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DISPERSION MODIFICATION OF DENDRITE STRUCTURE OF WELD METAL

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The paper deals with the effect of dispersed particles of refractory compounds (Al_2O_3, MgO, ZrO_2) added as cold filler to 1.6 mm flux-cored wire, on modification of the dendrite structure in low-alloy weld metal of C–Mn–Cr–Ni–Mo–Si–Cu system of K65 strength class. Obtained results allow expanding a data base on the mechanism of the effect of refractory oxides on dendrite structure modification. 5 Ref., 6 Tables, 14 Figures.

Keywords: *arc welding, low-alloy steel, weld metal, modification by refractory oxides, dendrite structure, mechanical properties*

Formation of weld metal structure starts from the processes of nucleation and growth of dendrite phase in a metallic melt of weld pool. Dendrites nucleation centers are the boundaries of fused grains of the base metal on fusion line and refractory inclusions present in the melt. Reduction of size of inclusions leads to rise of relationship between amount of particles on their surface and in volume, respectively, increase of energy of particle interaction with melt that promote enhancement of their efficiency as modifiers. Application of dispersed inclusions [1] is perspective from this point of view. Works [2, 3] showed that addition into a steel melt of 3–30 μm size refractory particles results in formation on their surface of cluster shells of up to 30–60 μm thickness. It is proved by decrease of melt toughness index. Such clusters can be effective centers of new phase nucleation in the melt and promote change of dendrite morphology [4]. Aim of the present work lied in investigation of possibility of effect of dispersed nonmetallic inclusions on modification of dendrite structure of weld metal of low-alloy high-strength steels.

Procedure of work. Investigations were carried out on weld metal obtained in welding with flux-cored wire of 1.6 mm diameter in shielding gas M21 medium on ISO 14175–2010 of butt joints of low-alloy steel. Welding was carried out using 240–250 A reverse polarity direct current at arc voltage 31–32 V and welding rate 10–12 m/h. Scheme of welded joint assembled in accordance with the requirements of ISO 14171 is given in Figure 1. Figure 2 shows a scheme of groove filling, according to which passes 1–9 were carried out in welding using a wire of basic alloying system, and in performance of passes 10–18 a flux-cored wire of 1.6 mm diameter having a core with particles of dispersed refractory compounds was introduced in a weld pool in form of cold filler. The particles of aluminum, magnesium and zirconium ox-

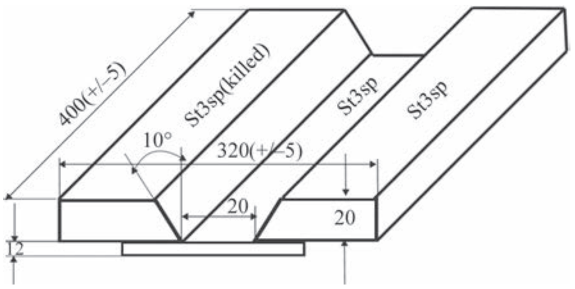

Figure 1. Scheme of preparation of welded joint

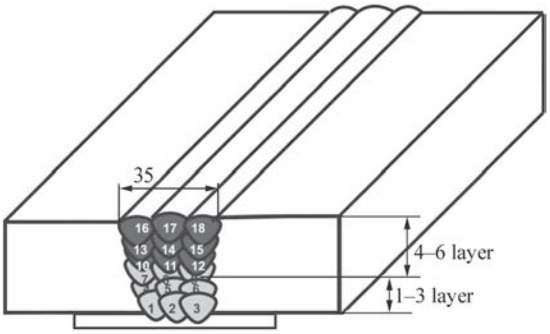

Figure 2. Scheme of arrangement of beads in filling of butt joint groove

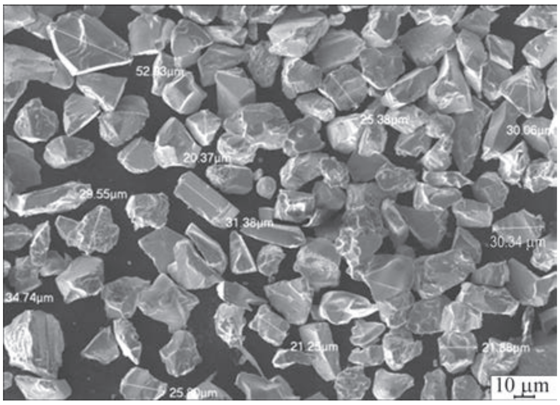

Figure 3. Particles of refractory oxides added in weld pool

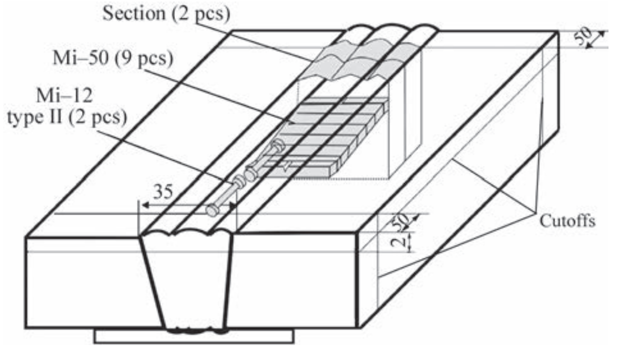

Figure 4. Scheme of samples cut out for determination of composition, mechanical properties and weld metal microstructure

ides of 20–60 μm size (Figure 3) were used as modifying additives (Figure 3).

The basic alloying system C–Mn–Cr–Ni–Mo–Si–Cu provided formation of weld metal with ferrite-bainite structure, which on their mechanical properties correspond to low-alloy steels of K65 strength category.

The transverse samples for investigation of structure and phase composition of weld metal as well as mechanical properties of welded joints on scheme presented in Figure 4 were cut out of the welded joints.

Metallographic examinations were used for determination of weld metal composition, fraction of separate constituents of its microstructure, volume fraction and distribution nonmetallic inclusions on sizes. Microstructure was examined by methods of optical and electron metallography using optical microscope Neophot-32 and scanning electron microscope JSM-840 of JEOL Company equipped with frame grabber MicroCapture with next registration of images on computer screen.

Quantitative determination of microstructural constituents was carried out in accordance with ASTM E112-12 procedure. Microhardness of separate structural constituents was measured on M-400 hardness gage of LECO Company at 100 g loading and integral hardness was determined on Vickers at 1 kg loading. A digital image was obtained using Olympus camera.

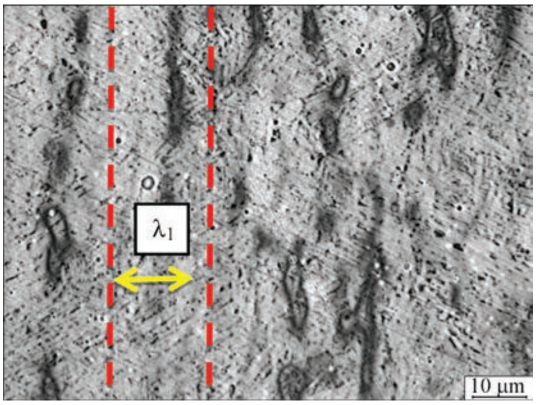

Figure 5. Scheme of determination of distance between the dendrite axes

A weld metal primary structure was examined on polished samples etched in boiling saturated solution of sodium picrate in water. A microstructure of the last pass of metal in multipass weld (i.e. cast structure) was examined. The samples were cut out in a direction normal to weld longitudinal axis in such a way that on the surface of the section it was possible to see the dendrites, which grew in direction of the highest thermal gradient in a weld pool. Sizes of columnar dendrites (λ_1 sizes in Figure 5) were determined in examination of the primary structure on images obtained by method of optical microscopy.

Obtained results. Tables 1 and 2 show the results of determination of composition and mechanical properties of metal of examined welds.

The results of metallographic analysis revealed that microstructure of examined welds consists of austenite decay products in process of metal cooling and contains some amount of nonmetallic inclusions. Figure 6 provides the histograms, which were obtained as a result of analysis of distribution of inclusions on sizes in metal of the examined welds. Total fraction of nonmetallic inclusions ($V_{\text{n.in}}$) is shown in Figure 3.

Metallographic analysis of microstructure of weld metal using optical and electron metallography meth-

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

Modifier	C	Si	Mn	S	P	Cr	Ni	Mo	Al	Ti	Zr
0	0.042	0.340	1.19	0.021	0.020	0.11	2.13	0.28	0.028	0.029	–
Al_2O_3	0.034	0.424	1.40	0.017	0.023	0.12	2.15	0.29	0.032	0.015	–
MgO	0.031	0.227	1.11	0.025	0.024	0.14	1.85	0.29	0.023	0.030	–
ZrO_2	0.033	0.223	1.05	0.024	0.024	0.12	2.02	0.30	0.024	0.031	0.06

Table 2. Mechanical properties of examined welds

Modifier	σ_t	$\sigma_{0.2}$	δ	ψ	*KCV*, J/cm² at *T*, °C				
	MPa		%		+ 20	0	–20	–40	–60
0	693	605	14	49	97	87	75	53	37
Al_2O_3	728	621	17	54	82	58	50	36	22
MgO	644	586	19	60	103	85	69	60	34
ZrO_2	622	533	19	65	120	107	73	65	41

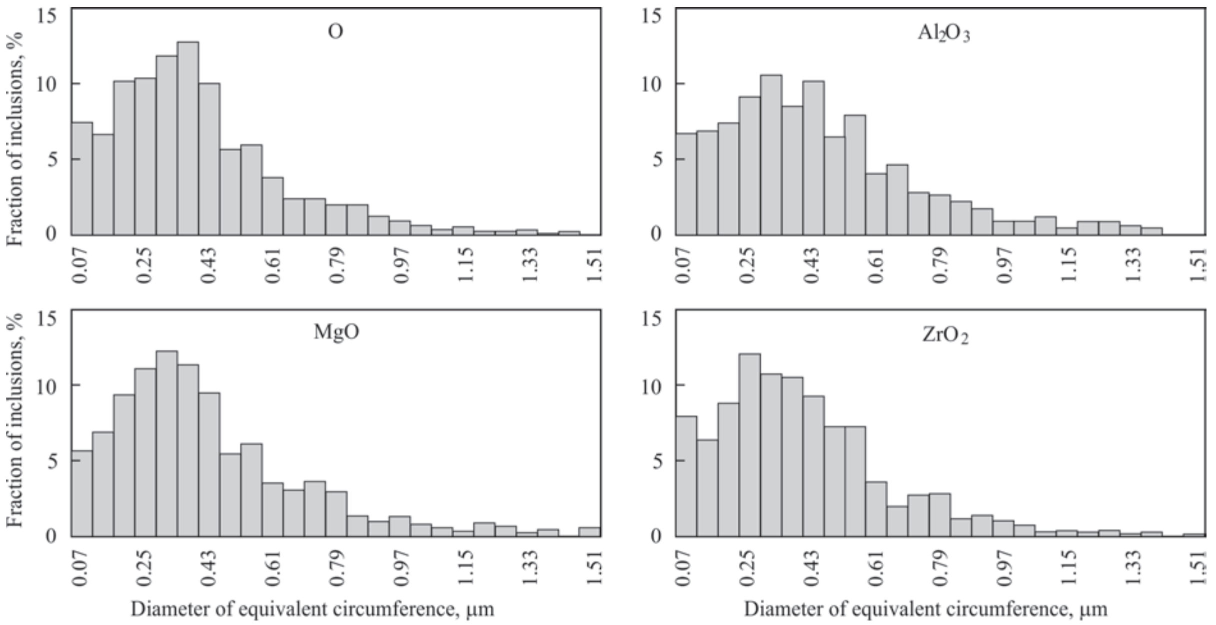

Figure 6. Histograms of distribution on sizes of nonmetallic inclusions in metal of examined welds

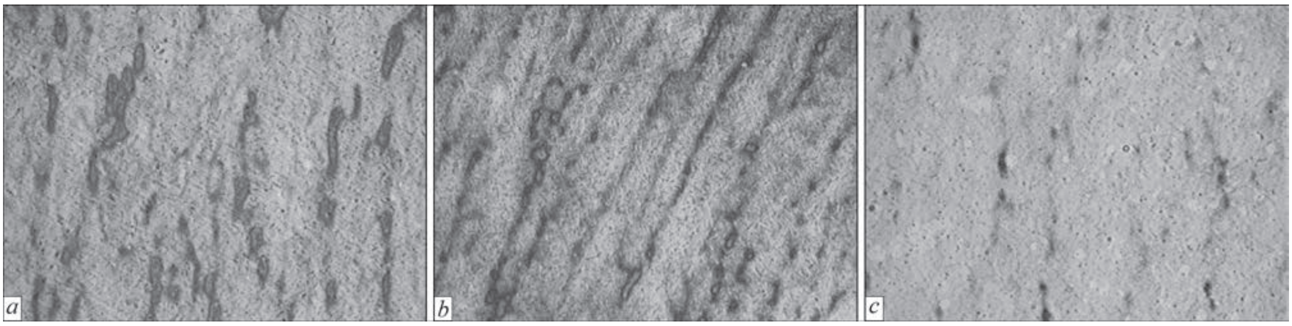

Figure 7. Dendrite structure of weld metal (x630): *a* — without modifier; *b* — Al_2O_3 modifier; *c* — ZrO_2 modifier

ods showed that each grain of the primary structure contained two or more structural constituents of secondary structure.

The most widespread secondary structures, which were observed in weld metal was grain-boundary allotrimorphic ferrite (GBA), intragranular polygonal ferrite (IPF), globular ferrite (GF), Widmanstatten ferrite (WF), acicular ferrite (AF), upper and lower bainite (UB and LB), phase containing martensite, austenite and carbides (MAC). Content of the main constituents in the weld metal microstructure is given in Table 4.

Table 5 shows the results of measurement of distance between the dendrite axes in the structure of metal of investigated welds. They demonstrate presence of significant differences in their morphology depending on modifying additive (Figure 7).

The structure of weld metal, which did not include modifiers in its content (modifier — 0), is characterized with high content of nonmetallic inclusions of not more than 0.3 μm (Figure 8). The grain boundaries are well-pronounced and have elongated morphology. Ferrite precipitates along the brain boundaries mostly in the form of Widmanstatten ferrite. Precipitations mainly from intragranular ferrite and lower bainite with mod-

Table 3. Volume fraction of nonmetallic inclusions in weld metal

Modifier	0	Al_2O_3	MgO	ZrO_2
$V_{n.in}$, %	0.42	0.74	0.62	0.55

Table 4. Content of main structural constituents in weld metal

Modifier	AF	GBA	IPF	GF	WF	UB	LB	MAC
0	8	5	8	2	15	40	17	5
Al_2O_3	2	2	8	4	30	36	11	7
MgO	32	10	5	10	7	12	19	5
ZrO_2	30	15	2	6	7	10	25	5

Table 5. Results of measurement of distance between dendrite axes

Modifier	Results of measurement of distance between dendrite axes, μm	Average value
0	50; 50; 60; 25; 40; 50; 45; 50; 40; 55	46
Al_2O_3	50; 30; 30; 40; 45; 30; 50; 40; 30; 30	57
MgO	140; 150; 120; 140; 90; 120; 100; 130; 80; 150; 300	152
ZrO_2	240; 200; 150; 140; 120; 120; 200; 80; 240; 90	158

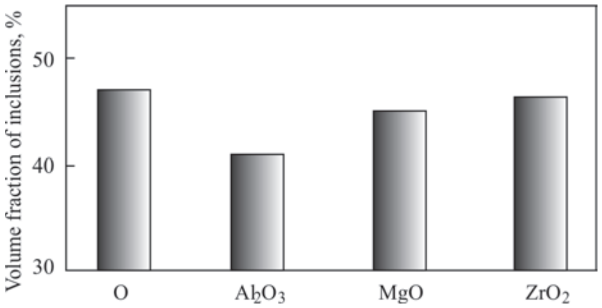

Figure 8. Content in weld metal of nonmetallic inclusions of < 0.3 μm

erate level of microhardness (Figure 9) are observed in the grain body. Such structural composition provides high indices of weld metal strength (at the level of steels of K70 strength category) and sufficiently high level of ductility and impact toughness (Table 2).

Sufficiently high fraction of nonmetallic inclusions of up to 0.3 μm size (Figure 8) is kept in addition of the particles of magnesium oxide into the weld pool. A weld metal microstructure is characterized with high content of intragranular polygonal ferrite with small inclusions of acicular ferrite. Ferrite on the grain boundaries precipitates in form of small fringes of allotriomorphic ferrite with reduced level of microhardness and Widmanstatten ferrite (Figure 10). Such composition of structural elements results in significant increase of weld metal ductility in comparison with basic alloying system and insignificant drop of impact toughness.

Modification of the weld metal with aluminum oxide leads to decrease of content of nonmetallic inclusions of size less than 0.3 μm (Figure 8) in comparison with the weld metal, which did not contain modifiers. The weld metal microstructure is characterized with high content of intragranular polygonal ferrite and lower bainite with frequent inclusions of upper bainite. Also there is an increased content of Widmanstatten ferrite with high level of microhardness on grain boundaries (Figure 11). Such structural composition is characterized with increased level of strength of the weld metal (Table 2).

There is an increase of fraction of nonmetallic inclusions of not more than 0.3 μm size (Figure 8) in the weld metal during addition of zirconium oxide particles in the weld pool. The weld metal microstructure is characterized with high content of intragranular polygonal ferrite in combination with presence of upper

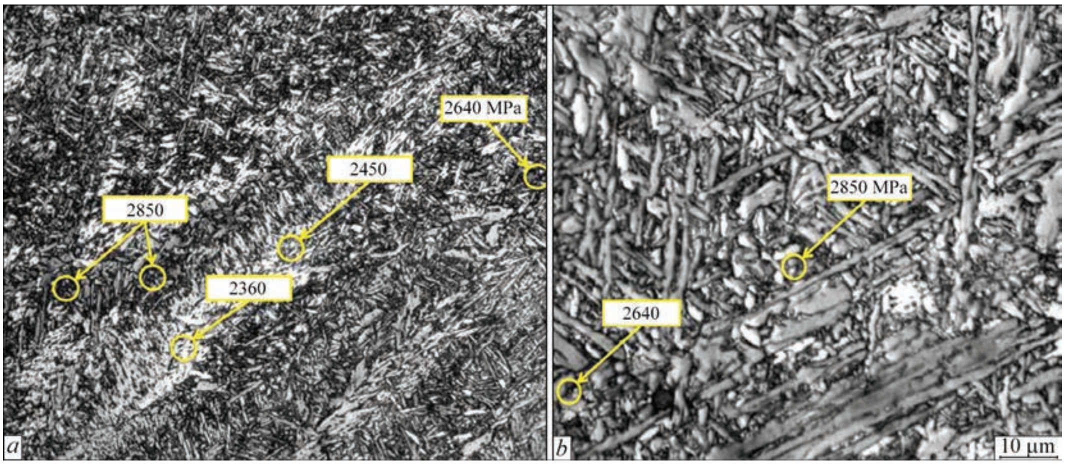

Figure 9. Microstructure and microhardness (*HV*1) typical for structural constituents of weld metal, without modifiers: *a* — ×320; *b* — ×1000

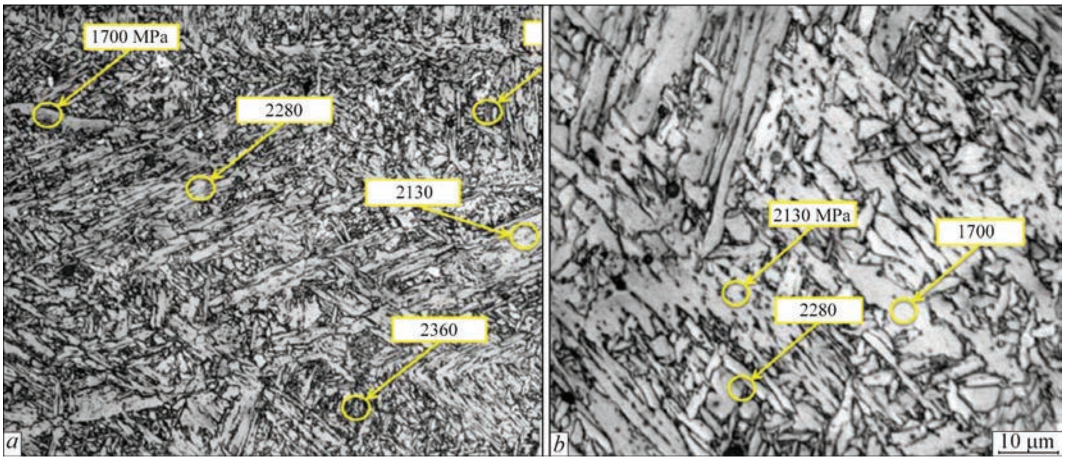

Figure 10. Microstructure and microhardness (*HV*1) of typical structural constituents of weld metal modified by MgO particles: *a* — ×320; *b* — ×1000

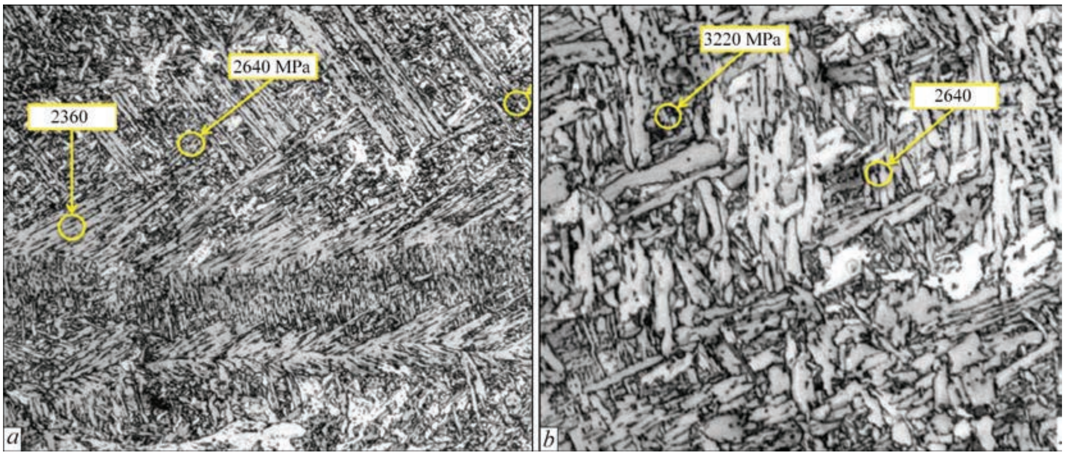

Figure 11. Microstructure and microhardness (*HV*1) of typical structural constituents of weld metal modified by Al_2O_3 particles: *a* — ×320; *b* — ×1000

and lower bainite. Massive precipitations of ferrite with moderate level of microhardness (Figure 12) are observed on the grain boundaries. Such structural composition provides combination in the weld metal of high indices of ductility and impact toughness (Table 2).

Analysis of obtained data. Analysis of the results of examinations was based on general ideas on mechanism of nucleation and growth of dendrites in the metallic melts. Today, there is considerably large amount of models describing these processes that indicates absence of some single approach, which would allow considering all complex of difficult and interrelated phenomena in the process of melts solidification. It is generally accepted that there should be specific solidification centers in the melt in order to start this process. The debates are holding on the issue what should be considered as such centers. Two approaches to solution of this problem are widely presented in scientific literature. In accordance with one of them such centers can be refractory nonmetallic inclusions, from other point of view, cluster formations can initiate solidification. Following from the considerations of thermodynamics the process of crystals nucleation in the metallic melt is possible under two main conditions: firstly, solidification centers should be of size more than critical size of nucleus, secondly, interphase energy on nucleus boundary with melt should be minimum.

Melt of the pool in arc methods of welding of steels contains large amount of refractory inclusions, size of which significantly exceeds a nucleus critical radius in solidification of iron melts (approximately $4\cdot10^{-7}$ m). Such inclusions are characterized with sufficiently high interphase energy on the boundary with metallic metal and, as a rule, do not satisfy the principle of structure-size correspondence in relation to iron crystals. Much more effective nucleuses of formation of new phase can be the fused boundaries of base metal grains, however, following the requirements of the minimum interphase surface energy, 2D nucleuses thermodynamically lose 3D ones. Globular nucleuses with minimum interphase energy can be the clusters of metal, presence of which in the melt was shown on practice [4]. Small size of such clusters (approximately $2\cdot10^{-9}$ m) causes their high surface activity. Sorption by clusters of structurally free atoms of melt promotes formation of micelles that was proved by

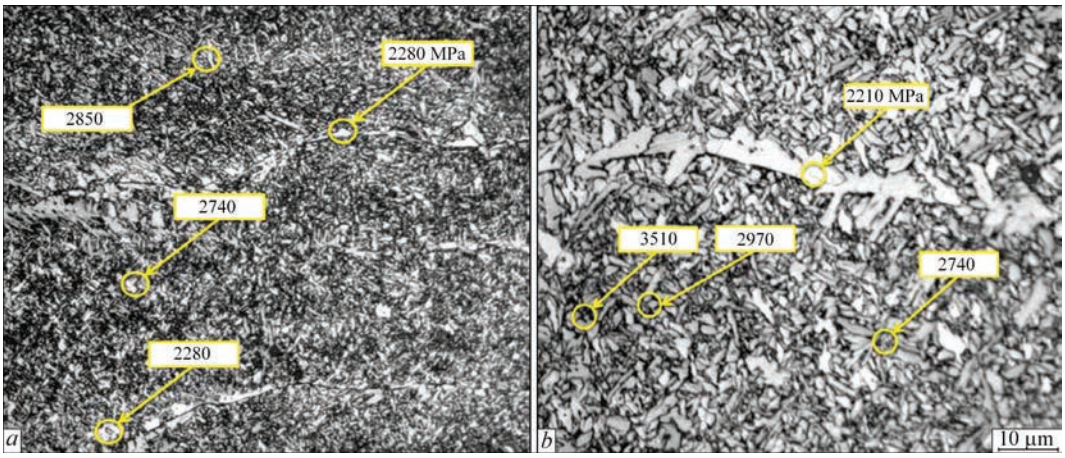

Figure 12. Microstructure and microhardness (*HV*1) of typical structural constituents of weld metal modified by ZrO_2 particles: *a* — ×320; *b* — ×1000

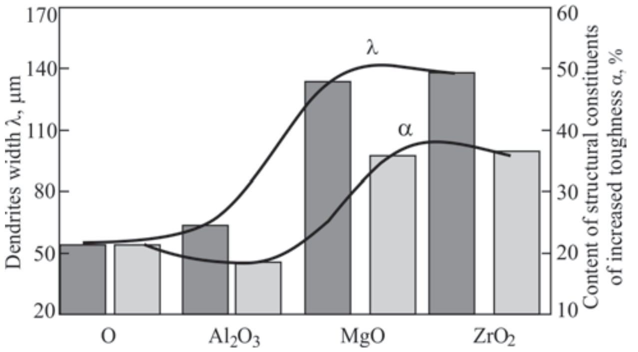

Figure 13. Interaction between sizes of dendrites and content of increased toughness constituents in composition of weld metal secondary structure

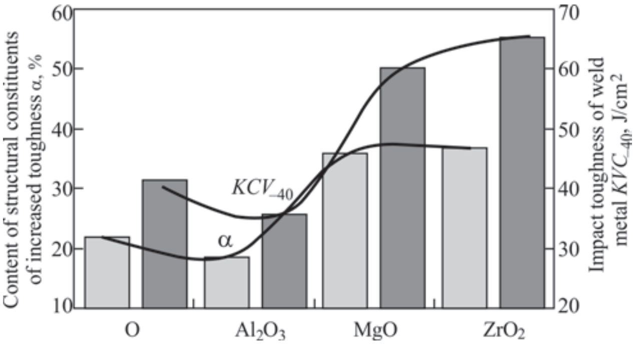

Figure 14. Interaction between content of increased toughness constituents in composition of weld metal secondary structure and weld metal impact toughness

experiments on investigation of effect of refractory oxides on toughness of liquid metals [3].

Table 6 shows the results of determination of dendrite size in comparison with data on thickness of adsorption cluster shells forming on the surface of inclusions at 1600 °C temperature obtained in work [5].

As can be seen from given data there is a specific dependence between the morphology of dendrites and physicochemical peculiarities of structure of interphase boundary in the system «metallic melt–oxide inclusion». It is noted that a modifying effect on the dendrite structure is observed in the weld metal, to content of which the inclusions with lower interphase tension and wetting angle were added. Increase of dendrite width promotes corresponding changes under conditions of formation of secondary structure that is presented by increase of fraction of low-temperature constituents of bainite transformation in weld metal structure (Figure 13) and change of indices of their strength and toughness (Table 2).

Rise of content of secondary structure constituents with increased resistance to nucleation and propagation of cracks, to which AF, GF, IPF and LB are referred, promotes formation of the weld metal with high indices of toughness. The results of our experiments, presented in Figure 13, correspond to this tendency. Following from the comparison of data on dendrite structure size and content in the weld metal of secondary structure constituents of increased toughness, shown in Figure 14, it can be seen that increase of dendrite width (λ) is accompanied by growth of content of secondary structure constituents of increased toughness (α).

Table 6. Comparison of the results of measurement of dendrite width with indices of interaction of inclusions with metallic melt

Modifier	Thickness of cluster shells, μm	Interphase tension on metal–inclusion boundary, mJ/m²	Wetting angle on metal–inclusion boundary, deg	Dendrite width, μm
0	29	–	–	46
Al_2O_3	43	630	130	57
MgO	51	502	108	152
ZrO_2	59	470	106	158

It is necessary to outline that the results obtained in this work broaden the ideas on possible mechanisms of effect of refractory oxides on dendrite modification. On the one hand, in accordance with reference data, presence in steel melt of magnesium and zirconium oxides provokes formation of coarser micelles in comparison with aluminum oxide inclusions. On the other hand, absence of the modifying effect at addition into the weld pool of aluminum oxides can be related with decrease in the weld pool of fraction of inclusions of not more than 0.3 μm, which can be considered as micelle formation centers. In order to answer this question it is necessary to develop the works in this direction, but, nevertheless, obtained results showed the possibility of application of dispersed particles of refractory compounds for modification of dendrite structure of weld metal, regulation of content of constituents of their secondary structure and indices of mechanical properties.

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