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Research Article

The Mechanism of Modification Influence on Non-Metallic Inclusions in the Weld Metal of High-Strength Low-Alloy Steels

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Abstract

An analysis of the effect of modification by dispersed particles of various compounds on the distribution, composition, and morphology of non-metallic inclusions and phase precipitates in the weld metal of low-alloy high-strength steel has been conducted. It has been established that modification with dispersed TiN or Al_2O_3 particles leads to the enlargement of non-metallic inclusions in the weld metal. It has been shown that some modifier particles of SiC or TiC dissolve in the liquid metal pool and precipitate as separate new phase inclusions on or near the surface of non-metallic inclusions, which overall results in changes in the composition and morphology of non-metallic inclusions in the weld metal. In the case of using ZrO_2 or TiO_2 modifiers, small 20-60 nm dispersed non-metallic inclusions are formed, enhancing the modification effect. During the analysis, no primary particles of modifiers were detected, but separate phase separations were detected, which may indicate the complete dissolution of particles in a liquid metal bath of some types of SiC, TiC separations and their subsequent separation from a supersaturated solid solution upon cooling welded joint. In cases where zirconium oxides ZrO2 or TiO_2 were used as modifying compounds, the size reduction of refractory oxides inoculated into the welding bath to nanosize (30...70 nm, the size of which can be compared to the size of the tip of the dendrite growing from the liquid metal of the weld pool during the crystallization process, increases the efficiency of the modification.

Keywords

Welding, Weld Metals, Microstructure, Nonmetal Inclusions, Modification, Refractory Particles

1. Introduction

High-strength low-alloy (HSLA) steels are a class of structural materials. These steels provide a balanced set of mechanical properties and, in many cases, can compete with traditional structural steels [1]. Since the 1980s, such steels have been widely used in various industries. These include oil and gas pipelines, shipbuilding, bridge and offshore structure construction, power transmission lines (PTL), lighting poles, construction beams, the automotive industry, the production of construction and agricultural machinery, industrial equipment, storage tanks, and the manufacturing of mining and railway wagons [2-5].

The expansion of HSLA steel usage is associated with the effective combination of mechanical properties achieved through complex manufacturing processes [6]. Welding pro-

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cesses have a significantly smaller range of technological approaches to solving the problem of ensuring the set of mechanical properties in welded joints. Since welding remains the primary method for producing metal structures, the issue of ensuring the strength of welded joints is highly relevant. Recently, scientific and technical literature has seen publications demonstrating the feasibility of introducing nanoscale refractory compound particles into the metal melt to modify the metal during crystallization and microstructure formation [7, 8]. The process of modification with dispersed particles can also be applied to improve the mechanical properties of the weld metal [9, 10].

Non-metallic inclusions (NMI) influence the formation of the crystalline structure of the metal, and the metal's structure ensures its mechanical properties [11-13]. Modification also affects the composition and morphology of NMI. The insertion of modifier particles into the liquid metal pool can lead to the presence of primary modifier particles in the weld metal; the dissolution of particles and changes in the chemical composition of the solid solution of the crystallized metal; the precipitation of dispersed secondary NMI from the supersaturated solid solution; the coagulation and agglomeration of modifier particles, and the formation of separate phase precipitates (PP); and the changes in the morphology of dispersed NMI (Figure 1) [14, 15].

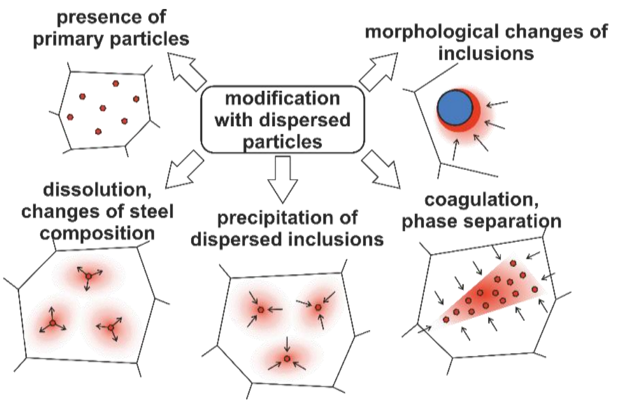

Figure 1. *Mechanisms of weld metal modification by dispersed particles.*

According to their action, modifying additives can be conditionally divided into three types: microcoolants, epitaxial centers for the nucleation of new phases, and surfactant compounds. For the research, refractory compounds were chosen, which allow conclusions to be drawn regarding the effectiveness of each of these approaches in forming the structure of weld metal in low-alloy steels with a yield strength up to 600 MPa.

To determine the effect of refractory compounds, it is advisable to maintain them in the form of a crystalline phase within the temperature range of the liquid metal pool. Calculations showed that when introducing the selected compounds into the weld pool, the size of the refractory particles should be no less than 200 μm. When particles of 200–500 μm in size are introduced, their participation in the crystallization process of the melt as crystalline inclusions of an exogenous type, with sizes of 50–100 nm, or the formation of complex non-metallic inclusions with a specific structure and chemical composition, is possible.

The aim of this work was to investigate the mechanism of the effect of dispersed modifiers on non-metallic inclusions in the weld metal of low-alloy high-strength steel.

2. Materials and Methodology

The study of the effect of modification on the parameters of non-metallic inclusions was carried out on specimens of deposited metal, obtained from the last layer of the butt weld metal, welded using experimental flux-cored wire Oerlicon Fluxocord 35.22 with a diameter of 4 ±0.1 mm under the flux OP-121TT. Butt joints of type 1.4 according to ISO 9692-1 were welded with direct current and reverse polarity at 540-560 A, with an arc voltage of 34-36 V and a welding speed of 1.19 ±0.5 cm/s. After each pass, the butt joint was air-cooled to a temperature of no more than 120 ℃. The process energy per unit length was 14-15 kJ/cm.

To determine the nature of the effect of modifying particles on non-metallic inclusions, they were introduced into the weld metal in the "cold" part of the weld pool through flux-cored wire with a diameter of 1.6 mm, whose core contained a mixture of 10% refractory compound particles ranging from 0.040 to 0.200 mm and 90% iron powder of grade PJW according to DSTU 9849. The modifiers used were chemical compounds of various types: ZrO_2, TiO_2, Al_2O_3, MgO, SiC, VC, NbC, TiC, TiN, FeTi.

Specimens for metallographic studies were prepared from the obtained weld metal. In addition, a control weld joint was made without the introduction of modifier particles.

The chemical composition of the metal from the obtained weld joints is given in Table 1.

Table 1. *Chemical composition of the metal from the obtained weld joints.*

Modifier type	C	Si	Mn	S	P	Cr	Ni	Mo	V	Cu	Al	Ti	Nb	Zr
Without modifier	0,042	0,34	1,19	0,021	0,02	0,106	2,13	0,282	—	0,72	0,028	0,029	0,004	—

Modifier type	C	Si	Mn	S	P	Cr	Ni	Mo	V	Cu	Al	Ti	Nb	Zr
FeTi	0,049	0,298	1,39	0,023	0,015	0,15	2,26	0,25	<0,02	0,44	0,039	0,008	0,006	—
TiN	0,035	0,317	1,4	0,019	0,009	0,14	2,29	0,26	<0,02	0,56	0,036	0,011	<0,002	—
SiC	0,053	0,321	1,2	0,02	0,025	0,22	2,42	0,26	<0,02	0,45	0,025	0,004	0,003	<0,002
TiC	0,046	0,34	1,39	0,021	0,019	0,13	1,7	0,24	<0,02	0,54	0,033	0,011	0,007	—
VC	0,052	0,227	1,21	0,022	0,021	0,14	2,03	0,25	0,07	0,51	0,027	0,004	0,004	—
NbC	0,049	0,253	1,19	0,021	0,02	0,13	2,25	0,27	<0,02	0,55	0,029	0,003	0,075	—
ZrO_2	0,041	0,288	1,32	0,021	0,024	0,12	1,36	0,25	<0,02	0,37	0,029	0,004	0,004	0,06
TiO_2	0,035	0,405	1,24	0,016	0,021	0,11	1,97	0,27	0,009	0,68	0,031	0,017	0,002	—
Al_2O_3	0,023	0,424	1,4	0,017	0,023	0,11	2,15	0,29	0,007	0,77	0,032	0,015	0,002	—
MgO	0,031	0,227	1,11	0,025	0,024	0,14	1,85	0,29	—	0,6	0,023	0,03	—	—

Metallographic studies were conducted using optical methods (Neophot 32 microscope equipped with a high-resolution digital camera), as well as electron microscopy methods – scanning electron microscopes JSM-840 and JSM 35CF and transmission electron microscope JEM 200CX from "JEOL" (Japan), equipped with microanalysis systems Link 860/500 and INCA 450 from "Oxford Instruments" (UK), as well as an Auger microprobe JAMP 9500F, equipped with a microanalysis system INCA 350.

The specimens were polished and photographed, and the obtained digital images (with a resolution of 24 pixels per μm) were processed to calculate the size of non-metallic inclusions (Figure 2). Due to the specifics of the analysis of the obtained digital images, only non-metallic inclusions larger than 3 pixels were included in the calculation.

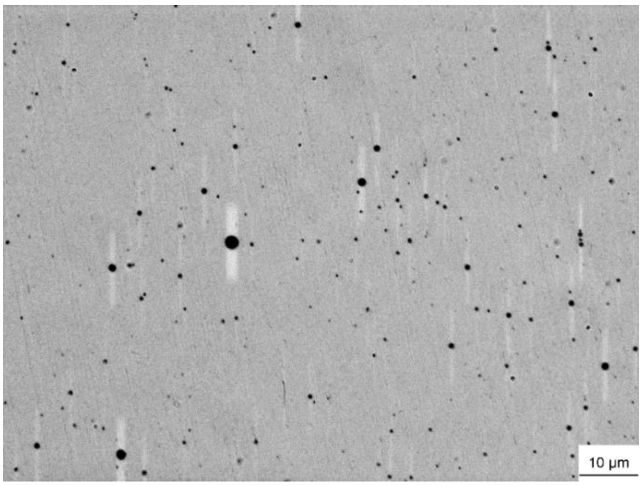

Figure 2. *Image of the weld joint metal grind without modification.*

3. Results and Discussion

After obtaining the inclusion size values for each specimen, the dependencies of the inclusion fraction (%) on the inclusion size (μm), i.e., the distribution of non-metallic inclusions by size, were plotted (Figure 3). The NMI size distribution data obtained for all types of modifiers were compared with the data for the weld metal without modification, and the corresponding dependencies were plotted (Figure 4). The summary of the modification effect on the NMI size distribution is presented in Figure 5.

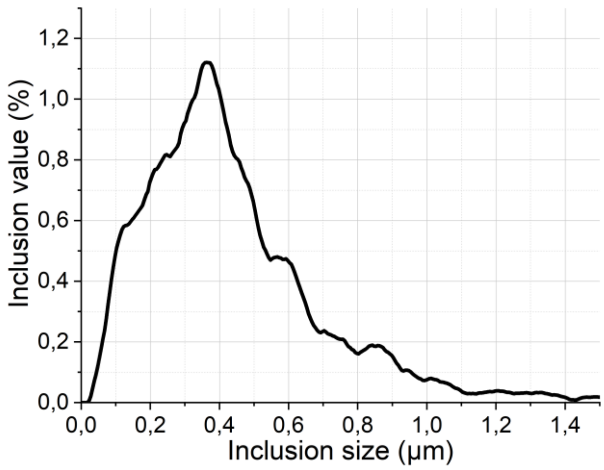

Figure 3. *Distribution of NMI by size for the weld metal without modification.*

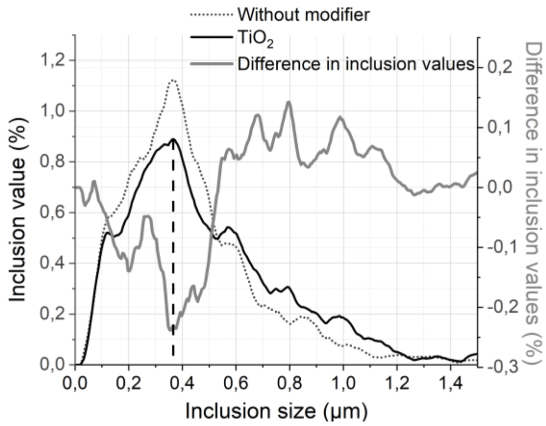

Figure 4. *Changes in the NMI size distribution with modification by TiO_2 particles.*

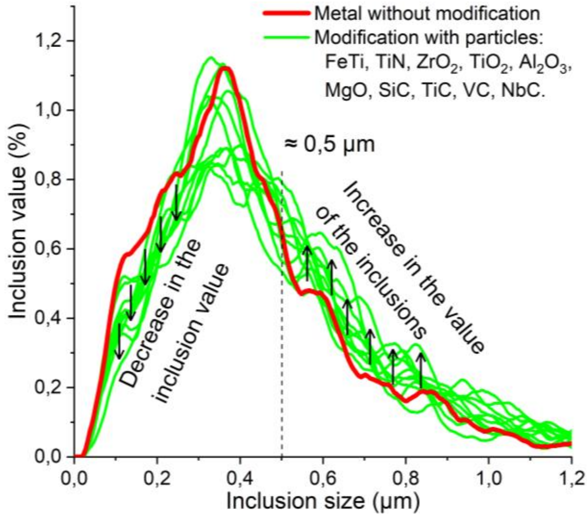

Figure 5. *Overall effect of modification on the NMI size distribution in weld metal.*

The analysis of the obtained results showed that modification leads to a decrease in the quantity of inclusions smaller than ≈ 0.5 μm, and an increase in the quantity of inclusions larger than ≈ 0.5 μm. In other words, modification results in the coarsening of NMI in the weld metal of high-strength low-alloy steel.

The analysis of the chemical composition and morphology of non-metallic inclusions showed that, depending on the type of modifier, inclusions of different compositions and morphologies form in the weld metal. For example, when welding is modified with refractory particles such as TiN, particles of almost regular shape (gray precipitates, Figure 6a) form, with aluminum oxide (Al_2O_3) located in their inner regions (dark precipitates). This suggests that during the crystallization of the molten metal at higher temperatures, Al_2O_3 particles form first, and then TiN particles are formed on them as substrates. At the same time, when Al_2O_3 particles are used as modifiers, simple non-metallic inclusions of Al_2O_3 of a rounded shape are formed.

Electron microscopic investigations of thin foils at magnifications up to 37,000x allowed for a more detailed determination of the distribution of non-metallic inclusions in the weld metal (Figure 7).

During the analysis, no primary particles of modifiers were found, but individual phase precipitates were detected, which may indicate the complete dissolution of certain types of precipitates, such as SiC and TiC (Figure 7a, b), in the liquid metal bath, followed by their precipitation from the supersaturated solid solution upon cooling of the weld joint.

In cases where zirconium oxides (ZrO_2) or titanium oxides (TiO_2) were used as modifying compounds (Figure 7c, d), the reduction in the size of the refractory oxides inoculated into the weld bath to nanoscale dimensions (30–70 nm, Figure 7c, d), comparable to the size of the dendrite tip growing from the liquid metal during solidification, improves the effectiveness of modification.

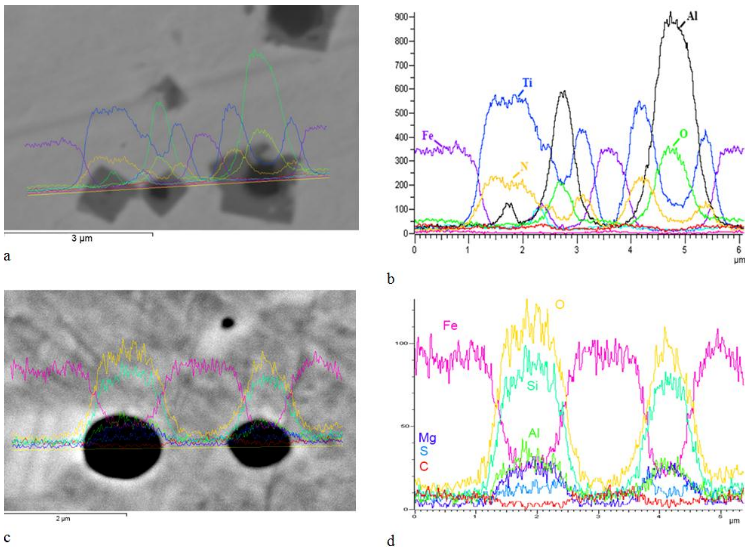

Figure 6. *Effect of modification with titanium nitride (TiN) (a, b) and aluminum oxide (Al_2O_3) (c, d) on the morphology of non-metallic inclusions (a, c) and the element distribution along the scan line (b, d) in weld metal. SEM study.*

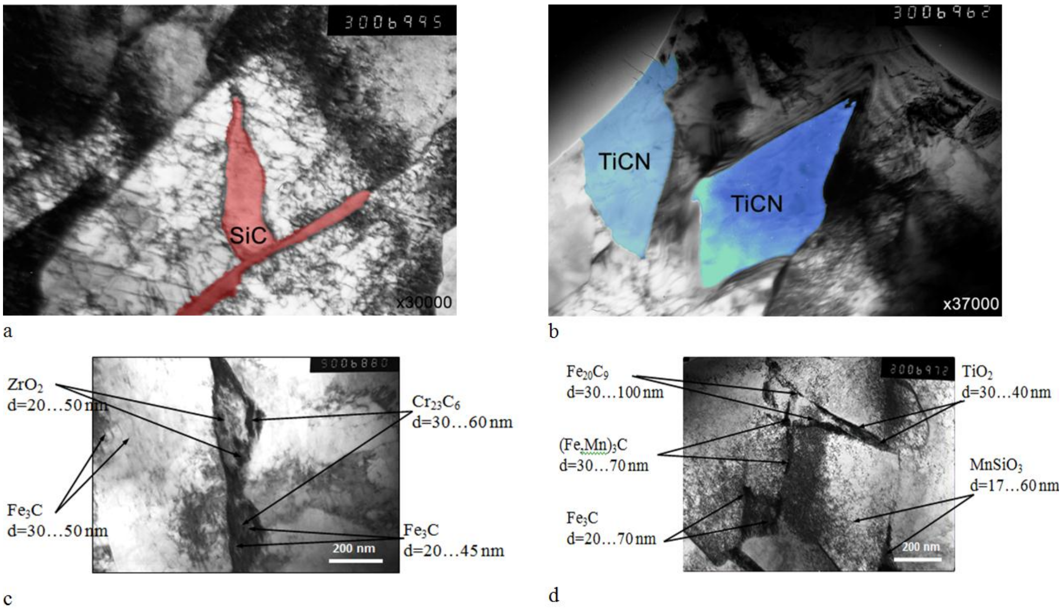

Figure 7. *Influence of modification with SiC and TiC carbides (a, b) and ZrO_2 and TiO_2 oxides (c, d) on the distribution of non-metallic inclusions in the weld metal: a – SiC; b – TiC; c – ZrO_2; d – TiO_2. SEM investigation.*

The summary of the obtained results shows that depending on the composition of the modifying additives, either relatively large non-metallic inclusions (1–3 μm) with complex morphology are formed on the weld metal of high-strength low-alloy steels, with areas enriched with chemical elements from the modifier particles on their surface. In other cases, the modifier particles form fine (20–60 nm) dispersed non-metallic inclusions, which enhance the strengthening modifying effect due to the so-called dispersion strengthening effect.

4. Conclusions

An analysis was conducted on the effect of modification by dispersing particles of various compounds on the distribution, composition, and morphology of non-metallic inclusions and phase precipitates in the weld metal of low-alloy high-strength steel. It was established that modification with dispersing particles such as TiN or Al_2O_3 leads to the coarsening of NMI in the weld metal. It was shown that some modifier particles, such as SiC or TiC, dissolve in the liquid metal bath and precipitate as new distinct phase precipitates on the inclusion surfaces, which in turn leads to changes in the composition and morphology of non-metallic inclusions in the weld joint. In the case of using modifiers such as ZrO_2 or TiO_2, fine dispersed non-metallic inclusions (20–60 nm) are formed, which enhance the modifying effect.

Abbreviations

HSLA	High-strength Low-alloy
PTL	Power Transmission Lines
NMI	Non-metallic Inclusions
PP	Phase Precipitates

Author Contributions

Zhukov Viktor: Formal Analysis, Investigation, Methodology, Resources, Visualization

Kostin Valery: Conceptualization, Formal Analysis, Investigation, Project administration, Writing – original draft,

Holovko Viktor: Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing

Reminnyi Maksym: Formal Analysis, Investigation, Software, Visualization

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

Zhukov Viktor: Metallography analyses, Thermal gravimetric analyses, Metal diagram transformation, Weld metal structure, Nonmetal inclusions, Solid transformation

Kostin Valery: Metallography analyses, Weld metal structure, Weld metal alloying, Weld metal structure, Solid solution Harding, Weld metal transformation

Holovko Viktor: Low alloyed steels, Physical-chemical processes in welding arc, Weld metal alloying, Weld metal structure, Nonmetal inclusions, Weld metal mechanical properties

Reminnyi Maksym: Nonmetal inclusions, Weld metal structure, Metal structure transformation, Weld metal chemical composition, Weld metal mechanical properties, Solid state transformations in weld metal