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STRENGTHENING PHASES, STRUCTURE AND PROPERTIES OF LOW-ALLOY STEEL MODIFIED WELDS

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Effect of dispersoid inoculants (phase inclusions) in form of TiC, SiC and ZrO_2 refractory compounds on kinetics of structural transformations in weld metal of high-strength low-alloy steels was investigated. Effect of the inoculants of different type on displacement of bainite transformation into area of higher temperatures is shown. Electron microscopy is used to analyze the nature of structural-phase changes in formation of bainite structure, i.e. peculiarities of fragmentation, distribution of dislocation density and morphology of carbide phase precipitation. The estimations of specific contribution of all structures and their parameters (phase composition, grain, subgrain and dislocation structures etc.) on carried change of strength characteristics and crack resistance of weld metal at inoculation of disperse phase inclusions were out. The optimum composition was determined for dispersoid inoculants used in welding of high-strength low-alloy steels. They provide for necessary mechanical properties of welded joints, including their crack resistance. 14 Ref., 7 Figures, 4 Tables.

Keywords: *structure of high-strength steels, welded joints, alloying, phase precipitates, dislocations, strengthening factors, local internal stresses*

Analysis of current state of the world steel production shows a tendency to stable growth of total volumes of steel casting as well as constant rise of level of metal quality requirements [1]. At that, portion of flat products from high-strength low-alloy steels in ferrous metallurgy range is noticeably increased [2]. It is noted that development of new non-standard approaches to formation of structure of such materials [3] is necessary in order to reach higher values of strength, ductility and crack resistance of steels, used in different areas of engineering. Possibility of estimation the effect of inoculation in a metal melt of refractory non-metallic inclusions on nucleation and growth of structural constituents is considered as one of the perspective directions for this problem solving [4].

At that, it is determined that a role of non-metallic inclusions, having, as a rule, negative effect on complex of mechanical properties of steels, varies under certain conditions, i.e. reduction of their size decreases the inclusions' negative effect, and fine inclusions of certain chemical composition and morphology can be used for regulating the processes of nucleation and growth of some structural constituents. Such inclusions are called «dispersoids» [5, 6].

Thus, dispersoid inoculants are used in making of HSLA steels for the purpose of formation of necessary structural composition [7]. There is a series of investigations showing perspectives of the inoculants loading in a weld pool [8].

This work is also dedicated to investigation of effect of the dispersoid inoculants on conditions of structure formation and mechanical properties of weld metal of HSLA steels.

The investigations were carried out on weld specimens produced in welding of butt joints of HSLA steel using flux-cored wire in M1 (Ar + 18 % CO_2) shielding gas in accordance with ISO requirements. Composition of metal of examined welds is given in Table 1, size of austenite grains in the weld metal and critical points of structural transformations in it are shown in Table 2. Composition of dispersoid inoculants was selected based on the fact that, in accordance with data published in [9], formation of structural constituents depends on a value of free energy of their nucleation at metallic matrix to non-metallic inclusions interface as well as on physical-chemical characteristics of inclusions and temperature range of transformations.

Investigation procedure. Work [10] showed that weld pool loading with TiC, SiC and ZrO_2 refractory compounds in form of the dispersoid inoculants has positive effect on morphology of primary structure grains forming at weld metal crystallization. Investigation of a relationship between inoculants influence on the primary metal structure and formation of the secondary weld microstructure was also interesting. Mentioned above refractory compounds in form of disperse particles were inoculation in the weld pool by means of their introduction in a flux-cored wire

Table 1. Composition of metal of examined welds, wt.%

Designation of weld	C	Si	Mn	S	P	Cr	Ni	Mo	Ti	Zr
«0»	0.050	0.290	1.32	0.024	0.014	0.16	2.19	0.27	0.008	N/D
«Ti»	0.049	0.170	1.39	0.023	0.015	0.15	2.26	0.25	0.019	Same
«SiC»	0.066	0.298	1.22	0.019	0.014	0.14	2.12	0.23	0.005	»
«ZrO_2»	0.053	0.263	1.24	0.020	0.014	0.12	2.25	0.23	0.005	0.06
«TiC»	0.054	0.138	1.28	0.025	0.011	0.13	2.22	0.26	0.012	N/D

core. The results were compared with data obtained in welding of metals with similar technological parameters of the process, but without application of the dispersoid inoculants (weld «0»). In order to have better determination of the inoculation effect, the data received in testing of specimens of «TiC», «SiC» and «ZrO_2» weld metal, were compared with the results of examination of titanium-alloyed weld metal (weld «Ti») without inoculants.

Structural analysis of the specimens was carried out using optical microscope «Neophot-30» at from ×200 to ×1000 magnifications. Digital image was recorded with the help of digital camera «Olympus». Microhardness of structural constituents was measured on LECO hardness gage M-400 at 100 g and 1 kg loading, respectively, on GOST 2999–59. Peculiarities of microstructure were detected using JEOL scanning electron microscope JSM-840, equipped with image capture system MicroCapture, with its further registration on display monitor, and scanning electron microscope JSM (Holland) equipped with energy dispersive analyzer Link.

Determination of microstructure in the specimens was carried out by method of chemical etching in 4 % alcoholic solution of nitric acid. The specimens for investigations were manufactured on standard procedures using diamond pastes of different dispersion. Size of structural constituents was determined in accordance with GOST 5639.

Direct transmission investigations of the fine structure were carried out on JEOL unit JEM-200 CX at accelerating voltage 200 kV for investigation of fine (dislocation) structure of welded joint metal, substructure as well as nature of intergrain and subgrain boundaries. The foils for electron microscopy investigations were prepared by means of electroerosion cutting with further mechanical thinning on sandpaper of different grit, preliminary electrolytic thinning of prepared disks (d = 3 mm) in PTF unit with further final thinning in developed unit for ion thinning by ionized flows of argon.

Nature of structural transformations in the weld metal was studied under conditions of simulation of welding thermal-deformation cycle using Gleeble 3800 complex equipped with fast dilatometer. The investigations were carried out using cylindrical specimens of 6 mm diameter and 80 mm length, produced from weld metal.

Investigation results. The results of dynamometric investigations showed that loading of the inoculants promotes for increase of temperature of austenite decay in weld metal cooling (A_{c3}) as well as start (B_s) and finish (B_f) of bainite transformation (see Table 2), whereas titanium alloying promotes for opposite effect. Such changes in location of structural transformation critical points were observed in size of the primary structure grain (D_γ) as well as in composition of the weld metal secondary structure (Table 3).

Data of optical microscopy showed that the secondary microstructure of weld metal consists of bainite-martensite mixture with insignificant portion of ferrite constituent (Figures 1 and 2)[*]. Bainite is presented by morphological forms of upper, lower and

Table 2. Size of austenite grains in weld metal and critical points of structural transformations in it

Designation of weld	D_γ, μm	A_{c3}, °C	B_s, °C	B_f, °C
«0»	70 ± 5	843	603	430
«Ti»	45 ± 5	840	583	432
«SiC»	80 ± 6	851	644	435
«ZrO_2»	90 ± 7	859	662	461
«TiC»	80 ± 6	870	648	435

Table 3. Composition of weld metal secondary structure

Designation of weld	Portion of constituents in weld microstructure, %			
	Lower bainite	Upper bainite	Martensite	Ferrite
«0»	50	30	10	10
«Ti»	30	57	10	3
«SiC»	30	50	10	10
«ZrO_2»	65	20	10	5
«TiC»	25	60	10	5

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[*] S.N. Stepanyuk and D.Yu. Ermolenko took part in metallographic investigations.

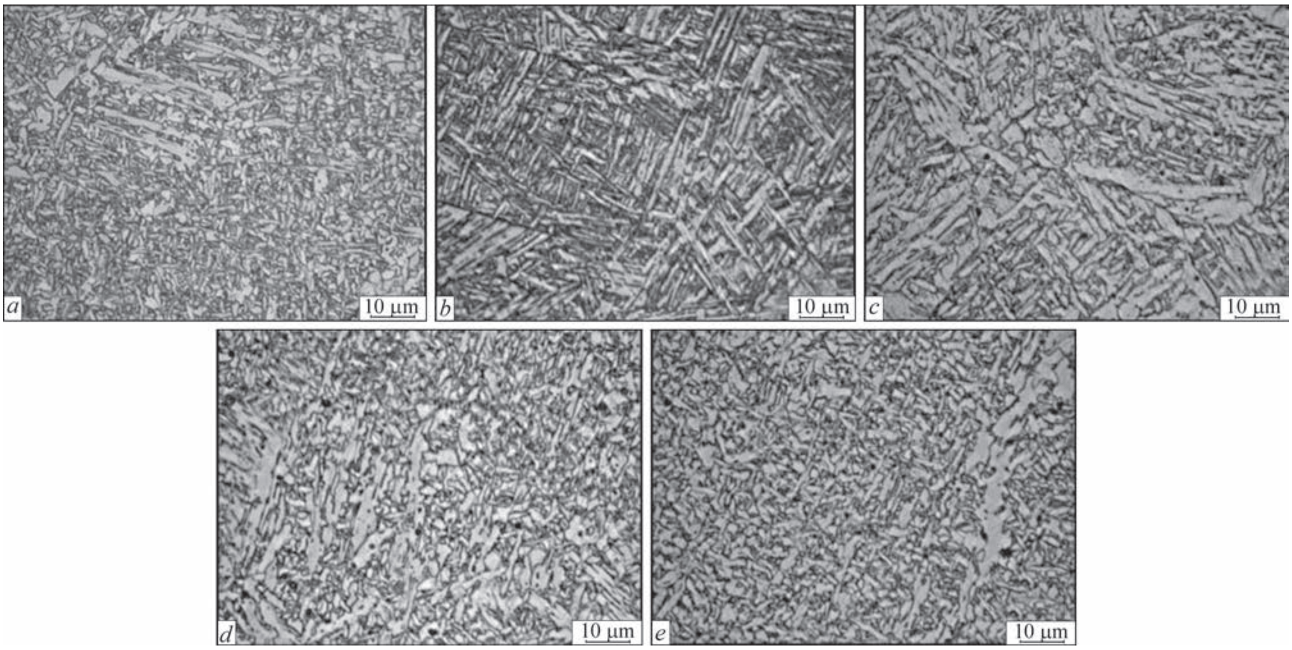

Figure 1. Microstructure of weld metals (Neophot-30) at weld pool loading with disperse refractory inclusions: *a* — «Ti»; *b* — «SiC»; *c* — «ZrO_2»; *d* — «TiC»; *e* — «0»

inter-grain bainite, and ferrite — by broken polygonal precipitates and Widmanstatten ferrite along grain boundaries. Martensite is formed as a traditional acicular structure. As can be seen from given data, titanium alloying of weld metal («Ti» weld) as well as TiC and SiC inoculation promoted rise of the portion of upper bainite in the microstructure and reduction of ferrite constituent content, while weld pool loading with ZrO_2 dispersoids had opposite effect.

The results of determination of mechanical properties of the weld metal, given in Table 4, showed that, regardless the absence of changes in martensite content, mechanical properties of «Ti», «SiC» and «TiC» weld metal, close on content of bainite phase in composition of structural constituents, have some differences on strength indices, ductility and toughness. Besides, significant difference on level of composition of structural constituents and mechanical properties of «ZrO_2» weld metal is noted.

Methods of transmission electron microscopy were used for more detailed analysis of effect of dispersoid inoculation in the weld pool on processes of

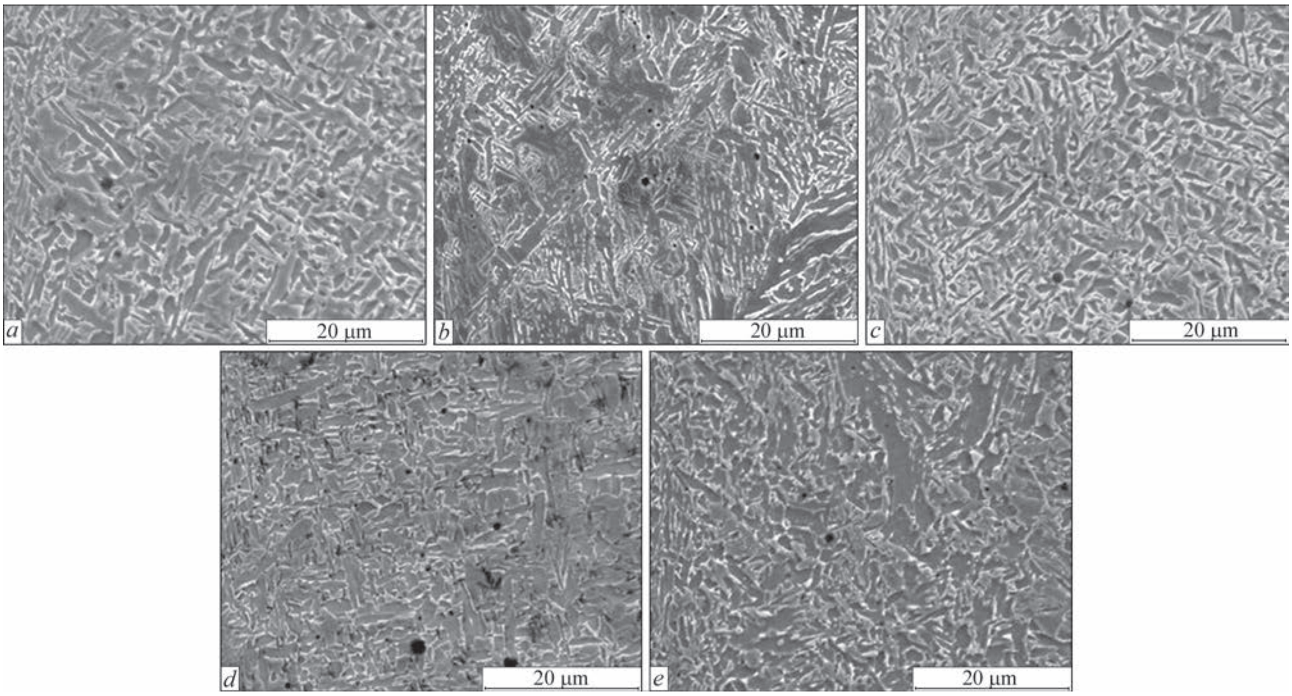

Figure 2. Microstructure of weld metals (JSM-840) at weld pool loading with disperse refractory inclusions: *a* — «Ti»; *b* — «SiC»; *c* — «ZrO_2»; *d* — «TiC»; *e* — «0»

Table 4. Weld metal mechanical properties

Designation of weld	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	S_k, MPa	*KCV*, J/cm^2, at *T*, °C	
						20	–20
«0»	775	738	16	54	1384	61	43
«Ti»	746	689	19	60	1865	60	57
«SiC»	726	650	21	62	1910	85	65
«ZrO_2»	645	556	21	60	1612	116	98
«TiC»	728	665	19	61	1867	82	63

S_k — real fracture resistance.

weld metal structure formation. Figures 3 and 4 show typical patterns of structural constituents of metal of investigated welds, peculiarities of fragmentation, phase precipitates in them and distribution of dislocation density.

Analysis of contribution of the structural-phase parameters in change of strength characteristics of the welds showed that a lath substructure and disperse particles of phase precipitates make the largest contribution in strengthening of all considered specimens of the weld metal. The analysis were made based on developed experimental-analytical approach on evaluation of differential contribution of structure parameters in mechanical characteristics of high-strength steel welded joints [11]. Dramatic increase of strengthening, typical for upper bainite, differing by high grain boundary dislocation density ($\rho \sim (2–3)\cdot 10^{11}$ cm^{-2}) along boundaries of the lath structure and higher saturation of this area with phase precipitates, is caused by rise of dislocation and dispersion strengthening (Figure 5).

As can be seen from given examination results, the weld pool loading with the dispersoid inoculants is accompanied by change of carbide phase morphology, that should promote for structure stabilizing and rise of metal properties [12]. Presence of the refractory dispersoids in a crystallizing weld metal promotes for partial replacement of the cementite precipitates on the grain boundaries with alloying carbides of Me_7C_3, $Me_{23}C_6$ and Me_3C_2 type, that allows reducing inhomogeneity of dislocation density distributions on the grain boundaries. In the cases, when increase of

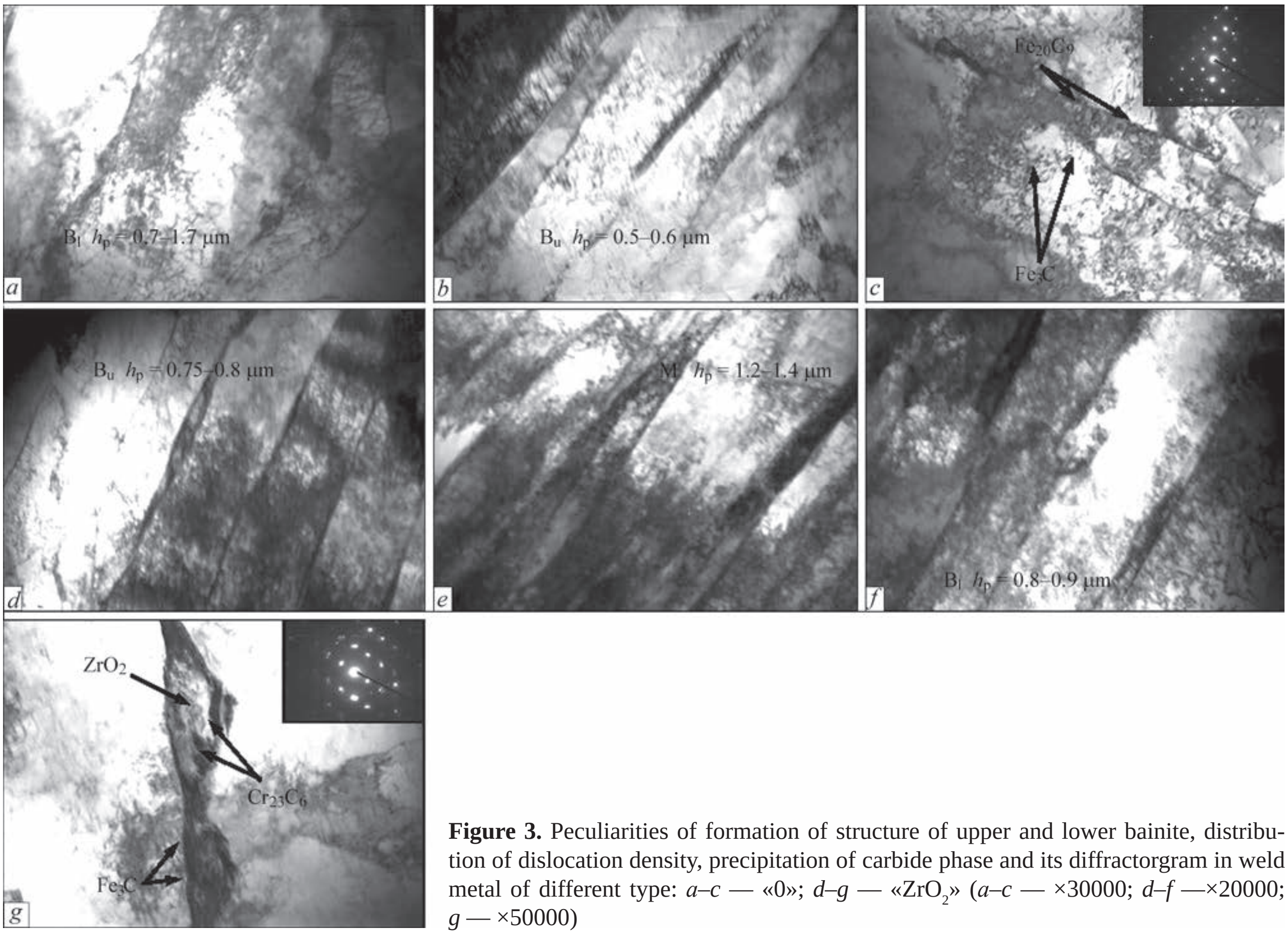

Figure 3. Peculiarities of formation of structure of upper and lower bainite, distribution of dislocation density, precipitation of carbide phase and its diffractorgram in weld metal of different type: *a–c* — «0»; *d–g* — «ZrO_2» (*a–c* — ×30000; *d–f* —×20000; *g* — ×50000)

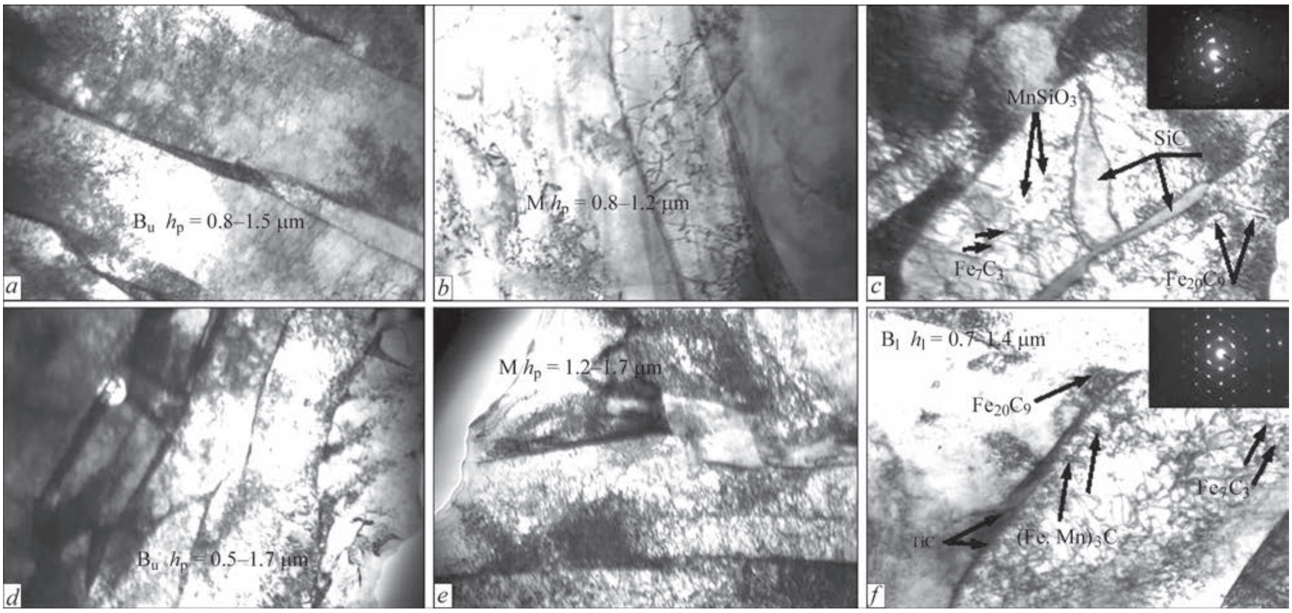

Figure 4. Peculiarities of formation of structure of upper, lower bainite and martensite, distribution of dislocation density, precipitation of carbide phase and its diffractorgram in weld metal of different type: *a–c* — «SiC»; *d–f* — «TiC» (*a*, *b*, *d*, *e* — ×20000; *c* — ×30000; *f* — ×37000)

substructure strengthening is caused by formation of a fine-grain fragmented substructure, the particles of phase precipitates have uniform distribution at uniform distribution of the dislocation density. There are no areas in form of accumulations and chains of the precipitates on the grain boundaries as well as in some volumes of the lath structure (ZrO_2).

Non-uniform distribution of the particles of phase precipitates results in increase of the dislocation density in local microvolumes close to the precipitates and on the grain boundaries, that promotes for increase of strength indices and reduction of level of weld metal ductility (welds «0» and «Ti»). Reduction of temperature of the bainite transformation start promotes for non-uniform re-distribution of the defects of crystalline lattice at their different density. It results in rise of the dislocation density from $\rho \approx (4–6)\cdot10^{10}$ (in lath volume) to $(2–3)\cdot10^{11}$ cm^{-2} in the local microvolumes (close to phase precipitates) and formation of the zones with deformation localizing, that pro-

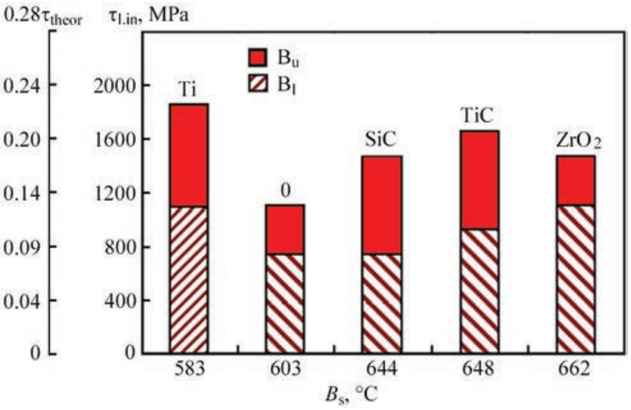

Figure 6. Results of calculation estimation of internal stresses in local structural zones

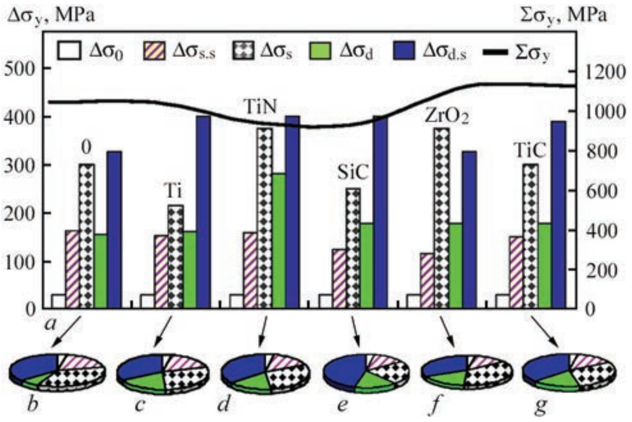

Figure 5. Change of integral values of yield point ($\Sigma\sigma_y$), differential contribution of structural constituents ($\Delta\sigma_y$) in calculation value of yield point (*a*), and percent relationship of structural contribution (grain, subgraine, dislocation, dispersion) in total change of yield point in weld metal at disperse inclusion inoculation (*b–g*)

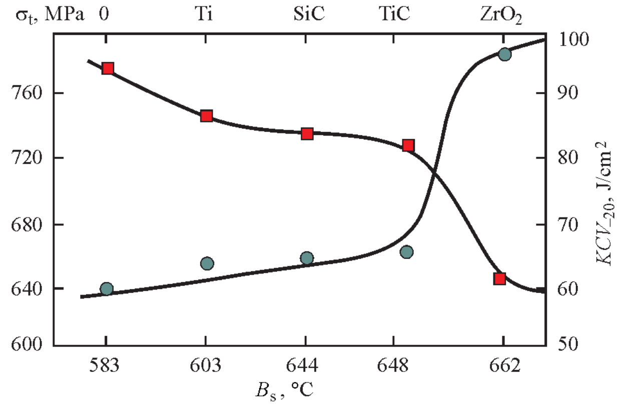

Figure 7. Effect of temperature of start of bainite transformation on mechanical properties of investigated weld metal

motes for non-uniform level of mechanical properties and reduction of metal crack resistance (see Table 4).

The calculation methods of estimation of the internal stresses in local structural zones, based on experimental data of fine structure analysis [13, 14], allowed determining that the maximum local internal stresses are concentrated along the boundaries of upper bainite (welds «Ti», «SiC» and «TiC») and are the potential sources of nucleation and propagation of cracks, i.e. processes of crack formation (magnitudes of these values is approximately 2–3 times higher than in lower bainite structures (Figure 6)).

Increased level of the local stresses typical for upper bainite structure allows providing specific level of indices of the weld metal strength, while presence of lower bainite structure in the composition allows rising their toughness indices. Required complex of mechanical properties of the weld metal in HSLA steel welding is achieved in each case by setting a specific balance between these two morphological forms of ferrite. The results, given in Figures 6 and 7, show that the weld pool loading with the dispersoid inoculants allows rising weld metal ductility with simultaneous retain of strength level.

Conclusions

1. Weld pool loading with the dispersoid inoculants is accompanied by change of temperature of start of bainite transformation in weld metal, that makes effect on optimum transformation of structural-phase constituents, nature of dislocation distribution, change of composition and distribution of phase precipitates, i.e. carbide phases.

2. Increase of B_s rises the portion of phase precipitates of alloyed carbide type in bainite grain body as well as along their boundaries, that is accompanied by formation in intergrain boundary zone of nanosized particles of compounds, inoculated in the weld pool.

3. It is shown that rapid and gradient rise of strengthening in upper bainite structure is caused by significant increase of the dislocation density in near-boundary zones of the lath structures, which are the most saturated by phase precipitates, that promotes for rise of portion of dislocation and dispersion strengthening in grain boundary areas.

4. Use of the dispersoid inoculants in welding of HSLA steels promotes for optimization of structure-phase composition of weld metal and its service properties.

1. Flik, A. (2014) Strategic assessment of prospects in metallurgy. *Chyorn. Metally*, **6**, 81–84.
2. Ritterbach, B. (2014) Main tendencies of research development in ferrous metallurgy. *Ibid.*, **9**, 75–78.
3. Gorynin, I.V. (2008) Sparcely-alloyed steels with nanomodified structure for service under extreme conditions. *Voprosy Materialovedeniya*, **2**, 7–12.
4. Amondarain, Z., Aribas, M., Arana, J.L. et al. (2013) Mechanical properties and phases derived from TiO_2 nanopowder inoculation in low carbon steel matrix. *Materials Transact*., 54(**10**), 1867–1876.
5. Zhang, L., Thomas, B. (2006) State of the art in the control of inclusions during steel ingot casting. *Metallurg. and Mater. Transact. B*, 37(**10**), 733–761.
6. Grong, O., Kolbeinsen, L., Eijk, C. et al. (2006) Microstructure control of steels through dispersoid metallurgy using novel grain refining alloys. *ISIJ Int*., 46(**6**), 824–831.
7. Oryshchenko, A.S., Khlusova, E.I., Golosienko, S.A. (2014) Principles of alloying and requirements to technological processes of production of high-strength hull steels of new generation. *Voprosy Materialovedeniya*, 78(**2**), 9–25.
8. Cherepanov, A.N., Afonin, Yu.V., Orishich, A.M. et al. (2010) Effect of nanodispersed powders on joint properties in CO_2-laser welding of carbon steel. In: *Abstr. of 6th All-Union Conf. on Mechanics of Inhomogeneous Materials and Fracture*, 109.
9. Gregg, J.M., Bhadeshia, H.K.D.H. (1997) Solid-state nucleation of acicular ferrite on minerals added to molten steel. *Acta Materialia*, Vol. 45, Issue 2, 739–748.
10. Golovko, V.V., Stepanyuk, S.N., Ermolenko, D.Yu. (2015) Effect of titanium-containing inoculants on structure and properties of weld metal of high-strength low-alloy steels. *The Paton Welding J*., **2**, 14–18.
11. Markashova, L.I., Alekseenko, T.A., Berdnikova, E.N. et al. (2011) Role of structure in optimization of strength, plasticity and crack resistance properties of welded joints. In: *Stroitelstvo, Materialovedenie, Mashinostroenie*, Issue 58, 446–452.
12. Gorynin, V.I., Kondratiev, S.Yu., Olenin, M.I. et al. (2014) Concept of carbide designing of higher cold resistance steels. *Metallovedenie i Termich. Obrab. Metallov*, 712(**10**), 32–38.
13. Markashova, L.I., Poklyatsky, A.G., Kushnaryova, O.S. et al. (2014) Structure and service properties of welded joints of complexly-doped alloys. In: *Abstr. of 7th Int. Conf. on Mathematical Modelling and Information Technologies in Welding and Related Processes* (Odessa, Ukraine, 15–19 Sept. 2014), 19–20.
14. Markashova, L.I., Shelyagin, V.D., Kushnaryova, O.S. et al. (2015) Effect of technological parameters of laser and laser-plasma alloying on properties of 38KhN3MFA steel layers. *The Paton Welding J*., **5/6**, 124–129.

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