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PROSPECTS OF DEVELOPMENT OF WELDED SINGLE-CRYSTAL STRUCTURES OF HEAT-TEMPERATURE NICKEL ALLOYS

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Heat-temperature nickel alloys with single-crystal structure are used in such branches of production as turbine manufacture, aerospace engineering and power engineering. However, their further mastering is restrained by complexity, and sometimes impossibility of production of structure elements of large sizes and developed geometry. Production as well as repair using traditional methods of single-crystal products with developed geometry such as, for example, long or cooled gas turbine blades etc., represents a complex technological problem. Manufacture of assemblies, parts, structures of such type by means of their welding from separate elements or building-up often seems to be more reasonable and allows developing products with single-crystal structure on virtually new basis. The aim of the presented work is development of new approaches applicable to manufacture of the single-crystal welded structures of critical designation with increased mechanical characteristics and service parameters. The results of investigations and examples of pilot welded structures of such type, produced at the E.O. Paton Electric Welding Institute of the NAS of Ukraine, are presented. 30 Ref., 9 Figures.

Keywords: *hight-temperature nickel alloys, single-crystals, welded structures of complex geometry, electron beam welding, gas turbine blades, conditions of formation of single-crystal structure*

Development of aerospace, power-generating and others branches of industry require application of materials, which can withstand a complex of high service loads with increase of the terms and reliability of operation. The particularly high requirements are made to the materials of parts of a hot gas path of gas turbine engines (GTE) and systems on heat resistance, ductility, high thermal and low-cycle fatigue as well as increased resistance to effect of operating medium [1, 2].

To some extent, heat-temperature nickel alloys (HNA) with poly- and single-crystal structure [3] meet these requirements. However, substantial improvement of mechanical and service characteristics due to multicomponent alloying and formation of single-crystal structure result in deterioration of materials' workability, including to weldability reduction [4–8].

HNA has the widest application in manufacture of the elements of GTE hot gas path, i.e. rotor and nozzle turbine blades, to some extent combustion chambers, vectoring nozzle petals and others. Particularly critical and thermostressed of them are high-pressure turbine blades. Application of HNA with single-crystal structure for their manufacture allows significant increase of capability to keep the whole complex of loads, service parameters of GTE, their workability and reliability. At that, there is more than 15 % rise of main characteristic of alloy, namely heat resistance [9, 10].

Regardless the successes of a technology of single-crystal growing by investment casting, manufacture of such products present itself not very simple technical task. The problems of manufacture of such products as cooled single-crystal blades with complex system of inner channels and their reaching the surface as well as long and different-thickness blades are of particular importance. A technology of manufacture of products of such type using the method of directed crystallization is characterized with significant complexity, labor and energy intensity, low percent of product yield.

It becomes obvious that manufacture of such products by welding or building-up of their separate constituents is more reasonable that allows developing fundamentally new structures. Thus, for example, Rolls-Royse Company produces hollow welded polycrystal GTE titanium blades [12] that allows reducing weight of the blade, increasing its aerodynamic characteristics and thermodynamic efficiency of the turbine in whole.

Replacement of GTE rotors with lock retention of the blades to all-welded of «blisk» type allows up to 25 % reduction of structure weight from the initial and increase of product life [13].

A problem is raised on development of a technology for manufacture, growing and formation of complex-geometry structures from HNA with single-crystal structure using the methods of welding, surfacing,

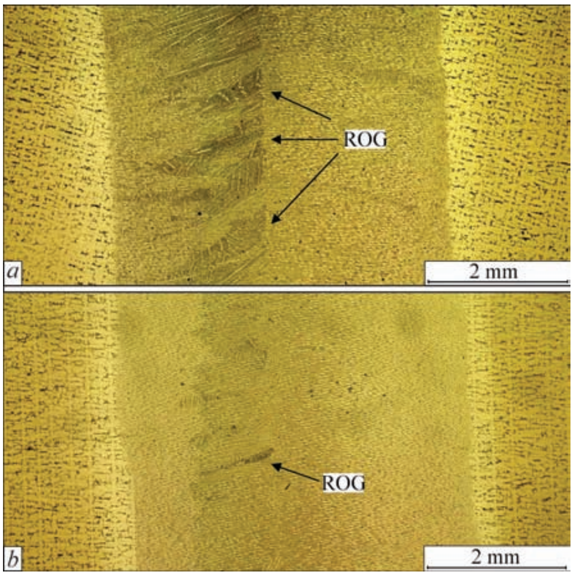

Figure 1. Structure of welded joints with different deviation of crystallographic orientation of joint edge surface from {001}: *a* — 20° (multiple formation of ROG); *b* — 5° (single ROG)

coating deposition as the most mastered in the technological sense.

However, up to the moment there are neither theoretical (formation and preservation of single-crystal structure), nor practical (technology, structure) developments and recommendations on welded structures of particular such type.

E.O. Paton Electric Welding Institute actively has been carrying out the works in this direction [14–24]. The complex investigations of weldability of commercial cast alloys ZhS26, ZhS32, ZhS36, TsNK8 with single-crystal structure were performed.

The main criteria of assessment of welded joint quality were:

• orientation homogeneity of weld metal and heat affected zone with base metal;

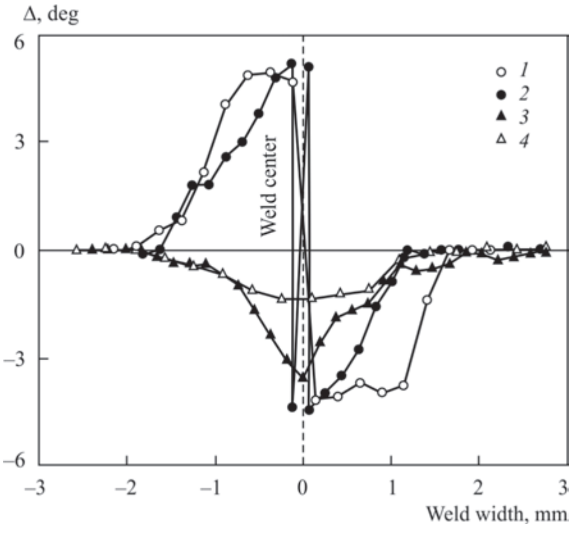

Figure 2. Deviation of orientation on weld section depending on crystallographic orientation of joint edg: *1* — joint edge {111}; *2* — {112}; *3* — {011}; *4* — {001}. Width of welds is approximately 3.5–3.8 mm

• absence of cracks and defects of weld formation;

• absence of random orientation grains (ROG);

• level of mechanical properties of welded joints.

Evaluation of the main crystallization parameters at a weld solidification front, namely temperature gradient (G) and front displacement rate (R), responsible for perfection of the single-crystal structure, was carried out using a procedure of local thermometry of weld pool melt and analysis of thermokinetic curves [14].

Examination of peculiarities of structure of the welded joints depending on temperature-time conditions of weld formation was carried out using micro X-ray spectrum analysis, metallography, X-ray diffractometry and EBSD analysis.

Initial crystallographic parameters of the welded joint assembly were set by orienting using X-ray method. Crystallographic orientation of the weld metal, presence and amount of ROG and their relative area were judged following the analysis of pole figures. Dislocations' density and their distribution were evaluated on width, shape and homogeneity of intensity distribution of X-ray reflections $I_{q\perp}$.

As a result of complex investigations there were determined the dependencies of formation of the single-crystal structure in welding of HNA single-crystals of 0.5–5.0 mm thickness. Effect of technological factors on crystallographic and temperature-time parameters of process of the weld metal structure formation were examined. They determine perfection of the single-crystal structure.

Figures 1–3 illustrate the results of effect of the technological factors on the crystallographic parameters of the process of weld metal structure formation. Figure 1 shows formation of ROG and change of crystallographic orientation of the weld metal (Figure 2) in variance of the crystallographic orientation of welded edges of high symmetry. It is determined that appearance of up to 10 % of the random orientation grains is possible even at strict conformance to the indicated conditions of the weld symmetry. Such violations of single-crystallinity of the weld can be related with the fact that the weld pool has a curvature and, therefore, direction of the maximum temperature gradient (G) changes on the solidification front in relation to direction of primary growth of crystals <001> (Figure 3). This leads to violation of one of the main conditions of directed crystallization, namely, orientation effect of a substrate on single-crystal growth. Violation of the crystallographic orientation and single-crystal structure is mainly concentrated in that areas of weld metal, where the direction of maximum temperature gradient at the weld pool solidification front deviates from the orientation of primary growth by the angles more than 15° (zone B) (Figure 3). This permitted to

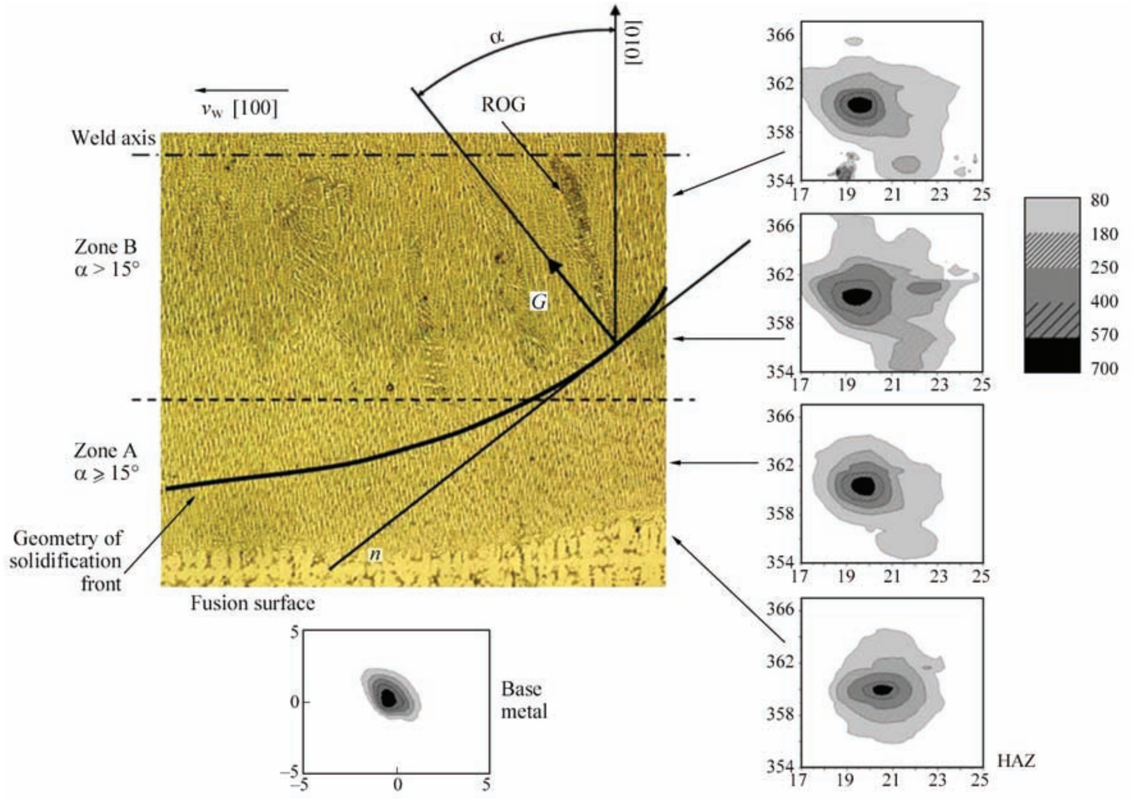

Figure 3. Microstructure (×100) and isointense lines of distribution $I_{q\perp}$ of separate weld metal sections, corresponding to different deviation of the maximum temperature gradient at weld pool solidification front: α — angle of deviation of maximum temperature gradient G on direction of primary crystallization

determine allowable disorientation, which provides formation of the weld with single-crystal structure.

Figure 4 is a generalization of a complex of investigations of temperature-time conditions of the weld metal structure formation. A calculation-experimental way [14] was used to determine a dependence between the main temperature-time parameters of G/R process at the liquid pool solidification front, nature of forming structure and value of deviation of the welded joint crystallographic orientation from the crystal high symmetry. It is shown that formation of directed cellular-dendritic and dendritic structure limiting appearance of the grains of other orientation in welding of HNA single-crystals is possible in deviation of crystallographic orientation, exceeding the set limits. The complexity of technical realization of such approach lies in the need to limit the welding stresses, strains and fulfillment of the general requirements made to the quality of formation of sound joints. This is, in particular, obvious in welding of the complex geometry structures.

Thus, it is shown that production of the welds with perfect single-crystal structure and crystallographic orientation, corresponding to the initial metal is reached due to:

• providing initial crystallographic orientation in the joint area in the range of deviation from direction of axes of single-crystal high symmetry for not more than 5° (Figures 1, 2);

• keeping the relationship of direction of maximum heat sink at the weld pool solidification front and direction <100> (light increase) with deviation for not more than 15° (Figure 3);

• development of temperature-time conditions (G/R) of the directed crystallization according to Figure 4 for different initial crystallographic orientation and welding modes. There is control of G – temperature gradient at the weld pool solidification front and R — solidification rate.

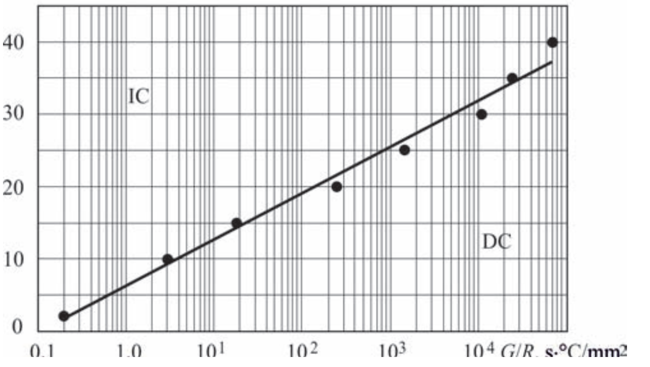

Figure 4. Calculation-experimental dependence of allowed deviations α of direction of maximum temperature gradient G on orientation of crystal primary growth <100> at weld pool solidification front in EBW of ZhS26 alloy on G/R value: DC — area of directed crystallization; IC — area of irregularity of directed crystallization

Violation of one of these conditions promotes formation of weld structural defect, i.e. random orientation grains (ROG) and, as a result, cracks. Figures 1–3 in general form demonstrate irregularity of perfection of the single-crystal structure as a result of deviation of each from indicated conditions in production of common butt joints of small thickness plates.

Analysis of HNA industrial structures indicate that transfer to their production from the single-crystal billets using welding will provoke problems with fulfillment of indicated conditions, connected with different geometry, random crystallographic orientation, alloys of different kind and others.

Area of investigations necessary for development of such structures was determined based on the analysis of structure peculiarities of products from HNA single-crystals and experiments on welding of the reference samples as well as taking into account the main theoretical and fundamental technological conditions for the perfect single-crystal weld structure. Main of them lied in investigation of effect of technological factors on temperature-time and crystallographic-orientation characteristics of weld formation process, and, respectively, on quality of the single-crystal structure. The method, scheme, modes and procedures of welding were selected based on the investigation results.

The main attention was given to power and technological peculiarities of welding. Taking into account high specific power, precision, mobility of heat source, the most perspective in this sense are such methods of welding as electron beam and laser. Welding with electron beam in vacuum provides reliable protection of weld metal from contamination by impurities, which not only provoke deterioration of HNA main properties, but can initiate irregularity of perfection of the single-crystal structure.

Realizing the set physical conditions of the single-crystal structure formation and preservation of the initial crystallographic orientation are carried out by means of regulation of mode parameters, application of corresponding schemes and welding procedures. At that, regulation of the weld pool metal temperature and its gradient at the solidification front, rate of crystallization and cooling, time of melt existence, geometry of macrofront of the weld pool solidification are performed. As a result the better indices of HNA structure are obtained, namely refinement of dendrites; γ'-phase, carbides, eutectic size and other phases, their chemical inhomogeneity decreases. This promotes improvement of mechanical properties as well as service characteristics [1, 3].

It should be noted that the problems of development of complex geometry structures, including from HNA using welding technologies in the recent years are actively solved by the methods of 3D printing (3D) or additive manufacturing (AM) [25–29].

It is informed that Siemens Company has successfully carried out the bench tests of the GTE experimental blades, produced on 3D printer. They were tested in the engine under conditions of complete loading at temperature more than 1250 °C. Blades material is polycrystal nickel superalloy. General Electric Company started using additive technologies in manufacture of the elements of gas turbines [30] from polycrystal HNA.

Regardless the advantages of the indicated technologies, it is necessary to pay attention on a series of disadvantages, which complicate their application in manufacture of the complex geometry single-crystal structures from HNA.

First of all, production of the single-crystal product requires presence of an initial single-crystal billet, absence of which is one of the advantages of 3D-technology. Secondly, it is obvious, that during the whole process it is difficult to keep the conditions necessary for formation of single-crystal HNA structure, including G/R relationship. The powders of corresponding composition are necessary. They have very high requirements on grain size and chemical composition, yield, production and storage conditions. Even insignificant deviations from AM technological process result in change of object geometry, nonuniformity of structure, including deterioration of single-crystallinity, unsatisfactory surface quality, partial lack of fusions and overlaps, that all together complicate production of structures of complex geometry by 3D printing method.

An alternative to the 3D printing method in manufacture of the single-crystal structures of complex geometry can be a technology based on discrete and successive melting of billet of specific composition by concentrated power source. Up to the moment the technology is updated in a part of determination of heat, deformation and orientation conditions and dependencies of structure formation.

In development of the single-crystal complex geometry welded structures there were proposed and tested the technological schemes based on:

- dosed heat input in welding of structure elements of different thickness or different chemical composition, realized due to discrete asymmetry scanning with regulation of frequency, amplitude, time of beam delay;
- regulated heat input on depth of weld pool in welding of structure elements up to 10 mm, performed, mainly, due to discrete beam scanning in combination with high welding rate;
- development of temperature range in the area of successive local melting and quasistationary thermal

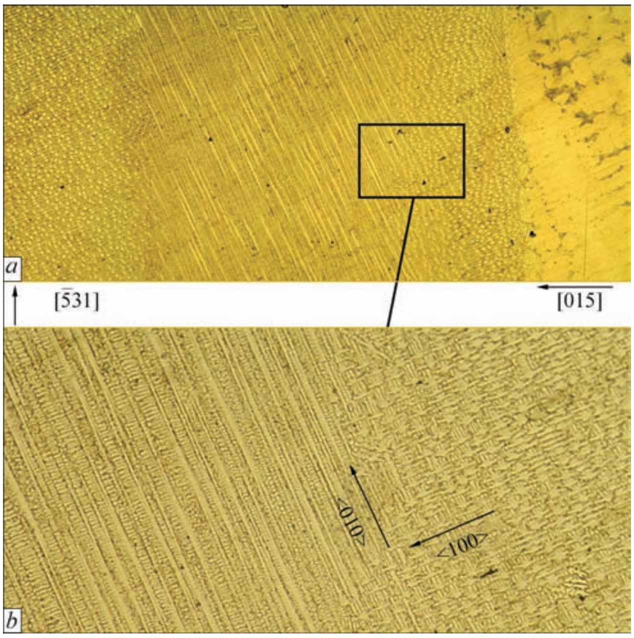

Figure 5. Microstructure of weld metal with initial asymmetric crystallographic orientation of welded joint produced with regulation of temperature-rate parameters of weld pool solidification: *a* — ×30; *b* — ×50

field, at which direct crystallization and formation of single-crystal structure will take place;

• providing specific *G*/*R* relationship in joining the elements of different crystallographic orientation (Figure 5), thickness and various grades of welded alloys in the joining zone due to optimum for each case relationship of the welding mode parameters.

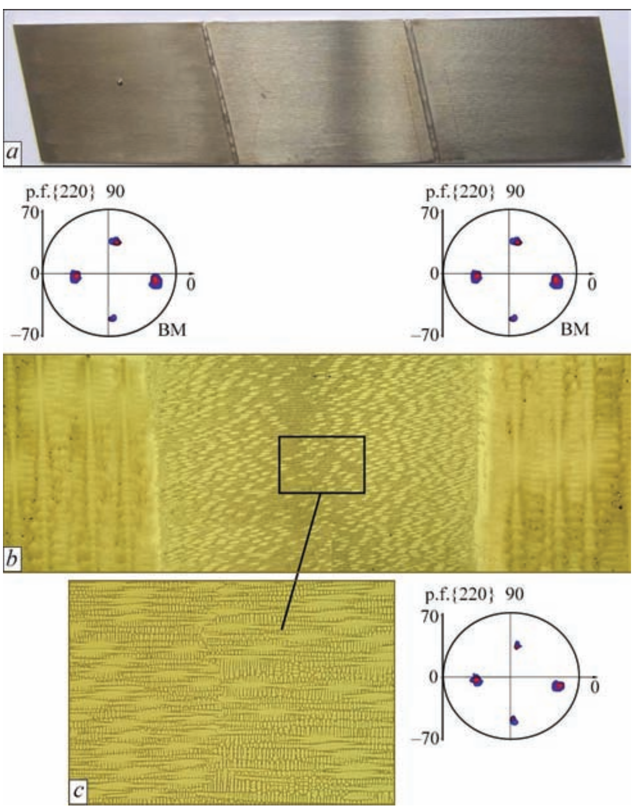

Figure 6. Example of coarsening of single-crystal of billets from ZhS32 alloy of 2 mm thickness using EBW. General view (*a*), microstrucutre (*b* — ×50; *c* — ×100) and pole figures {220} of welded joint (*b*)

Figures 6–9 illustrate some of the results of application of such schemes.

Figure 6 illustrates the possibility of development of the coarse single-crystals and structures by means of EBW of the billets, produced by directed solidification method. Oriented cutting of the billets and their assembly for welding provided symmetrical structure of the joint with deviation of the crystallographic orientation for not more than two degrees. Except for

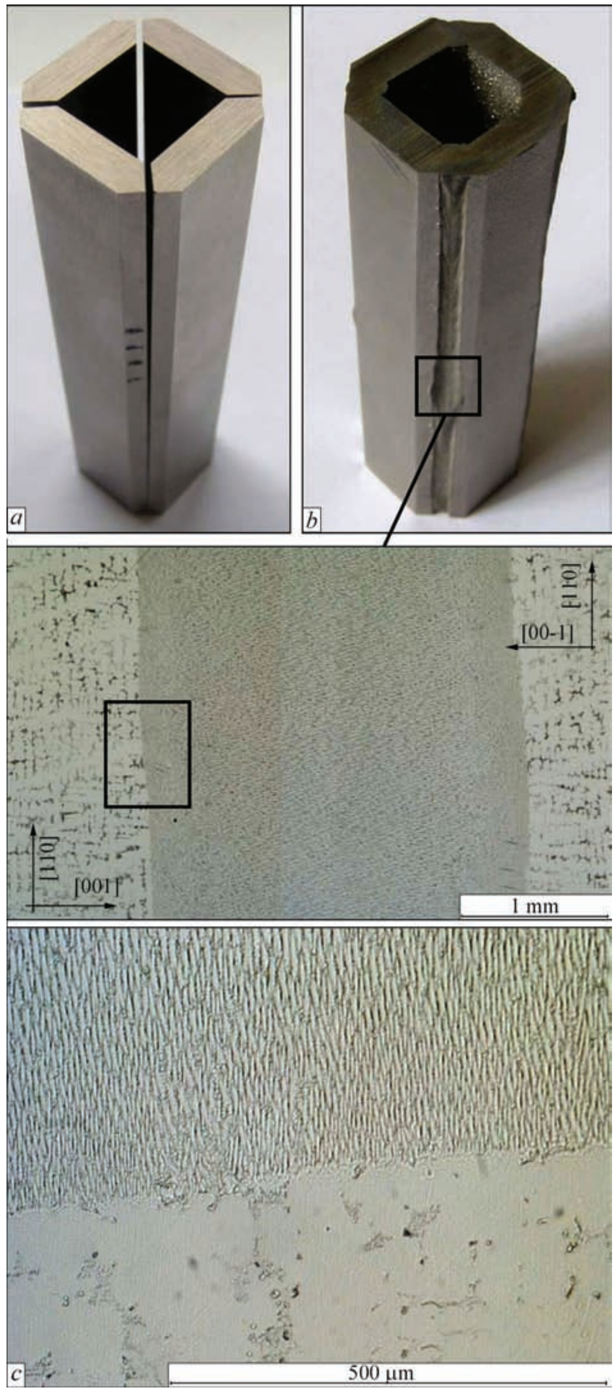

Figure 7. Variant of welded single-crystal structure of ZhS32 alloy billets made by EBW: *a* — initial single-crystal billets of 5 mm thickness; *b* — welded element; *c* — joint microstructure

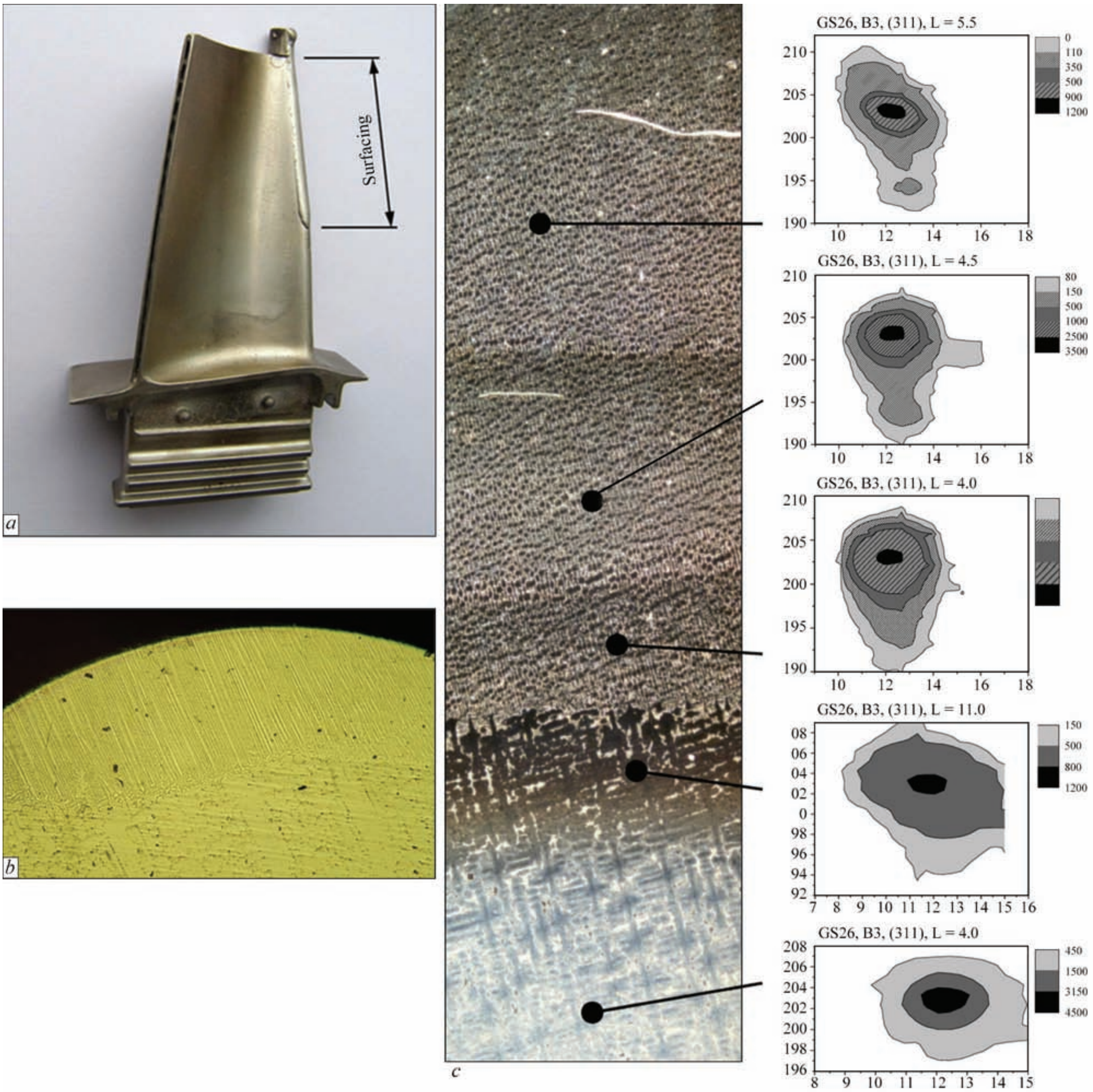

Figure 8. Appearance (*a*) and structure (*b* — ×100; *c*— ×50) of single-crystal blade from ZhS32 alloy of high-pressure turbine in aircraft GTE with leading edge repaired by singlepass (*b*) and multi-pass (*c*) electron beam surfacing

preserving the initial crystallographic orientation, there were developed a technology eliminating warping of longitudinal welded joint.

Figure 7 shows a single-crystal hollow billet of rectangular section, welded by electron beam of 5 mm thickness single-crystal plates. As it is shown by X-ray and metallographic examinations of the joints, absence of ROG, orientation homogeneity of the weld metal and heat-affected zone with the base metal, which does not exceed five degrees, describe the single-crystal nature of welded structure in whole. High crystallographic homogeneity of the joints is reached due to set values and combinations of technological parameters, modes, EBW procedure and providing of crystallographic symmetry of butt joints in manufacture of the initial billets and their assembly. At that, it is possible to ensure fulfillment of conditions of directed crystallization, namely temperature (G/R relationship approximately 600 s·°C/mm^2 at deviation of the joint edges from high symmetry up to 20°) and orientation (formation of macroflat solidification front of pool in through penetration with the parallel fusion edges).

Figure 8 demonstrates a variant of surfacing repair of the most loaded leading edge of single-crystal blade of high-pressure turbine of ZhS32 alloy. Deposit metal inherits the initial crystallographic orientation of the blade substrate with deviation, not exceeding two degree. Height of the one deposit layer was set in the limits of 0.7–0.8 mm. In multipass surfacing the sum

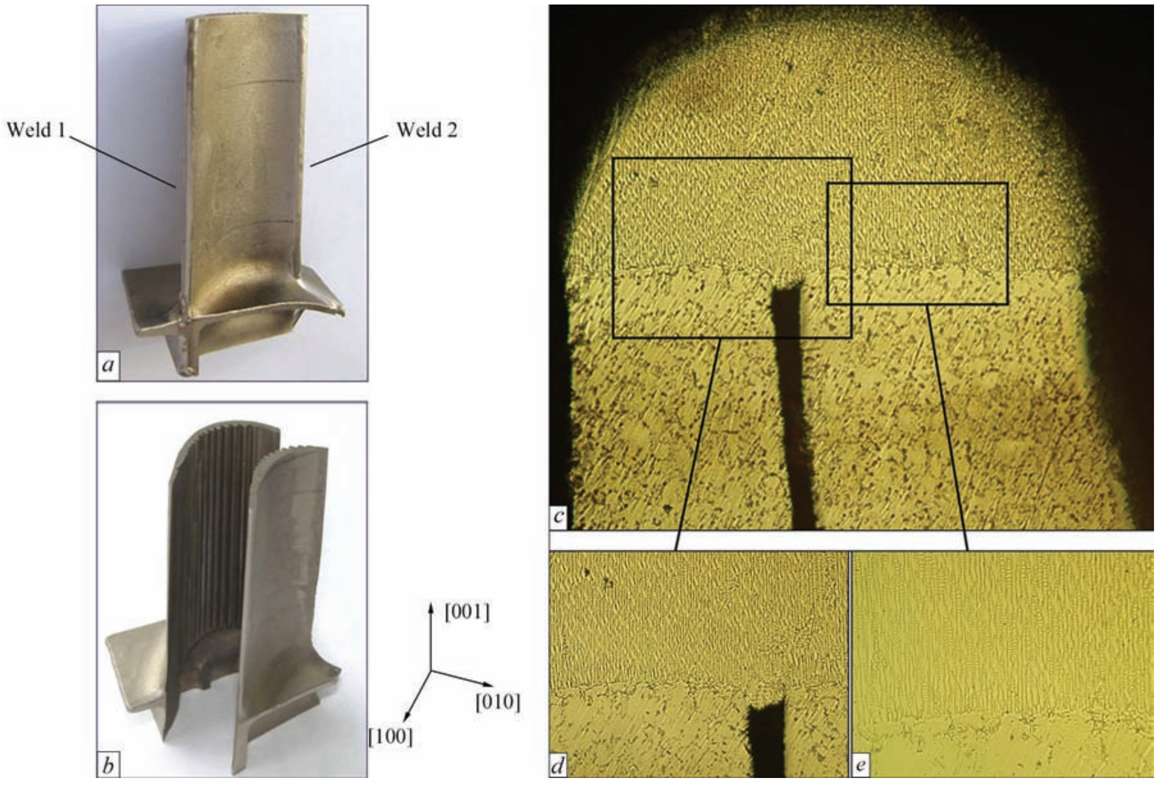

Figure 9. Prototype of all-welded single-crystal cooled blade of ZhS26 alloy (*a*) made by EBW of billets (*b*) with typical crystallographic structure, and microstructure (*c*, *d*) of joint metal

height can reach 3 mm and more. The filler material corresponded to composition of the deposited blade. Analysis of the results of X-ray examination on shape and broadening of the isointense lines of $I_{q\perp}$ distribution indicates homogeneity of dislocation distribution and absence of ROG with formation of substructure with low-angle disorientation.

Figure 9 presents the variant of complex structure of cooled blade, produced by EBW. Such a solution in addition to simplification of production technology allows getting the optimum innovative geometry of the inner channels at lower expenses. This provides the maximum coefficient of inner blade cooling.

A basic scheme of welding technology was develop based on the results of investigations. It allows providing preservation of the single-crystal structure with disorientation of structural constituents, which does not exceed 5°, absence of cracks and random orientation grains. Except for known technological activities on repair of polycrystalline blades, the technology includes the following basic operations:

• determination of crystallographic orientation of the defective zone;

• optimizing the weld pool shape;

• selection of parameters of mode and procedure of electron beam welding, which provide the necessary weld pool geometry and temperature-time parameters at the solidification front.

The technology was realized in repair of blades of ZhS26 and ZhS32 alloys. The experimental works on coarsening of single-crystal billets of 1.5–5.0 mm thickness were carried out.

The level of mechanical properties of joints of single-crystal alloy ZhS26 makes:

• short-term mechanical properties of welded joints from alloy in 500–1000 °C temperature range not lower than the level of properties of initial single-crystal in the whole investigated temperature range;

• long-term strength of welded joint on the basis of 100 h at 900 °C reaches $\sigma_{100} \geq 240$ MPa that makes approximately 75 % of the base metal.

Given results show the possibility of formation of the welded joints of complex geometry and deposits with single-crystal structure that potentially allows using fusion welding in repair and production of the single-crystal parts. Absence of grains in such a product and, respectively, high-angle boundaries, makes the grounds for high service parameters and working capacity of the welded structures.

It is obvious that application of these technologies allows:

• providing development of innovative products based on new principles with improved mechanical characteristics and service parameters.

• reduce laboriousness and production cost;

• decrease material consumption;

• provide energy saving;

• increase compatibility of the products on the international market.

Naturally, that proposed solutions require further development from point of view of design and technological improvement together with developers and manufacturers of the products.

Taking into account outlined fundamental and applied developments it can be concluded that application of welding technologies currently can be the most reasonable, if not single in some cases, solution of the problem of development of complex geometry products of HNA with the single-crystal structure.

1. Stroganov, G.B., Chepkin, V.M. (2000) *Cast high-temperature alloys for gas turbines*. Moscow, ONTI MATI [in Russian].
2. Petukhov, A.N. (1993) *Fatigue resistance of GTE parts*. Moscow, Mashinostroenie [in Russian].
3. Kablov, E.N. (2001) *Cast blades of gas-turbine engines (alloys, technology, coatings)*. Moscow, MISIS [in Russian].
4. Sorokin, L.I. (2004) Weldability of high-temperature nickel alloys (Review). Pt 2. *Svarochn. Proizvodstvo*, **10**, 8–16 [in Russian].
5. Sorokin, L.I. (2004) Weldability of high-temperature nickel alloys (Review). Pt 1. *Ibid*., **9**, 3–7 [in Russian].
6. Lippold, J., C., Cotecki, D.J. (2005) *Welding metallurgy and weldability of stainless steels*.Wiley Interscience. A J.Wiley@ sons inc. Publication.
7. Pollock, T.M., Murphy, W.H. (1996) The breakdown of single-crystal solidification in high refractory nickel-base alloys. *Metall. Mater. Transact. A*, **27A**, 1081–1094.
8. Park, J.-W., Baby, S.S., Vitek, J.M. et al. (2003) Stray grain formation in single crystal Ni-base superalloy welds. *J. of Applied Physics*, 94(**6**), 4203–4209.
9. Czyrska-Filemonowicz, A., Dubiel, B., Zietara, M., Cetel, A. (2007) Development of single crystal Ni-based superalloys for advanced aircraft turbine blades. *Ingynieria Materialowa*, **3–4**, 128–133.
10. Reed, R.C. (2006) *The superalloys: Fundamentals and application*. Cambridge, Cambridge University Press.
11. (2004) Aviation materials. In: *Sci.-Techn. Coll.: High-rhenium high-temperature alloys, technology and equipment for production of alloys and casting of single crystal GTE blades*. Moscow, VIAM [in Russian].
12. Fitzpatrick, G.A., Broughton, T. (1986) Rolls-Royse wide chord fan blade. In: *Proc. of Int. Conf. on Titanium Products and Applications* (San, Francisco, California, USA, October 1986).
13. Inozemtsev, A.A., Nikhamkin, M.A., Sandratsky, V.L. (2008) *Principles of design of aircraft engines and power units*. Vol. 2: Compressors. Combusion chambers. Afterburners. Turbines. Output devices. In: *Manual for higher education institutes*. Moscow, Mashinostroenie [in Russian].
14. Yushchenko, K.A., Zadery, B.A., Gakh, I.S., Karasevskaya, O.P. (2016) Formation of weld metal structure in electron beam welding of single crystals of high-temperature nickel alloys. *The Paton Welding J*., **8**, 15–22.
15. Yushchenko, K.A., Gakh, I.S., Zadery, B.A. et al. (2013) Main theoretical backgrounds of welding of metal single crystals. In: *Physical and technical problems of modern materials science*. Vol. 1. Akademperiodika, 148–176 [in Russian].
16. Yushchenko, K.A., Gakh, I.S., Zadery, B.A. et al. (2013) Influence of weld pool geometry on structure of metal of welds on high-temperature nickel alloy single-crystals. *The Paton Welding J*., **5**, 45–50.
17. Yushchenko, K.A., Zadery, B.A., Gakh, I.S., et al. (2013) On nature of grains of random orientation in welds of single-crystal high-temperature nickel alloys. *Metallofizika i Novejshie Tekhnologii*, 35(**10**), 1347–1357 [in Russian].
18. Yushchenko, K.A., Zadery, B.A., Zvyagintseva, A.V. et al. (2009) Peculiarities of structure of metal deposited on edges of single-crystal blades made from nickel superalloys. *The Paton Welding J*., **8**, 36–42.
19. Yushchenko, K.A., Zadery, B.A., Gakh, I.S. et al. (2009) On possibility of inheritance of single-crystal complexly-alloyed nickel alloys under nonequilibrium conditions of fusion welding. *Metallofizika i Novejshie Tekhnologii*, 31(**4**), 473–485 [in Russian].
20. Yushchenko, K.A., Zadery, B.A., Kotenko, S.S. et al. (2008) Sensitivity to cracking and structural changes in EBW of single crystals of heat-temperature nickel alloys. *The Paton Welding J*., **2**, 6–13.
21. Yushchenko, K.A., Zadery, B.A., Karasevskaya, O.P. et al. (2006) Structural changes in crystallization process of nickel superalloys in crystallography-asymmetric location of welding pool. *Metallofizika i Novejshie Tekhnologii*, 28(**11**), 1509–1527 [in Russian].
22. Yushchenko, K.A., Zadery, B.A., Karasevskaya, O.P. et al. (2006) Structure of welded joints in tungsten single crystals. *The Paton Welding J*., **8**, 29–36.
23. Yushchenko, K.A., Karasevskaya, O.P., Kotenko, S.S. et al. (2005) Inheritance of structure-oriented state of metallic materials by welded joints. *Ibid*., **9**, 2–9.
24. Zadery, B.A., Kotenko, S.S., Polishchuk, E.P. et al. (2003) Peculiarities of crystalline structure of welded joints in single crystals. *Ibid*., **5**, 13–20.
25. Clark, D., Bache, M.R., Whittaker, M.T. (2008) Shaped metal deposition of nickel alloy for aero engine applications. *J. Materials Proc. Technology*, **203**, 439–448.
26. Ding, D., Pan, Z., Cuiuri, D., Li, H. (2015) Wire-feed additive manufacturing of components: technologies, developments and future interests. *Int. J. Adv. Manuf. Technol*., 81(**1–4**), 465–481.
27. Frazier, W.E. (2014) Metal additive manufacturing (Review). *J. Mater. Eng. and Performance*, 23(**6**), 1917–1928.
28. Brandla, E., Baufeld,?, Leyens, C., Gauitd, R. (2010) Additive manufactured Ti-6Al-4V using welding wire: Comparison of laser and arc beam deposition and evaluation with respect to aerospace materials specification. *Proc. of the Laser Assisted Net Shape Engineering*, **5**, Pt B, 595–606.
29. (2018) *Additive manufacturing: Siemens uses innovative technology to produce gas turbines*. Press-Siemens Global Website, Munich, Mar 19. www.siemens.com/press/en/
30. Rockstroh, T., Abbott, D., Hix, K., Mook, J. (2013) *Lessons learned from development cycle. Additive manufacturing at GE Aviation — Industrial Laser Solutions*, 1–6. www.industrial-lasers.com/articles/print/volume-28/issue-6/features/additive-manufacturing-at-ge-aviation.html

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