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INFLUENCE OF THE NATURE OF DISTRIBUTION OF NONMETALLIC INCLUSIONS ON THE MECHANICAL PROPERTIES OF WELD METAL OF LOW-ALLOY STEELS

V.V. Holovko[1], O.O. Shtofel[1], D.Yu. Korolenko[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
37 Peremohy Prosp., 03056, Kyiv, Ukraine

ABSTRACT

A complex of works was carried out on establishing the nature of distribution of nonmetallic inclusions in the metal structure of low-alloy welds. As a result of metallographic examinations, the values of the volume content of inclusions in the structure and their distribution by sizes were established. The rationality of using such an additional indicator as the distribution density for a more informative description of nonmetallic inclusions when evaluating their influence on the mechanical properties of weld metal was shown. The use of fractal analysis to reveal the features of the distribution density of nonmetallic inclusions in the weld metal was proposed.

KEYWORDS: welds, microstructure, nonmetallic inclusions, distribution density, tendency to brittle fracture, fractal analysis

INTRODUCTION

Nonmetallic inclusions are an integral part of the structure of low-alloy steels and that is why a great attention is traditionally paid to their influence on the mechanical properties of welds. It is believed that nonmetallic inclusions in the welding pool are formed as a result of the course of thermodynamic reactions or they enter when melting base metal and welding consumables. Fundamental monographs on this issue [1, 2] showed the features of the influence of the volume content of inclusions, their chemical composition and morphology on the formation of structure and mechanical properties of welds. The carried out studies have shown that some inclusions of a certain morphology may contribute to the formation of microstructural components of a higher toughness in the weld metal of low-alloy steels. Based on these results, the researchers came to the idea not to count on the formation of the required nonmetallic inclusions in the weld metal, but to provide their presence in the metal by inoculation of a controlled number of refractory compounds of a certain size and chemical composition to the welding pool. Recently, publications appeared, which study the features of influence on the structure and mechanical properties of the weld metal of nonmetallic inclusions, which were purposefully inoculated to the welding pool [3, 4]. In a high-temperature metal melt, nonmetallic inclusions are dissolved. Therefore, in order to inhibit this process in relation to inoculants, they are introduced into the "cold" area of welding pool. Accordingly, the conditions of distribution of nonmetallic inclusions in the weld metal are changed. Our research works were aimed at finding out the peculiarities of the distribution of nonmetallic inclusions in the structure of weld metal of low-alloy steels, expanding the knowledge base regarding the influence of certain indicators describing these features on the mechanical properties of the weld metal of low-alloy steels, in particular, the tendency to brittle fracture.

The aim of the work was to determine the possibility of taking into account the distribution density of nonmetallic inclusions in the metal matrix when evaluating their influence on the mechanical properties of weld metal of low-alloy steels.

The studies were performed on nonmetallic titanium-based inclusions, the presence of which in the weld metal provided inoculation of welding pool with appropriate refractory compounds.

PROCEDURE OF INVESTIGATIONS

The studies were conducted on the specimens of weld metal, produced according to the procedure [5] during arc welding in shielding gas (82 % Ar, 18 % CO_2) using a flux-cored wire with a diameter of 1.6 mm of type "metal core" at the direct current of 200 (±5) A, voltage 30 (±2) V with the input energy of 21 (±2) kJ/cm. To determine the nature of distribution of nonmetallic inclusions in the weld metal to the "cold" part of the welding pool, a flux-cored wire with a diameter of 1.6 mm was introduced, whose core contained a mixture of 10 % of particles of refractory compounds of 0.040–0.200 mm and 90 % of the iron powder of grade PZhV according to DSTU 9849. As inoculants,

Table 1. Chemical composition of weld metal

Weld number	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Al	Ti
FeTi	0.050	0.290	1.32	0.024	0.014	0.16	2.19	0.27	0.36	0.039	0.019
TiC	0.054	0.263	1.28	0.025	0.011	0.13	2.22	0.26	0.49	0.035	0.009
TiN	0.035	0.317	1.40	0.019	0.009	0.14	2.29	0.26	0.56	0.036	0.011
TiO_2	0.035	0.405	1.24	0.016	0.021	0.11	1.97	0.27	0.68	0.031	0.017

Table 2. Mechanical properties of weld metal

Weld number	Rm	Re	A	Z	*KCV*, J/cm² at *T*, °C			
	MPa		%		20	0	–20	–40
FeTi	788	739	11.4	35	60	58	57	52
TiC	716	644	19	63	111	97	85	73
TiN	712	580	5.3	14.7	55	47	40	35
TiO_2	709	636	19	57	85	72	60	50

the following titanium-based compounds were selected: titanium oxide (TiO_2 weld), titanium carbide (TiC weld), titanium nitride (TiN weld). The obtained results were compared with the data of the specimens of the weld metal produced during welding using flux-cored wire, into the core composition of which ferrotitanium (FeTi weld) was introduced.

Metallographic examinations were performed on the cross-sections cut out from welded joints. The structure of the weld metal was examined in an optical microscope, the influence of the distribution of nonmetallic inclusions on the features of metal fracture was determined by the results of fractographic images obtained in the scanning electron microscope JSM-35.

The distribution of inclusions by sizes and plotting the corresponding diagrams was performed directly from the sections. According to the program set in the device, the amount of inclusions in each specimen was calculated by dimensional groups — from the minimum to the maximum size.

The distribution density of nonmetallic inclusions in the structure of weld metal was determined by the procedure given in [6].

The mechanical properties of the weld metal were evaluated according to the results of standard tests in accordance with the requirements of DSTU ISO 6892-1:2019, DSTU EN 10045-1:2006 and DSTU ISO 15792-1:2009.

RESEARCH RESULTS

In Tables 1 and 2, the results of determining the chemical composition and mechanical properties of the metal of the studied welds are shown.

In Figure 1, the histograms of distribution by sizes and a volume fraction of nonmetallic inclusions in the weld metal are shown.

In Figure 2, the specimens of microstructure of the weld metal produced by the methods of optical metallography are shown.

The weld of FeTi metal is characterized by a fine-grained bainitic-martensitic structure according at some of its fragmentation and the formation of intravolume dispersed phases, which should provide a high level of mechanical properties. The bainitic component is represented mainly by the lower (more than 50 %) and upper one. Also, up to 10 % of martensitic component was recorded. In the volume of bainitic grains, the phases of the dispersed sizes of a carbide type are clearly viewed.

In the weld metal of TiC specimens, a bainitic-martensitic structure is formed, which contains mainly upper bainite (about 60 %), the lower bainite amounts to about 25 % and martensite (up to 10 %) at a slight fragmentation of the structure. In the volume of grains of the bainitic structure, the particles of phase precipitates of dispersed sizes of a carbide type are observed with their relatively uniform distribution. For inner microvolumes of the structure, a relatively low distribution density of nonmetallic inclusions is characterized.

In the metal of TiN weld, a heterogeneous bainitic-martensitic structure is formed, which contains about 60 % of upper bainite, lower bainite (about 20 %) and martensite (up to 10 %). In the grains of bainitic structure, the particles of phase precipitates of dispersed sizes of a carbide type at a relatively uniform distribution are observed. On the boundaries of ferritic grains, the presence of chains of phase precipitates is observed, which are the phases of a carbonitride type TiCN, which should lead to a decrease in the level of mechanical properties and a noticeable decrease in the crack resistance of a weld.

TiO_2 weld metal is characterized by a nonuniform bainitic-martensitic structure at its slight fragmentation. The bainitic component is represented mainly by the upper (more than 50 %) and lower (about 30 %) bainite. The content of martensite does not exceed

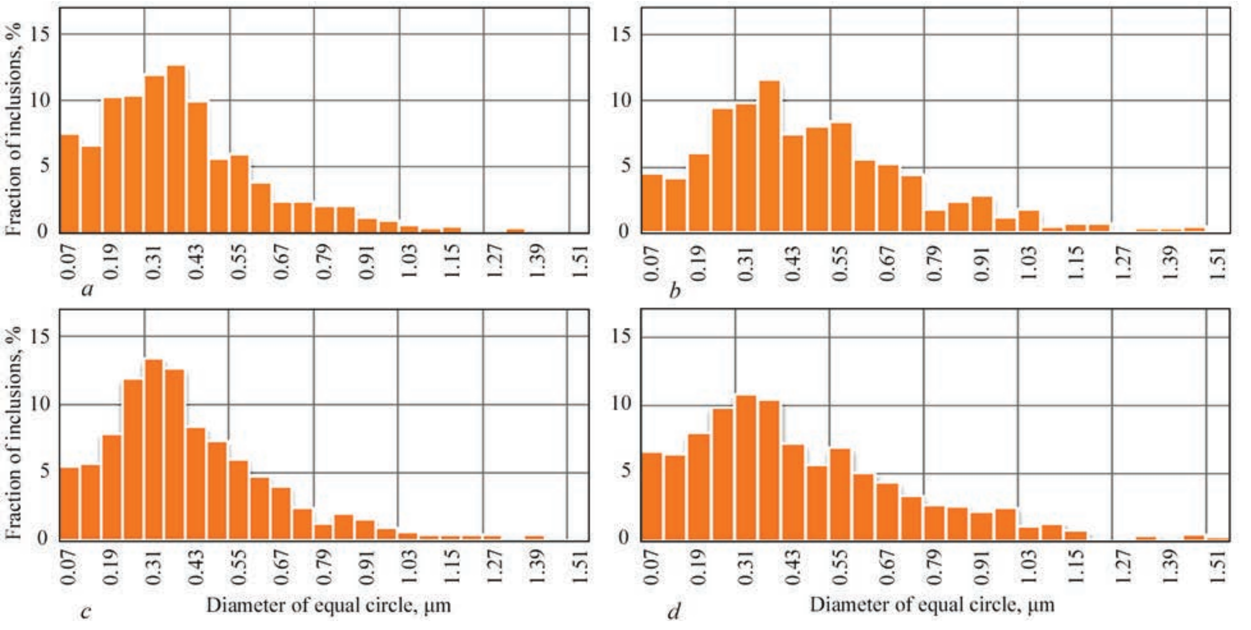

Figure 1. Histograms of distribution by sizes and volume fraction (V) of non-metallic inclusions in the weld metal: *a* — FeTi; *b* — TiC; *c* — TiN; *d* — TiO_2 (*a*, *b* — V = 0.62 %; *c* — 0.77; *d* — 0.47)

10 %. In the body of bainitic grains of the structure, the particles of phases of the dispersed sizes of a carbide type, as well as single phase precipitates of a type of titanium oxides of larger sizes are viewed.

ANALYSIS OF RESEARCH RESULTS

The influence of the composition, content and morphology of nonmetallic inclusions on the structure and mechanical properties of low-alloy steels in general and the weld metal in particular traditionally attracts great attention [1–3]. The reduction of mechanical properties, which was obtained on the specimens of TiN weld metal, fully corresponds to the description of the impact of nitrides, which is presented in the mentioned monographs. The attention should be paid to the difference in the distribution of nonmetallic inclusions in the structure of the metal of the studied welds. Metallographic analysis showed that a certain

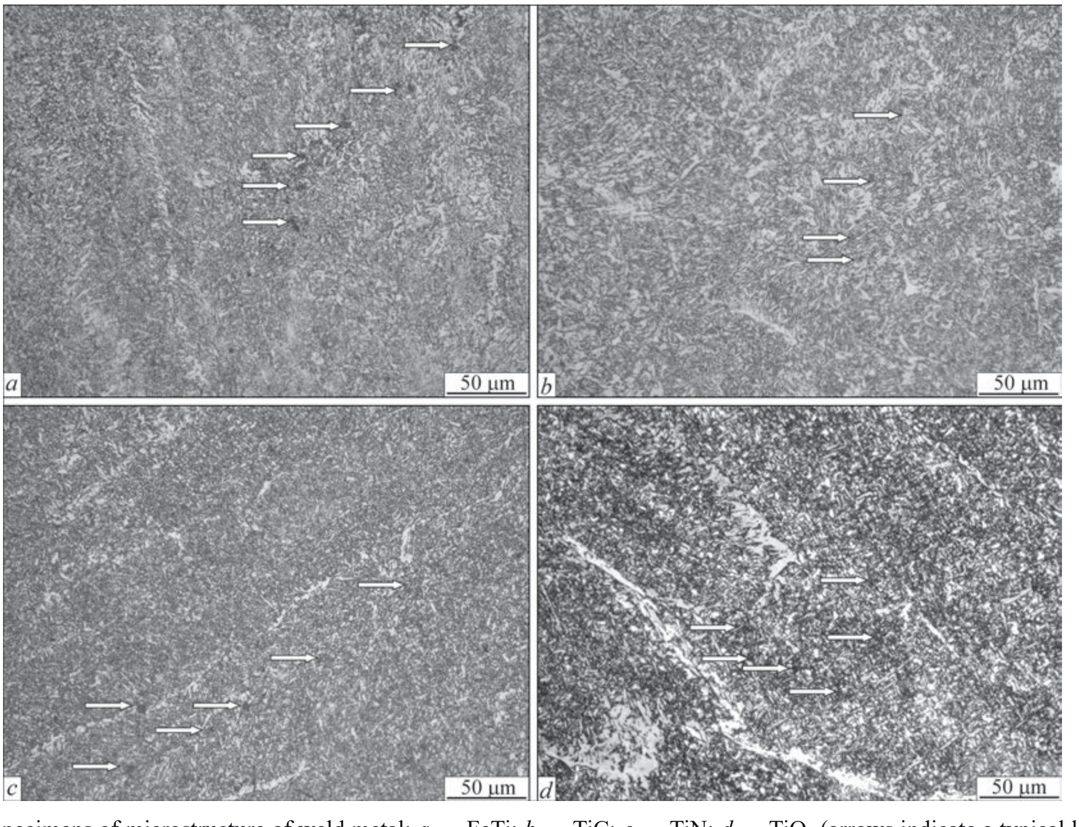

Figure 2. Specimens of microstructure of weld metal: *a* — FeTi; *b* — TiC; *c* — TiN; *d* — TiO_2 (arrows indicate a typical location of nonmetallic inclusions)

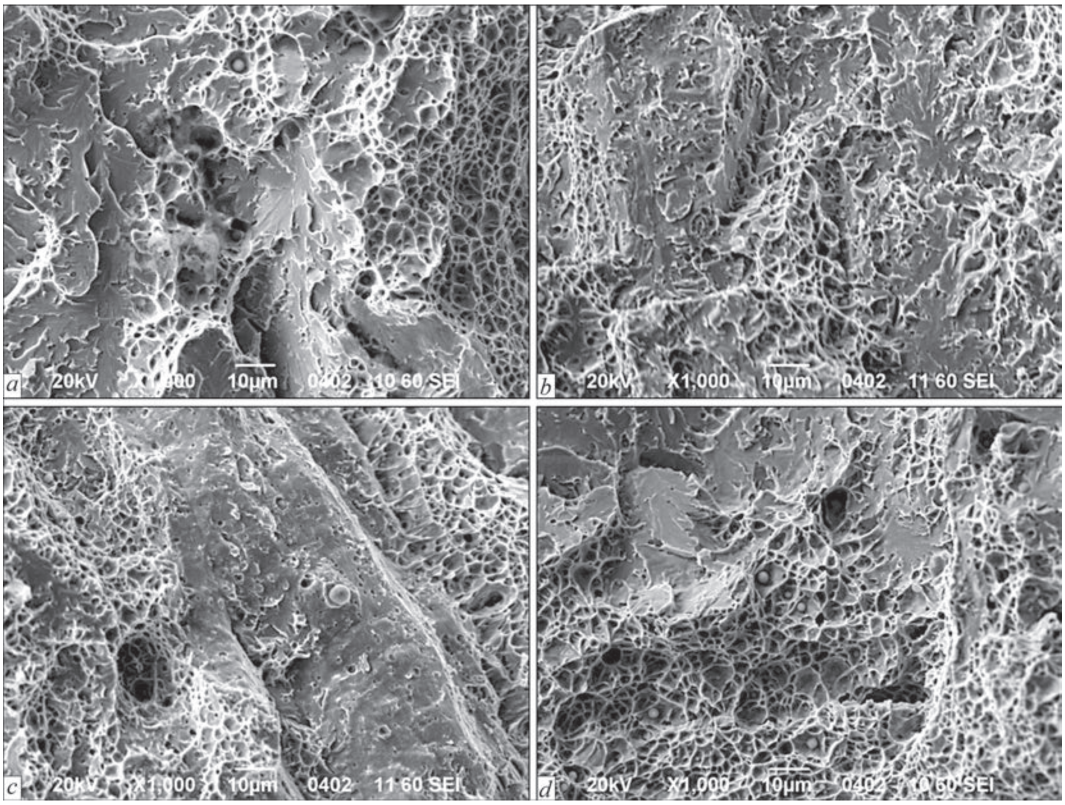

Figure 3. Fractographies of fractures of specimens: *a* — FeTi; *b* — TiC; *c* — TiN; *d* — TiO_2

number of nonmetallic inclusions in FeTi and TiM weld metal are located on the boundaries of ferritic grains, whereas the structure of the welds of TiC and TiO_2 is characterized by the predominant distribution of inclusions in the body of ferritic grains. This feature of the distribution of inclusions is illustrated in Figure 2, where the location of nonmetallic inclusions is marked with arrows.

To find out how such a feature of the distribution of inclusions affects the mechanical properties of the weld metal, fractographic examinations of the specimen fractures were conducted, which were produced during determination of the impact toughness of the weld metal at –40 °C. The results of the examinations are shown in Figure 3.

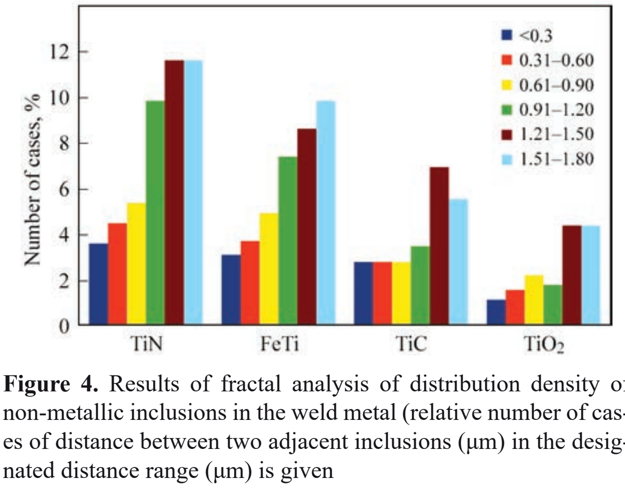

Figure 4. Results of fractal analysis of distribution density of non-metallic inclusions in the weld metal (relative number of cases of distance between two adjacent inclusions (μm) in the designated distance range (μm) is given

The abovementioned data show that dispersed nonmetallic inclusions, located on the boundaries of ferritic grains, serve as sources of initiation of cracks of type of brittle spalling, as is seen in Figure 3, *a*, *c*. In those cases when most inclusions are located in the body of ferritic grains (Figure 3, *b*, *d*), dispersed inclusions are not the centres of brittle crack initiation.

DETERMINING THE NATURE OF DISTRIBUTION OF NONMETALLIC INCLUSIONS

According to modern notions, the influence of nonmetallic inclusions on the tendency of metal to brittle fracture is associated with the stress fields initiated around them. Single-phase inclusions, whose thermal expansion coefficient is lower than in the metal matrix, contribute to the formation of a higher level of stresses compared to inclusions consisting of several layers of different composition. In the case when inclusions are located in the metal matrix at some distance from each other, which exceeds the action radius induced by the stresses, their effect on the tendency of metal to brittle fracture is lower compared to the situation when inclusions are located much closer. Based on these notions, the distance between inclusions is one of the important characteristics of the distribution of nonmetallic inclusions in the weld metal.

The methods of computer processing of optical images of the polished surface of the sections of the examined welds make it possible to obtain digital information both of the total content of nonmetallic inclusions in the metal as well as of their distribution by sizes (see Figure 1). These data give a notion of the generalized characteristics of inclusions, but do not allow revealing the features of their distribution in the structure of the weld metal. Information on the total content of nonmetallic inclusions and the nature of their distribution by size does not give grounds to find out the factors that cause the difference between the toughness and ductility values of the weld metal. In order to solve this problem, it is advisable to involve the methods of fractal analysis of nonmetallic inclusions.

In [6], a method of fractal analysis of structural components of the metal was proposed, which allows determining the features of density (distance between adjacent inclusions) of the distribution of nonmetallic inclusions. The impact of inclusions on the tendency to spalling formation in the surrounding metal matrix depends on the level of stresses occurring at the interphase boundary and on the distance to adjacent inclusions. Based on the abovementioned reasons, the works on fractal analysis of the specimens of weld metal were performed in order to determine the nature of their distribution relative to the distance to the nearest adjacent inclusions. The results of the research works are shown in Figure 4.

As is seen from the abovementioned data, the highest distribution density of inclusions is in FeTi and TiN welds. Namely these welds are characterized by a structure in which an increased presence of inclusions on the boundaries of ferritic grains (Figure 2) is noted and this is accompanied by a decrease in the values of toughness and ductility (Table 2). It should be noted that the higher distribution density of inclusions in the metal of TiN weld is accompanied by a lower level of toughness and ductility values.

In the metal of TiC and TiO_2 welds, a number of cases with an increased distribution density of inclusions is noticeably lower, which can serve as an explanation of a higher level of relevant values.

The obtained results indicate that the combination of such two factors as the presence of nonmetallic inclusions on the boundaries of grains and an increased density of their distribution leads to a decrease in the toughness and ductility values of weld metal of high-strength low-alloy steels.

CONCLUSIONS

A complex of works was carried out on establishing the nature of the distribution of nonmetallic inclusions in the metal structure of low-alloy welds. As a result of metallographic examinations, the indicators of volumetric content of inclusions in the structure and their distribution by sizes were established. The feasibility of using such an additional indicator as the distribution density of inclusions when evaluating their impact on the mechanical properties of the weld metal is shown. The use of fractal analysis to find out the features of the influence of nonmetallic inclusions on the mechanical indicators of the weld metal of high-strength low-alloy steels, taking into account the distribution density of inclusions.

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ORCID

V.V. Holovko: 0000-0002-2117-0864,
O.O. Shtofel: 0000-0003-0965-6340

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.V. Holovko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: v_golovko@ukr.net

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