTE and GTU is achieved mainly due to increase of gas temperature at the turbine inlet and lowering the rotor metal content and weight that requires creation and application of new high-temperature materials [4, 5]. Increase of high-temperature strength due to more complex alloying, application of alloys, particularly those with a single crystal structure, has now reached its limit, chiefly, in connection with the accompanying deterioration of their adaptability-to-manufacture. Therefore, the majority of designers and manufacturers choose the path of improvement of the turbine design, including application of welding [3, 6]. However, the higher the alloy high-temperature strength, the lower is their weldability, which is manifested in a high susceptibility of high-temperature nickel alloys to cracking and deterioration of the specially created structural state, especially single crystallinity, which ensures an optimal combination of the mechanical characteristics in a broad range of temperatures and loads.

The majority of publications on welding of single crystals of high-temperature nickel alloys (HTNA) consider the conditions of initiation and prevention of formation in the welds of the so-called defects of single crystal growth structure and cracks [7–10]. Results of studying the mechanical characteristics and features of welded joint formation [11, 12] point to the need for a more detailed study of the structure orientation changes, occurring as a result of thermodeformational impact in welding. This applies, in particular, to the crystallographic orientation spectrum, both as a whole, and as individual structural components: presence of local structures, microstresses and strains; nature, morphology and size of structural elements, boundaries and extent of their misorientation as factors, which determine the welded joint mechanical and service properties.

The objective of the work is determination of the influence of the sample initial crystallographic orientation on the structural features of HTNA single crystal welded joint and its change over the weld width.

INVESTIGATION PROCEDURE

Commercial high-temperature alloys with more than 61 % of the intermetallic dispersion-strengthening γ'-phase were selected for investigation performance.

These alloys are widely used as structural material in manufacture of blades of aviation GTE hot section.

Studies conducted by us [8, 9] and other authors [7, 10] of the crystallographic orientation of the joint and influence of the curvature of weld pool solidification macrofront on inheritance of the initial crystallographic orientation by the weld metal and perfection of its structure showed that in order to prevent grain and crack formation, it is necessary to ensure a deviation of the direction of temperature gradient passage through the solidification front from <001> direction. In terms of technology, it is achieved by the correspondence of the plane of welded butt joint edges to the high symmetry orientation {100} and formation of macroplanar front of weld pool solidification. Two main crystallographic combinations: {001}, <100> and {110}, <011> were selected at analysis of possible variants of crystallographic orientation in the welded sample joint (initial metal plane {UVW} and welding directions <hk1>. Collection of samples of the selected crystallographic orientations for welding was performed with up to 5° accuracy. Test samples of {110}, <011> orientation had deviations from the selected one within 10° in some cases, which during welding can result in different value of the angle of deviation of the maximal temperature gradient from <001> direction over the solidification front [8]: up to 15° — favourable conditions, above the indicated level — unfavourable conditions for single crystal structure formation. Samples of 2 mm thickness were cut out by electric spark method from single crystal castings produced by high-gradient directional solidification, with subsequent grinding and etching.

Electron beam welding was performed in modes ensuring stable formation of through-thickness uniform penetration and the temperature-time conditions of single crystal structure formation.

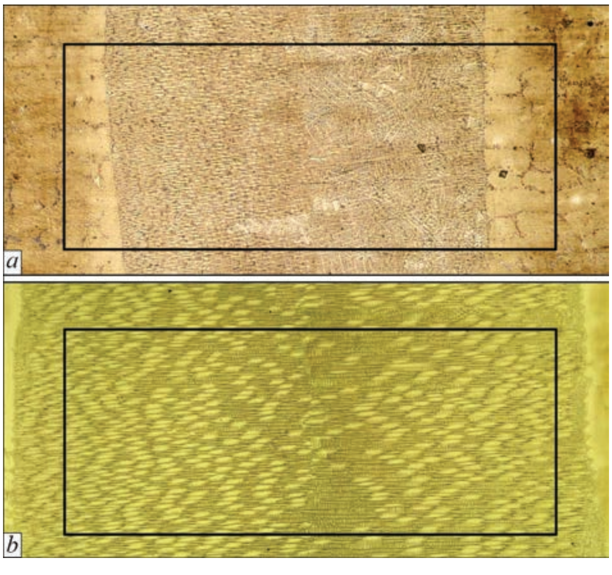

Figure 1. Structure (×50) of HTNA welded joint with sample surface close to (101) (*a*) and (001) (*b*) with outlined areas studied by EBSD

Over the recent years EBSD analysis is becoming successfully applied for evaluation of structural changes in single and polycrystalline materials as a result of technological and service effects, due to automated combination of step-by-step assessment of local (0.05–1.0 μm) structural-deformational changes and subsequent plotting of generalized patterns [13, 14]. Its application provides broader information, compared to the traditional methods of structure evaluation: X-ray structural, electron diffraction in TEM, neutron diffraction, optical metallography, etc., which are chiefly directed at detection and subsequent investigation of the main defects of single crystal growth structure, such as jet segregation, parasitic grains, surface carbides, etc. At the same time, it is known that optimization of HTNA structure parameters is one of the ways to meet the high requirements to the mechanical and service properties of these alloys [12–16]. Moreover, more detailed quantitative and qualitative evaluation of the structure and development of methods to control its formation in welding are becoming ever more urgent.

The advantages of EBSD analysis are especially evident, when studying the single crystal welded joints which are a composition of areas of different structure and crystallographic orientation. Its application provides a large scope of information, required for assessment of the joint structure evolution, important when solving both the theoretical and applied issues of structure formation and control during welding. One of the important advantages of EBSD analysis is the possibility to determine the type and ratio of structure elements and its formation mechanism. When studying the single crystals, the main object of research is the availability and characteristics of grain boundaries as the main factor determining the structure performance: their type, morphology, parameters of shape and dimensions, orientation and specific share of each type. A not less important factor and advantage of EBSD analysis of the welded joints is the clear presentation of the crystallographic orientation of both individual areas and elements of the structure by colour coding in the respective research maps and as a whole.

Investigations of structural-crystallographic state of the welded joints were performed on microsections taken from the sample surface with application of Neophot-32 optical microscope and Verios 460 XHL electron microscope with HKL Nordlys System attachment for EBSD analysis. The general area of scanning by the electron beam is 796×2000 μm, with 2×4 μm locality. Figure 1 illustrates the area studied

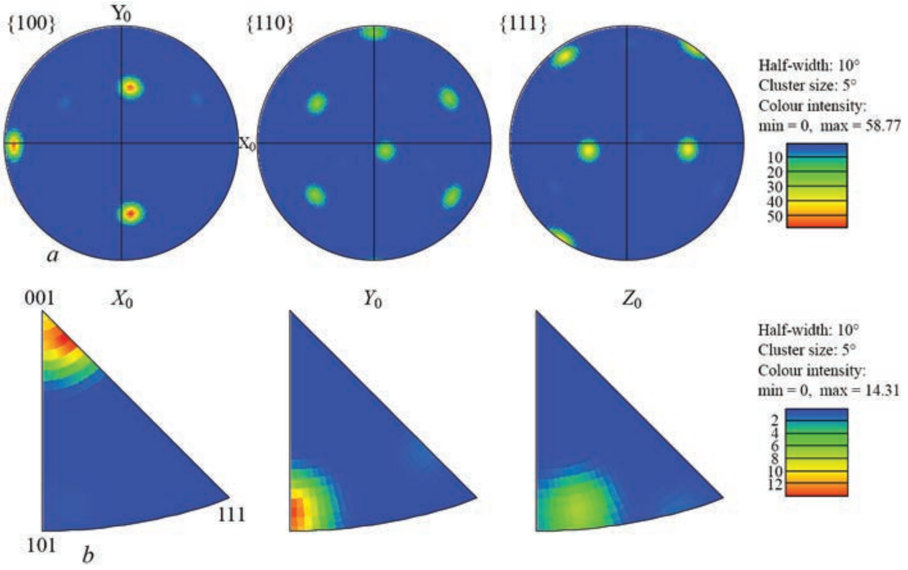

Figure 2. Straight (*a*) and inverse (*b*) pole figures of base metal of single crystal HTNA welded joint with sample surface close to (101)

by EBSD analysis on the welded joints. The characteristic areas of single crystal welded joints revealed during analysis [16, 17] were considered: base metal, HAZ, fusion line, epitaxial growth zone and weld areas with different deviations of the crystallographic orientation from the initial one.

In some cases the crystallographic orientation of the structure was evaluated by metallographic etching patterns. The structure was recorded using an optical microscope. Structure visualization was here performed by microsection surface etching.

Sample preparation for EBSD analysis included a special grinding-polishing technology [13, 14], which allows avoiding the sample surface cold hardening, ensuring a high accuracy of the results. During investigations, the focus was on the welded joints and their individual areas, for which the conditions of directional solidification of the single crystal and formation of a perfect single crystal structure were fulfilled or were not ensured [7–9, 16, 17]. The features of crystallographic orientation and dimensional-morphological characteristics of individual characteristic zones of welded joints, depending on fulfillment of the above-mentioned conditions were considered.

INVESTIGATION RESULTS

The base metal structure is characterized by a typical developed homogeneous coarse-dendritic architecture [15] with directional crystallographic orientation (Figures 2, 3), which corresponds to sample orientation as a whole, and which is determined by the conditions of high-gradient growing of the initial single crystal.

The HAZ metal preserves the initial crystallographic orientation. When moving closer to the fusion line, however, a change in the morphology and

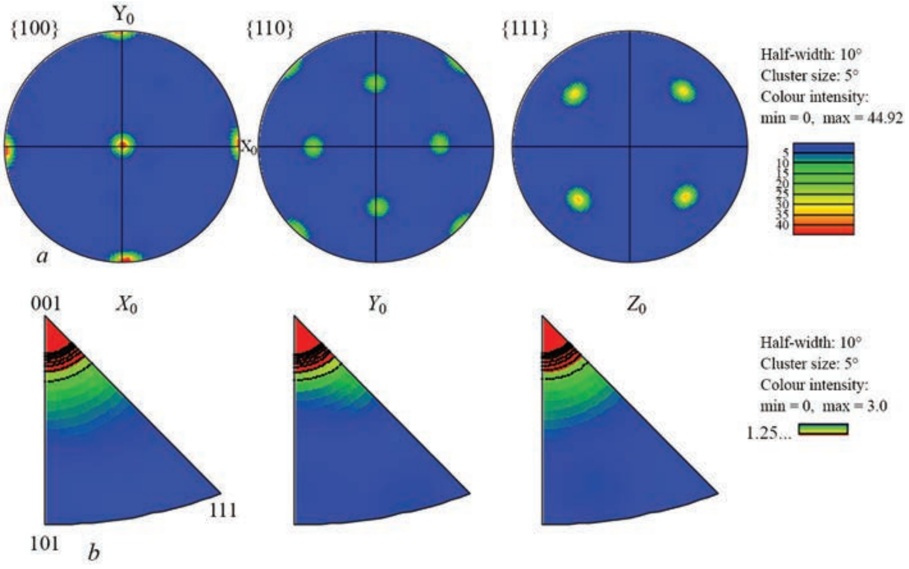

Figure 3. Straight (*a*) and inverse (*b*) pole figures of base metal of single crystal HTNA welded joint with (001) sample surface

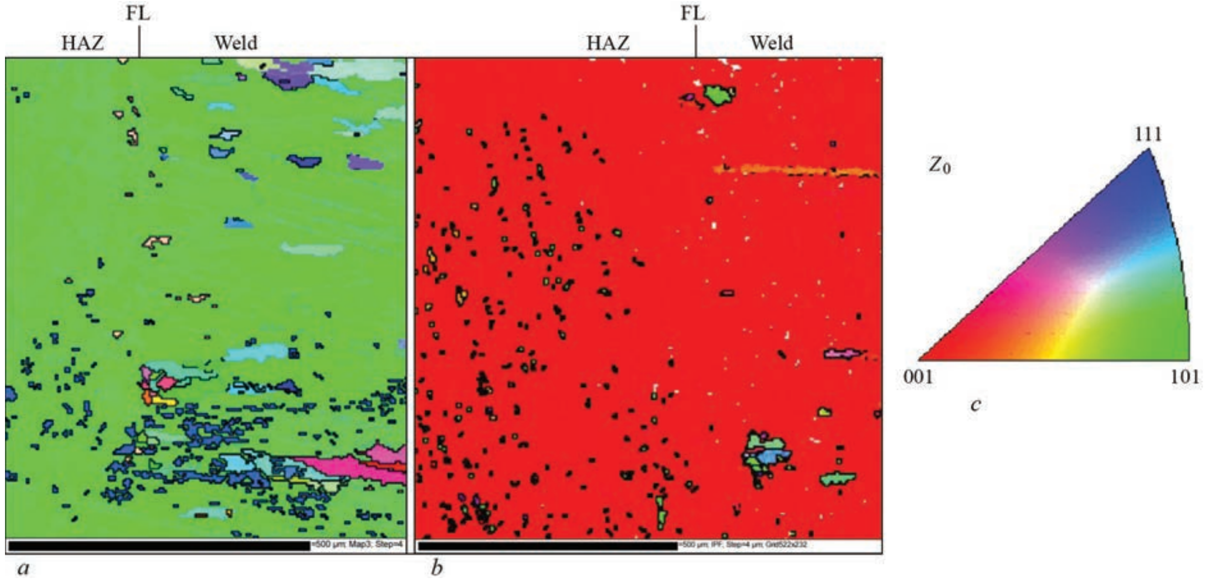

Figure 4. Orientation maps of epitaxial growth zone and HTNA sample fusion areas with surface close to (101) (*a*) and (001) (*b*) at compliance of initial crystallographic orientation (CGO) with directional solidification conditions. CGO is the legend for orientation map, HAZ is the heat-affected zone, FL is the fusion line

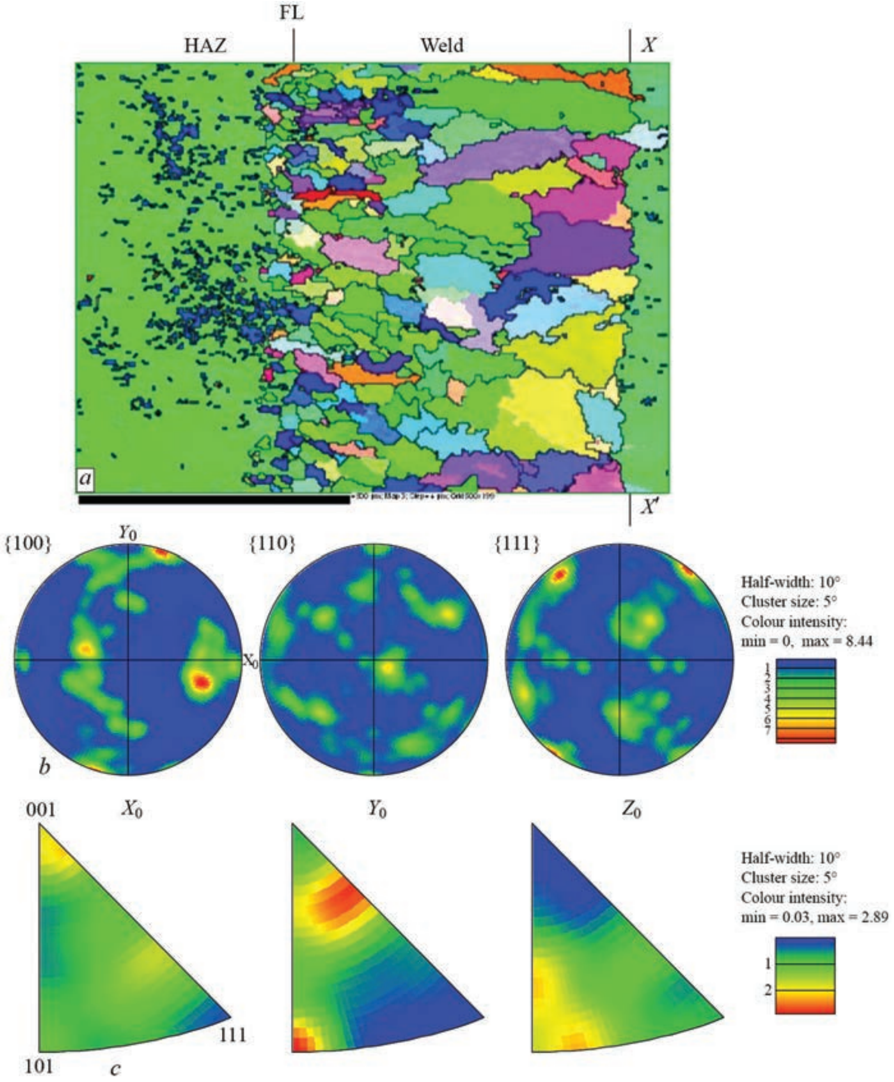

Figure 5. Orientation maps (*a*) of a welded joint area with sample surface close to (101), straight and inverse pole figures (*c*) at non-compliance of weld area with directional solidification conditions. CGO is the legend for orientation map (Figure 4, *c*), HAZ is the heat-affected zone, FL is the fusion line, *X*–*X*′ is the weld axis

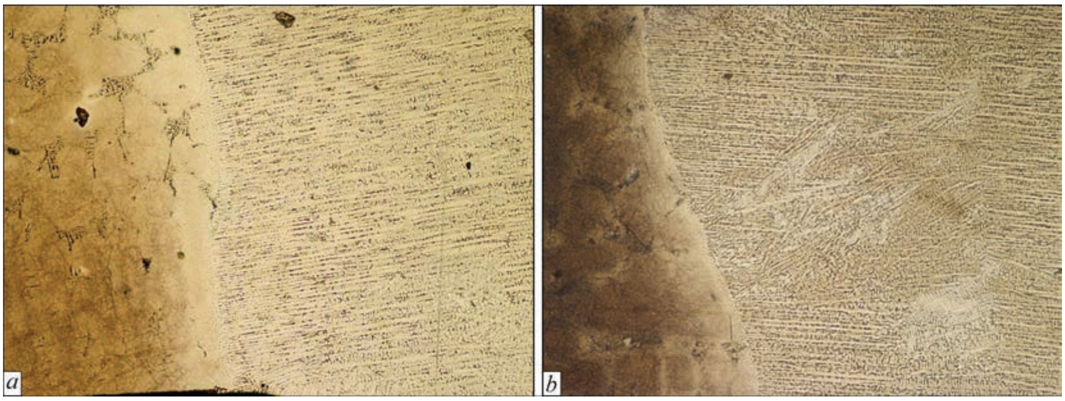

Figure 6. Microstructure (×100) of HTNA weld area near the rectilinear fusion zone (*a*) and local change of its geometry (*b*)

dimensions and distribution of the main strengthening component of the alloy, namely γ- γ′-phase is in place, which was discussed in detail in work [17]. In the HAZ microstructure of a sample with a favourable crystallographic orientation, formation of up to 10 % of scattered fine grains of up to 10 μm size of [111] orientation is observed for [101] initial orientation (Figure 4, *a*), and of [101] orientation — for [001] initial orientation (Figure 4, *b*), respectively, which may be indicative of their deformation nature. Alongside a certain crystallographic orientation, the deformation nature of the detected grains is indicated by their morphology, dimensions and results of comprehensive analysis of the maps of orientations and microstresses, as well as their location in the welded joint. The number of the grains, similar to their orientation, correlates with the degree of deviation of the initial crystallographic orientation from the high symmetry direction. Note that they were not revealed by metallography.

In case of noncompliance of the welded joint crystallographic orientation with the high-symmetry (Figure 5), the quantity of grains of [111] orientation in the HAZ grows to 20 % at a pronounced tendency to their concentration.

The fusion line zone is a transition area from the HAZ to the zone of weld metal epitaxial growth. Its structure is characterized by presence of partially melted dendrites and interdendritic gaps [17]. Partially melted dendrites take the shape of cells, a change in the crystallographic orientation being hardly noticeable. Now, in case of noncompliance of the welded joint crystallographic orientation with the high symmetry (Figure 5), this zone is characterized by a fine-grained structure (5–40 μm) with prevalence of the crystallographic orientation, corresponding to initial one and to orientation of deformation type grains.

The zone of epitaxial growth was defined from the very beginning of investigations as an area, which in metallographic presentation consists of orthogonal fusion lines of fine dendrites located in parallel [17]. In the case of a symmetrical welded joint, its structure points to preservation of the initial crystallographic orientation and presence of individual fine (5–40 μm) grains of [111] orientation (Figure 4, *a*) or [101] orientation (Figure 4, *b*). In case of noncompliance of crystallographic orientation of the welded joint or weld area with high symmetry (Figure 5, *a*) this zone is characterized by a fine-grained structure (40–70 μm).

For samples with a favourable crystallographic orientation, a certain increase of individual grain size

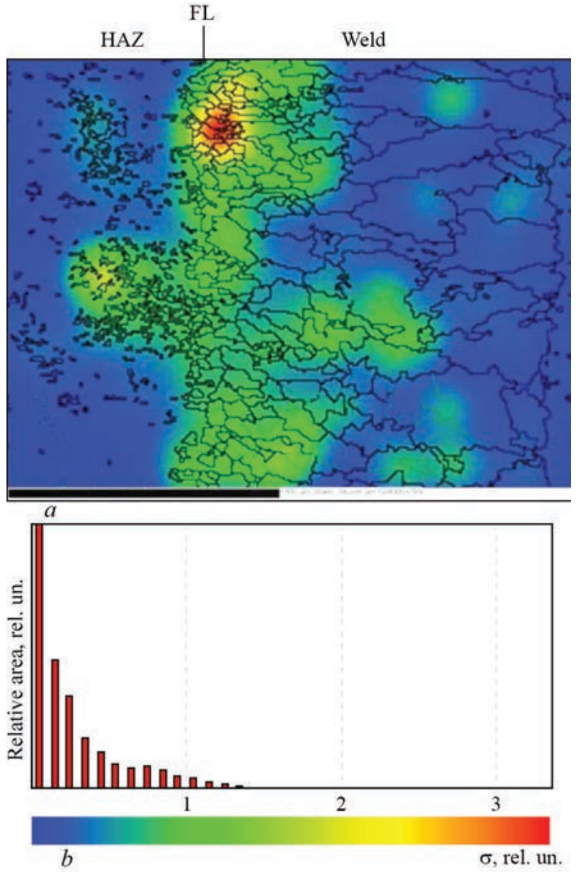

Figure 7. Map of microstresses (*a*) of the fusion zone of HTNA sample weld with surface close to (101) and frequency histogram (*b*) at noncompliance of the weld area to crystallographic conditions of directional solidification. HAZ is the heat-affected zone, FL is the fusion line

in the weld metal structure with preservation of base metal orientation (Figure 4, *a*, *b*) is possible, when moving closer to the axis.

For a sample with welded joint crystallographic orientation noncompliant with the high symmetry, the structure develops coarse grains of different size (up to 300 μm), predominantly oriented orthogonally to the weld pool solidification front, when moving closer to the axis, both in the metallographic and EBSD presentation. In addition to grain size increase, a violation of single crystallinity is clearly manifested. In the straight pole figures appearance of new reflexes, shifting and blurring of the main ones is observed; in reverse figures a decrease of the intensity and accent of the reflexes are found (Figure 5). Maximal increase of the dimensions and defectiveness of the structure, orientation deviation from the initial one are observed in the vicinity of the weld axis (Figure 5), where a local change in the curvature of weld pool solidification macrofront results in violation of the main condition of directional solidification — the relationship of crystal growth direction and its orientation [001]. It is exactly the area where hot cracking and destruction of the joint is the most often observed at high-temperature testing [7, 10, 11, 16]. A similar situation was also observed in the areas of local changes of weld geometry (Figure 6), as a result of different technological disturbances, or weld pool fluctuations even in crystallographic symmetry of the welded joint (Figure 4, *a*, *b*).

Note that appearance of a high concentration of deformation-induced fine grains with [111] orientation for the initial [101] orientation is found around formations of longitudinal solidification grains (Figure 4, *a*).

Clusters of fine grains of different crystallographic orientation, more often found in the zone of the fusion line, leads to microstress concentration (Figure 7), which has a negative influence on the performance of the joint as a whole.

Comparison of the results of EBSD-analysis and metallographic examination [9, 14, 17] points to the nature of grains of a different orientation, which can form in welding of HTNA single crystals: solidification and deformation-induced. The solidification grains boundaries form during metal solidification at abutment of weld dendrite blocks of different orientation, those of deformation-induced grains form as a result of stress relaxation at metal cooling by the mechanism of, most probably, polygonization and

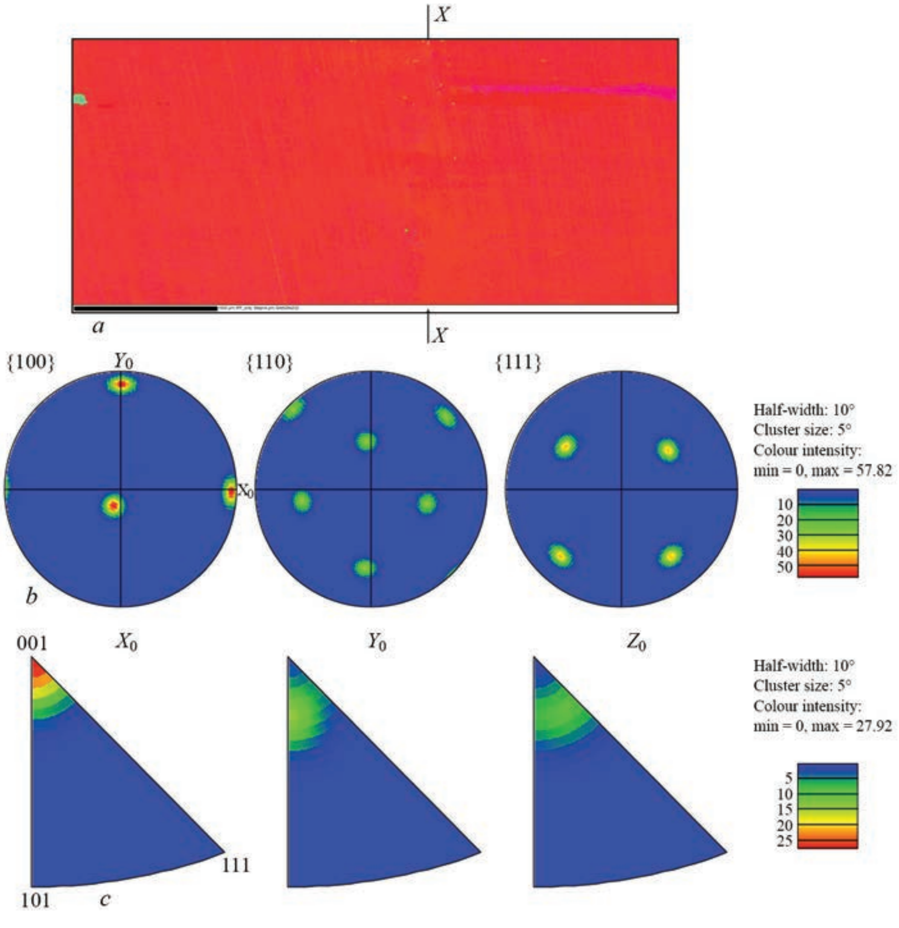

Figure 8. Orientation maps (*a*) of the central part of the weld on single crystal HTNA with (001) sample surface, straight (*b*) and inverse (*c*) pole figures at compliance with the directional solidification conditions. CGO is the legend for orientation map (see Figure 4, *c*), *X*–*X*′ is the weld axis

dynamic recrystallization. The deformation-induced grain boundaries can pass both through the interdendritic gaps and through the dendrite body, depending on the relative orientation of acting stresses and dendrites. Here, the dimensions, morphology and orientation of deformation-induced grains correlate with the respective parameters of the solidification grains and dendrites.

In view of the different nature of the considered grains, despite a certain similarity of their parameters, the technological paths for prevention of the abovementioned grain formation will be different. However, the geometry of weld pool solidification front and crystallographic orientation of the joint line are of prevailing important.

It should be further noted that under the same temperature conditions of making the welded joint, the quantitative and dimensional-orientational parameters of the deformation structure of the HAZ metal have a certain correlation with similar parameters of the weld structure elements. The established dependencies can be indicative of the influence of the weld metal solidification structure on the nature of deformation distribution, also in the HAZ, at the welded joint cooling stage.

It should be emphasized that under favourable crystallographic conditions, due to formation of the appropriate geometry of the weld pool and technological guarantee of the values of temperature-time parameters [8, 16, 18] at the solidification front by the directional solidification conditions, it is possible to produce welds with satisfactory perfection of the single crystal structure (Figures 3, 8).

By the results of the conducted investigations with application of EBSD-analysis when studying the structural evolution of welded joints in HTNA single crystals, there is an obvious need to perform work on regulation of the dimensions, morphology, misorientation, number and nature of distribution of the structure components and expansion of the technological control methods.

CONCLUSIONS

1. One of the main factors, which determine the features of structure formation in welding HTNA single crystals, is not only the initial crystallographic orientation of the welded joint, but also its change over the weld pool solidification front.

2. The methods of EBSD-analysis and optical microscopy were used to show that deviation of the initial crystallographic orientation of welded joints in 2 mm single crystal HTNA by more than 5° and of the front of weld pool solidification by more than 15° from the direction of prevailing crystal growth of <001> leads to violation of the epitaxial inheritance of the initial orientation by the weld metal and to formation of grains of a different orientation.

3. To achieve the specified perfection of single crystal structure of the welded joints, in addition to following the main conditions of directional solidification (temperature-time and crystallographic-orientational), it is necessary to ensure limitation of local changes of weld pool geometry, which is determined by the joint design, service conditions, welding modes and scheme.

4. Failure to fulfill the crystallographic orientation and temperature-time conditions of formation of a perfect single crystal structure of weld metal leads to development of a grain structure of solidification and deformation origin (nature), of different morphology and dimensions. After a narrow zone 100–150 μm wide of fine equiaxed grains (up to 40–70 μm), a transformation of the structure into a directional coarse-grained one (40–300 μm) is found near the fusion line when moving closer to the weld axis, which is associated with a change of temperature-time and crystallographic orientation conditions of solidification over the joint cross-section. A correlation of the parameters of secondary (final) and solidification (initial) structure is found. Clustering of fine grains, particularly, in the zone of the fusion line, promotes a concentration of microstresses.

5. It is shown that under the same temperature parameters of making the welded joint, formation of deformation type grains is in place in the HAZ. Depending on orientation conditions, it is up to 10% under favourable, and up to 20 % under unfavourable conditions, which is attributable to different susceptibility of the metal to deformation localization.

6. The following structure elements are considered to be critical:

- transverse elongated grains of different crystallographic orientation in the weld central part, the boundaries of which are the crack initiation site during welding;
- concentration of fine grains of different orientation, particularly near the fusion line, where localization of stresses and strains occurs, thus increasing the susceptibility to destruction at high-temperature mechanical loads, and lowering the welded structure performance.

7. Results of the conducted studies improve our understanding of structure formation and its evolution, depending on the welding process factors, and they indicate the possibility of creation of industrial welded structures from HTNA single crystals.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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