The Measurement of Hardness and Elastic Modulus of non-Metallic Inclusions in Steely Welding Joints

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***Abstract* – Trunk pipelines work under a cyclic dynamical mechanical load because when oil or gas is pumped, the pressure constantly changes - pulsates. Therefore, the fatigue phenomenon is a common reason of accidents. The fatigue phenomenon more often happens in the zone of non-metallic inclusions concentration. To know how the characteristics of non-metallic inclusions influence the probability of an accident the most modern research methods should be used.**

It is determined with the help of the modern research methods that the accident rate of welded joints of pipelines is mostly influenced by their morphological type, composition and size of nonmetallic inclusions, this effect is more important than the common level of pollution by non-metallic inclusions. The article presents the results of the investigations of welded joints, obtained after the use of different common welding materials. We used the methods, described in the state standards: scanning electronic microscopy, spectral microprobe analysis and nano-indentation. We found out that non-metallic inclusions act like stress concentrators because they shrink, forming a blank space between metal and non-metallic inclusions; it strengthens the differential properties on this boundary. Nonmetallic inclusion is not fixed, it can move.

The data that we have received mean that during welded joints' contamination (with non-metallic inclusions) monitoring process, more attention should be paid to the content of definite inclusions, but not to total contamination.

***Keywords* – pipeline, non-metallic inclusions, reliability, fatigue, hardness, shrinkage, nano-indentation.**

1. Introduction

The overall length of pipelines in Russia is 242 000 km, 90% provide the pumping of petroleum, gas and oil-products [1], [2]. The statistical survey shows that accidents and emergency cases on a pipeline happen approximately ten times a year. That kind of accidents entail a huge financial and environmental damage, therefore, the reduction of the pipelines' accident rate is an actual direction of studies.

The measures of accident rate reduction can be divided into two main directions: the statistical survey of accidents' reasons and the results of mathematical simulation of pipeline's strength.

Most pipelines work in dynamic mechanical pressure conditions because they are pumping the products and the pressure on the pipe's inside surface changes periodically during all the working time. Such load on the structure of a pipeline material causes fatigue stresses of a border between a non-metallic inclusion and a metal in welding joints and mainly of the metal, which provokes the growth of fatigue cracks. It happens because of the differences between the mechanical characteristics of inclusions and basic and joint's metal. Two out of ten accidents happen because of non-metallic inclusions.

The presence of non-metallic inclusions in metal is unavoidable, but not all inclusions are dangerous. Math simulation can determine the inclusions, which present potential sources of fatigue stresses and cracks; this data can be used for pipeline quality monitoring. The value of the main mechanical characteristics of inclusions (hardness and elastic module) should be known to do the abovementioned simulation.

2. The objective, samples and methods

The objective of the research is evaluation of hardness and elastic modulus of real non-metallic inclusions in steel welding joints with the help of nano-indentation method.

The investigation of mechanical characteristics of non-metallic inclusions was done on samples of steel welding joints, which were produced out of typical for pipelines construction materials. The samples' materials are shown in table 1.

For the right interpretation of nano-indentation, it is necessary to add the results of the investigations of non-metallic inclusions with some other methods.

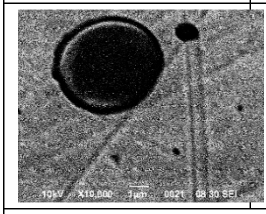
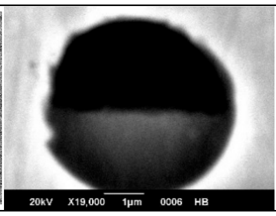
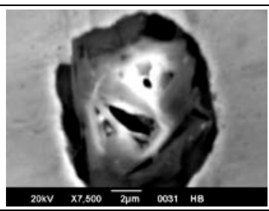
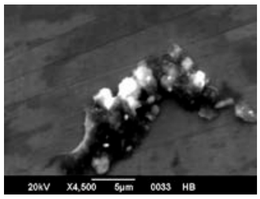
The common pollution with non-metallic inclusions was investigated by optical microscopy (Russian State Standard GOST 1778-70), a part of results was analyzed by the software VideoTest2.0.

The parameters of non-metallic inclusions (size, shape, composition) were investigated with an X-ray microscope and microprobe analysis «JSM7500FJEOL».

Table 1. Materials of the researchedsteel welding joints samples

Manual Metal Arc (MMA) welding	
steel grades* (Russianstandards); The size of tube (mm)	welding electrodes (∅, mm)*
17Г1С-У; 1220×12,4	LB-52U (2,6); УОНИ 13/55 (4,0)
17Г1С-У; 1220×12,4	Fox Cel(4,0); МТГ-02 (4,0)
Х70; 1420×18,7	LB-52U (3,2); Cassel 5520 Mo (4,0)
The root: flux-cored arc welding (FCAW) with shielding gas CO_2 The filler metal: surface tensor transfer (STT) and flux-cored arc welding (FCAW)	
Х70; 1420×15,7	L-56 (1,14)+CO_2; NR-208S (2,0)
17Г1С-У; 1220×11,0	L-56 (1,14)+CO_2; NR-207 (1,7)
The root: MMA; The filler metal: Submerged arc welding (SAW) + MMA	
Х70;1420×18,7	LB-52U (3,2); Св08ХМ (3,0); АН47
Х70;1420×15,7	FoxCel (4,0); FoxCel Mo (4,0); Св08ХМ (3,0); АН47
The root: MMA; The filler metal: MMA + FCAW	
Х70; 1420×15,7	LB-52U (3,2); NR-208S (2,0)
Х70; 1420×15,7	Fox Cel (4,0); Fox CelMo (4,0); NR-208S (2,0)
* grades of materials are presented in the original spelling (Russian by Russian letters)	

Table 2. The composition of different non-metallic inclusions investigated by an X-ray microscope anda microprobe analysis

component	type of non-metallic inclusion			
	a	b	c	d
				
	concentration, %			
SiO_2	64.80	54.45	53.60	4.54
Al_2O_3	-	-	0.60	5.30
SO_3	-	-	-	29.24
Na_2O	-	-	-	7.25
MgO	30.49	15.5	30.15	3.15
TiO_2	-	-	-	0.72
Cr_2O_3	0.14	-	0.11	-
MnO	-	-	0.11	-
CaO	-	-	-	26.23
FeO*	4.22	25.22	14.95	17.26
ZnO	-	-	-	3.82
NiO	0.35	-	0.43	-

The nano – indentation was done by NanoTest-600.

3. Results and discussion

All non-metallic inclusions are divided into size groups on the basis of welding joints quality assessment according to the Russian standards. On the basis of the data of optical microscopy (analysis the diagram, which describes the percentage of inclusions of different size groups to the common number of inclusions in each type of samples was built (fig. 1) [3].

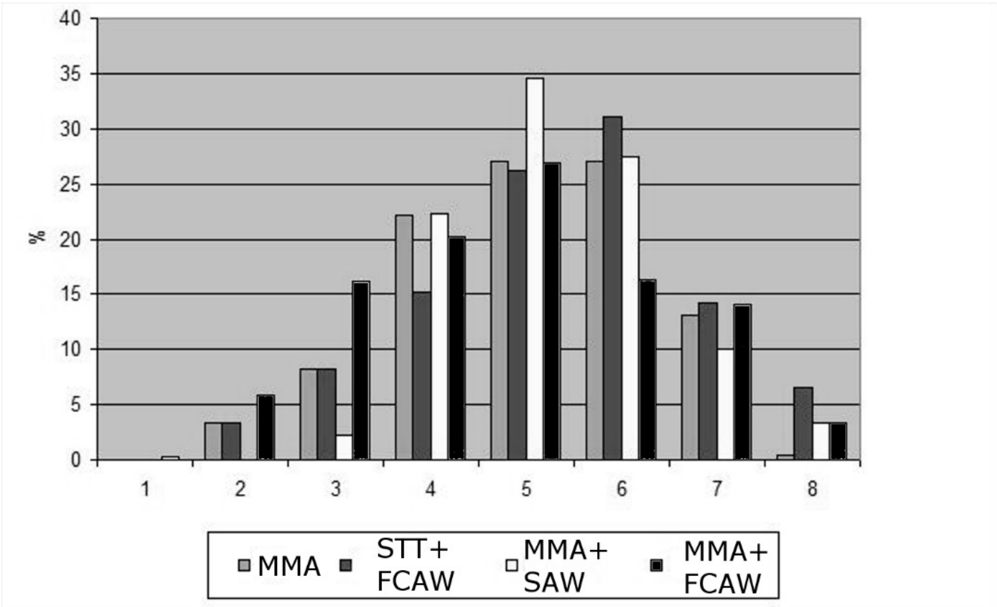


Figure. 1. The concentration of non-metallic inclusions from different size groups in welding joints produced by different ways of welding

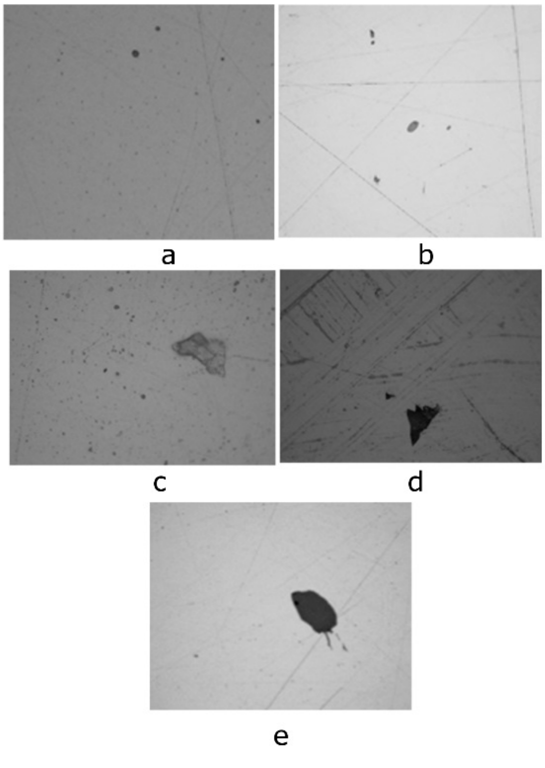


Figure. 2. Non-metallic inclusions investigated by an optical microscope:
a – 1-2 size group (x500), b – 3-4 size group (x500), c, d – 5-6 size group (x1000), e – 7-8 size group (x100)

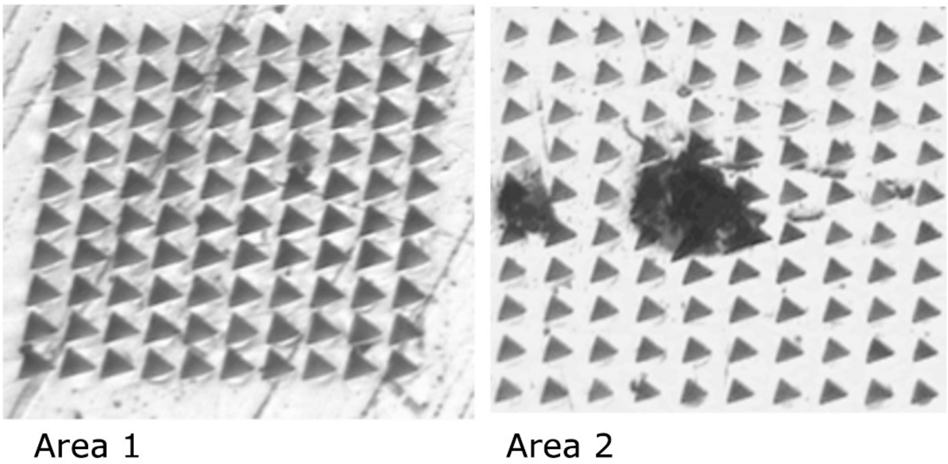


Figure. 3. The area of evaluative nano-indentation on the sample's surface

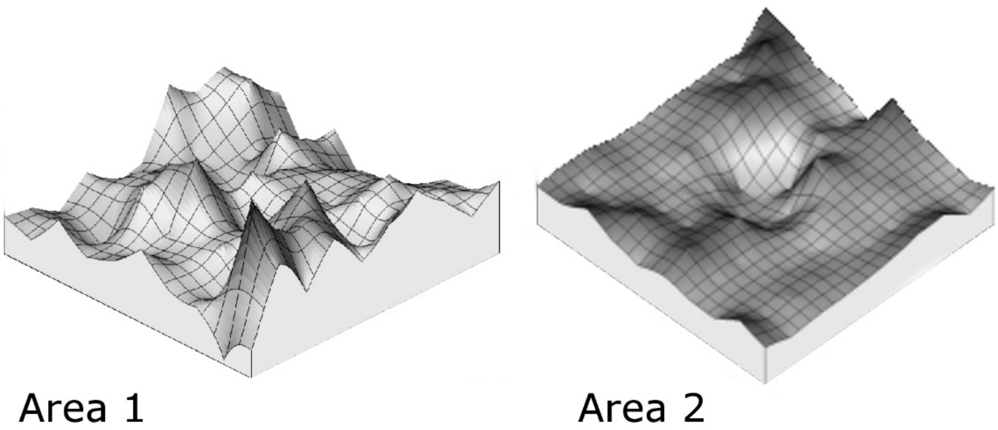


Figure. 4. The distribution of hardness on the surface of the investigated areas

According to studies [4], [5], non-metallic inclusions from different size groups correspond to different structure and composition types. For example, inclusions of groups 1-3 often have an amorphous structure and consist of silicon dioxide, inclusions of groups 4-6 often have a crystalline structure and consist of complex silicate compounds, the largest inclusions of groups 7-8 often contain sulfur.

The inclusions of groups 1-2 have a spherical shape (fig. 2, a), inclusions of groups 3-4 have an oval shape (fig. 2, b), inclusions of groups 5-6 have an acute-angled shape (fig. 2, c, d) and inclusions of groups 7-8 have a soft shape with a visually detected structure (fig. 2, e).

Inclusions less than 15 mkm (which size was less than the size of inclusions in the first size group)were investigated with the help of X-ray methods, and the results of those studies are shown in table 2.

Among the smallest inclusions the following types can be singled out: sphere-shaped (tab.2, a), sphere-two-phases (tab.2, b), acute-angled (tab.2,c) and compared (tab. 2,d). On the surface of some inclusions there are pores, the size of pores is equal to 50-60 nm. In some cases, small spaces between metal matrixes and inclusions were discovered. It can be explained as the shrinking of liquid inclusions in the process of pipes' cooling right after forming operations in the process of manufacturing. This empty space between a metal matrix and an inclusion provide the inclusion with the opportunity to move in the body of a pipeline under the working load.

The composition of inclusions was determined with the help of a microprobe method. The sphere-shaped inclusions have a mixed composition amorphous phase and a crystalline phase, which is closer to sepiolite - $(Mg_{2.792}Fe_{0.218}Ni_{0.015983}Cr_{0.002})_{3.025}[Si_3,O_{11}]$; the oval-shaped consistof two amorphous phases; the acute-angled-shaped are close to bronzite $(Mg_{1.616}Fe_{0.449}Ni_{0.012}Mn_{0.004})_{2.081}[(Si_{1.929}Al_{0.025}Cr_{0.002})_{1.956}O_6]$; soft shaped consist of different phases including a mineral with the high concentration of sulfur (anhydride-$CaSO_4$, melanterite -$FeSO_47H_2O$, astrakhanite-$Na_2Mg[SO_4]_4H_2O$), halite –NaCl, silicates and aluminosilicates.

The results of experiments show, that non-metallic inclusions whose size is less than 15 mkm can influence the development of fatigue stress as well as the concentration of inclusions, which is controlled by standards.

Therefore, nano-indentation experiments were made with non-metallic inclusions of two types: of the size more than 15 mkm and less.

The method of nano-indentation implies a step by step implantation of a microscopic indenter into the part of the surface of samples with a visible inclusion. The indenter is a diamond pyramid.

The plottage of the sample's surface, which gave us the basis for the evaluation, was equal to 90x90 mkm. The load was equal to 100 kN for each implantation. The results of nano-indentation are the maps, which visualize the distribution of valuation hardness and elastic modulus on the investigated surface's parts. Such way of experiments gives opportunity to assess the hardness and elastic modulus of inclusions and of the metal matrix around inclusions. We show typical results on fig. 3 and 4.The experiments were made with non-metallic inclusions of the size less than 15 mkm (area1) and more than 15mkm (area2).

4. Conclusion

The hardness of non-metallic inclusions of the size less than 15 mkm is 2.64 ÷ 3 GPa, elastic modules 525 ÷ 580 GPa. The hardness of non-metallic inclusions of the size more than 15 mkm is 1.32 ÷ 1.00 GPa, elastic modules 147 ÷ 95 GPa. The hardness of steel metal matrix is 1.5 ÷ 2 GPa, elasticmodules 465GPa.

The empty space on the metal/inclusion border plays the role of an additional agent and creates conditions for micro impact of inclusion on metal in the process of workand this circumstance must be taken into account at math simulation.

The interconnection between the size, shape and composition of non-metallic inclusions prove that inclusions from different size groups have different characteristics (physical, mechanical etc.) and have different behavior while a pipeline is working. It means that non-metallic inclusions classification can be organized in accordance with the kind of mechanical characteristics' level.

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