STRUCTURE AND STRENGTH PROPERTIES OF BRAZED JOINTS OF JS26NK CAST NICKEL ALLOY Part 2*

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Materials science problems of formation of brazed joints in the JS26NK cast nickel alloy are considered. Physical-chemical properties of brazed joints, produced with application of standard boron-containing brazing alloy and brazing alloy containing silicon as second depressant, and different binders are presented. It is shown that application of a binder in the form of solution of acrylic acid in acetone is efficient in case of application of complex brazing alloys containing 20 % of the Ni–12 % Si (NS12) commercial brazing alloy powder. Achieved at room temperature strength and fracture toughness of a brazed joint from the JS26NK alloy exceed similar characteristics of the JS26VI alloy. Connection of mechanical properties of brazed joints with direction of dendrite growth in the metal being brazed is shown.

K e y w o r d s : brazing in vacuum, JS26NK cast alloy, complex boron- and silicon-containing brazing alloy, NS12 brazing alloy, brazed joint, hardness, elongation, failure, structure, fusion line

Deformation process is often brought under laboratory conditions to uniaxial extension. The most interesting results, registered at such action on the investigated joints, are abnormal tensile properties and character of strain hardening of a specimen, whereby main attention has to be paid to elongation of the specimen [8].

Multiphase character of the brazed joint metal structure and shrinkage microporosity are main reasons of premature failure of brazed joints (BJ) in loading. Type of the fracture and microstructure of the specimen in locus of failure are main sources of information of the BJ being investigated [9, 10].

In making analysis of the brazed structure failure, when it was necessary to find locus of failure in the seam, heat-affected zone or base metal, both parts of the failed specimen were investigated, because work with just one half of the fracture is ineffective.

Fractography of tensile BJ specimens. Strain hardening curves (see Figures 4 and 5 in No.4, 2007) of BJ are supplemented with results of the fractography investigation of fractures of respective specimens [11]. Character of deformation of the specimens is stipulated by different crystallographic orientation of dendrites in structure of the brazed metal. This is confirmed by pictures of failure, presented in Figures 10–12, obtained on longitudinal microsections of BJ specimens of the JS26NK alloy of directed solidification (DS). Fracture character of the specimens was connected with chemical composition of brazing alloys, used at first stage of the investigations (Table 4).

Different character of two types of the strain hardening curves of the BJ specimens, formed with application of brazing alloy #1 + 20 % NS12 + 60 % Rene-142 (see Figure 4) [11], is confirmed by the fractographic analysis data of typical Z1 and Z5 specimens (Figure 10, *a*–*d*). Failure in these specimens with sufficiently high value of ultimate tensile strength (1065–1067 MPa) and relatively low yield strength (i.e. maximal strain hardening) occurred in the base metal.

In fracture of the Z5 specimen tough structure of the base metal was detected with clear direction of growth of branches of main dendrites (Figure 10, *b*). On surface of the fracture axes of dendrites had clear single directedness and loss of orientation in relation to main direction of applied load.

One may judge by structure of the base alloy on picture of failure and microstructure of the brazed seam in plane of applied load about possible crystallographic orientation of dendrites in the Z5 specimen, corresponding to <111>. Steepness of strain curves of Z5 and Z1 specimens confirms existence of this orientation.

Trajectory of main crack propagation in the Z5 specimen passes over boundaries of dendrites of 2nd and 3rd order (i.e. over interdendrite carbide phases). BJ failure originated in surface of end part of the flat specimen and propagated over interdendrite spaces of adjacent dendrites of 2nd order.

In this case width of the formed seam did not exceed 250 μm. High quality of the BJ with minimal amount of secondary carbide phases in matrix solution was noted. In specimens with <111> orientation insignificant development of the diffusion zone was reg-

*Part 1 see in No.4, 2007.

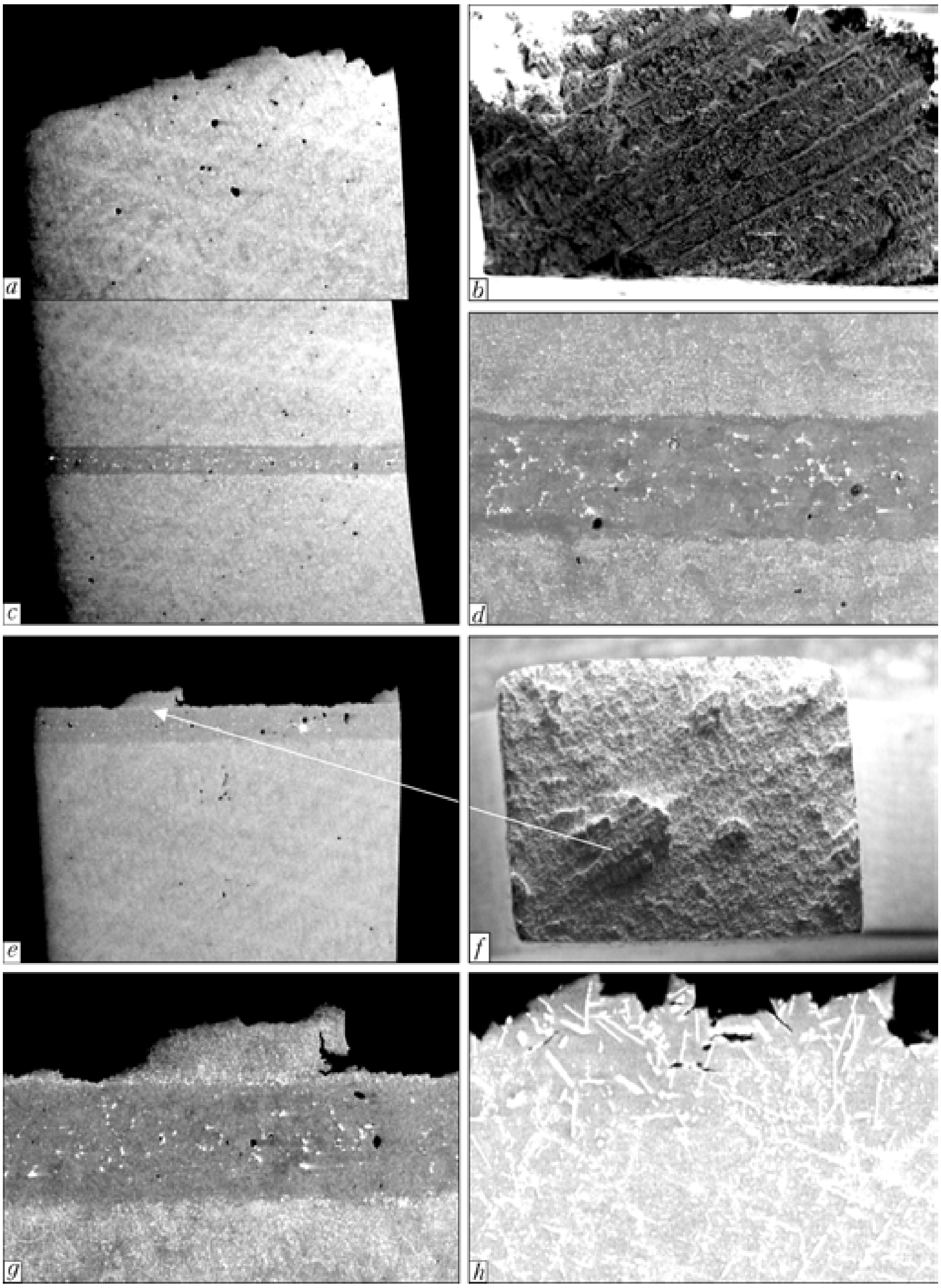

Figure 10. Picture of fracture of BJ specimens, formed with application of 20 % NS12 + 20 % #1 + 60 % Rene-142 complex brazing alloy, of JS26NK alloy of different crystallographic orientation: *a–d* — specimen Z5 with <111> orientation (σ_t = 1065 MPa, ε = = 23 %); *e–h* — Z3 with <111> orientation (σ_t = 823 MPa, ε = 17.3 %); *a, b, e, f* — fractography of failure of specimens (×50); *d, g* — BJ microstructure (×100)

istered. Course incising carbide phases were completely absent in the seam at boundary of fusion with the base metal. Quality of BJ in the considered experiment was guaranteed by fulfillment of full heat treatment cycle, including high-temperature ageing at 1050 °C for 4 h. The heat treatment ensured full diffusion interaction of solidified brazing alloy with the base metal and refining of secondary phases in the seam body and at the interphase boundary. This allowed uniform redistributing of applied load within the brazed seam volume.

Another type of failure had Z3 and Z9 specimens. These BJ are peculiar for minimal disperse hardening, and strain curves had sufficiently flat character, whereby yield strength achieved 657–674 MPa and ultimate strength — 760–823 MPa. Failure of the Z3 specimen, produced by the complex brazing alloy (with silicon), occurred over fusion line and went deeper into the base metal (see Figure 10, *e–h*). On pictures of failure direction of growth of dendrites in the brazed metal is registered.

Trajectory of the crack propagation demonstrates good connection between metal to be brazed and seam metal. The diffusion zone in case of other orientations of growth of dendrites in the BJ specimens is more developed (has significant width and contains big

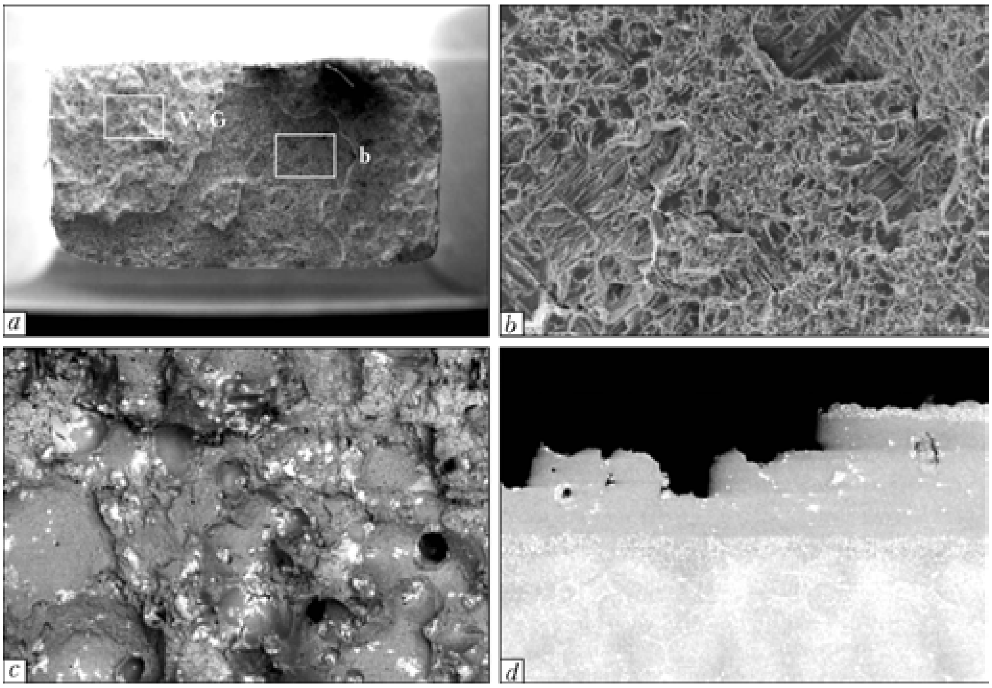

Figure 11. Fractography of brittle fracture of specimen Z11 formed with application of 20 % NS12 + 20 % #1 + 60 % Rene-142 complex brazing alloy: *a* — general picture of failure (×50); *b*, *c* — passage of main crack over base metal and diffusion zone respectively (×200); *d* — trajectory of specimen failure over fusion line (×100)

amount of secondary hardening phase, in particular acicular Me_6C carbides characterized by incising properties under loading).

So, in the BJ specimens in case of <111> orientation failure occurred mainly in the base metal over the diffusion zone. Formed seam in the Z3 specimen had quality structure with minimal amount of carbide phases. Available discrete microporosity did not enable formation of microcracks in the seam under loading. General relative elongation of BJ, equal to 17.3 %, proved high density of the seam metal, determined by parameters of brazing and conditions of the finish heat treatment. Big elongation of BJ is connected, in our opinion, with the fact that in test of the joint coincidence of direction of preferential growth of dendrites with the applied load vector was registered. Failure of the specimen is caused by cracking of the acicula-like carbide phase near the fusion line (see Figure 10, *h*).

General pattern of brittle fracture of the Z11 BJ specimen of the JS26NK alloy actually at the yield strength ($\sigma_{0.2}$ = 613 MPa, σ_t = 615.8 MPa, ε = 0.85 %) is reflected on longitudinal microsection (see Figure 11 *a*, *b*). This specimen is an exception from general pattern of fracture of the BJ specimens, formed with application of brazing alloy #1 + 20 % NS12 + 60 % Rene-142. At small width of the natural gap (up to 200 μm) and relative homogeneity of the brazed seam results of mechanical tests turned out to be rather low. In the failure transcrystalline fracture over seam metal and diffusion zone was combined with tough fracture of the base metal (see Figure 11, *a*, *d*). The crack propagated over carbide phase in the seam body and fusion line on side of the seam metal (see Figure 11, *d*).

Seam metal and base alloy had good cohesion bond due to development of the diffusion processes at the interphase boundary in finish heat treatment (ageing at 1050 °C). Microporosity, detected in the fracture, turned out to be one of the reasons of reduced BJ strength due to weakening of free cross-section area of the seam in case of extension of the specimen. Mainly intergranular character of failure is stipulated by precipitation of excessive carbide phases over boundaries of the seam grains. Trajectory of failure covers the brazed metal, which is proved by tough fracture, containing elements of brittle fracture that include skeleton-like interdendrite carbide phases over boundaries of axes of 2nd and 3rd order (Figure 10, *c*).

In case of application of the base boron-containing brazing alloy #1 + 60 % Rene-142, results of mechanical tests were satisfactory.

Strength, as well as ductility of BJ, depends upon filling of the gap (density of the seam metal). If the gap is wide, greater volume of metal solidifies with formation of shrinkage microporosity and even looseness. Such dependence is especially clearly seen when classic system of brazing alloy #1 + 60 % Rene-142 with a higher toughness in comparison with silicon-containing brazing alloys is used. In this case seam metal is a weak place in the BJ specimen, and fracture in case of uniaxial extension occurs in it. This is illustrated by the fact that at the minimal 125 μm gap in the Z8 specimen maximal 23 % elongation was achieved. Load curve of this specimen proves its monotonous strain hardening and correspondence of growth of the dendrites of <111> orientation (see Figure 5). Picture of the Z8 specimen failure demonstrates dendrite structure of the specimen material,

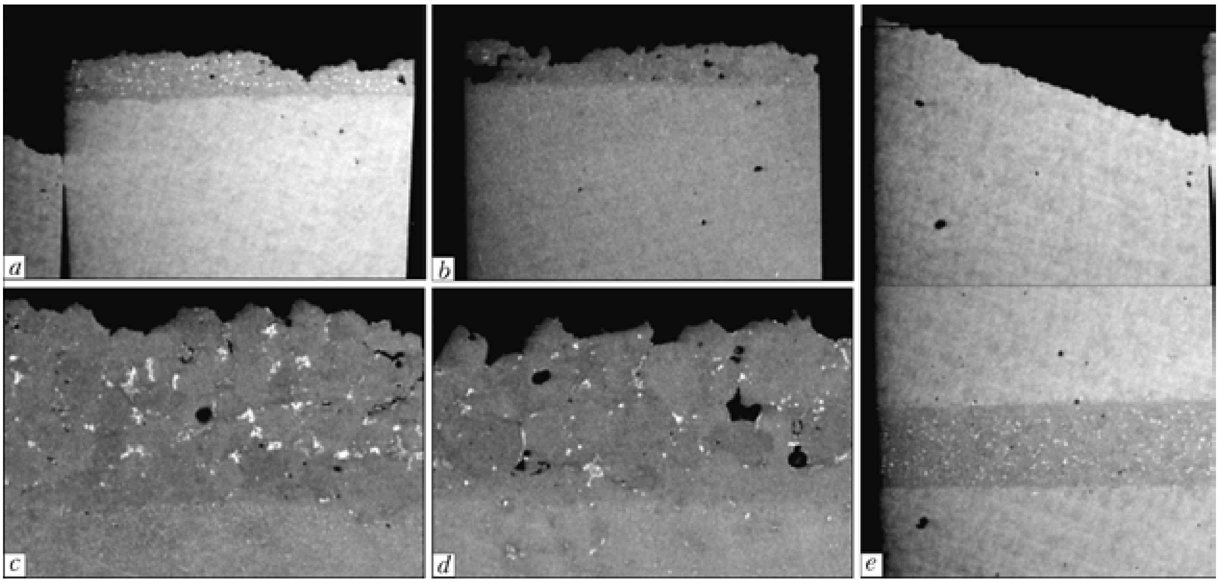

Figure 12. Typical microstructures of fracture surface of BJ specimens, formed with application of 20 % NS12 + 20 % #1 + 60 % Rene-142 complex brazing alloy, at different directions of cutting out of NK billet: *a*, *c* — longitudinal over fusion line (×50; ×100); *b*, *d* — cross over seam metal (×50; ×100); *e* — cross (over base metal) (×23)

direction of which coincided with long of the specimen axis (see Figures 7, *g* and 13, *c*).

Peculiarity of the considered specimen is the fact that its natural gap was minimal in comparison with the rest ones (see Table 1). Due to this structure of the seam metal had high degree of homogeneity — secondary carbide phases were practically absent in it (see Figures 11, *d* and 13, *c*). At high toughness of classic brazing alloy #1 + 60 % Rene-142 application of its minimal volume share in the gap and finish annealing at 1050 °C within 4 h allowed obtaining structure of the brazed seam with satisfactory characteristics of strength and ductility of the joint close to the ideal one.

In absence of secondary phases in the seam main crack in case of failure propagated mainly over diffusion zone in the fusion area (see Figure 11, *a*, *c*). Wavy relief of the fracture surface is connected with oriented growth of dendrites, when a grain body elongates in direction of the acting load, and interphase base–brazing alloy boundary is strengthened by precipitates of secondary carbide or carboboride phases, which make easier transfer of plastic flow of the matrix through boundary from grain to grain.

Typical for the BJ specimens, formed with application of the base brazing alloy #1 + 60 % Rene-142, was transcrystalline or intergranular failure over the solidified seam metal. By means of growth of volume share of a rather tough complex brazing alloy and the gap width from 225 to 400 μm, heterogeneous structure of the seam with different kinds of secondary hardening phases was formed.

These brittle phases acted as stress concentrators in the tests. This is confirmed by fractography of the Z6 specimen fracture with 1.2 % elongation and ultimate strength 822.3 MPa (see Figure 7, *b*, *f*, *h*). Fracture occurred over interdendrite areas of the seam metal, where precipitation of phases was registered, consisting of enlarged carbide particles (see Figure 7, *d*). Picture of similar brittle fracture of the Z0 specimen with zero ductility is illustrated by the diagram of its extension (see Figure 5) [11].

So, in case of application of base brazing alloy #1 + 60 % Rene-142 in brazing of the JS26NK alloy fracture of the BJ specimens in tensile tests occurred mainly over solidified seam metal because of their more pronounced multiphase character (see Figure 13, *d*).

In case of application of brazing alloy #1 + 20 % NS12 + 60 % Rene-142, BJ failure occurred most frequently over the base metal or line of fusion with it. At relative homogeneity of the seam metal and minimal content of secondary phases in the seam, front of failure in the tests shifted into the diffusion zone area, where after high-temperature ageing disperse carbide phases and carbides of acicular type in a limited amount precipitated from the solution during cooling.

At second stage of the investigations when width of the natural gap was increased the BJ specimens, formed with application of complex brazing alloy #1 + 20 % NS12 + 60 % Rene-142, had rather stable mechanical properties irrespective of direction of growth of dendrites in the brazed billets (see Table 1) [11].

Longitudinal specimens had insignificant strain hardening and relative elongation within 3.9–5.5 % (see Table 1). For these specimens developed diffusion interaction between the base being brazed and the seam metal is characteristic as a result of annealing at 1050 °C within 5 h (see Figure 12, *a*, *b*). The specimens mainly failed over the BJ fusion line. Diffusion processes at the boundary are connected with direction of growth in the specimen billets and crossing by the forming brazed joints of boundaries of the growing dendrites, which are favorable places for progress of metathetical processes in the cast alloy.

In case of cross specimens, when the formed brazed joints are parallel to axes of dendrites in the billets,

Table 4. Chemical composition of different phases in metal of BJ seams produced with application of two kinds of brazing alloys in process of isothermal brazing after tests at 950 °C

System of brazing alloy	Analysis spectrum	Weight share of components, %													
		Si	C	Al	Ti	V	Cr	Co	Ni	Nb	Mo	Hf	Ta	W	Re
#1 + 60 % Rene-142	1	–	2.74	5.10	0.87	0.98	5.01	8.66	60.59	0.73	0.64	–	–	13.11	1.57
	2	–	2.21	5.54	–	–	8.36	10.44	63.47	–	0.88	–	2.58	4.80	1.73
	3	–	1.82	5.23	–	–	8.04	12.02	65.37	0.14	0.75	–	3.01	3.24	0.37
	4	–	6.86	3.83	0.34	–	2.29	4.44	41.88	0.62	0.06	14.33	23.10	1.54	0.71
	5	–	3.47	4.64	–	–	8.83	11.57	63.58	0.25	0.67	0.21	2.45	2.79	1.52
	6	–	5.68	2.65	–	–	7.79	9.38	47.02	0.54	0.67	10.34	13.54	1.84	0.54
	7	–	3.66	–	–	–	48.69	4.75	4.99	0.13	5.46	–	0.14	12.99	19.20
	8	–	3.80	1.47	–	–	22.33	5.18	17.45	–	8.05	–	5.36	28.55	7.79
	9	–	3.58	0.22	–	–	47.18	4.41	5.16	–	5.44	–	–	14.42	19.60
	10	–	4.09	4.64	0.47	0.78	5.34	8.63	55.31	0.70	1.33	–	–	17.90	0.81
	11	–	4.01	–	–	0.43	28.80	4.31	7.74	–	10.88	–	4.21	30.51	9.10
#1 + 20 % NS12 + + 60 % Rene-142	1	–	1.55	5.16	0.93	0.96	4.77	8.82	61.80	1.44	0.94	0.45	–	12.00	1.23
	2	–	3.19	6.91	1.86	0.77	2.11	7.24	67.50	3.16	0.71	–	–	6.59	–
	3	1.25	2.42	4.67	–	–	7.29	10.80	65.80	–	0.38	–	2.33	3.58	1.43
	4	1.92	3.08	4.73	–	–	7.20	10.30	65.70	–	0.68	–	2.29	2.82	1.29
	5	–	4.83	–	–	0.41	23.10	3.00	6.27	0.75	12.60	–	4.03	33.20	11.80
	6	–	5.63	–	–	–	24.00	2.73	5.98	–	10.10	4.05	13.00	21.30	13.10
	7	–	3.94	3.72	0.38	0.50	5.05	8.29	51.40	0.67	1.43	–	2.87	20.60	1.19
	8	–	3.96	3.92	0.29	–	5.83	9.54	55.60	0.40	1.50	–	4.12	13.00	1.82
	9	1.36	3.02	4.54	–	–	6.92	9.57	65.10	–	0.65	–	3.31	3.73	1.80

a limited diffusion interaction was detected between the metal being brazed and the brazing alloy. This may be explained by the fact that the solidified seam metal contacts mainly with axes of dendrites of 1st order, because the brazed joint is parallel to the growing dendrites, whereby direct contact of the seam metal with boundaries of main hydrides is weakened. That's why in case of tensile testing of the cross specimens the occurring crack passes either over defects of the seam metal (microporosity) (see Figure 12, *c*, *d*) or over the base metal (see Figure 12, *e*). In the latter case influence of a wide natural gap is compensated by reduced toughness of the silicon-containing brazing alloy, good filling of the gap, and flawless quality of the seam being formed.

In tests of the cross specimens small reduction of yield strength was noted (down to 681–752 MPa), ultimate strength being 766–927 MPa. Insignificant growth of strain hardening of the base metal in comparison with longitudinal samples was also registered (see Figure 7).

Increase of the natural gap width in the BJ specimens did not exert significant negative influence on quality of the formed brazed seams and mechanical characteristics thereof (see Table 1). In case of the gap width increase up to 630–780 μm, in BJ σ_t = = 890.0–926.8 MPa (specimens Nos. 14 and 17) at relative elongation 9.5–10.5 % (see Table 1).

Comparison of fracture pictures of the JS26NK alloy BJ specimens, produced with application of different brazing alloys, tested at 950 °C (Figure 14), showed that their general feature is high cohesion strength of the seam metal and the metal being brazed in comparison with strength of central (axial) part of the seam. BJ failure occurred over the seam metal, but in case of a standard bi-component brazing mixture, when a seam contained course carbide phase, the metal disintegrated into separate grains, demonstrating noticeable weakening of the boundaries at high temperature. At the same time the seam, formed from the complex brazing mixture, which included silicon, showed an increased density and higher strength of BJ, combining transcrystalline fracture with intergranular one. This was ensured by a higher dispersiveness of the carbide phase and reduction of weight share of boron in the seam metal in comparison with the first case. Smaller size of the hardening phase over the boundaries creates prerequisites for formation of small microvoids around the particles.

So, character of failure of BJ, produced by the high-temperature brazing method, is in direct dependence upon phase composition of the seam metal, determined by its heat treatment.

In the solidified seam metal, formed with application of the #1 + 60 % Rene-142 composite boron-containing brazing alloy, after multistage heat treat-

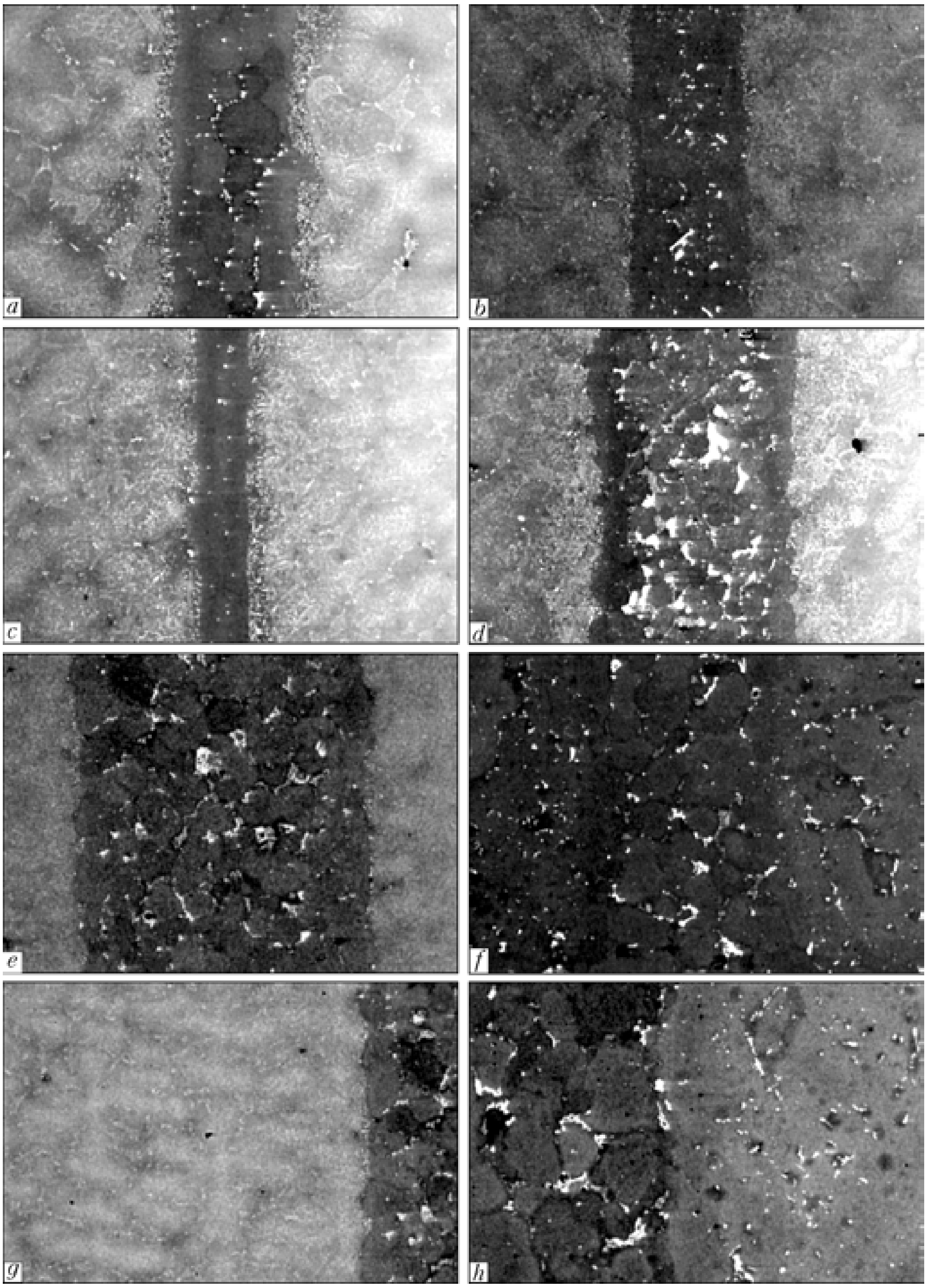

Figure 13. Typical microstructures (×100) of BJ specimens formed with application of complex 20 % NS12 + 20 % #1 + 60 % Rene-142 (*a*, *b*, *e*–*h*) and standard 40 % #1 + 60 % Rene-142 (*c*, *d*) brazing alloys: *a*, *b* — specimens Z9 with <111> orientation and Z5 with <111> orientation (*c*, *d*); *e* — specimen Z18 cut out in cross direction; *f* — specimen Z20 cut out in longitudinal direction; *g*, *h* — diffusion zone in BJ in case of cross and longitudinal cutting out of specimens, respectively

ment boundary course carbide phases of the $Me_{23}C_6$ type on basis of chromium, tungsten, molybdenum, rhenium and phases of eutectic type, corresponding to the Me_6C formula with maximum content of tungsten (up to 30 %), are available (see Table 4 and Figure 15).

In case of application of silicon-containing brazing alloy with 20 wt.% NS12, content and structural diversity of secondary phases in the solidified seam metal sharply reduce. They are represented manly by rare Me_6C carbides on basis of tungsten, molybdenum, rhenium and disperse MeC carbides on basis of hafnium, tantalum and tungsten (see Table 4 and Figure 15).

Discussion of the results obtained. Quality of BJ, determined by continuity of the seam, depends upon intensity of the molten metal feeding to the interdendrite areas in those parts of the joint, where process of solidification has already started. Continuity is achieved when conditions of full flowing through the gap of the brazing alloy melt, under which solidification terminates, are ensured. Density (quality) of the metal is determined by optimal values of temperature of the isothermal brazing process and rate

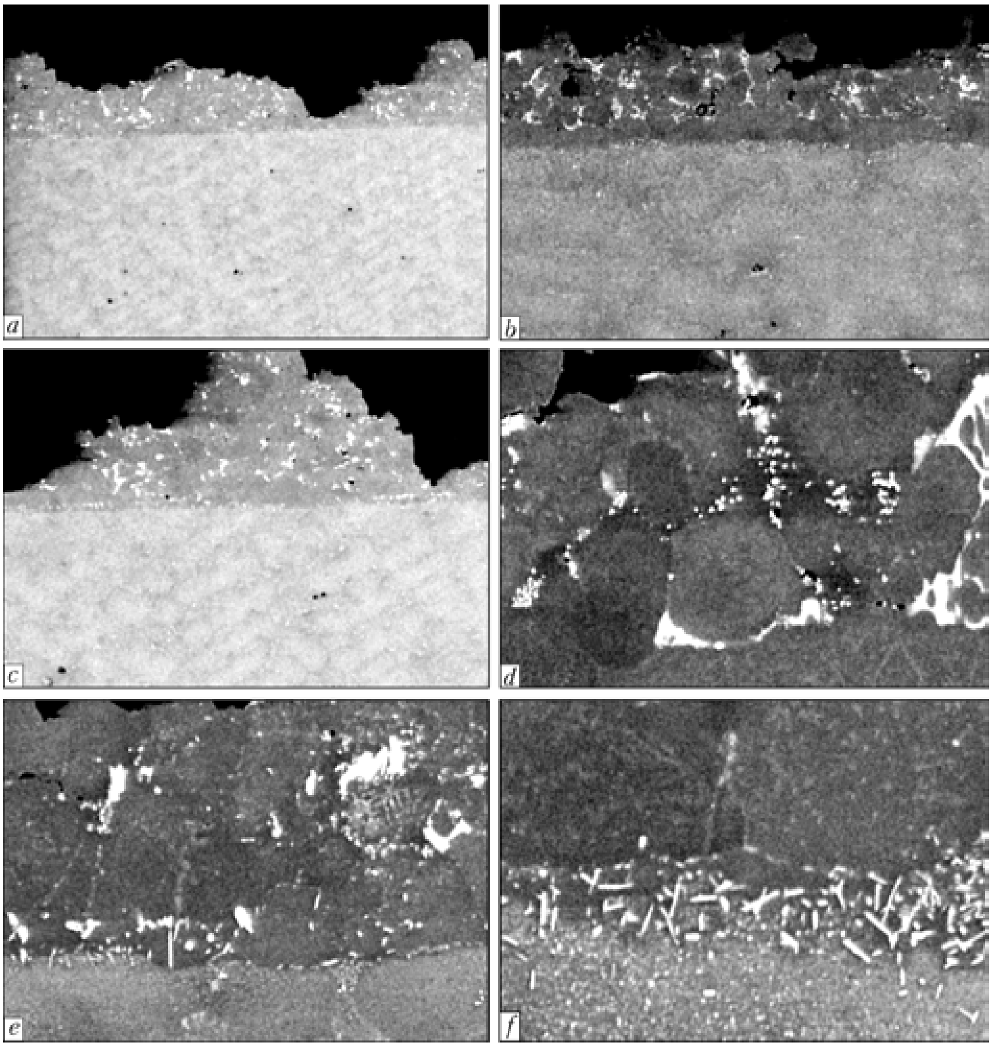

Figure 14. Character of fracture of seam metal of JS26NK alloy BJ produced with application of standard #1 + 60 % Rene-142 (*a*, *c*, *e*) and complex #1 + 20 % NS12 + 60 % Rene-142 (*b*, *d*, *f*) brazing alloys at 950 °C: *a* — ×50; *b*, *c* — ×100; *d*, *e* — ×500; *f* — ×1000

of hardening (solidification) of the formed seam, which ensure completeness of phase transformations, occurring in the seam metal.

Process of brazing of the directed solidification alloy does not provide single-crystal or oriented structure in the seam metal. However, crystallographic orientation of grains in the seam metal may be repeated, when direction of growth in the base metal is clearly pronounced in relation to the BJ seam being formed.

Chosen conditions of isothermal brazing of specimens from the JS26NK alloy allowed forming BJ of good quality with minimal number of microdefects in seams at different natural gaps (see Figure 13).

It was found at the first stage that the joints, produced with application of complex (silicon- and boron-containing) brazing alloy #1 + 20 % NS12 + 60 % Rene-142, had denser homogeneous structure of the seam metal (see Figure 13, *a*, *b*) than in case of application of the #1 + 60 % Rene-142 brazing alloy (see Figure 13, *d*). In first case amount of secondary carboboride phase in the seam reduced, grain has refined, and intergranular complex alloyed eutectics were absent. The #1 + 60 % Rene-142 brazing alloy enabled formation of cellular solidification with structurally developed interdendrite areas.

Two-stage conditions of heat treatment after brazing, which included homogenization at 1160 °C and high-temperature ageing at 1050 °C for 4 h, reduced structural inhomogeneity of the seam metal, enabled development of the diffusion metathetical processes at the brazed metal–brazing alloy boundary and thus ensured higher level of strength and plastic properties of the joints. Development of mutual diffusion of components on fusion line of BJ is pledge of their high strength. In tensile tests failure of the specimens mainly occurred over the diffusion zone, containing, in addition to fine disperse carbide phases, Me_6C phases of acicular type, which affect with their «incisivezz» morphology process of origination and propagation of a crack in BJ.

It is determined that optimal chemical composition of a brazed seam metal after homogenization annealing and high-temperature ageing, which ensures high functional parameters of BJ, is the following, wt.%: Ni (base)–(11.2–12.4) Co–(6.3–6.7) Cr–(4.2–4.6)

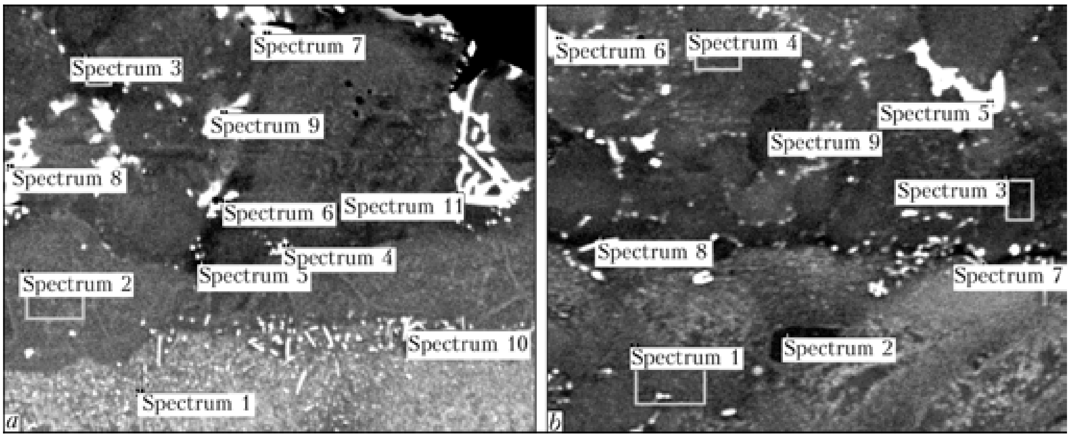

Figure 15. Areas of X-ray spectral microanalysis of separate phases, which constituted seam metal after BJ tests at 950 °C (see Table 4), ×500: *a* — #1 + 60 % Rene-142; *b* — #1 + 20 % NS12 + 60 % Rene-142 brazing alloy

W–(1.0–1.3) Mo–(2.9–3.5) Ta–(0.5–0.7) Nb–(3.5–4.3) Al–(1.2–1.5) Re–(0.7–0.8) Si–(0.6–1.0) Hf–1.0 B–0.12 C.

For avoiding formation of developed multiphase diffusion zone, at second stage of the tests time of annealing at 1050 °C was increased up to 5 h, which allowed avoiding formation of the diffusion zone with acicular carbide phases. On the microstructures smooth transition from matrix solution of the seam metal to matrix of the base alloy was detected (see Figure 13, *e, f*).

Width of the natural gap of the formed brazed joint did not effect development of the diffusion zone at the interphase boundary. Difference was registered only in the BJ specimens in second series of the experiments with different (longitudinal or cross) direction of cutting of the billets.

In longitudinal specimens direction of growth of dendrites was perpendicular to the brazed seam axis. Crossing of the array of the directing dendrites and subsequent contact of the incision surface with the brazing alloy melt ensured penetration of liquid phase over boundaries of butted dendrites of 1st order. Thermal diffusion interaction of the molten brazing alloy with the metal being brazed ensured satisfactory level of BJ strength and development of mutual diffusion in longitudinal specimens (see Figure 13, *f, h*). Diffusion proceeded without formation of course carbide phases or carboboride barriers. Distribution of components in separate zones of BJ was determined by X-ray spectral microanalysis. Width of the mutual diffusion zone was, approximately, 180–250 μm.

In cross specimens, where direct contact of the brazing alloy molten metal with boundaries of dendrites of 1st order was absent (the seam is parallel to direction of growth of dendrites), mutual diffusion processes proceeded feebly at the depth up to 30 μm (see Figure 13, *g*).

Fine (γ–γ')-microstructure of main BJ zones, produced with application of #1 + 20 % NS12 + 60 % Rene-142 brazing alloy, is presented after finish heat treatment in Figure 16. Uniform precipitation of hardening γ'-phase in the seam metal, diffusion zone, and metal being brazed was detected (Figure 16, *a, c, e, h*). In the course of homogenization partial dissolution of primary γ'-phase occurred in the base, and during cooling (together with the furnace) — its precipitation from solid solution of hardening γ'-phase. In the course of subsequent ageing at 1050 °C for 4 h the precipitated hardening phase enlarged, and in the process of cooling additionally precipitated disperse γ'-phase from the matrix γ-solution (Figure 16, *c*).

In long-term ageing share of the supersaturated matrix solution exceeded share of γ'-phase both in the base metal, diffusion zone, and over axes of dendrites of the alloy being brazed.

In high alloy diffusion zone at the seam–JS26 alloy interphase boundary at temperature of ageing in solid solution, carbides of Me_6C type have formed in the form of plates (aciculae) in the places enriched with tungsten. Such morphology of carbides and their edging by the pellicle γ'-phase prove beginning of carbide transformations in high alloy matrix at the interphase boundary (Figure 16, *g*).

Variation of the finish heat treatment conditions (at second stage of the experiment) caused change of the BJ (γ–γ')-microstructure. So, in the base metal growth of the volume share of hardening phase of clear cubic shape and smaller size (up to 0.2–0.7 μm) was detected (Figure 16, *d*). Content of γ'-phase increased both in the seam metal and in the diffusion zone (Figure 16, *f, h*), whereby size of the latter reduced.

In second series of the experiments after homogenization at 1160 °C and cooling with furnace the BJ specimens were not removed from the furnace, but were soaked at 650–700 °C within 10 min, which might affect stability of precipitated from the matrix solution stoichiometric γ'-phase, which in the course of further ageing was less subjected to dissolution and preserved primary shape of the particles. Increase of the ageing duration up to 5 h increased diffusion of components at the boundary, but did not create premises for transition of the alloying elements from joints into the matrix solution and progress of subsequent processes of carbide formation at the fusion line.

Me_6C carbides, formed at the saturated with alloying elements high-alloy interphase boundary, ex-

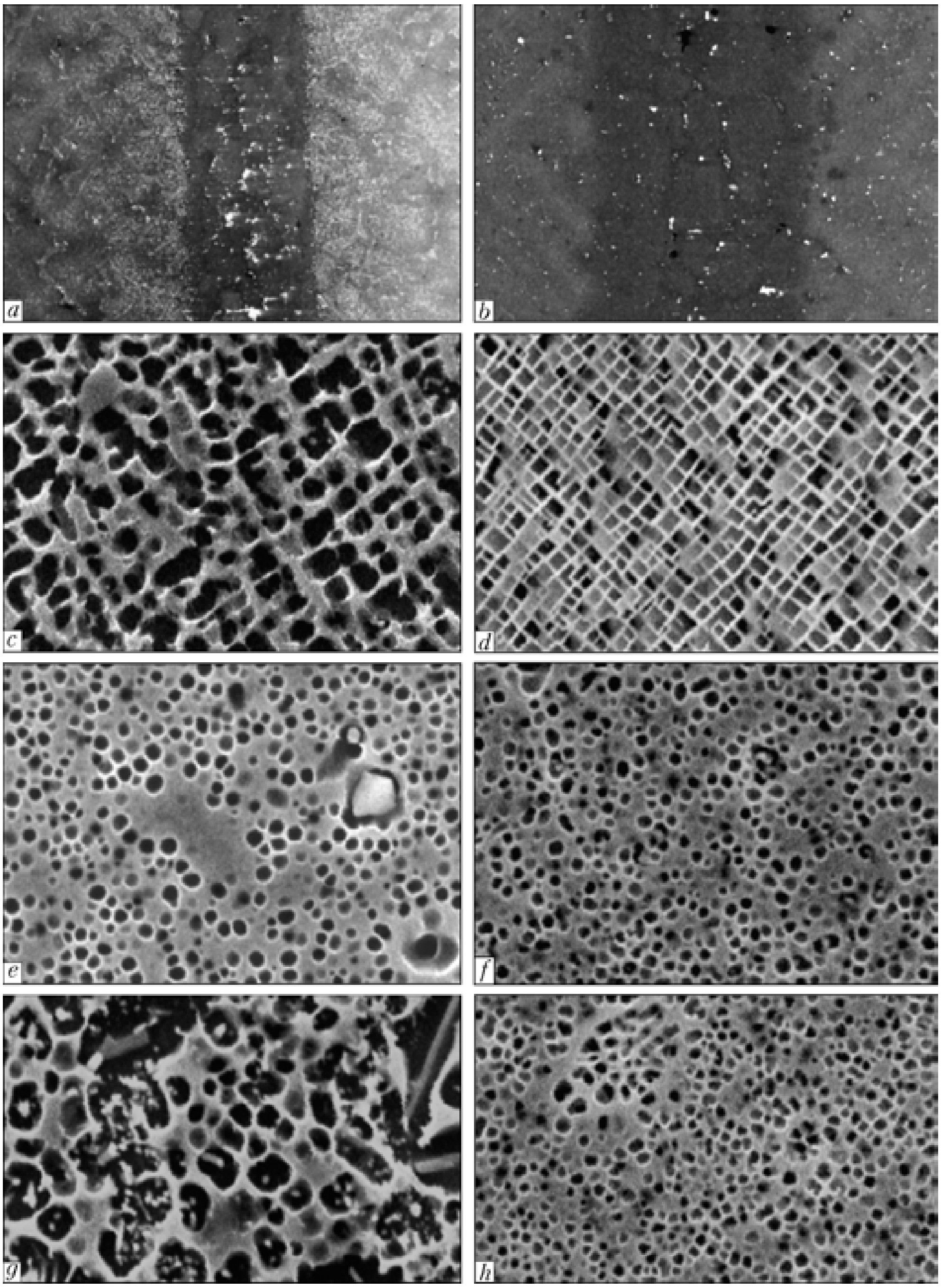

Figure 16. Peculiarities of BJ (γ–γ′)-microstructure under different conditions of finish heat treatment: *a, c, e, g* — ageing at 1050 °C for 4 h; *b, d, f, h* — ageing at 1050 °C for 5 h with preliminary soaking in vacuum at 700 °C (10 min); *a, b* — general appearance of seams after different finish heat treatments; *c, d* — precipitates of γ′-phase in base metal; *e, f* — in seam metal; *g, h* — in diffusion zone

erted harmful influence on fatigue properties of the alloy being brazed. Increase of the high-temperature ageing duration and stabilization of stoichiometric γ′-phase enabled intensification of the mutual diffusion processes and reduction of content of strongly segregating elements (tungsten, titanium, niobium, hafnium and rhenium) at the base–brazing alloy boundary, and this, in its turn, prevented formation of plastic (acicular) carbide phases of the Me_6C type.

Refining of hardening γ′-phase and increase of its volume share in γ-solution enabled increase of yield strength of the alloy being brazed and small reduction of its ductility.

High dispersity of γ′-phase in the alloy being brazed ensured higher yield strength of BJ of the specimens at second stage of the investigations. For example, yield strength of the Z23 BJ specimen was 803 MPa, while that of the Z1 specimen was 652 MPa (Figure 16).

CONCLUSIONS

1. Materials science fundamentals of high-temperature brazing of the JS26NK high-temperature nickel alloy with application of standard boron-containing Ni–Co–Cr–Al–2.5 % B brazing alloy, silicon-containing NS12 brazing alloy (20 wt.% Si) and 60 wt.% of

filler in the form of powder of the Rene-142 alloy were developed.

2. It was shown that stable strength of BJ of the JS26NK alloy, produced with application of the NS12 complex brazing alloy, exceeded strength of the JS26VI joints after similar heat treatment. Difference consisted only in the fact that in case of the NK alloy duration of high-temperature ageing was 4–5 h, while in case of the JS26VI alloy — 2 h. Maximal BJ strength value was 1067 MPa, relative elongation — 15–23 %.

3. Application of the complex brazing alloy, in which simultaneously boron and silicon were used as the depressant, allowed producing BJ, characterized by stably high values of ultimate strength and relative elongation in comparison with BJ, produced with application of the #1 + 60 % Rene-142 base brazing alloy.

4. It was found that in case of coincidence of the dendrite growth direction with vector of the applied load, strength of the specimens and their ductility depended upon crystallographic orientation of growth of dendrites in the NK alloy.

5. It was shown that BJ mechanical characteristics of the JS26NK alloy, determined on the specimens cut out both along and across of the dendrite growth direction, are close at room temperature. Yield strength of longitudinal specimens is somewhat higher than that of the cross specimens.

6. Application of the #1 + 20 % NS12 + 60 % Rene-142 complex brazing alloy allowed producing high-strength flawless BJ of the JS26NK alloy with natural gap 400–780 MPa at the brazing temperature 1225 °C (15 min).

7. The weakest place in case of extension of the BJ specimens of the JS26NK alloy is fusion line, in which segregations of carboboride phases and Me_6C carbides of acicular shape was detected. Heat treatment (ageing at 1050 °C, 4–5 h) allows forming BJ structure with uniformly distributed hardening γ-phase. In case of increase of its volume content growth of yield strength of the BJ metal was registered.

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IMPROVEMENT OF STRUCTURE AND PROPERTIES OF CAST FERRITE-PEARLITE STEELS FOR TRANSPORT MACHINE BUILDING

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Technology for complex modification of casting from low-alloy ferrite-pearlite steels by titanium, aluminium and nitrogen was developed, which ensures increase of the lower level of yield strength in normalized (≥ 380 MPa) and temper hardened (≥ 450 MPa) state, the rest requirements to mechanical properties of the 20GL steel being preserved.

K e y w o r d s : steel, casting, carbonitride hardening, titanium, aluminium, nitrogen, grain index, yield strength, impact toughness

Main task of freight railway car building is increase of the car run before the first planned repair from 100–120 to 500 thou km, whereby guaranteed service life of cast elements of the carriage and the car as a whole should be not less than 16 years before the planned repair, its full service life being up to 32 years [1].

An efficient measure for ensuring these requirements, in addition to new design solutions, is improvement 1.2–1.3 times of strength characteristics of metal of the railway car cast elements, first of all yield strength up to ≥ 380 MPa, the rest mechanical properties being not lower than the normative ones (according to the valid standards).

The simplest solution of this task is increase of degree of steel alloying by the elements, which form substitution solution with iron (silicon, manganese, chromium and nickel). Application of the latter is

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