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EFFECT OF ION AND ELECTRON BEAM AS WELL AS ULTRASONIC TREATMENTS ON STRUCTURE AND PROPERTIES OF 12Cr1MoV STEEL

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Abstract: *Investigations of structure and mechanical properties of heat resistant 12Cr1MoV steel after ion-beam, electron-beam and ultrasonic treatments were carried-out. The comparison of changes to take place under various types of surface modification and their influence onto fatigue durability of the heat-resistant 12Cr1MoV steel was performed.*

Key words: surface, steel, treatment, fatigue

1. INTRODUCTION

The vast majority of products and machine parts under operation experiences cyclic loads that can give rise to fatigue failure. In this regard, one of the most actual problems in mechanical engineering is development of technique for increasing fatigue durability of materials [1].

The method based on ion implantation technique as well as installation for vacuum arc treatment was developed in ISPMS RAS that allows by beam irradiation of metal ions to modify the surface layer structure at the depth of several microns. It is more than an order higher as compared to the traditional modes of ion implantation [2]. It is of scientific and practical interest to study the influence of this type of treatment on changing the structure and mechanical properties (including fatigue life) of a number of structural steels used in the industry. Preliminary studies have shown technological prospects of zirconium ion beam for surface modification.

Heat-resistant 12Cr1MoV steel was chosen as an object of the study. One of the main reasons of fracture of machine parts made of this steel is fatigue fracture due to thermomechanical effect [3]. Thus, the development of methods for increasing fatigue durability as well as study of mechanisms responsible for deformation and fatigue fracture of surface modified 12Cr1MoV steel is an actual problem.

The effect of ion-beam vacuum arc treatment (IBT) on the structure and mechanical properties of 12Cr1MoV steel is offered to compare with two other types of surface modified techniques such as electron-beam (ELT) and ultrasonic (UST) treatment. The purpose of the study is to compare the effect of ion beam treatment on the structure and fatigue life of 12Cr1MoV steel with an electron-beam and ultrasonic ones.

The aim of this work is to study the relief and the methods of its technological and operational formation.

2. OBJECTS AND METHODS OF RESEARCH

Heat resistant 12Cr1MoV steel is intended for the manufacturing of parts and products of power equipment to operate at the temperature range of 570...585 °C. Standard thermal treatment for this steel is normalization (960...980 ºC) and a subsequent high-temperature tempering (740...760 ºC). Specimens of 12Cr1MoV steel for testing were cut out from a pipe fragment by the electric spark method. The specimens have the shape of rectangular plates of 70×10×1 mm with a stress concentrator in the form of central hole with the diameter of 2 mm. Static tension tests were carried-out at electromechanical testing machine *Instron 5582*. Cyclic tension tests were performed at the servo-hydraulic testing machine *Biss UTM 150*.

Ion-beam treatment. Vacuum-arc ion-beam treatment (IBT) of specimens was performed with the use of high-current vacuum-arc source of metal ions on the installation *UVN-0.2 Kvant* (Table 1) [4]. The rotation of the specimens during irradiation was realized by planetary scheme where each specimen is rotated either around its own as well as general axis. According to the pyrometry data the surface of specimen during irradiation experienced short-time heating up to the temperatures of 700...900 °C. Time of the treatment by the ion beam made ~4 minutes at the entire time of specimen exposure in the chamber of 18 minutes. In this regard, it can be said that in addition to the irradiation, the specimens experienced cyclic thermal effect that would lead to structural changes not only in a thin surface layer, where zirconium ions can penetrate. The loading parameters at fatigue cyclic tension tests are: the maximum load was 320 MPa, the minimum one – 115 MPa.

Electron-beam treatment. The irradiation was carried-out the use of the device *ELS 0.5–6*. Surface modification was performed by a direct electron beam with longitudinal movement relative to the axis of specimens. The electron beam was defocused across its width. Parameters of the treatment are given in Table 1. Fatigue tests were fulfilled with the cycle asymmetry *Ra*=0.1 at the maximum load of 320 MPa and frequency of 20 Hz.

Ultrasonic treatment. The modification of specimens was performed with the use of industrial equipment for ultrasonic impact treatment, which includes: IL4 generator and a working unit that converts electrical oscillations into mechanical ones. Fatigue test parameters were the same as those described for the specimens subjected to EBT.

Table 1. Parameters of ion-beam and electron-beam treatment of steel

IBT	Current I, A	Voltage U, V	Speed of rotation, ν_{rot}, rev/min		Time t, min	Pressure P_{Ar}, Pa
	100	–900	0.5		18	0.007
ELT	U, kV	I, mA	F, cm	I_{focus}, mA	V, m/s	Cooling media
	28	30	17	380/551	15	Air

3. RESULTS AND DISCUSSION

Metallography. The microstructure of the specimen in as-received state possesses ferrite-pearlite structure shown in Fig. 1, a. As the result of the **ion-beam treatment** not only a thin surface layer to be formed due to the penetration of zirconium ions was modified. The underlying layers including the core were modified as well. The increase of the grain size form 27±3 µm for the specimens in the initial state up to 48±6 µm in the surface layer with the depth up to 130 µm (Fig. 1, b) of the irradiated specimens evidences for the heating to high temperatures (up to ~900 °C). Heating to the pointed temperature during the ion beam treatment and partial subsequent cooling should give rise to thermal cycling. Such periodic heating and cooling to take place under IBT of 12Cr1MoV steel have led to the formation of ferritic-sorbite structure in the core of the specimens, that was accompanied by reducing the grain size by 33 %.

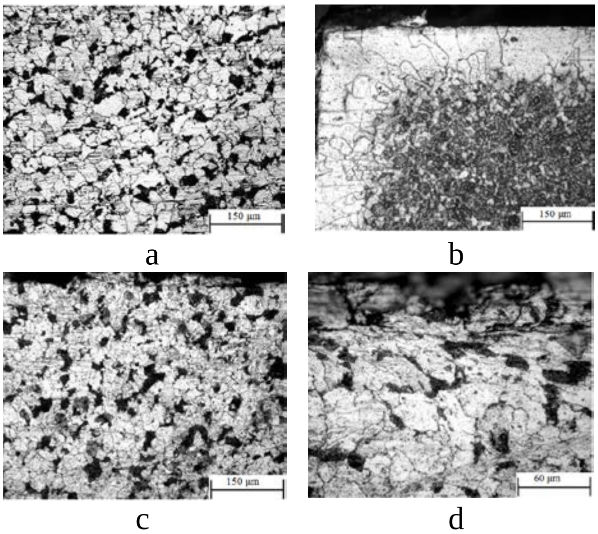

Fig. 1. Optical micrographs of cross-section of specimens 12Cr1MoV steel: a – as-received state; b – after the IBT; c – after the ELT; d – after the UST

Average size of ferrite grains after the **electron-beam treatment** was 24±2 µm which is by ~11 % less than that of the specimen without the treatment. There are no obvious marks of modified layers formation being judged by the optical micrographs of cross-section at used magnifications (Fig. 1, c). **Ultrasonic treatment** has led to deformation of grains and formation of texture in the surface layer at the depth of 50...60 µm (Fig. 1, d).

Microhardness. In the specimen subjected to the **ion-beam treatment** surface layer softening to the depth of ~100...150 µm is observed while at the greater depth the microhardness has increased by ~20 % (Fig. 2, a, Table 2). Microhardness after the **electron-beam treatment** increased by ~7 % (140 MPa), and this change occurred uniformly over the entire bulk. Since the specimen had small cross-section it can be expected that heating during the irradiation was uniform. Thus, this processing type cannot be regarded as a surface modification one but rather the technique of thermal treatment. It is similar to the normalized annealing or normalization. The depth of the hardened layer after the **ultrasonic treatment** was about 50...100 µm, which is quite consistent with the data on cross section microstructure.

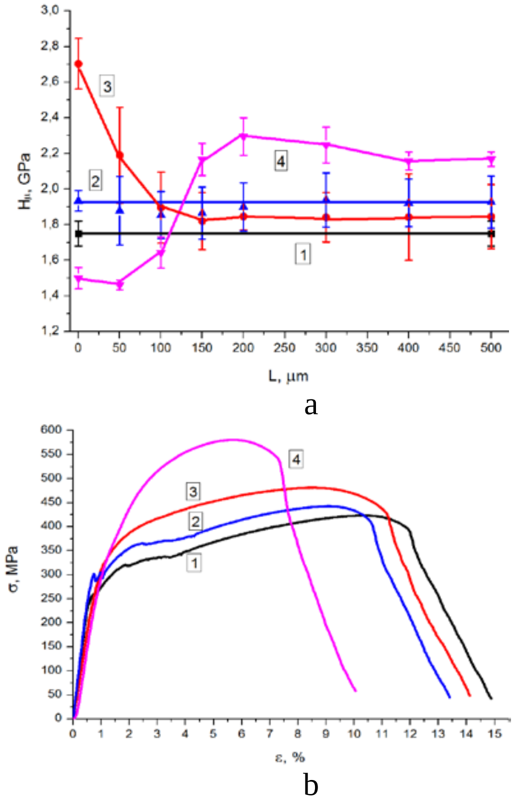

Fig. 2. Microhardness changing as a function of distance from the surface of 12Cr1MoV steel specimen (*a*); stress-strain curves for the specimens (b): 1 – as-received state; 2 – after the ELT; 3 – after the UST; 4 – after the IBT.

Static tension tests. Fig. 2 shows the loading diagram of 12Cr1MoV steel specimens (see Table 2 as well). After the **ion-beam treatment** an increase in the tensile strength of irradiated steel by $\Delta\sigma$ = 155 MPa (↑ 28%) is revealed. The **electron beam treatment** leads to the increase in tensile strength from σ = 425 MPa up to 440 MPa (~↑ 4%) and to the decrease in elongation from ε=15 % to 13.5 % (~10% ↓). Thus, the comparison of data of the structure, microhardness and mechanical properties have shown that the increases of the strength of 12Cr1MoV steel after the EBT is related to the thermal influence during irradiation, which is similar to normalization. After the **ultrasonic treatment** tensile strength has increased to 480 MPa (by ~11 %) while the elongation decreased by ~14 %. Thus, the ultrasonic impact treatment of 12Cr1MoV steel has led to a pronounced increase in yield stress as compared to the specimens after the EBT.

Table 2. Mechanical properties of 12Cr1MoV steel after various treatments under study

Type of speci-mens	Micro-hard-ness, GPa	Chan-ges	Tensile strength, MPa	Elonga-tion, %
Initial state	1.75 ±0,07	–	425	15
After ELT	1.92 ±0.1	Increa-se by 9%	440 (↑4%)	13.5
After UST	2.7 ±0.1 (surface)	Increa-se by 35%	480 (↑11%)	14.0
After IBT	1.5±0.06 (surface)	Decrea-se by 14%	580 (↑28%)	14.0

Table 3. Results of fatigue test

Modifi-cation	Specimen	Number of cycles prior to failure, $\times10^3$	Chan-ges
IBT	Without treatment	127±0.6	–
	After IBT	232±32.6	↑ 45%
ELT and UST	Without treatment	69±6.8	–
	After EBT	101±30	↑ 32
	After UST	115.7±5.7	↑ 40%

Cyclic tension tests. Results of the test are given in Table 3. According to the presented data the **ion-beam treatment** ensures two-fold increase in the number of cycles prior fracture, while the time before the main crack nucleation was also increased by ~2 times. Analysis of the graph to illustrate the dependence of crack length vs the number of cycles has shown that the main reason relates to the time of initiation and growth rate of the main crack. Increased fatigue life after the e**lectron beam treatment** is caused in the first turn by improving the mechanical properties of steel that occurred as a result of microstructure changing. The main reason for increasing the number of cycles before fracture after the **ultrasonic treatment** is increased mechanical properties of the surface layer, which should suppress fatigue cracks origin.

4. CONCLUSIONS

Ion-beam treatment. It is shown, that the result of Zr ion-beam treatment of 12Cr1MoV steel specimens with the thickness of 1 mm is the structure modification that occurs across the entire cross section. There is a decrease of microhardness in the surface layer to the depth of 130 μm while in the core, it is somewhat higher in contrast with non-treated specimen.

At cyclic tension tests there was shown that the structure modification resulted in delay of nucleation and growth of the main fatigue crack. As the result, an increase in the fatigue life of the irradiated specimen of steel 12Cr1MoV was made up to 2 times.

Electron-beam treatment. This regime of 12Cr1MoV steel specimen's treatment gave rise to structure modification over the entire cross section of thin specimen that was found through microhardness measurement. As the result, the tensile strength was increased while the value of elongation at break was reduced. The fatigue durability as compared to specimens in the as-received state has enhanced by 30 %. This type of treatment cannot be regarded as surface modification, as the structure changes occurred over the entire section of the specimen.

Ultrasonic impact treatment. Ultrasonic treatment under used mode of the treatment resulted in a marked increase of the microhardness in the surface layer at the depth of 50...100 μm while keeping constant its value in the core. The resultant surface hardening has led to the higher flow stress, tensile strength as well to a slight decrease in the value of elongation at break. Implemented structural modification ensures hindered initiation and development of main fatigue cracking that enhanced the fatigue life by 40 %.

The revealed variation in fatigue durability increase of 12Cr1MoV steel specimens under the various treatments (by 2 times at the ion beam, by 30 % at the electron-beam and by 40 % at the ultrasonic impact one) is related to the intensity of plastic deformation process development in the surface layer that are characterized by gradient nature of the microhardness change that can delay the nucleation and propagation of (micro)cracks.

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