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COMPUTATION AND EXPERIMENTAL EVALUATION OF FORMATION OF PRIMARY STRUCTURE IN WELD METAL WITH REFRACTORY INOCULANTS

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Possibility of regulation of structure and properties of weld metal of high-strength low-alloy steels was considered. It can be done with the help of introduction in a weld pool of the disperse refractory inoculants as surface-active elements. A procedure was described for performance of the experiments on introduction of the different refractory inoculants (TiC, TiN, SiC, TiO_2, Al_2O_3, Zr_2O, MgO) in the weld pool in high-strength low-alloy steel welding. The results of investigation of effect of the introduced inoculants on primary structure parameters and main mechanical properties of investigated weld metal are given. A model of interaction of refractory inoculants with solidification front was briefly discussed. Parameters of primary weld metal structure with the refractory inoculants, which were received by means of experimental investigations and computation experiment, were compared. The results of this comparison showed adequacy of a proposed model of interaction of refractory inoculant with solidification front. 9 Ref., 2 Tables, 7 Figures.

Keywords: *arc welding, high-strength low-alloy steels, dendrite structure, primary structure, disperse refractory inoculants, solidification*

Introduction in a weld pool of the refractory inoculants as surface-active particles is a perspective method for optimizing the structure and properties of weld metal of high-strength low-alloy (HSLA) steels due to regulation of structure parameters and, respectively, weld metal mechanical properties. It is known fact [1, 2] that grain size of primary structure effects nature of $\gamma \rightarrow \alpha$ transformation processes. If nucleation of α-phase in a disperse dendrite structure starts at the boundaries of austenite grains in the upper area of bainite transformation, then nucleation of ferrite inside primary grains at the interface with non-metallic inclusions at temperatures close to bainite transformation end [3, 4] are typical for coarser dendrites.

Previous works [5, 6] proposed a solidification model, which allows modelling quality changes of weld metal dendrite structure depending on surface properties of the introduced inoculants. This model was verified by experimental investigations on effect of the disperse refractory inoculants, playing a role of surface-active particles, on primary structure and mechanical properties of the weld metal of HSLA steels.

Procedure. The welds with different refractory inoculants were produced to study an effect of the refractory inoculants on a value of interphase energy in solidification process and formation of weld metal final structure in HSLA steels welding. Flux-cored wire of 1.6 mm diameter was used for (Ar + CO_2) shielded gas welding. Assembly and welding of butt joints of 20 mm thick St3sp(killed) steel sheets was carried out in accordance with the requirements of ISO 14171:2010 [7] using 240–250 A reverse polarity direct current at 31–32 V arc voltage. A welding rate was kept in 10–12 m/h limits. Inoculants were introduced in a wire core. 2 series of experiments were performed. TiC, TiN and SiC carbides and nitrides were introduced as refractory inoculants in the first series of the experiments, TiO_2, Al_2O_3, ZrO_2 and MgO oxides were entered in the second series of the experiments. Base alloying system C–Mn–Cr–Ni–Mo–Si–Cu (without introduction of the refractory inoculants), realized in NN-0 (the first series of the experiments, heat input 20–23 J/cm) and NN-20 (the second series of the experiments, heat input 26–28 J/cm) variants, was directed on formation of the weld metal with bainite structure, which on its mechanical properties corresponds to low-alloy steels of K65 strength category (Table 1).

Selection of an inoculant type for investigations was based on their surface activity at interaction with iron-based melt. Inoculants' size was selected taking into account their further solution in the weld pool melt. Table 2 shows characteristics of the materials taken for experiments.

Weld metal primary structure was examined using optical metallography methods (optical microscope «Neophot-30») on polished samples, etched in boiling solution of sodium picrate $C_6H_2(NO_2)_3ONa$ in water. Microstructure of the final pass of multipass weld metal (i.e. cast structure) was examined. The samples were cut out in normal to longitudinal weld axis direction in a way to observe dendrites on a microsec-

Table 1. Results of measurement of parameters of weld metal primary structure and mechanical properties

Inoculant type	Weld number	Average value of size of primary dendrites λ_{1exp}, μm	Angle of inoculant wetting by iron melt θ, deg	Ultimate strength σ_t, MPa	Impact toughness *KCV*, J/cm²	
					+20 °C	–20 °C
–	NN-0	25.23	–	774	92	74
TiC	NN-6	26.89	125	715	112	85
TiN	NN-7	23.10	132	712	55	40
SiC	NN-9	30.20	82	726	85	65
–	NN-20	34.94	–	693	97	75
TiO_2	NN-22	41.63	≈ 0	709	85	60
Al_2O_3	NN-23	31.60	40	728	82	50
Mg0	NN-24	27.22	123	644	103	69
ZrO_2	NN-25	29.41	102	622	120	73

Table 2. Properties of refractory inoculants T_{ml} and their boundary angles of wetting by iron melt θ [8]

Inoculant type	Melting temperature, T_{ml}, °C	Surface tension of liquid phase σ_1, mJ/m²	Boundary wetting angle θ, deg	Adhesion work W_a, mJ/m²
TiC	3260	1780	125	760
TiN	2930	1780	132	590
SiC	2730	1780	82	2030
TiO_2	1843	1780	≈ 0	3560
Al_2O_3	2044	1785	40	3155
ZrO_2	2715	1785	102	1020
MgO	2852	1810	123	825

tion surface. These dendrites grew in a direction of the largests heat gradient in the weld pool (Figure 1). Mechanical properties of the weld metal were determined according to GOST 6996–66 [9].

Sizes of columnar dendrites (λ_1 size in Figure 2) were determined by examination of primary structure on the images received by optical microscopy method. Sizes of secondary dendrites were not defined since they are very weakly expressed under given welding conditions. Figure 1 gives the images of typical dendrite structures of the investigated samples. The results of measurement of primary structure parameters and mechanical properties of the investigated samples are shown in Table 1.

Figures 3 and 4 show the diagrams of dependence of primary structure parameters on wetting angle of the refractory inoculants by iron melt for the first and second series of the experiments, respectively. Received results indicate the possibility of regulation of the primary structure parameters, in particular primary dendrites' size, by means of introduction of the refractory inoculants as surface-active elements in the weld pool. Decrease of a size of columnar dendrites at wetting angle rise is related with a drop of local solidification rate in refractory inoculant to weld pool melt contact zone. However, reduction of the local solidification rate in the contact zone of melt and inoculant also assumes qualitative change in morphology

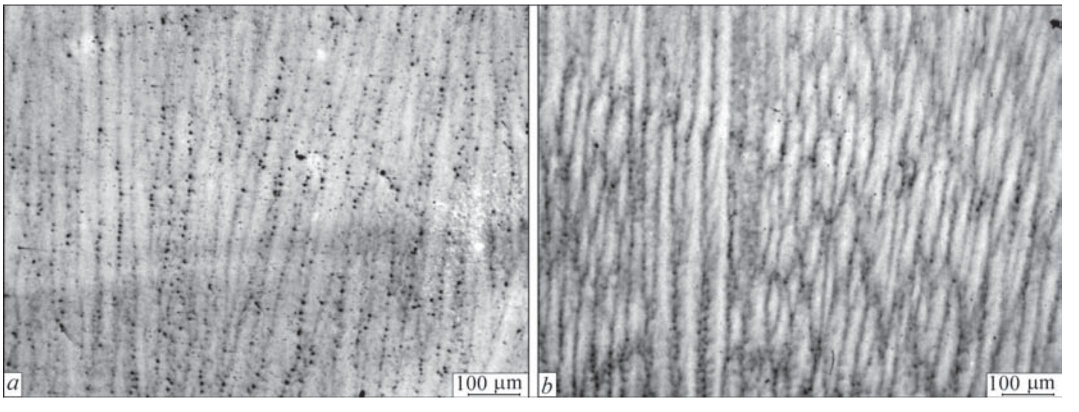

Figure 1. Primary structure (×320) of weld metal of examined samples: *a* — sample NN-23; *b* — sample NN-25

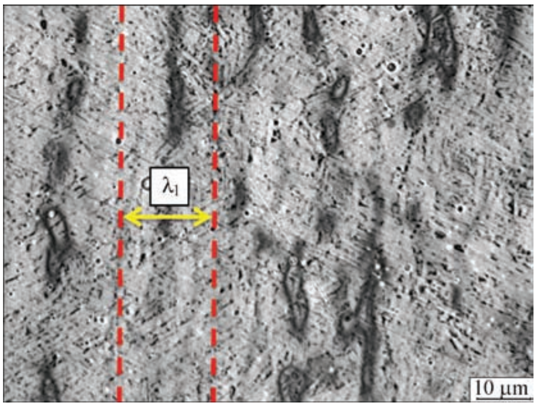

Figure 2. Primary structure (×1000) of examined sample: λ_1 — distance between primary dendrite axes

of the weld metal primary structure. This assumption is experimentally proved in analysis of the images of primary structure of weld metal with the inoculants having different melt wetting angles of the weld pool metal. This difference can be seen in Figure 1. Mainly straight columnar dendrites, passing through the whole visible region of the image (Figure 1, *a*), can be observed at weld metal inoculation with Al_2O_3 aluminum oxide. Short columnar dendrites formed as a result of competing growth (Figure 1, *b*) are observed at weld metal inoculation with ZrO_2 zirconium oxide.

Computation experiments. A model of interaction of refractory inoculants with solidification front relies on a data base, formed from a set of experimental results. This model describes interaction of the refractory inoculants with interface at solidification front, as a result of which change of interphase energy takes place. This leads to variation of the local rate of solidification front movement. The model assumes that the refractory inoculants are uniformly distributed in the weld pool volume with some coefficient $\varphi(0 \leq \varphi \leq 1)$. It is also assumed that the refractory inoculants are stable in process of solidification and have similar size, which is comparable with size of a cell

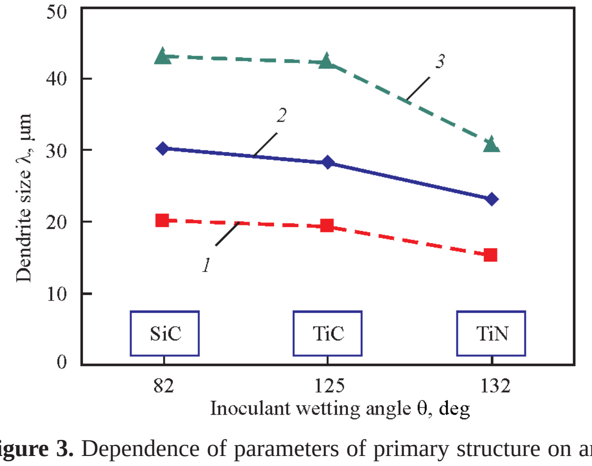

Figure 3. Dependence of parameters of primary structure on angle of wetting of refractory inoculants by iron melt of the first series of experiments: *1* — minimum values; *2* — averaged; *3* — maximum

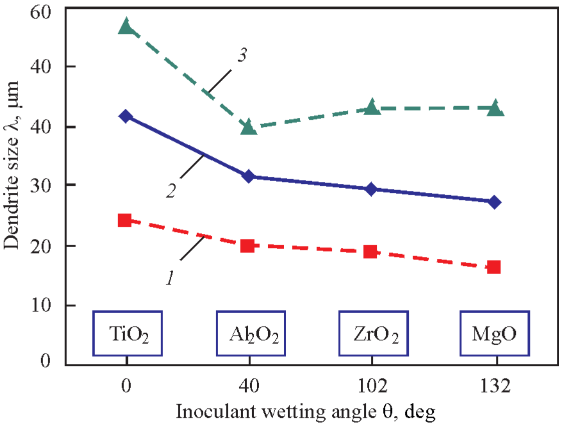

Figure 4. Dependence of parameters of primary structure on angle of wetting of refractory inoculants by iron melt of the second series of experiments: *1* — minimum values; *2* — averaged; *3* — maximum

of used computation mesh (≈ 0.4 μm). A parameter of distribution of the refractory inoculants in the weld pool metal φ was taken equal 0.3 for all computations; such a choice is based on the results of work [5].

Figure 5 shows visual correspondence of dendrite structures of NN-0 and NN-20 samples, obtained in experimental and computation experiment ways. It should be noted that the structures reflecting mor-

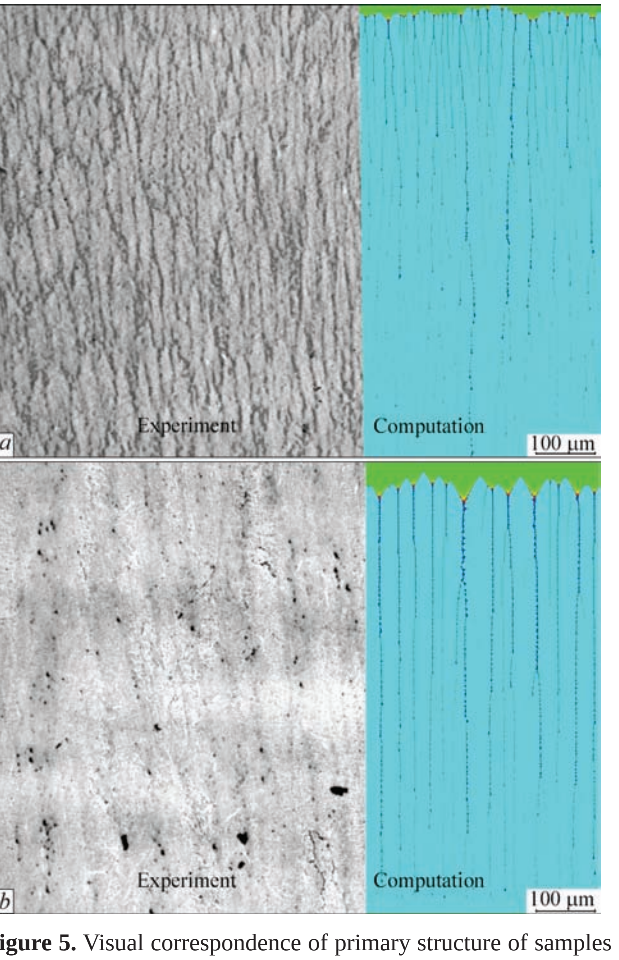

Figure 5. Visual correspondence of primary structure of samples NN-0 (*a*) and NN-20 (*b*) to primary structure, received by means of computation experiment

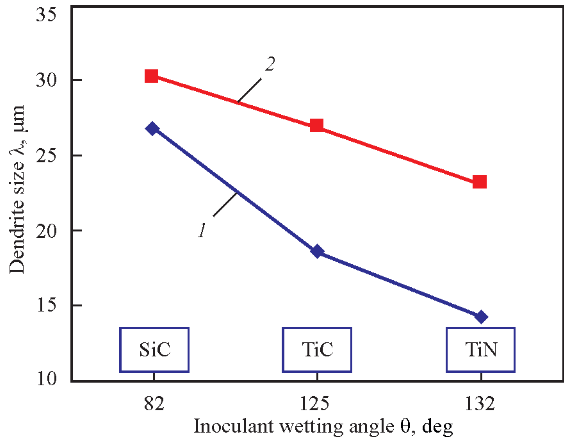

Figure 6. Correlation of experimental and computation results of measurement of parameters of primary structure in weld metal of first series experiment samples: *1* — λ_{1comp}; *2* — λ_{1exp}

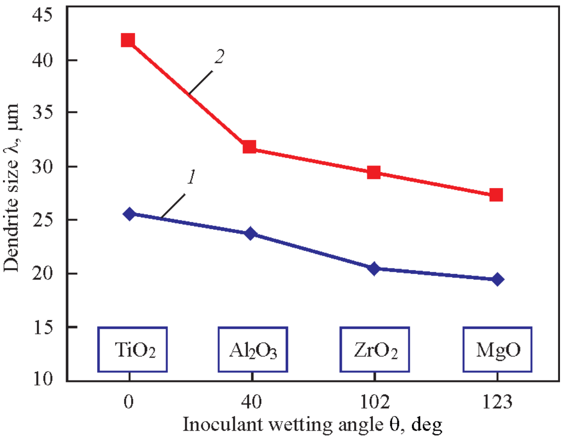

Figure 7. Correlation of experimental and computation results of measurement of parameters of primary structure in weld metal of second series experiment samples: *1* — λ_{1comp}; *2* — λ_{1exp}

phology of dendrite structure of the real samples were received as a result of computation.

Measurements of a distance between the axes of primary dendrites λ_{1comp} of the samples with addition of different refractory inoculants (TiC, TiN, SiC, TiO_2, Al_2O_3, ZrO_2, MgO), received by computation experiment, were carried out similar to a procedure of processing of primary structure images, obtained by optical metallography (Figure 2).

Figures 6 and 7 show a comparison of sizes of primary structure dendrites, received in computation λ_{1comp} and experimental ways λ_{1exp} for the samples of the first and second series, respectively. Analysis of the present dependencies allowed concluding that a tendency to distance reduction between the axes of primary dendrites at rise of the wetting angle of refractory inoculants by weld pool melt is preserved according to obtained experimental data, described above. Thus, it should be assumed that the proposed mathematical model and software developed on its basis allow receiving valid predictions of the parameters of primary structure of HSLA steel weld metal.

An average error of data, received by means of computation experiment, makes around 25 %. Such a difference in received results should be related with a parameter of refractory inoculants distribution in weld pool metal φ, which was taken equal 0.3. This, apparently, does not have complete correspondence to the conditions of carried experimental investigations. Insignificant growth of the error at increase of the angle of inoculant wetting by weld pool melt is related with a change of nature of their distribution in the weld metal due to qualitative change of morphology of dendrite structure at introduction of the inoculants with high wetting angles. These remarks should be taken into account for further development of the model.

Conclusions

Proposed model of effect of the refractory inoculants as surface-active parts on the weld pool metal solidification process is suitable for prediction of size parameters and morphology of primary structure of HSLA steel weld metal. Software developed based on given model allows selecting the refractory inoculants and their amount for optimizing the parameters of weld metal primary structure, and, as a consequence, its mechanical properties in accordance with set requirements.

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