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Peculiarities of the Titanium-Containing Inclusions Influence on the Weld Metal Microstructure Formation

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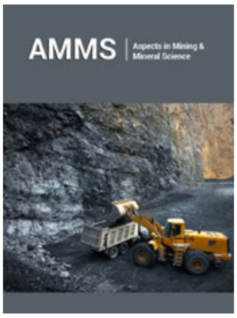

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Abstract

The peculiarities of the nn-metallic inclusions containing titanium influence on the low-alloy steels weld metal microstructure formation were studied. It was shown that ferrotitanium and titanium oxides inoculation into the welding bath promotes the amorphous manganese silicate inclusions formation with a layer of crystalline (Ti,Mn) oxides on the surface. In the case of titanium carbide inoculation, the content of multiphase morphology inclusions in the weld metal increases, which have an external layer with a high carbon content on the surface. It was shown that the mechanism of AF nucleation may be different depending on the nature of the titanium-containing phase located on the inclusions surface. The zone depleted in manganese content formation mechanism is triggered in the case of Ti_2O_3 inclusions dominance, and a low level of interfacial energy is triggered in the case when a layer of (Ti,Mn) oxides is retained on the inclusions surface.

Keywords: Metallurgy; Welding; Metallography; Non-Metallic Inclusions; Microstructure; Inoculants

Introduction

It is known that non-metallic inclusions play a significant role in the weld metal microstructure evolution due to their ability to serve as centers of acicular ferrite nucleation process activation. The certain number of inclusions presence, however, does not yet guarantee the formation of a microstructure with an acicular ferrite high content, because their ability to form a new phase during the $\gamma \rightarrow \alpha$ transformation depends on the chemical composition and morphology of the inclusions. From the chemical composition point of view, the most attention in scientific research has been paid to inclusions containing titanium compounds [1-5]. It has been noted that refractory inclusions inoculated into the metal melt play a certain role in these processes [6,7]. The experiments results [8,9] have shown the weld pool inoculation effectiveness on the low-alloy steels weld metal microstructure formation.

The aim of the work was to obtain a new of scientific knowledge base regarding the peculiarities of the non-metallic inclusions based on titanium compounds influence on the acicular ferrite formation process in the low-alloy steels weld metal. To achieve this goal, studies were conducted to establish the type of inclusions in the weld metal, which include titanium, and to clarify the mechanism of their influence on the new phase nucleation during the $\gamma \rightarrow \alpha$ transformation.

In order to study the non-metallic inclusions containing titanium compounds influence on the weld metal structure formation and mechanical properties, butt welds of low-alloy steel strength category $\sigma_B \geq 690$MPa with a thickness of 20mm were made in accordance with the ISO 14171 requirements at a reverse polarity direct current 240…250A at an arc voltage 31…32V. The input welding energy was 26…28kJ/cm. Arc welding was performed in an environment of protective gas M1 (82%Ar+18%CO_2) using a flux-cored wire with a diameter of 1.6mm, which meets the AWS A5.20 E71T-1 EN 758 T42 2 PC 1H10 requirements. Figure 1 shows a scheme for filling the edges of butt joints, according to which the passes from the first to the ninth were performed with a flux-cored wire, and the passes from the tenth to the eighteenth with additional inoculation into the weld pool of refractory titanium compounds dispersed particles through a flux-cored wire core with a 1.6mm diameter, which was fed to the tail portion of the weld pool. Particles of ferrotitanium (25% Ti), titanium oxide (TiO_2) and titanium carbide (TiC) with a size no more than 200μm were used as inoculants.

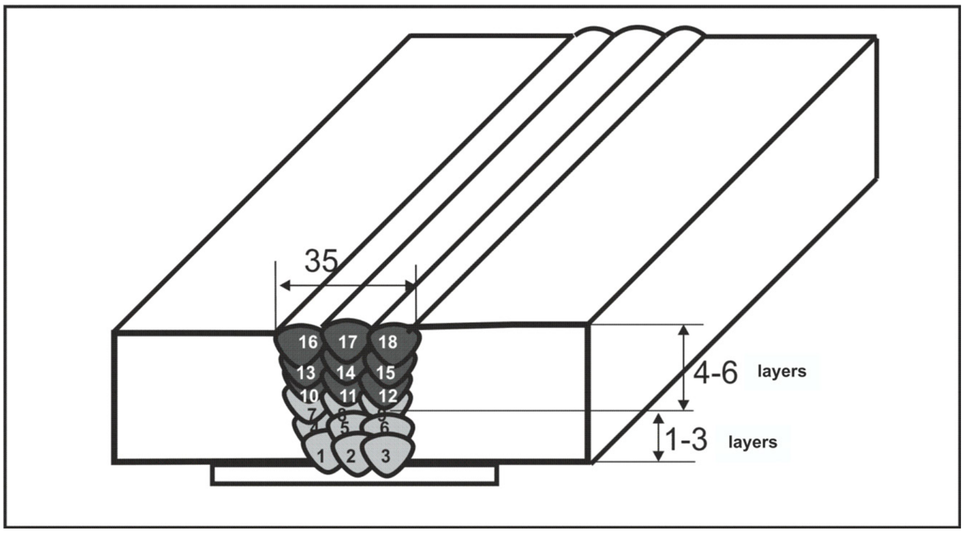

Figure 1: Scheme of applying rollers when filling the butt joint (1..3 layers - without inoculants, 4…6 - layers with inoculants).

Structural analysis of the samples was carried out using a NEOPHOT-30 light microscope at magnifications from x200 to x1000. The digital image was recorded using an Olympus digital camera. To identify the features of the microstructure, a JSM-840 scanning electron microscope (JEOL) was used, equipped with a MicroCapture image capture system with its registration on the monitor screen. The microstructure of the samples was detected by chemical etching in a 4% alcoholic solution of nitric acid. Samples for research were prepared according to standard methods using diamond pastes of different dispersion. The structure and chemical composition of the weld metal structural components were studied on scanning electron microscopes JSM-840 and JSM 35CF, which contained microanalyzers Link 860/500 (Link Analytical) and INCA 450 (Oxford Instruments) with operating parameters: U=20kV, I=10^{-10} ...10^{-7} A. To study the characteristic elements of the structure at a magnification of x20,000, a JAMP 9500F Auger microprobe with an INCA 350 microanalysis system was used.

Results of Analyses

Chemical compositions and mechanical properties are shown in Table 1 & 2, respectively.

Table 1: Chemical composition of the welds metal.

Weld №	C	Si	Mn	S	P	Cr	Ni	Mo	Al	Ti	In*
HH-0	0,050	0,301	1,30	0,025	0,014	0,17	2,50	0,27	0,043	0,003	non
HH-4	0,050	0,290	1,32	0,024	0,014	0,16	2,19	0,27	0,039	0,019	FeTi
HH-5	0,049	0,298	1,39	0,023	0,015	0,15	2,26	0,25	0,039	0,008	TiO_2
HH-6	0,054	0,263	1,28	0,025	0,011	0,13	2,22	0,26	0,035	0,009	TiC

Note: Innoculant type.

Table 2: Mechanical properties of weld metal inoculated with titanium compounds.

Weld №	$\sigma_в$,	KCV, J/cm²	
	MPa	+ 20 °C	– 20 °C
HH-0	695	61	43
HH-4	788	60	57
HH-5	747	74	63
HH-6	716	91	85

Secondary microstructure of weld metal

The results of the weld metals microstructure study, which were obtained using an optical and scanning electron microscope, are shown in Figure 2. It is noted that the change in the titanium content in the weld metal from 0.003 to 0.019% is accompanied by an increase in the proportion of Acicular Ferrite (AF) in the microstructure from 43.5% to 73.7% due to a decrease in the ferrite content with the second phase (Figure 2, Table 3). Such changes in the microstructure correspond to the results of determining the mechanical properties of the weld metal, in particular the level of impact toughness (Table 2).

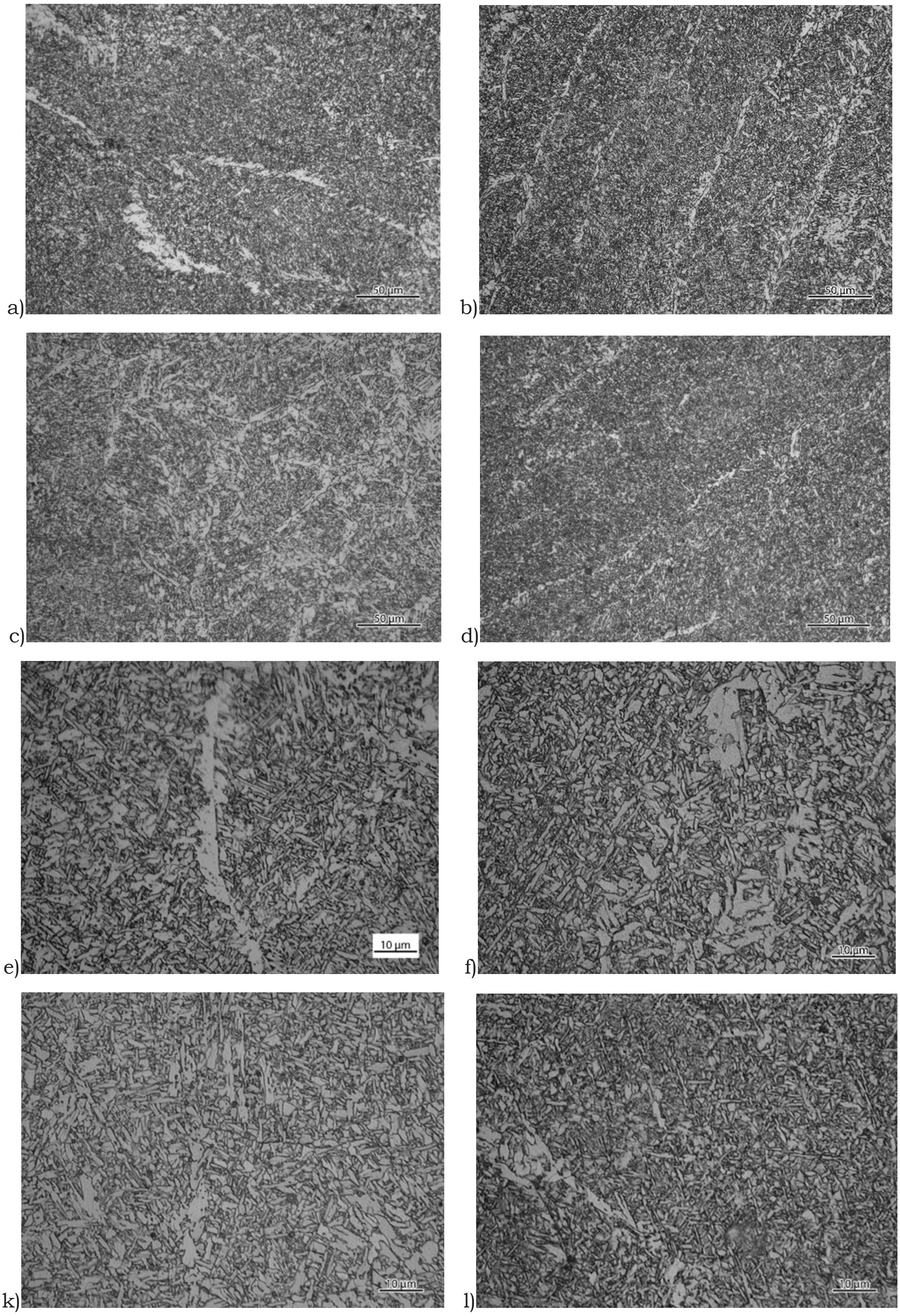

Figure 2: Microstructure of weld metal: a), b), c), d) - x320, f), e), k), l) - x1000 a), f) - without inoculation; b), e) - FeTi inoculant; c), k) - TiO_2 inoculant; d), l) - TiC inoculant.

Table 3: Composition of the microstructure of the weld metal.

Welds №	Microstructure	Phase Content, %
HH-0	Acicular ferrite	43,5
	Polyhedral ferrite	39,9
	Polygonal ferrite	16,6
HH-4	Acicular ferrite	73,7
	Polyhedral ferrite	24,0
	Polygonal ferrite	2,3
HH-5	Acicular ferrite	60,0
	Polyhedral ferrite	20,6
	Polygonal ferrite	11,7
	Upper binate	7,7
HH-6	Acicular ferrite	56,3
	Polyhedral ferrite	28,3
	Polygonal ferrite	2,0
	Upper binate	13, 4

Non-metallic inclusions

The study of the non-metallic inclusions size, distribution density and morphology was carried out on polished weld metal samples using optical and electron microscopy methods. The studies result is given in Table 4 & Figure 3. Based on the above, we can conclude that the introduction of refractory inoculants into the weld pool leads to the formation of a non-metallic inclusions complex in the weld metal, the size distribution density of which contributes to the microstructure formation with an AF and bainite high content. As the analysis result of metallographic images, it was found that not all non-metallic inclusions are nucleation centers of the ferrite phase (Figure 4). Such analysis results, which are summarized in Figure 5, indicate that the most effective in this regard are inclusions with a size of 0.3 to 1.0μm, which have a specific morphology.

Table 4: Results of non-metallic inclusions the size distribution and oxygen content in the weld metal determination.

Weld №	Inclusion Distribution Density (%) in the Size Range, μm				Oxygen Content in the Weld Metal
	< 0,3	0,3-0,5	0,5-1,0	1,0-3,0	%
HH-0	24,5	38,7	30,5	6,3	0,0726
HH-4	28,3	44,5	22,4	4,8	0,0712
HH-5	27,4	44,9	22,7	5,0	0,0780
HH-6	24,5	37,3	32,5	5,7	0,0730

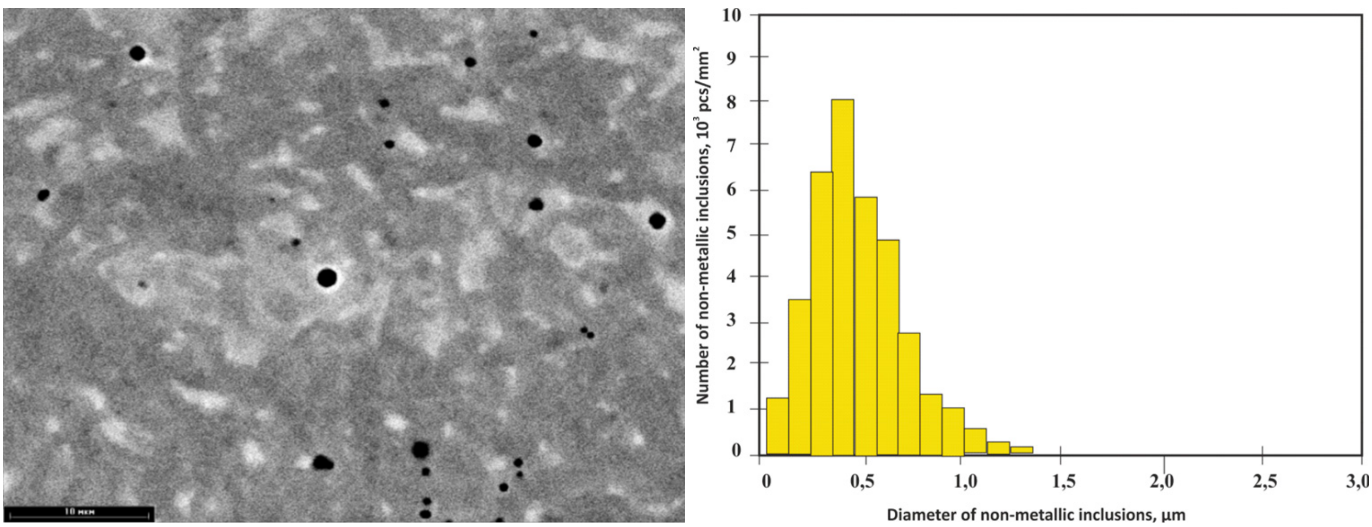

Figure 3: The nature of the non-metallic inclusions size distribution in the weld metal.

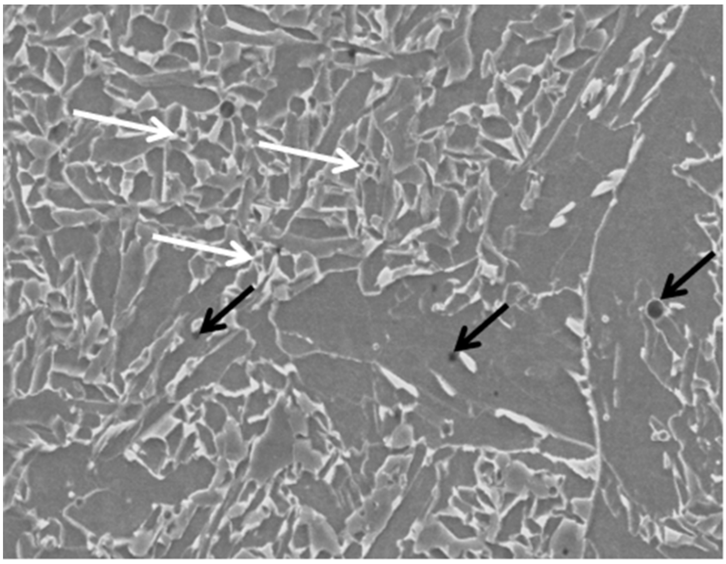

Figure 4: Microstructure of the weld metal obtained on a JSM-35 scanning electron microscope at a magnification of 1000. Light arrows indicate non-metallic inclusions that were centers of ferrite nucleation during the recrystallization process. Dark arrows indicate inclusions that did not participate in ferrite nucleation.

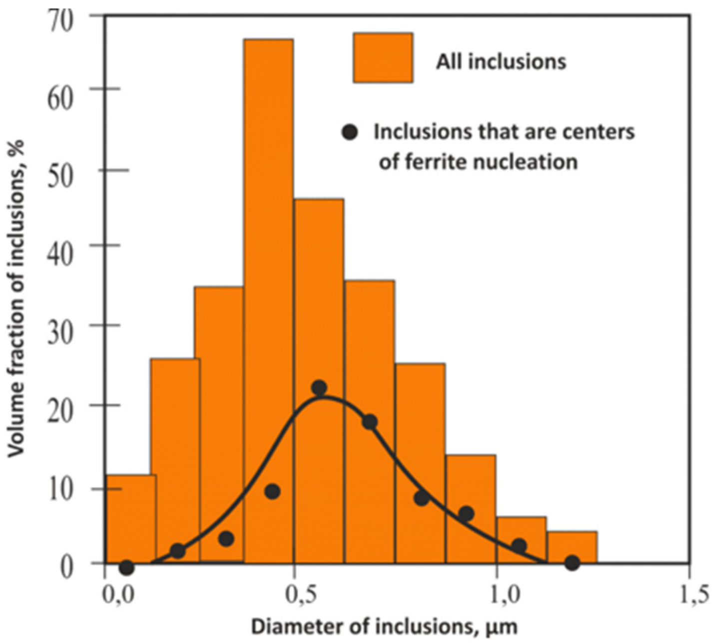

Figure 5: Histogram of the inclusions size distribution in the weld metal, as well as inclusions that serve as an acicular ferrite nucleation centers.

In order to clarify the reasons for such interaction of inclusions with the metal matrix, a linear scan of the most typical inclusions representatives and the surrounding metal matrix was carried out using a Link energy dispersive spectrometer. The study's results in Figure 6, showed that those inclusions on the surface of which there is a titanium carbide compounds thin film (Figure 6f) have an increased manganese concentration in the outer layer and a reduced manganese content in the solid solution zones adjacent to the inclusion (Figure 6e). The manganese distribution and oxygen in non-metallic inclusions of the welds metal inoculated with ferrotitanium and titanium oxide (Figure 6) indicates that titanium is located on the inclusion's periphery in the complex oxides form $MnTiO_3$, Mn_2TiO_4 or $MnTi_2O_4$ type, which have a crystal structure. An increase in the metal alloying with titanium leads to an increase in the non-metallic inclusions content in the welds, which have a titanium oxides thin layer on the surface, and this leads to an increase in the probability of the intragranular ferrite formation of acicular morphology. The driving mechanisms of such a process may be a low difference in the $MnTi_2O_4$ crystal lattice parameters with Fea and a decrease in the manganese content in the solid solution zones adjacent to such inclusions.

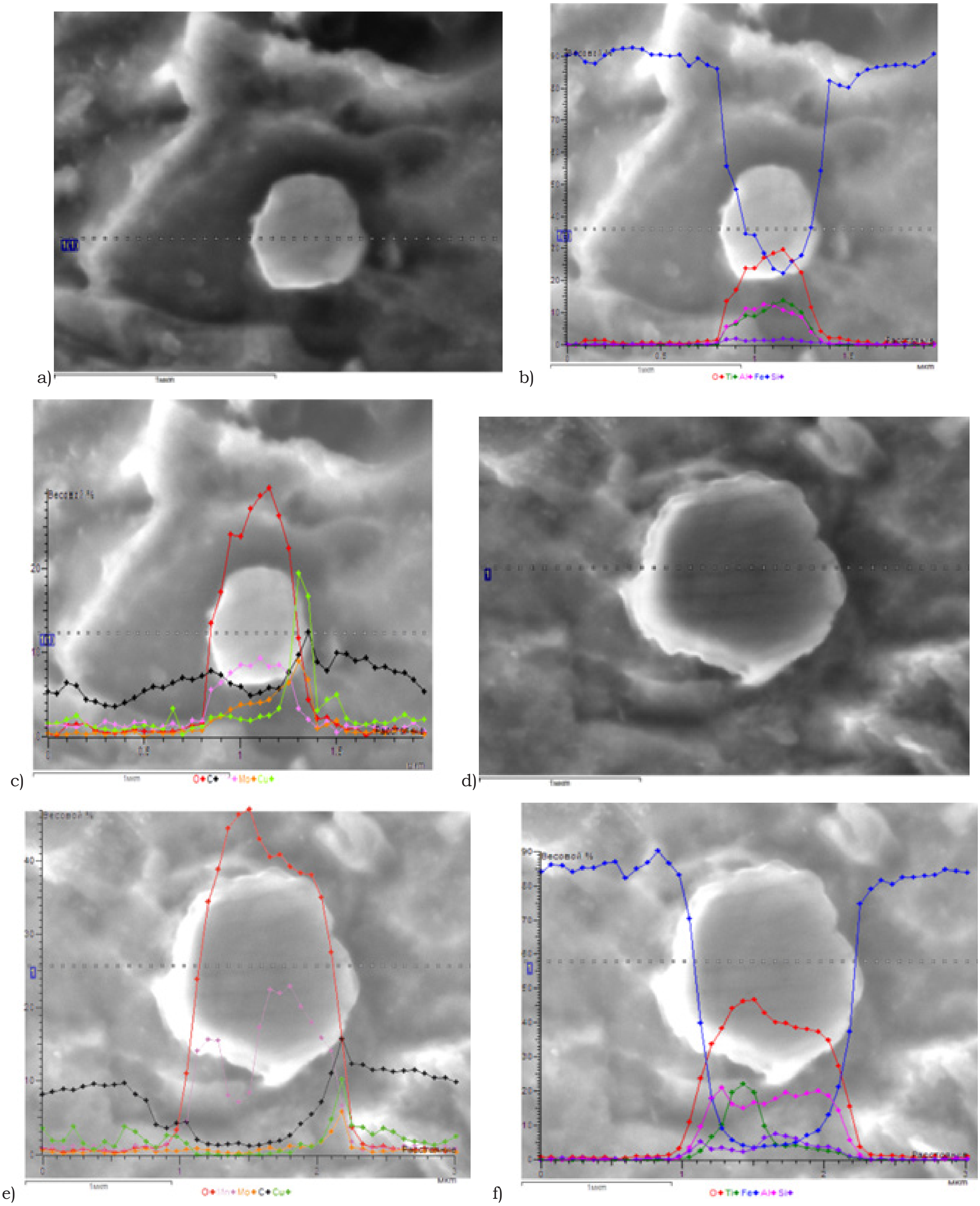

Figure 6: Distribution of elements in non-metallic inclusion and adjacent zones of solid solution: a – scanning trajectory; b – distribution of O, Ti, Fe, Al, Si; c – distribution of O, Mn, Mo, C, Cu. Distribution of elements in non-metallic inclusion and adjacent zones of solid solution: d – scanning trajectory; f – distribution of O, Ti, Fe, Al, Si; e – distribution of O, Mn, Mo, C, Cu.

Analysis of the Research Results

The obtained data showed that the inoculants introduction into the weld pool affects both the non-metallic inclusions size and the size distribution density, as well as the morphology and chemical composition of the inclusions. The inoculants' introduction into the weld pool is accompanied by a decrease in the inclusions average size, which contributes to an increase in the bainite proportion in the microstructure. The use of titanium-containing inoculants leads to an increase in the inclusions content with multiphase morphology, which have an outer layer with a high titanium oxides content on the surface. In the areas of the solid solution adjacent to such inclusions, zones with a reduced manganese content are formed, and this contributes to an increase in the new phase intragranular nucleation probability in the acicular ferrite form.

During the work, weld metal samples were studied, which have a similar oxygen content and a significant difference in titanium content (Table 2). This approach allowed us to link the in the weld metal microstructure difference with a change in the titanium-containing inoculants content in the weld metal. Based on the data obtained, it can be stated that the acicular ferrite formation is associated with the introduction of titanium-containing inoculants into the weld pool in a titanium content wide range in the weld metal from 0.003 to 0.019%.

The titanium influence on the new phase nucleation process can be explained by the correspondence of the phase crystal lattice parameters on the inclusion surface and the surrounding matrix. However, inclusions of the type Mn_2TiO_4 and other (Ti,Mn)-oxides do not have a good such parameters correspondence, so this mechanism does not work in this case. There is another possible mechanism associated with a decrease in the surface energy of the inclusion caused by the Mn_2TiO_4 particles formation on its surface.

It should be noted that the authors of [10,11] showed that the interfacial energy at the interface between Ti_2O_3 and BCC iron is significantly lower than that between Al_2O_3 and BCC iron. This fact was used to explain the increased tendency of Ti_2O_3 inclusions to nucleate AF in the manganese-depleted zones absence in the solid solution. It was later shown [12] that $MnTiO_3$ inclusions also have a high tendency to nucleate AF and it was suggested that the inclusions ability to nucleate a new phase increase with increasing titanium content in the inclusions. This fact and the results obtained by us allow us to assume that (Ti,Mn) oxides have a low interfacial energy at the interface with BCC iron, and this contributes to an increase in the inclusions ability containing such oxides to form AF. However, a physical description of the (Ti,Mn) oxides influence mechanism on the AF nucleation is still lacking and this requires further research in a wide stoichiometric compositions range.

The study results indicate that the increase in titanium content from 0.003 to 0.019% led to a noticeable increase in AF, which corresponds well with the presence of manganese-depleted zones in the solid solution regions adjacent to Ti_2O_3 inclusions. There is data in the literature on the presence of the manganese-depleted zones presence near Ti_2O_3 inclusions [13-15]. The distance over which manganese diffuses in austenite at 1200 °C in one second is about 100nm, so a manganese-depleted zone may well form during the thermal cycle. The results of the conducted studies confirmed that a manganese-depleted zone is formed in the solid solution regions adjacent to the inclusions (Figure 6), and this contributes to the chemical driving force growth for the $\gamma \rightarrow \alpha$ transformation in Ti_2O_3 inclusions, as a result of which intragranular ferrite nucleates on the inclusions surface and the AF content in the weld metal microstructure increases [16,17].

Conclusion

The influence of refractory titanium compounds dispersed particles inoculation into the weld pool on the low-alloyed high-strength steel weld metal microstructure formation was studied. As a result of the microstructure composition and non-metallic inclusions characteristics study of weld metals containing from 0.003 to 0.019% titanium and approximately the same oxygen content, it was established:

a. The microstructure of the metal deposited using the GMAW welding method contained bainite and acicular ferrite, the content of which changed with the change in the titanium content in the weld metal. The content of AF in the microstructure changed from ~43% in the weld metal alloyed with 0.003% titanium to 73% when alloyed with 0.019% titanium. The change in the weld metal microstructure also affected the change in the strength indicators level and the increase in the impact of the toughness values of the weld metal containing 0.019% titanium.

b. The non-metallic inclusions chemical composition and the titanium content in the weld metal are determined by the type of titanium-containing inoculant introduced into the weld pool. When inoculating the weld pool with ferrotitanium and titanium oxide with a titanium content, a crystalline (Ti,Mn) oxides layer is formed on the inclusions surface of the amorphous manganese silicate type. In this case, (Ti,Mn) oxides are responsible for the AF formation in the weld metal in an amount up to 50%. As a mechanism explaining this effect, it is possible to assume the low level of interfacial energy presence at the inclusion-matrix interface.

c. The titanium carbide use as an inoculant leads to the content multiphase morphology inclusions increase in which have an outer layer with a high carbon content on the surface. In the solid solution adjacent areas to such inclusions, zones with a reduced manganese content are formed, and this contributes to an increase in the new phase intragranular nucleation probability in the acicular ferrite form.

d. Based on the obtained data, it can be concluded that the AF nucleation mechanism may be different depending on the nature of the titanium-containing phase located on the inclusion surface. The manganese-depleted zone formation mechanism is triggered in the dominance of Ti_2O_3 inclusions case, and an interfacial energy low level is triggered in the case when a (Ti,Mn) oxides layer is retained on the inclusions surface.

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