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INFLUENCE OF PARAMETERS OF ULTRASONIC MECHANICAL OSCILLATIONS ON THE STRUCTURE AND MECHANICAL PROPERTIES OF WELD METAL IN LASER WELDING OF FERRITIC STEELS

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The problems of welding pool control in welding of ferrite stainless steels were considered. A comparative analysis of the works in the field of effect of ultrasonic and vibration oscillations on the weld was carried out. The results of preliminary experimental and metallographic examinations of specimens of joints produced by laser welding with additional ultrasonic effect on welding pool were reflected. The effect of positioning of clamps and the source of ultrasonic waves relative to the butt interface on the character of oscillations arising in it was studied. The most favorable frequencies and amplitudes of oscillations for generation of oscillations in the butt area were determined. The results on influence of the material thickness on the oscillations arising in it were obtained, which can exert an effect on stability and cooling rate of welding pool and, as a result, on the microstructure of weld metal. 11 Ref., 1 Table, 5 Figures.

Keywords: *laser welding, ultrasonic waves, ferrite stainless steels, welding pool, microstructure*

Ever often for welding of ferrite stainless steels the modern lasers, such as fiber or disc ones, are applied. This minimizes the thermal deformations of the structure at high welding speeds and subsequent treatment of welds, making stages of production shorter. However, in welding of these steels there are problems of increased tendency of welds to intercrystalline corrosion (ICC) and reduced mechanical properties (strength and hardness) as compared to the base metal. Traditionally, the following methods are used to prevent the problem of ICC: stabilization (Ti and Nb alloying), reduction of carbon content in steel to the value lower than 0.03 % or heat treatment. The technologies of stabilization and reduction of carbon content in steel are cost consuming, and the heat treatment is a power intensive and environmentally unfriendly process requiring large industrial areas. In this regard, the researchers attempted to create the more simple methods for solution of the problem. Among the methods the vibration or ultrasonic oscillations of welding pool during welding process may be used, however it is not completely clear what are the capabilities of application of this additional source for the control of weld properties.

The aim of the present investigations was the study of effect of positioning of the source of ultrasonic mechanical oscillations and clamping devices on formation of oscillations in the area of welded butt for the control of formation of the microstructure of weld metal in the laser welding of ferrite stainless steels, at the same time improving its mechanical, metallurgical characteristics and reducing the tendency to ICC.

Analysis of investigation results from the materials of published works. In the investigations of effect of mechanical oscillations in the welding pool on reducing the tendency to ICC the scientists in Ufa were involved [1–3]. They came to the conclusions that the vibration and ultrasonic impact treatment in the process of welding allows increasing the resistance of the welded joint metal of austenitic stainless steel 12Kh18N10T to ICC. The ultrasonic impact treatment at the frequency in the range of 25–27 kHz increases the resistance to fatigue fracture by 24–26 % as compared to the vibration one. The latter allows decreasing the grain size, which contributes to the formation of a more uniform structure in the weld metal. In the works [4, 5] it was shown that the ultrasonic mechanical oscillations in laser welding of high carbon steels result in the displacement of different layers of metal in the welding pool. The molten metal is moved to the edge of the melt pool, which indicates about the elasticity of the pool. The effect of oscillations on the weld shape and distribution of elements in it was established. The forces acting on the molten metal during ultrasonic oscillations improve the contact between the melt pool and the solid substrate, which depends on the welding speed and acoustic power.

In the course of this effect the molten metal is located symmetrically around the vertical axis of the weld symmetry. From the center of welding pool it is forced out to the edges resulting in a deep penetration and forming hemispherical areas with a slight inclination in the regions of a central hemisphere in the melt pool. The application of ultrasound improves mechanical properties of the weld metal during its crystallization due to refinement of structure and better removal of gases.

Typically the frequency range of 18–80 kHz is used. Such oscillations allow welding metals with an oxidized surface, covered with a layer of lacquer, etc., reducing or relieving residual stresses arising at that time. Applying ultrasound it is possible to stabilize the structural components of weld metal, eliminating the probability of spontaneous deformation of welded structures with time [6, 7]. At the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the RAS the investigations of effect of ultrasound on improvement of plastic properties of the joints were performed. As a result of experiments the yield strength and ultimate rupture strength were not significantly changed, but the plasticity increased to more than 20 % [8]. From the literature sources it is known that it is possible to obtain longitudinal, transverse and torsional oscillations depending on design of the waveguide and fixation of the tool in the welding zone. Their amplitude is usually in the range of 10–30 μm [9, 10]. From the aforesaid it is seen that the ultrasonic mechanical oscillations have a strong influence on the properties of the weld being produced, but, unfortunately, the effect of positioning of the source and clamping devices relative to each other and the butt on the value, quality and depth of the effect created in the welding pool was not completely studied. Due to this there is no complete understanding of the processes occurring here.

Experimental investigations and analysis of the results. As experimental specimens the plates of the size of 100×100×2 mm of ferrite stainless steel of grade 1.4016 (Kh6Cr17) of the following chemical composition (mass.%.): 0.08 C; 1.0 Si; 1.0 Mn; 0.04 P; 0.015 S; 16–18 Cr were used. According to BS EN 10088-1:2005 [11] the chemical characteristics of this grade are the following: $\delta = 20$ %; $\sigma_{0.2} = 260$ MPa; $\sigma_t = 400$–630 MPa; HV 126–197.

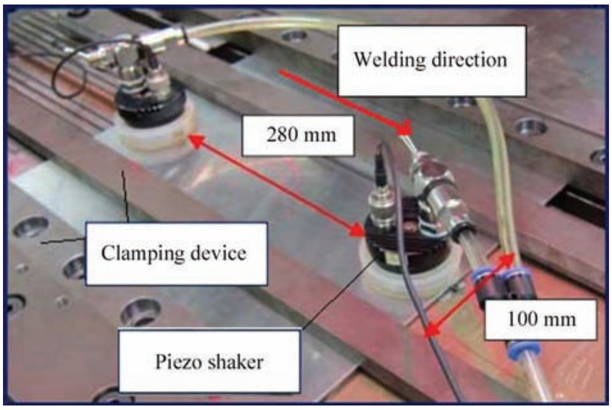

Figure 1. Appearance of specimens with fixed piezo shakers before laser welding

To check the effect of oscillations on properties of metal of the produced weld, caused by ultrasound, the preliminary experiments on laser welding were carried out. The experimental stand, designed on the basis of the technological complex for laser welding of Reis Company, was applied. As a radiation source the ytterbium fiber laser of the model LS-10 was applied produced by the Company IPG Laser GmbH (Germany) with the maximum output radiation power of 10 kW, and for its supply to the surface of welded specimens the laser head of the model MWO 54 of the Company Laseroptik REIS Lasertec was used, equipped with the air cross jet for protection of the optics from vapors and metal spatters, with a focusing lens having a focal distance of 300 mm and a beam diameter in the focus df 0.4 mm. The movement of specimens relative to the laser beam was carried out by means of the four-axis manipulator of the Company Reis. To create oscillations two piezo shakers of the model PS-X03-6/500 of the Company Isi-sys GmbH (Germany) with the oscillation frequency F in the ranges of 0–30 kHz and the amplitude of oscillations controlled in the range of 0–5 V were used, fixed on the surface of specimens. The specimens themselves and two piezo shakers were fixed on the manipulator axis by means of the specially manufactured technological rigging. The welding was carried out along the straight trajectory with a pitch of 15 mm to the both sides from piezo shakers. At first the welds without oscillations and then with added oscillations were produced. The arrangement of piezo shakers on specimens during the experiments is illustrated in Figure 1.

As a result, several welded butts of joints with and without the effect of oscillations in the area of a butt were produced. At the same time the power of laser radiation P (kW), welding speed v (m/min), focus position relative to the surface of specimens being welded zf (mm) were selected to provide a through penetration. From the produced welds the specimens were cut and metallographic sections were manufactured to study microstructure using the microscopes Leica Z16 APOA and Leitz Ergolux (×1000). Also the mechanical tensile tests in the stand of the model Z100 of the Company Zwick/Roell with the load of up to 10 kN were carried out and the microhardness of weld metal and the adjacent area were measured according to Vickers method at the load of 1000 N in the automatic durometer UT200 of the Company BAQ. The microstructure of the produced specimens is shown in Figure 2. The character of fracture of specimens

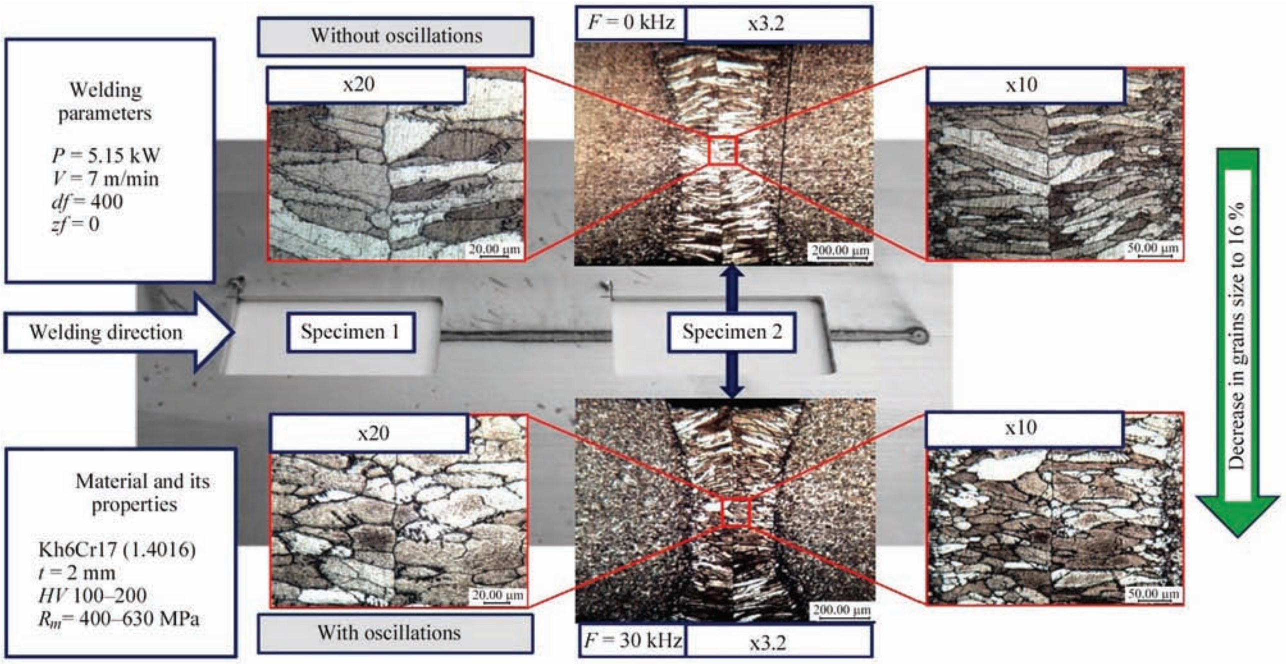

Figure 2. Microstructure of welds after laser welding without and with additional mechanical oscillations generated by piezo shaker

after tests and the results of measurement of microhardness are shown in Figure 3. In order to obtain a more detailed representation about the influence of oscillation parameters and intensification of the effect the investigations were carried out which allowed determining the optimum position for piezo shakers and clamps relative to the future welded butt. The experimental stand was designed consisting of the chamber for shearing speckle-interferometry (shearography), equipped with the system of diode laser illumination, piezo shaker of the model PS-X03-6/500, amplifier of piezo shaker signal of the Company Isi-sys GmbH and vacuum pump, which provides the fixation of piezo shaker at the surface of specimens.

In the course of these experiments the natural oscillations of the specimen surface, generated by piezo shaker, were registered. In order to develop the concept of the optimal position of piezo shakers the influence of the following factors on the formation of mechanical oscillations was studied: the parameters of the piezo shaker itself (amplitude of oscillations A (B), determined by the supplied voltage, the oscillation frequency f (kHz), generated by piezo shaker; position of piezo shaker relative to the butt (the distance between the edge of piezo shaker and the butt ×1 (mm) and relative to the edge of the specimen $y1$ (mm), and the location on the facial or rear side of the specimen); thickness of the specimen h (mm), arrangement of clamps on the numbers 1–4 relative to the edges of specimen and future butt (Figure 4). During the experiments, the clamps 1 and 2 changed their position relative to the butt, it was determined by the distance between the clamp center and the butt interface ×2 (mm). Before the beginning of experiments the surface of the specimen was coated with a thin layer of white paint, intended for shearography, which

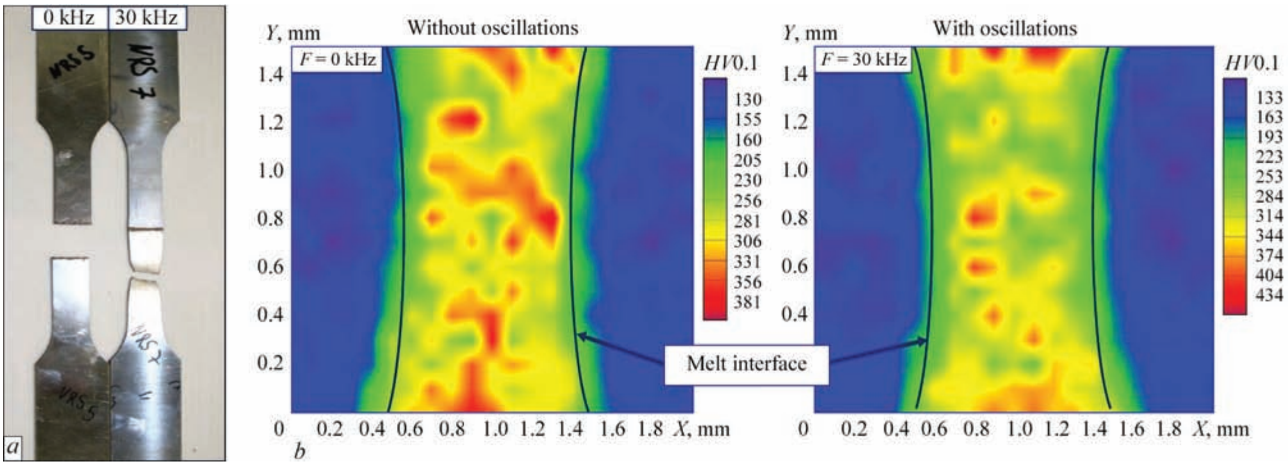

Figure 3. Results of mechanical tests: a — character of fracture of specimens during tensile tests; b — results of measurements of microhardness

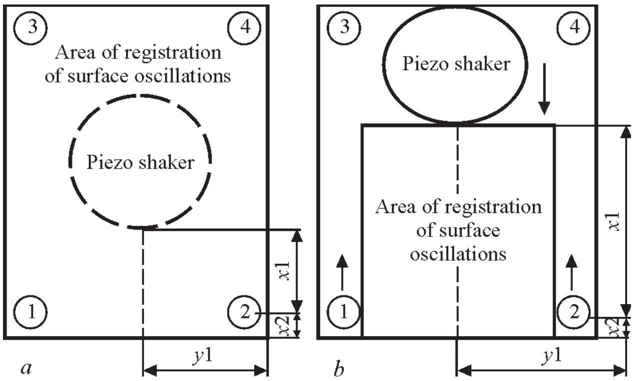

Figure 4. Scheme of arrangement of piezo shaker and clamps (1–4) relative to the specimen surface: *a* — from the rear side of the specimen without movement; *b* — from the facial side of the specimen with change of its position and also clamps 1 and 2

reduced reflection and enabled the receiving of a more distinct signal. The scheme of arrangement of a piezo shaker and clamps 1–4 is given in Figure 4. The arrows indicate the directions of change in the position of piezo shaker and clamps 1 and 2. The edge of the specimen closest to the observer was considered to be the interface of the future butt.

The results of measurements of ductility and microhardness of the weld metal of specimens (see Figure 2) obtained without the influence of oscillations: $\delta = 15$ %; *HV*0.1-205–381, after additional oscillations with a frequency of 30 kHz, $\delta = 40$ %; *HV*0.1-223–434.

The results (see Figure 3) indicate about the effect of mechanical oscillations, generated by means of ultrasound, on the properties of a weld (ductility and microhardness). Mainly microhardness of weld metal after the use of additional mechanical oscillations became more uniformly distributed within the limits of *HV* 284–314, whereas previously a large number of chaotically distributed areas with the increased microhardness of *HV* 331–381 was present.

The experiments on shearography were conducted in series changing one of the parameters. In the course of them the oscillation amplitude *A* (3, 5 V), the oscillation frequency *f* ranging from 10 to 30 kHz with a pitch of 100 Hz was changed, the thickness of specimens was changed applied in the range from 2 to 8 mm by combining the plates of 2 mm thickness with each other using clamps, the arrangement of clamps and piezo shaker relative to the specimen surface and the surface itself, where it was located (facial or rear), were changed. The values of parameters of the experiments on shearography are given in the Table.

In welding of the considered steels the weld metal, as a rule, has a ferrite microstructure. This is caused by the lack of α-γ-transformations at 1000 °C, necessary for grain growth. In welding these steels are characterized by the formation of the coarse-grained structure in the fusion zone (see Figure 2, specimen 2, upper), which is impossible to prevent using conventional methods. Usually, after welding a decrease in impact toughness with increasing chromium content in the weld is observed. It results in increased tendency to ICC. As a result of investigations it was revealed that in laser welding of the given steel the ultrasonic waves affect the welding pool, contributing to refinement of the crystal structure of the weld (decrease in the grain size to 16 %) (see Figure 2, specimen 2, lower), resistance to deformations at a lower microhardness and its more uniform distribution in the volume of weld metal due to mixing the melt in the welding pool.

From these experiments it was found that the mechanical oscillations generated by piezo shaker in the specimen, located in the center of the rear side of the specimen, even at the adjusted non-maximal parameters, are distributed for the depth of more than 8 mm. The noticeable areas of oscillations were registered in the area of the future butt at the increase of the specimen thickness from 2 to 8 mm. This will allow applying this method of effect for welding of structures of plane sheets, as far as usually the thickness of sheet of the given steel does not exceed 8 mm. The most stable and strong oscillations in the area of a butt at the location of piezo shaker at the facial surface of specimen occur at the frequencies of 13.4; 18.6 and 24.7 kHz. The greatest effect on the interface of the

Parameters changed in the course of experiments on shearography of specimens produced applying ultrasonic oscillations

Number of series of experiments	Arrangement of piezo shaker relative to the specimen	Arrangement of piezo shaker on the specimen surface (*x*1; *y*1), mm	Thickness of specimen *h*, mm	*A*,V	Position of clamps *1* and *2* (*x*2), mm
1	Rear side of specimen	In the specimen center	2	3	5
2			2 + 2	3	5
3			2 + 2 + 2	3	5
4			2 + 2 + 2	3	5
5	Facial side of specimen	5–45 (with a pitch of 10); 50	2	3; 5	5
6		15–45 (with a pitch of 10); 50	2	3; 5	10
7		15–45 (with a pitch of 10); 50	2	3; 5	15
8		15–45 (with a pitch of 10); 50	2	3; 5	30

Note. Frequency of ultrasonic oscillations *f* in all the experiments varied from 10 to 30 kHz (with a pitch of 100 Hz).

future butt is exerted by the frequency of 18.6 kHz. With increase in the oscillation amplitude from 3 to 5 V, the effect was increased slightly. When piezo shaker approaches the butt interface, the oscillations, arising in it, were disintegrated into pieces, but at the same time they were united from the separate zones into a new small one. The removal of clamps 1 and 2 from the butt interface leads to weakening of transfer of oscillations from piezo shaker and, consequently, weakening of the registered signal. As far as during welding the close arrangement of clamps and piezo shakers is not desirable to provide their preservation, the minimum possible distance for realization of their functions, namely 15 mm from edge of the butt, was selected.

To continue the further experiments on laser welding, as an optimal combination the following parameters, associated with mechanical oscillations, were selected: the oscillation frequency is 18.6 and 24.7 kHz; the oscillation amplitude is 5 V; the shaker position relative to the butt range from 15 to 25 mm; the positions of clamps relative to the butt are not more than 15 mm.

The example of registration of oscillations in combination of such parameters is shown in Figure 5.

In the Figure a change of color contrast of the occurred oscillation areas in the butt area as well as their packing are seen, which indicates about a large value of the influence exerted on the future welding pool by them.

In conclusion, the following should be noted. The experimental stand for laser butt welding with effect of ultrasound on the welding pool was designed. The investigations of vibration characteristics of ferrite stainless steel 1.4016 were carried out. The following optimal parameters for generation of maximum mechanical oscillations in the area of a butt were determined: the frequency is 18.6 kHz; the oscillations amplitude is 5 V; the position of piezoelectric shaker relative to the butt is 15 mm; the arrangement of clamps relative to the butt is 15 mm. It was found that in welding the use of oscillations of welding pool has a positive effect on the formation of fine-grained structure or decrease in the grain size, leading to increased resistance to deformations at a lower microhardness of weld metal. The effect of these oscillations on the degree of mixing the melt was noted, which is confirmed by obtaining a more uniform structure in the weld and a uniform distribution of microhardness in it.

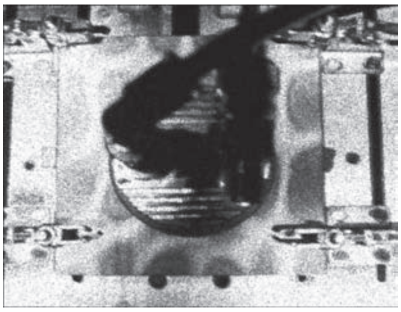

Figure 5. Registered oscillations of the specimen surface at the oscillation frequency of piezo shaker of 18.6 kHz and at the amplitude of 5 V, at the 15 mm distance between the interface of the future butt and piezo shaker, at the 15 mm distance between the interface of the future butt and the center position of the clamps

The results can be applied in the further investigations on laser welding of steels of a similar class, as well as transfer them for duplex stainless steels and fine-grained steels, or to take them into account for the joints of other type and thickness.

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