# INFLUENCE OF WELD POOL GEOMETRY ON STRUCTURE OF METAL OF WELDS ON HIGH-TEMPERATURE NICKEL ALLOY SINGLE CRYSTALS

**K.A. YUSHCHENKO**[1], **I.S. GAKH**[1], **B.A. ZADERY**[1], **A.V. ZVYAGINTSEVA**[1] and **O.P. KARASEVSKAYA**[2]

[1]E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

[2]G.V. Kurdyumov Institute for Metal Physics, NASU
36 Acad. Vernadsky Bd., 03680, Kiev, Ukraine. E-mail: Karas@imp.kiev.ua

The main defect, which prevents realization of the advantages of high-temperature nickel alloy single crystals in production of welded assemblies and parts of gas-turbine engine, are stray grains in the weld metal. The objective of this work was studying the features of weld metal structure, depending on curvature of macrofront of weld pool solidification and determination of admissible deviations of the direction of maximum temperature gradient from orientation of predominant crystal growth. Experiments were performed with application of electron beam welding on single-crystal samples from commercial high-temperature nickel alloys JS26 and JS32, containing more than 60 % of strengthening $\gamma'$-phase. Welded joint structure was studied by optical metallography and X-ray diffractometry methods. It is shown that the main conditions for preservation of single-crystal structure in welding of high-temperature nickel alloy single crystals are correspondence of fusion plane to single crystal high-symmetry axes and coincidence of the direction of maximum heat removal over weld pool solidification front with <001> orientation of predominant crystal growth. Limit deviations for studied alloys and welding conditions are established. 15 Ref., 9 Figures.

**Keywords:** *electron beam welding, single crystal, high-temperature nickel alloy, crystallographic orientation, weld, weld pool geometry, dislocation distribution, crystal growth direction, maximum heat removal direction, angle of deviation, stray grains*

Proceeding from analysis of temperature and orientation conditions of growing single-crystals of high-temperature nickel alloys and experimental work on welding conducted earlier [1–4], it is established that the main criteria of evaluation of welded joint quality are preservation of initial crystallographic orientation and single-crystal structure. The latter is evaluated by presence of stray grains in the weld metal, which differ from the initial crystallographic orientation of the material being welded. The best results are achieved under the condition when the fusion surface coincides with the high symmetry axes [4–8]. In this case crystallographic orientation of the plane of edges being welded should be close to {110}, that is achieved at correspondence of the plane and direction of welding: {100}, <100> and {110}, <011> (Figure 1). It is established that at such crystallographic conditions stray grains can amount from 2 to 10 % of weld volume. In case of deviation by more than 4° from symmetry conditions, the number of grains can rise up to 60–80 %.

It should be noted that appearance of 2–4 % of stray grains in the weld is possible even with strict following of the above conditions of symmetry. Such disturbances of single-crystal nature of the weld can be due to the fact that the weld pool has a certain curvature, so that over the solidification front the direction of maximum temperature gradient $G$ changes relative to the direction of predominant growth of crystals <001> (Figure 2). This involves violation of one of the main conditions of directional solidification, namely orientational influence of the substrate on single-crystal growth. Therefore, disorientation between $G$ and direction of predominant growth <001> on the solidification front leads to formation of high-angle grains.

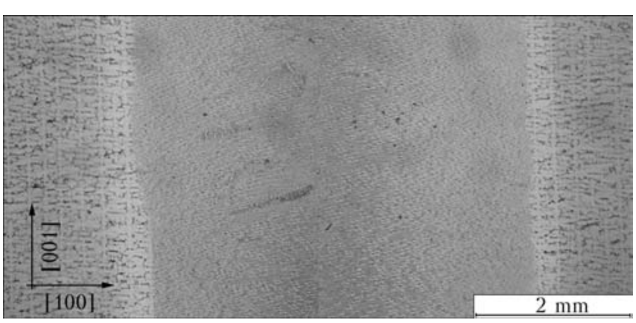


**Figure 1.** Microstructure of weld metal of JS26 alloy welded joint with symmetrical crystallographic orientation

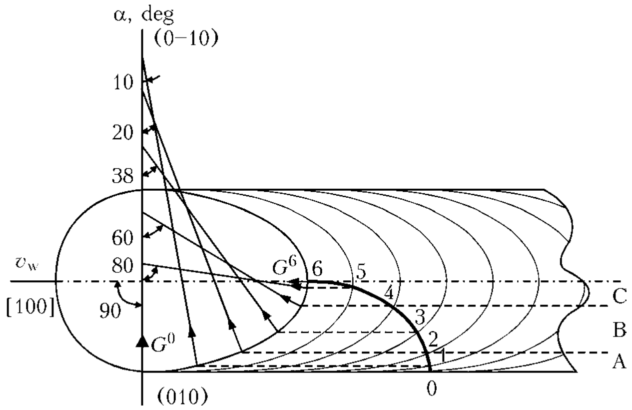


**Figure 2.** Schematic image of the change of direction of maximum temperature gradient $G$ over weld pool solidification front: A, B, C — characteristic structural zones of the weld; α — deviation angle $G$

The objective of this work was studying the features of weld metal structure depending on curvature of weld pool solidification macrofront and determination of admissible deviations of the direction of maximum temperature gradient from predominant growth orientation.

Experiments on welding were performed on single-crystal samples from commercial high-temperature nickel alloys JS26 and JS32 of 50 × × 40 × (1.5–2.5) mm size, cut out of blades or blanks produced by the method of high-speed directional solidification with more than 60 % of γ′-phase. The cut area was ground before welding. Samples were heat-treated before welding by standard modes. Welding was performed by the electron beam in vacuum at the speeds of 20–80 m/h. Specific values of welding parameters were selected from the conditions of producing welds of the required geometry. In order to create a more uniform temperature field and lower the welding stresses, welding was performed with preheating to 300–600 °C.

Structure of welded joints was studied on longitudinal and transverse sections with application of optical metallography and X-ray diffractometry methods [5–9]. Distribution of the intensity of scattered X-ray radiation near the reverse lattice nodes was evaluated. Sections were studied at irradiation of a region of 0.3 × 2.0 mm area and reflection position in the direction normal to butt plane, going sequentially through all the characteristic zones of the welded joint (BM–HAZ–weld–HAZ–BM). The (irradiated) studied area remained parallel to butt edge. 36 sections on sample surface 10 mm wide were studied. Displacement step was 0.28 mm. This procedure is described in greater detail in [4–9].

X-ray analysis was used to orient the samples and select welding direction. Crystallographic orientation of weld metal, presence and number of stray grains was evaluated, proceeding from pole figure analysis. Dislocation density and their distribution were assessed by the width, shape and uniformity of intensity distribution, i.e. by blackening of X-ray reflections.

Performed metallographic and X-ray investigations allowed identifying individual structural zones of weld metal, associated with weld pool curvature (Figures 2 and 3).

Zone A is part of the weld near the fusion line, characterized by prevalent coincidence of the direction of maximum temperature gradient with <001> orientation of predominant crystal growth. Directly near the fusion line one can see a narrow (0.3–0.5 mm) strip of epitaxial growth. Further in depth of the weld a finely-dendritic structure of directional solidification with quite accurate inheritance of the initial edge orientation is observed (Figure 4), and high-angle boundaries are absent (Figures 3 and 5). Metal of this zone is characterized by a negligible degree of degradation of single-crystal structure. Despite the marked increase of dislocation density, distribution of the intensity of X-ray reflection $I_{q\perp}$ is relatively smooth and close to base metal. Isointesive lines have the shape of smooth ellipsoidal curves (see Figure 3, *b*) that corresponds to single-crystal state of the metal with uniform distribution of edge dislocations.

Zone B is that of a critical deviation of maximum temperature gradient from the direction of predominant crystal growth, where the first part of the weld inherits the initial single-crystal orientation, and violation of directional solidification and formation of stray grains with possible cracking along the grain boundaries are found in the second zone (see Figure 3). In terms of roentgenography, this is manifested in additional reflections on pole figures (see Figure 5), presence of intensity deviations for considerable angle values from the maximum one in $I_{q\perp}$ distribution (see Figure 3). For metal of this zone, inheriting the initial orientation of single-crystal being welded, a characteristic feature is the pronounced non-uniformity and localizing of dislocations, that is indicated by irregular isointensive $I_{q\perp}$ curves. Widening of distribution of $I_{q\perp}$ reflections by different azimuthal directions is related to appearance of secondary dislocation systems and increase of their general density. Metal of this zone forms a multilevel dislocation structure that leads to stress localizing in non-uniform dislocation clusters. As a result, the weld forms stray grains with high-angle boundaries. Development of non-uniform disorientation causes an acceleration of deformations and single-crystal

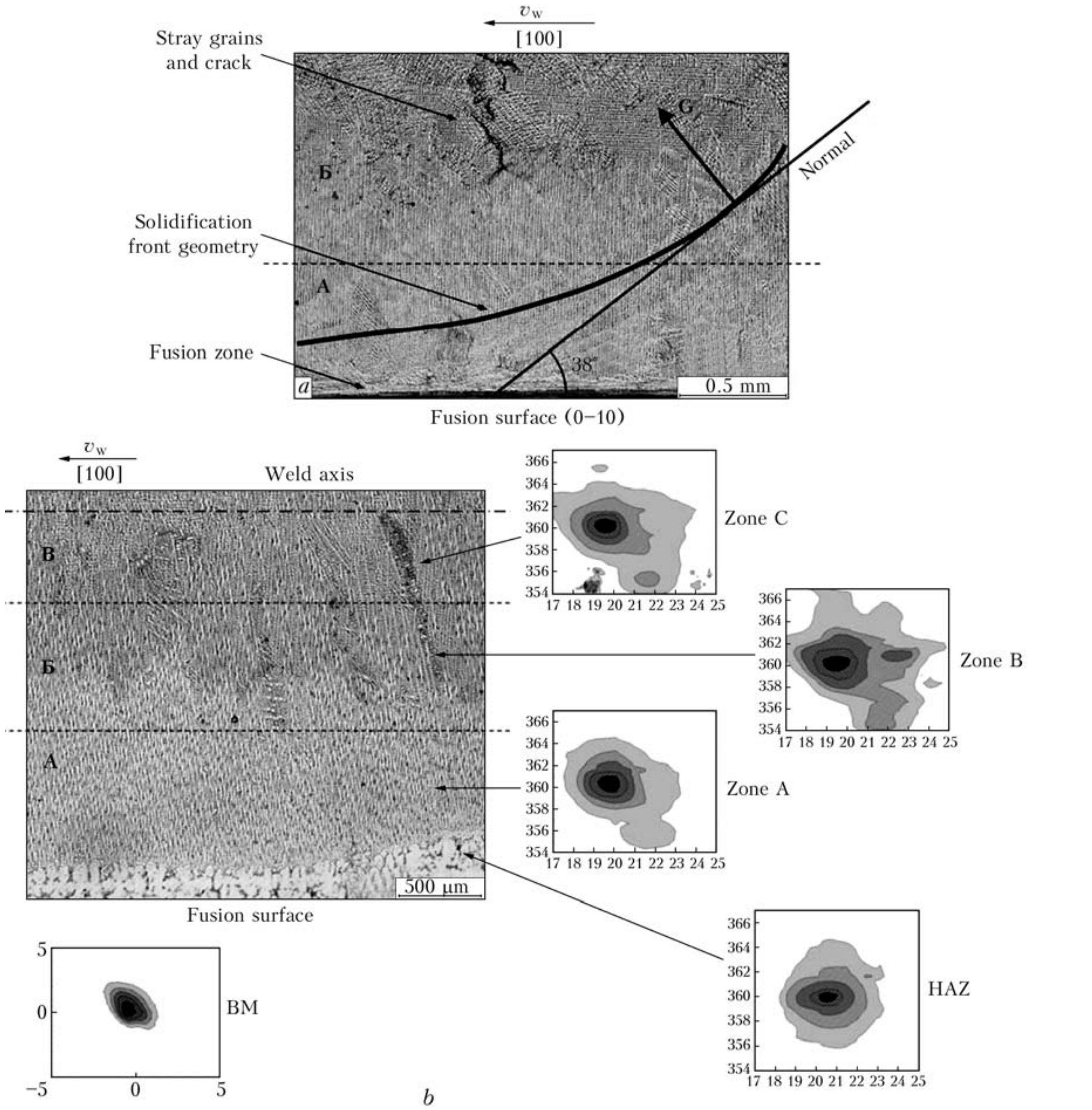


**Figure 3.** Microstructure ($a$) and isointensive $I_{q\perp}$ curves ($b$) of weld metal zones corresponding to different deviations from maximum temperature gradient over weld pool solidification front (acc. to Figure 2) (numerical values along zone axes are shown in degrees)

fracture, as well as crack initiation in welds of these materials [10–15]. In zone B, in addition to stray grain formation in that part which inherits the initial orientation, a successive deviation of crystallographic orientation by 1–2° from the initial one with greater distance from the edges being welded is observed (see Figure 4). Change of orientation characterizes the level of macro- and microstresses, compensation of which can lead to disturbance of single-crystal structure of the metal and formation of high-angle boundaries, because of considerable rotation of crystalline lattice through more than 5° [10–15].

Zone C is a section of weld metal, in which the direction of maximum temperature gradient practically coincides with crystallographic orientation of ready growth. In this zone formation of individual high-angle boundaries is possible as a result of mismatch of growing dendrites abutting from different sides of the weld pool.

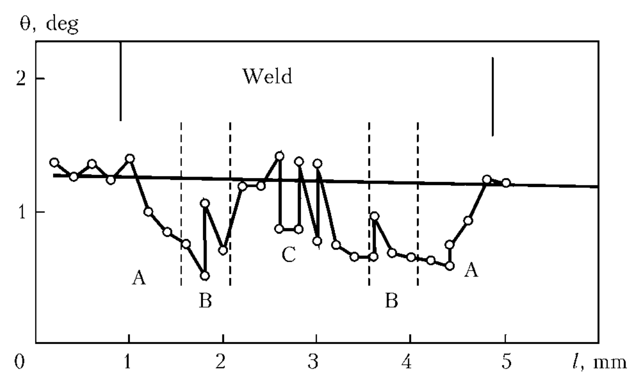


**Figure 4.** Change of crystallographic orientation close to {100} across welded joint width

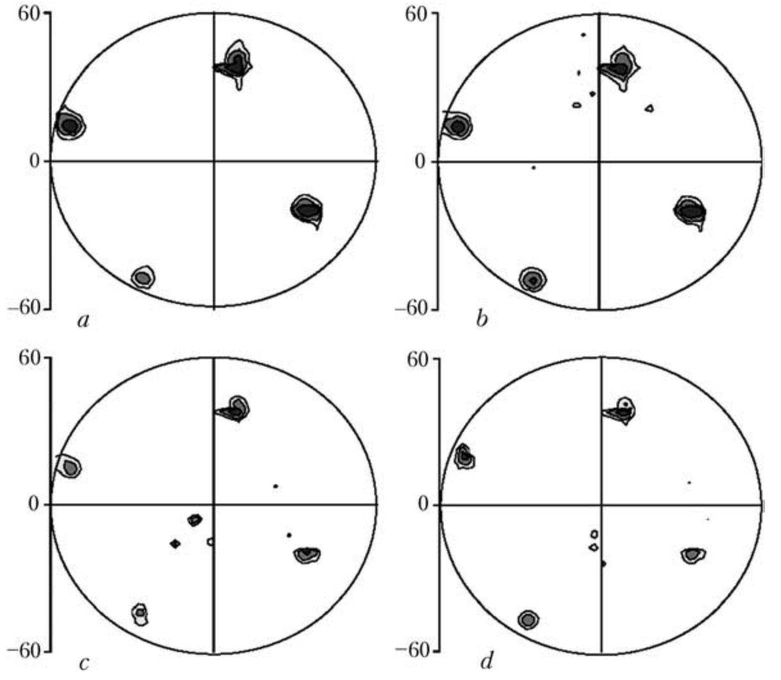


**Figure 5.** Pole figures for weld metal of welded joint with crystallographic orientation close to {100}: *a* — base metal; *b*–*d* — zone A, B, C, respectively (see Figures 3 and 4)

For welded joints with crystallographic orientation differing from high symmetry, the above structural zones are manifested more clearly. In this case, zone B becomes wider, and its position relative to weld axis, as well as the number of stray grains, alongside curvature of weld pool solidification front, also depends on how much the initial orientation of single-crystals differs (Figure 6) from high symmetry [7].

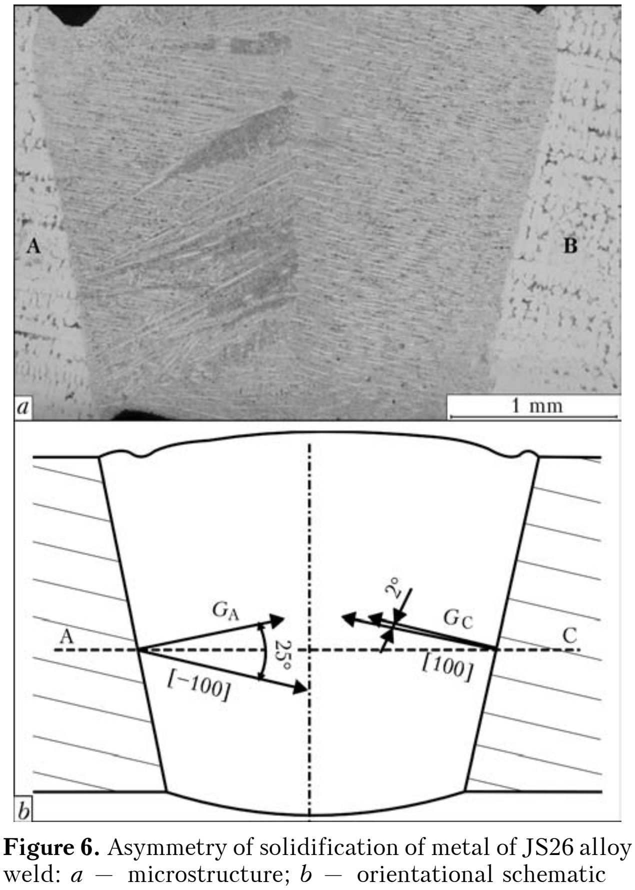


**Figure 6.** Asymmetry of solidification of metal of JS26 alloy weld: *a* — microstructure; *b* — orientational schematic

Thus, formation of single-crystal structure of weld metal is provided at constant direction of temperature gradient in each point of weld pool — a condition of flat solidification macrofront — and its coincidence with crystal growth predominant orientation <001>.

Variation of parameters of EBW modes, beam scanning over single-crystal samples of JS26 and JS32 alloys with different crystallographic orientation allowed forming welds with a flat solidification macrofront, at which the orientation of maximum temperature gradient was constant during solidification. Depending on orientation of welded single-crystal sample and fusion plane, the value of deviation of maximum temperature gradient from the direction of predominant crystal growth <001> varied from 0 up to 30°.

Studying the structure of the respective welds showed that violation of crystallographic orientation and single-crystal structure is concentrated, mainly, in those weld sections, where the direction of maximum temperature gradient on weld pool solidification front deviates from the predominant growth orientation by more than 15° angles. This allowed establishing admissible disorientation that ensures formation of a weld with single-crystal structure.

Proceeding from analysis of the results obtained during study of weld metal structure formation in single-crystal welding, it was proposed to control weld pool geometry so that the direction of temperature gradient over the entire solidification macrofront did not deviate from <001> by angles exceeding the admissible level that will allow preventing critical deviation zone in zone B (see Figure 3), in which stray grains are formed. In terms of technology, this is achievable by adjustment of parameters of EBW and orientation of the joint butt within admissible limits with crystallographic plane (100).

Metallographic (Figure 7) and roentgenographic examinations (Figures 8 and 9) illustrate the positive result of such an approach that is expressed in formation of weld metal with high enough crystallographic perfection and preservation of the orientation of initial material being welded. Comparison of pole figures of base metal and weld metal (see Figure 8) demonstrates preservation of the position of main reflections in absence of reflection reflexes of another orientation. $I_{q\perp}$ distribution of (200) reflection in different zones of the welded joint is indicative (see Figure 9) of uniform distribution of dislocations in the weld bulk, despite an increase of their density. If there is no division of $I_{q\perp}$ X-ray reflection, then the high-angle boundaries are also absent. Level of disorientation of structural components of weld metal is within 2°, and does not exceed the admissible value for high-temperature single-crystals (approximately 5°), at which the single-crystal nature of the material is violation. Principles of selection and control of weld pool

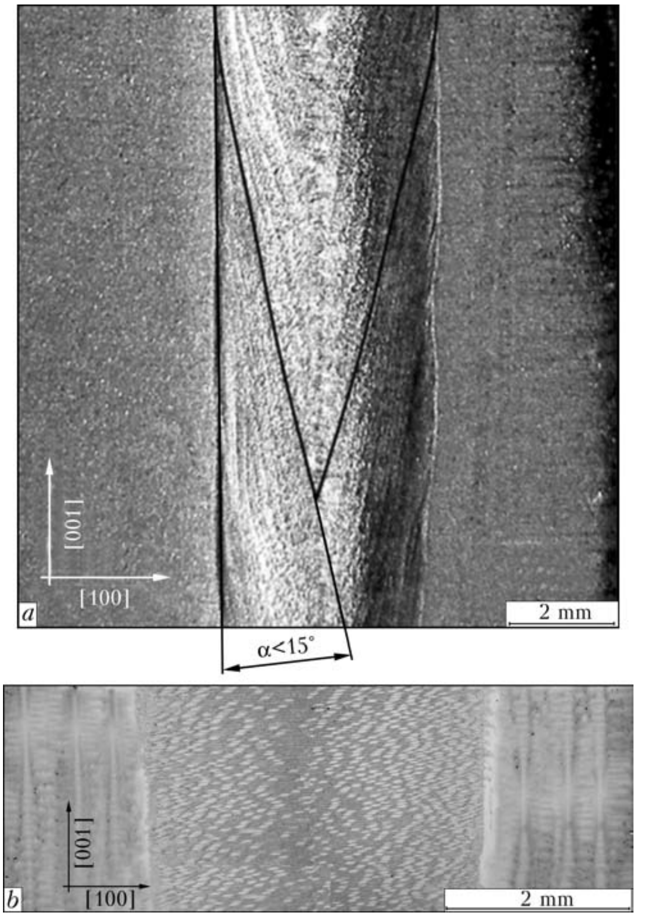


**Figure 7.** Appearance (*a*) and microstructure of single-crystal weld (*b*) of JS32 alloy made with control of weld pool solidification: α — angle of deviation of weld pool solidification macrofront from {100}

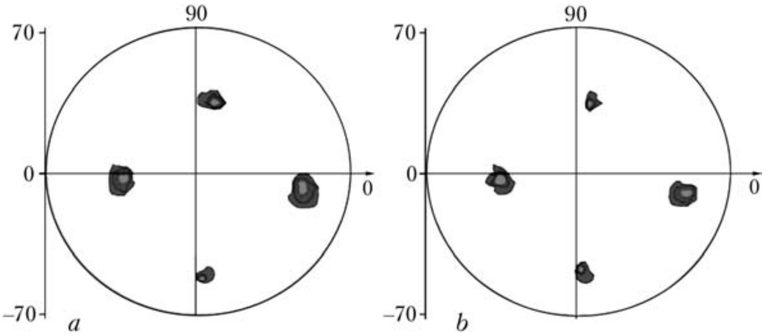


**Figure 8.** Pole figures {220} of base metal (*a*) and weld metal (*b*) made with control of weld pool solidification

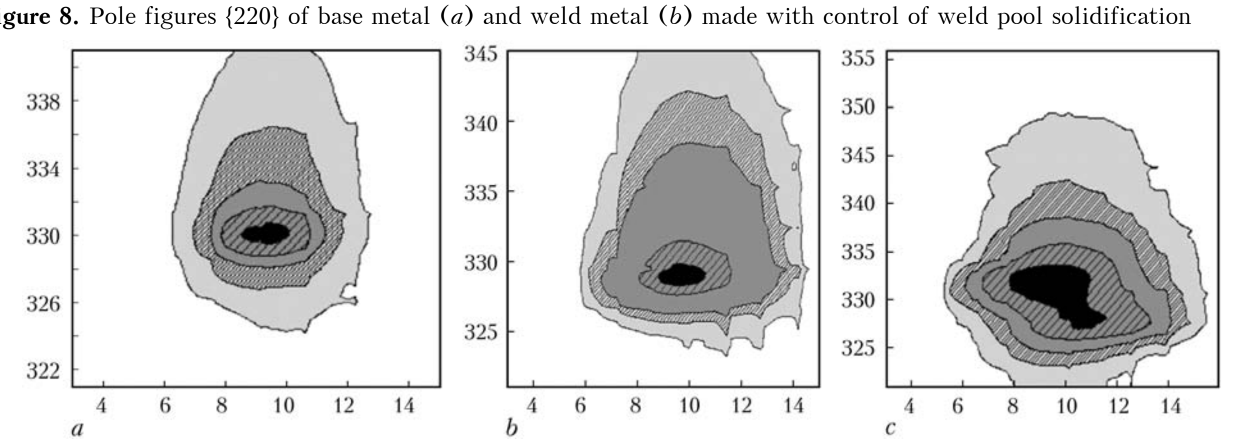


**Figure 9.** $I_{q\perp}$ distribution of (200) reflection in different zones of the welded joint: *a* — base metal; *b* — HAZ metal; *c* — weld metal (numerical values by axes are given in degrees)

shape were tried out at reconditioning of single-crystal blades from JS32 alloy.

Thus, in EBW of high-temperature nickel alloys the main crystallographic parameters of the welded joint are not only correspondence of the fusion plane to high-symmetry axes of a single-crystal, but also crystallographic orientation at the macrofront of weld pool solidification. There exists a critical angle of deviation of the direction of maximum heat removal relative to the direction of predominant crystal growth <001>. For the studied alloys and their welding conditions the critical angle of deviation is within 15°.

**Conclusions**

1. Experiments on EBW of single-crystals of high-temperature nickel alloys of JS type with more than 60 % content of $\gamma'$-phase revealed that characteristic weld defects is partial inheritance of base metal crystallographic orientation with formation of stray grains and possible formation of grain-boundary cracks.

2. Influence of curvature of weld pool solidification macrofront on inheritance of initial crystallographic orientation by weld metal and perfection of its structure was studied. It is shown that in order to prevent formation of stray grains or cracks, it is necessary to provide weld pool shape, which eliminates the possibility of deviation of the direction of temperature gradient passage over the solidification front from the required direction by an angle, exceeding the admissible one.

3. Results of performed investigations were used in development of basic technology of welding high-temperature nickel alloys, allowing preservation of single-crystal structure with substructure disorientation of ±2°, as well as absence of cracks or stray grains in weld metal.


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