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APPLICATIONS OF OPERATIONAL ULTRASONIC IMPACT TREATMENT (UIT) TECHNOLOGIES IN PRODUCTION OF WELDED JOINTS

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A. INTRODUCTION

The first results of investigating the influences of ultrasound on ductility and strength properties of steel and alloys were published in the late fifties [1] and during the sixties [2, 3]. At the same time the first attempt was made to control the deflected mode of a welded joint through its deformation treatment employing ultrasound [4].

The follow-up to this work found itself in machine building industry in the field of mechanical treatment [5, 6]. Attempts to apply ultrasound in welding were not successful at that time. The main problem was in the design of an operating tool and the rigid constraint of its waveguide with a working deforming element (an indenter). This solution limited the possibility for effective deformation treatment of an uneven weld surface. In addition, power characteristics of the ultrasonic equipment, its low specific power and big weight also failed to allow for development of mobile processing equipment meeting the specific requirements of welding production. During the seventies, when working on problems of relaxation of residual stress and of increase in corrosion-fatigue strength of welded joints, we succeeded in optimization of power and weight/size characteristics of the ultrasonic equipment as well as in development of an effective connection scheme providing moving constraint between a deforming element and a waveguide [7]. Based on this a set of technical solutions has been found to use ultrasound in welding [8-14].

Further joint studies carried out in the E. Paton Institute made it possible to create new technologies for welded joint fatigue life improvement at varying loads. Before we already had an opportunity to describe these results which mostly were achieved in the eighties and the nineties [15].

This document contains the information on a little-known application of ultrasound for control over welding stress and deformation, and for increase in corrosion-fatigue strength and cold-resistance of welded joints.

B. METHOD FOR ULTRASONIC IMPACT TREATMENT OF WELDED JOINTS

Experiences on production and use of welded structures shows that their quality is influenced by:
- load-carrying ability being the major reliability criteria;
- fatigue strength or fatigue limit of a welded joint being the endurance criteria;
- size stability, level of residual welding stress and deformation;
- corrosion and fatigue resistance in aggressive media at varying load;
- cold resistance.

Studies performed during the past few years have demonstrated the big role that post-weld treatment techniques play in producing high-quality welded structures and their elements when considering the above listed factors [16-19].

In current practice the problem of complex quality of welded joints (welded structure elements) along with the problem of development of the welding processes themselves is solved on a basis of the technology involving sequentially performed operations combining conventional straightening, thermal post-weld treatment including that for reduction in residual stress and strain, mechanical treatment of welds and structure elements, welding deposition of supplementary passes or rewelding of edge passes for formation of chamfers and reduction in concentration of operating stress, creation of favorable compression stress in a surface layer through strain strengthening of a welded joint (pneumopeening, shot peening, etc.).

The proposed UIT method combines the advantages of the above methods and achieves a complex effect of strain strengthening, reduction in welding strain, relaxation of residual stress and reduction in concentration of operating voltage stress in welded structures [20].

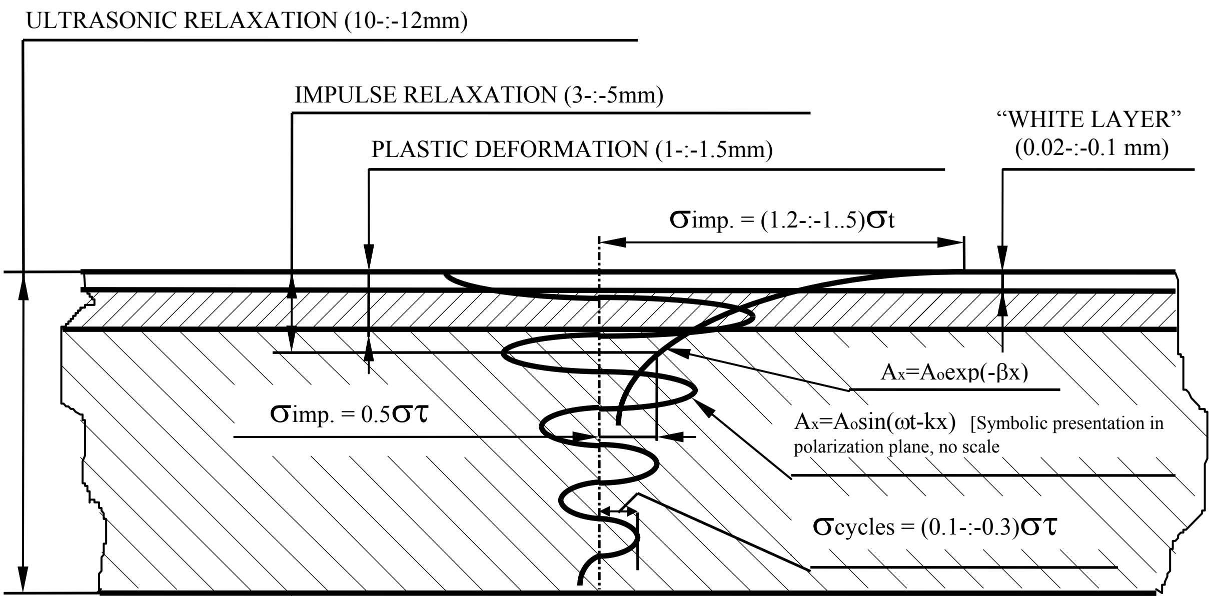
The method is based on instrumental conversion of harmonic oscillations of the ultrasonic transducer into peening impulses of ultrasonic frequency and their further conversion into harmonic oscillations of a treated surface and a structure element at an extinction frequency [21].

In the course of this development we achieved the optimization of an active element being a part of the tool which allowed us for minimization of sizes and increase in specific power (4-time increase as compared to the conventional manual tools) [22, 23].

The processing equipment has been developed to implement the UIT technique. The equipment specifications are tabulated below:

Generator:	frequency (Hz)	25-28
	power consumed (kW)	1.2
	sizes(mm)	400x400x200
	weight (kg)	25
Peening tool:	frequency (kHz)	26.9 - 27.2
	Q-factor	100-120
	max. power (kW)	1.00
	amplitude (mm)	40
	length of a connection cable, distance from the current source to work site (m)	40-80
	weight (kg)	3
System sizes, placed in a mobile module and equipped with autonomous power sources (mm)		600x600x600
System weight (kg)		up to 50

The UIT scheme is shown on Fig. 1 and demonstrates the zones of physical action on a welded joint in a cross-sectional view of surface layer of treated metal.



Zones	EFFECT
"White layer"	Wear-resistance, corrosion resistance
Plastic deformation	Cyclic endurance, compensation of deformation, corrosion-fatigue strength
Impulse relaxation	Reduction in residual welded stress and strain of up to 70% of the initial state
Ultrasound relaxation	Reduction in residual welded stress and strain of up to 50% of the initial state

Fig. 1. UIT action physical zones

The study of UIT action physical zones was carried out using rod resonant-frequency samples which were exposed to ultrasonic oscillations with the help of the UIT tool. The samples were made of high-strength steel and titanium alloys. The sizes of the samples are: length (resonance) - up to 150 mm, diameter - 20 mm. The maximum ultrasound displacement and the maximum ultrasound stress zones were formed in these samples by welding deposition method and welding method respectively in argon medium for a depth (height) of 15 mm. After deposition (welding) the samples were exposed to mechanical treatment and subsequent etching for a depth of 0.1 mm to remove a metal layer where plastic deformation occurred. Physical zones shown on Fig. 1 were identified by metallographic and X-ray diffraction analysis methods [24, 25].

The information shown on Fig. 1 and in the accompanied table reflects the results of those studies.

C. UIT IMPACT ON RESIDUAL STRESS AND STRAIN VALUES AT BUTTWELDING OF THICK-WALL PIPES [26]

1. Introduction

Residual stress occurs as a result of non-uniform plastic deformation in the course of cooling down the welds after welding is completed. In addition to technological stress influencing a structure, it is exposed to static and repeated loads. Double-effect produced by external load and internal stress results formation of cracks in welds and near-weld zones. This problem is especially crucial for welding of thick-wall pipes. Conventional technology employs accompanying heating during welding to remove diffusion hydrogen and to form a favorable metal structure and post-weld thermal treatment to remove primary stress. However, when dealing with large-size thick-wall structures thermal treatment is extremely complicated.

The objective of these studies was the evaluation of UIT efficiency in terms of reduction in residual welding stress in multi-layer welds with serial treatment of each layer.

2. Description of Test Setup.

The test setup comprises three pairs of thick-wall branch pipes (models) made of 48TC-3-40, ТУ 428-61-grade steel in an assembly jig (Fig. 2a) with V-shaped grooves ($\angle 60^0 \pm 2.5^0$) for welding and deposited beads (Fig. 2b). Deposition was preceded and accompanied by heating up to t=250÷300°C with UONI (УОНИ) 13/55 electrodes, ∅5 mm.. After deposition each model was exposed to thermal treatment in furnaces at initial t=450°C, temperature increase - up to 660 to 700°C, holding time - 5 hours, cooling off in a furnace - to 200°C and then in the air.

To make the welding convenient the models were previously tacked (Fig. 2c) in several points along the assemblage perimeter and fixed in assemblage jigs (Fig. 2a).

3. Test Preparation

As test preparation resistive-strain sensors were manufactured and calibrated, the pairs with equal temperature characteristics were selected, installed and assembled along with connectors for linking with measurement devices.

12 pairs of resistive-strain high-temperature sensors were installed on each model. To prevent mechanical damage and welding splash the sensors were protected with stainless steel foil. Deformation measurement was performed by ISD-3 device.

4. Model Welding

In the course of welding relative deformation of external surface of models was measured through:

- 5 mm filling of a weld according to groove height,
- 10 mm --------------------"--------------------------
- 20 mm --------------------"--------------------------
- 35 mm -------------------"--------------------------
- 50 mm filling of a weld according to groove height.

The first model was welded according to conventional technology.

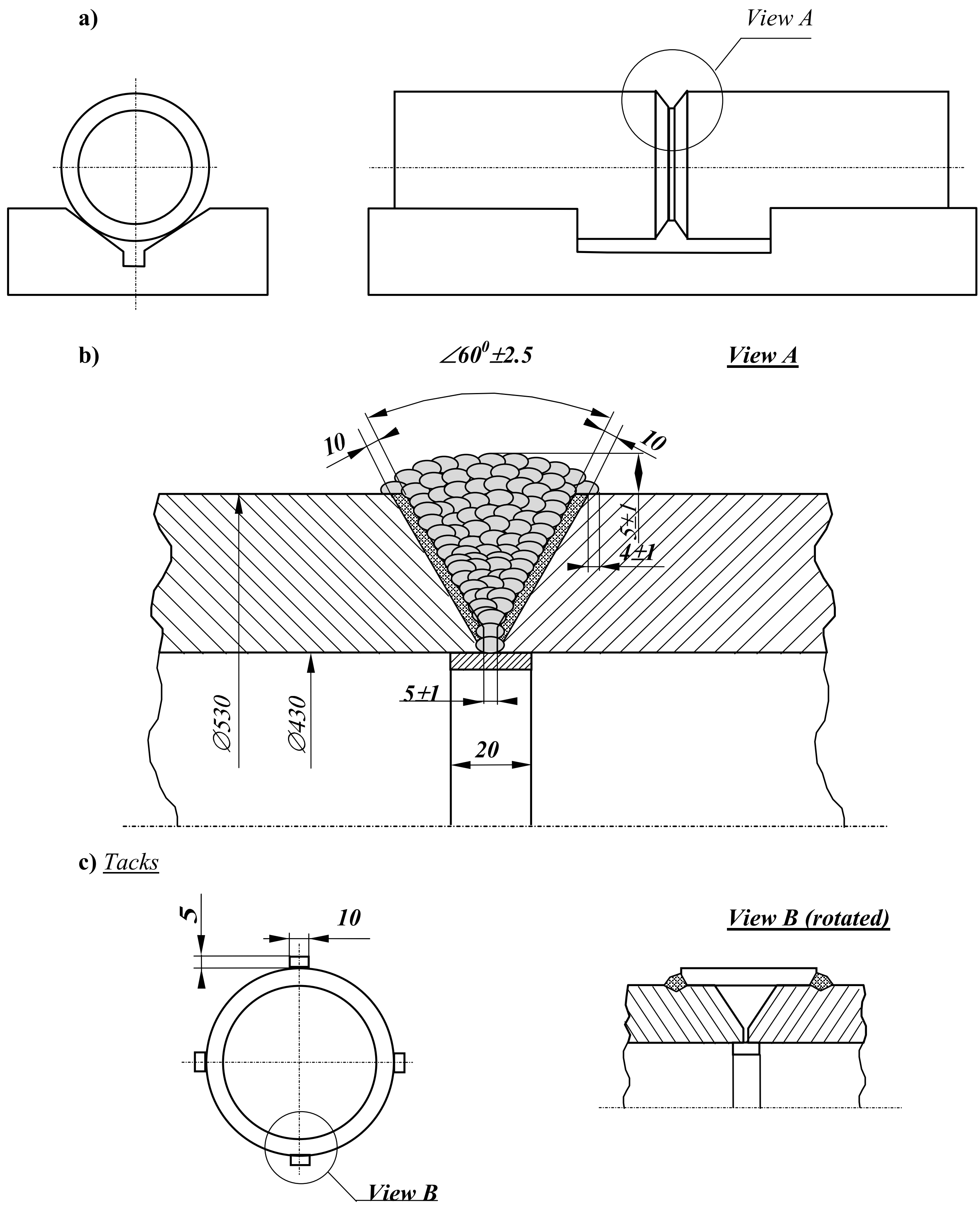


Fig. 2 Setup for UIT Testing

When welding 2nd and 3rd models UIT was performed after deposition of each succeeding layer.

5. *Model Drilling*

The technique for measurement of residual stress is based on measuring deformation during model boring along an internal diameter from their ends. Deformation recording was performed with the help of resistive-strain sensors by ISD-3 device.

6. *Results*

a. Presentation and comparison of results of stress in the process of welding and deformation - in boring were performed on the basis of their mean-square values.

b. The mean welding residual stresses when applying UIT as a comparison to those stresses as result of welding without UIT showed the following reduction in residual stresses:

1) Heat Affected Zone:
   a. Along weld line a reduction of 20%;
   b. Perpendicular to weld zone - 40%.

2) In a weld material:
   a. Along the weld line 45%;
   b. Perpendicular to the weld line 9 times.

c. In the course of conventional welding weld cleaning with an emery grinder was performed before depositing each layer. When applying UIT the welding cleaning was not performed. This was not needed as the UIT treatment is accompanied by simultaneous removal of slag and residual scale.

7. *Conclusions*

a) Welding method with UIT application results in reduction in residual welding stress to the point when it is possible to abandon thermal treatment in furnaces.

b) When using conventional technology a weld is loaded considerably greater that a near-weld area. When using arc welding and layered UIT the load in these both areas is practically the same in terms of maximum axial stress. Therefore, UIT allows for production of a an even strength structure.

c) UIT reduces labor consumption when forming multi-layer welds to 20% dependent on weld metal strength since this method is accompanied by removal of the slag and any residual scale and requires no additional abrasive cleaning of deposited metal.

D. RESIDUAL STRESS AT HIGH-AMPLITUDE UIT TOOL STRENGTHENING WELDED JOINTS OF U3-GRADE STEEL [25, 27]

1. *Introduction*

When manufacturing and repairing ship hulls made of U3-grade steel, shot peening is widely used [28]. This technique, being high-performance one, however, has a number of limitations in efficiency (depth of a strengthened layer) and in mobility when performing treatment in a narrow and hard-to-access areas. The UIT method has none of these shortages [27].

Thorough studies of metal surface layer residual stress distribution diagrams were performed to reasonably select a UIT mode.

2. Procedure [27]

Residual stress was measured through the method of layered metal etch removal in 50% solution of nitric acid according to Davidenkov's formula transformed -for flat plates of 120×35×6 mm in size [29]. In addition, the samples of 120×15×6 mm in size were measured for residual stress through the method of electrochemical metal etch removal using automatic equipment.

An electrical part of the unit is based on PS-1 (ПС-1) potentiometer providing automated recording ofresults (Fig.3). A balance of strain sensors is assembled with resistance of R_a=$R_к$=200 Ohm. Etching was made using orthophosphoric acid-70%, chrome anhydride-0.5%, water-29.5 %.

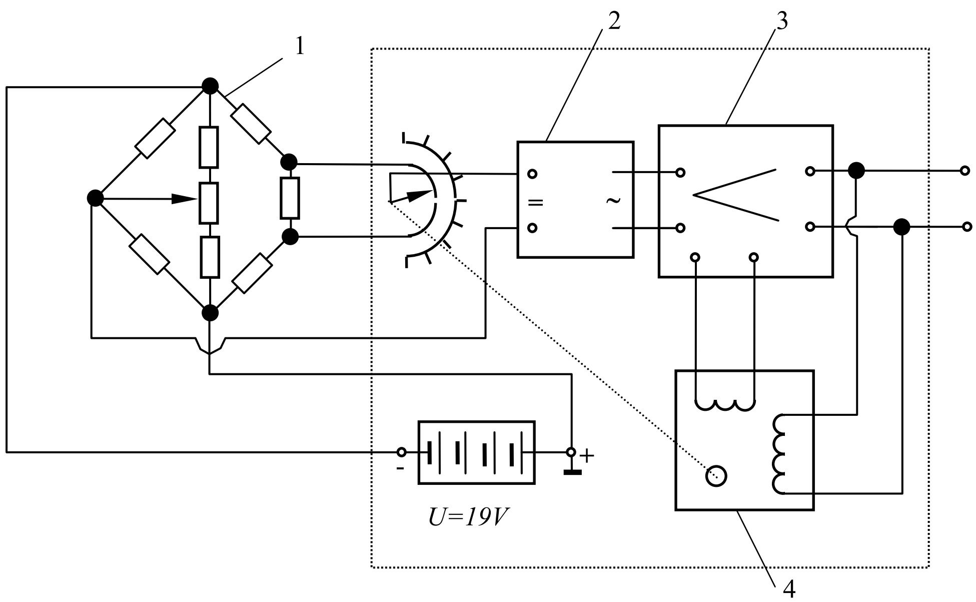


Fig. 3 Deformation meter Diagram
1 -resistance balance; 2 - vibrator inverter; 3 - amplifier; 4 - RD-0.9 (РД-0,9) engine

Stress values were computed according to the following formula:

$$\sigma_{(a)} = \frac{4E}{3l_1}\left[(h-a)^2\frac{dy}{da}(a) - 4(h-a)y(a) + 2\int_0^a y(\xi)d\xi\right],$$

where: a - depth of etched layer;
l_1 - length of etching area;
h - thickness of a sample before the etching is started;
y - camber value.

3. Experimental evaluation of UIT efficiency [25]

One of the main controllable parameters of the UIT method at the preset amplitude of ultrasound displacement which, in this experiment, was equal to 30 mcm as the working head traverse speed. Residual stress distribution diagrams varying with the working head traverse speed are shown on Fig. 4.

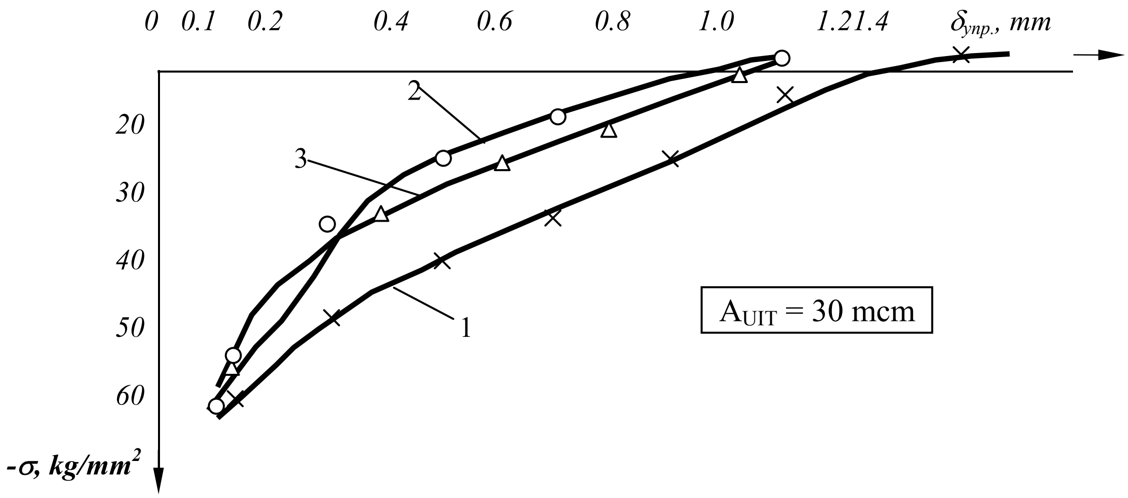


Fig. 4. Residual stress values in a surface layer at different treatment speeds
1 - V = 0.155 m/min.; 2 - V = 0.5 m/min.; 3 - V = 1.0 m/min.

It should be specified that according to a generally accepted procedure the measurement of residual stress can be performed starting from the etching depth of 100 mcm.

The analysis of experimental results proves that at A = 30 mcm the optimal traverse speed of a working tool should be equal to 0,5 m/min. As this takes place residual compressional stress of up to 60 kg/mm^2 is formed in a surface layer of base metal when the depth of a strengthened layer reaches up to 1,2 mm.

One of the UIT advantages its application for repair in hard-to-access areas. To determine the optimal traverse speed of a working tool UIT at the amplitude of 30 mcm and the efficiency of strengthening while repairing residual stress was measured at samples cut from metal being in use for 1.5 years in sea water and then exposed to UIT. As illustrated in Fig. 5, the residual stress distribution diagrams are insignificantly different from those shown on Fig. 4; only the depth of a strengthened layer is somewhat reduced.

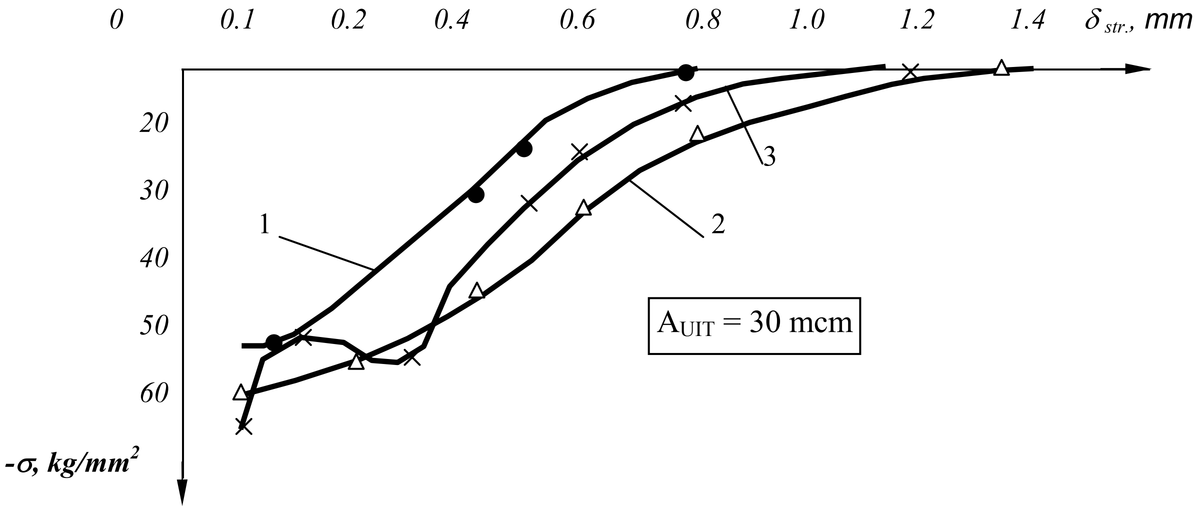


Fig. 5. Intensity of metal strengthening that had been in use at various treatment speeds: 1 - V=1 m/min; 2 - V= 0.155 m/min; 3 - V=0.5 m/min.

The optimal traverse speed of the working head is also 0.5 m/min.

4. Conclusions

1. When performing UIT of base metal (regardless of its conditions) a surface layer develops residual compressive stress of up to 60 kg/mm^2; the depth of a strengthened layer in this case is up to 1,4 mm. [25]
2. It is discovered that the recommended traverse speed of the UIT tool at the preset oscillation amplitude of 30 mcm amounts to 0,5 m/min. [25]

E. CORROSION-FATIGUE STRENGTH OF U3 (Ю3)-GRADE STEEL AT HIGH-AMPLITUDE UIT TOOL STRENGTHENING [25, 30]

1. Introduction

One of the main criteria of reliability of welded structures operating at varying load in aggressive media is their corrosion-fatigue strength [31, 32].

This paper presents the results of studies aimed at evaluation of UIT action on corrosion-fatigue strength of U3-grade steel at the high-amplitude strengthening of the treated surface. [25]

2. Experimental Procedure [30]

The tests were performed on the basis of 10^7 load reversal cycles in water containing 3% NaCl. Sample loading was achieved by flexural harmonic oscillation on a cantilever of 350 mm in length.

Samples

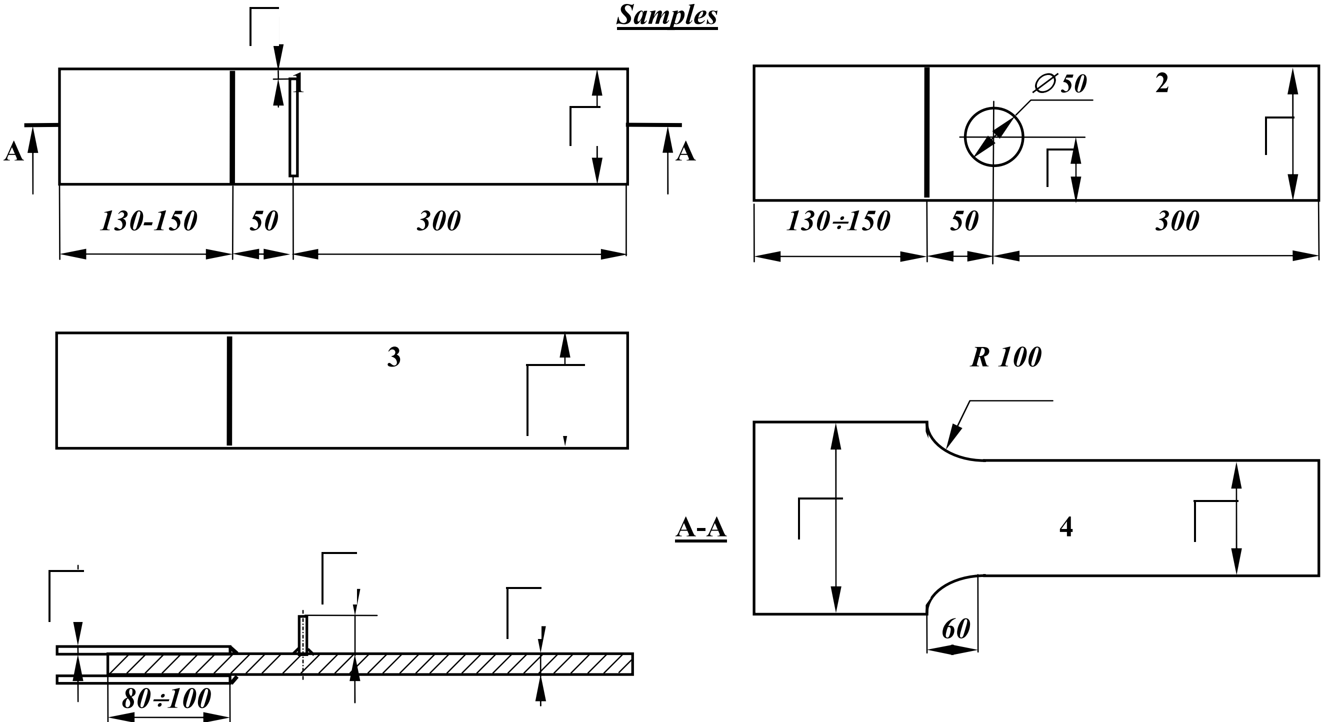


Fig. 6. Samples for corrosion-fatigue tests
1 - T-joint, deposition; 2 - hot spot; 3, 4 - base metal

3. Experimental results [25]

Fig. 7 illustrates the results of corrosion-fatigue testing the samples having hot spots, deposition, and T-joints. The treatment was applied to:

a) a spot - along the entire surface - in a circle of 60 mm in diameter;

b) deposition - along the entire surface including near-weld zone for 200 mm in both sides from weld borders;

c) T-joint - along the weld surface from both sides including a near-weld zone for 100 mm in both sides from the weld borders.

In all cases UIT was performed at the oscillation displacement amplitude of 30 mm and at the average traverse speed of the tool of 0.5 m/min while the zone of 10 mm in width was treated at a time.

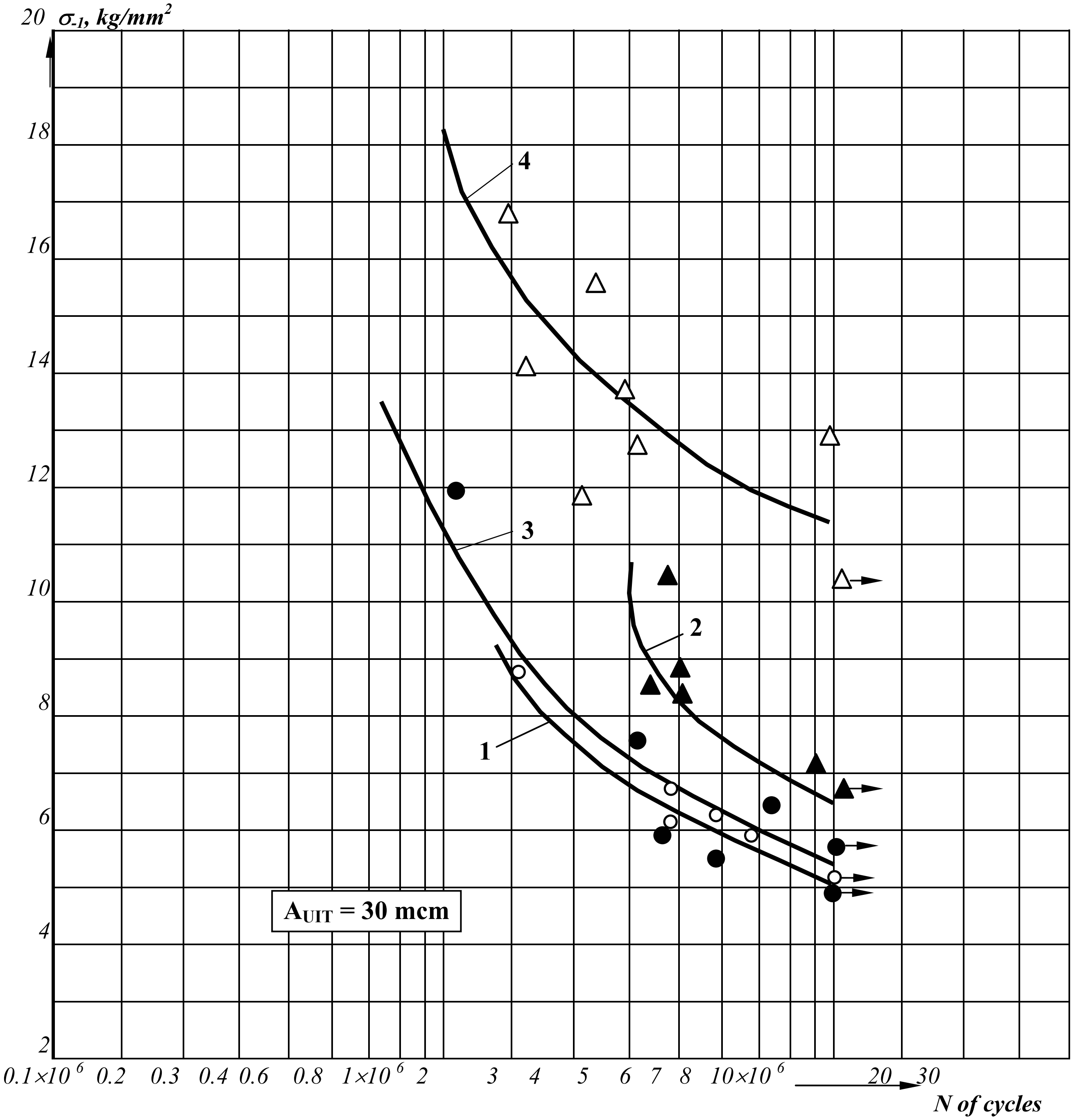


Fig. 7 Corrosion-fatigue strength of samples:
With a hot spot: 1 - without strengthening; 2- with strengthening by UIT.
With a T-joint and deposition: 3 - without strengthening; 4 - with strengthening by UIT.

Stable results were obtained at UIT of all types. The corrosion-fatigue resistance increased not less than 1.8 times - for T-joints and deposition, and 1.4 times - for hot spot

4. Conclusions

UIT provides:

a) a stable increase in corrosion-fatigue strength of U3-grade steel. [25, 30]

b) possibility for effective treatment in hard-to-access areas. [27, 30]

c) higher efficiency and productivity of strengthening process as compared to shot peening [25, 27, 30]

F. UIT INFLUENCE ON FATIGUE STRENGTH OF WELD T-JOINTS AT LOW TEMPERATURES. [9-11, 14, 33]

1. Introduction

The evaluation of the efficiency of UIT as a means for fatigue strength increase at room temperature, was carried out on T-joints of medium- and high-strength steels. The results proved the competitiveness of the method relative to the conventional methods for fatigue strength increase of welded joints of various metal structures under harmonic loading [25].

In addition, of special interest is the study of influence different post-weld treatment methods have on fatigue-strength of welded joints at varying load and subzero temperatures. This chapter is devoted to the UIT efficiency when dealing with samples of 09G2S (09Г2С)-grade steel under ramp loading conditions and at the temperature of -60^{0}C [33, 34, 35].

2. Test Procedure [33]

The UIT efficiency in terms of fatigue strength under conditions of ramp loading and at t =-60^{0}C was evaluated by the example of a welded T-joint of 09G2S-grade steel. The samples, shape and sizes of which are shown on Fig. 8, were cut of plates to which stiffeners had been welded by machine flux arc welding.

Samples of welded joints tested for fatigue strength

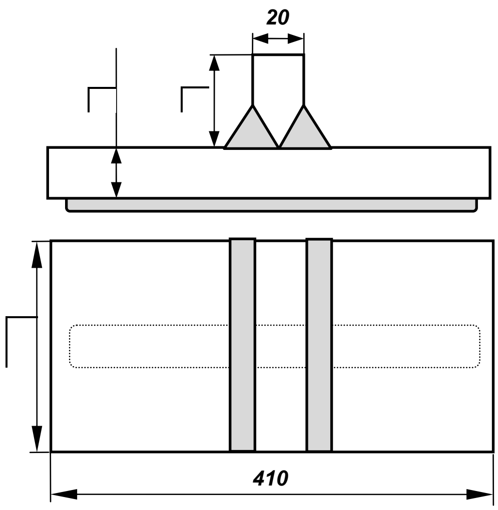
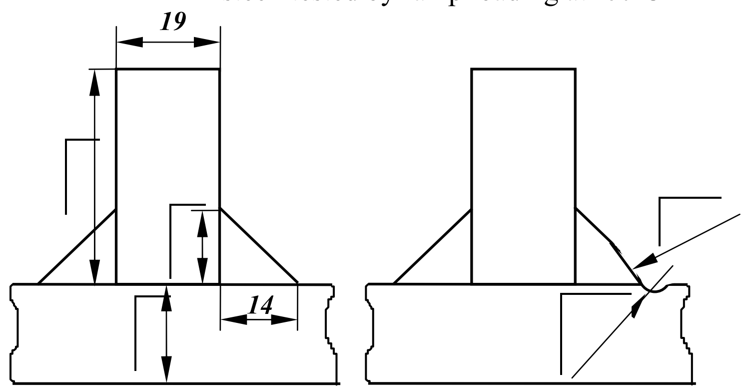


Fig. 8

Samples of welded T-joints of 09Г2С-grade steel tested by ramp loading at -60^{0}C



a **b**

a - *initial state*

b - after UIT

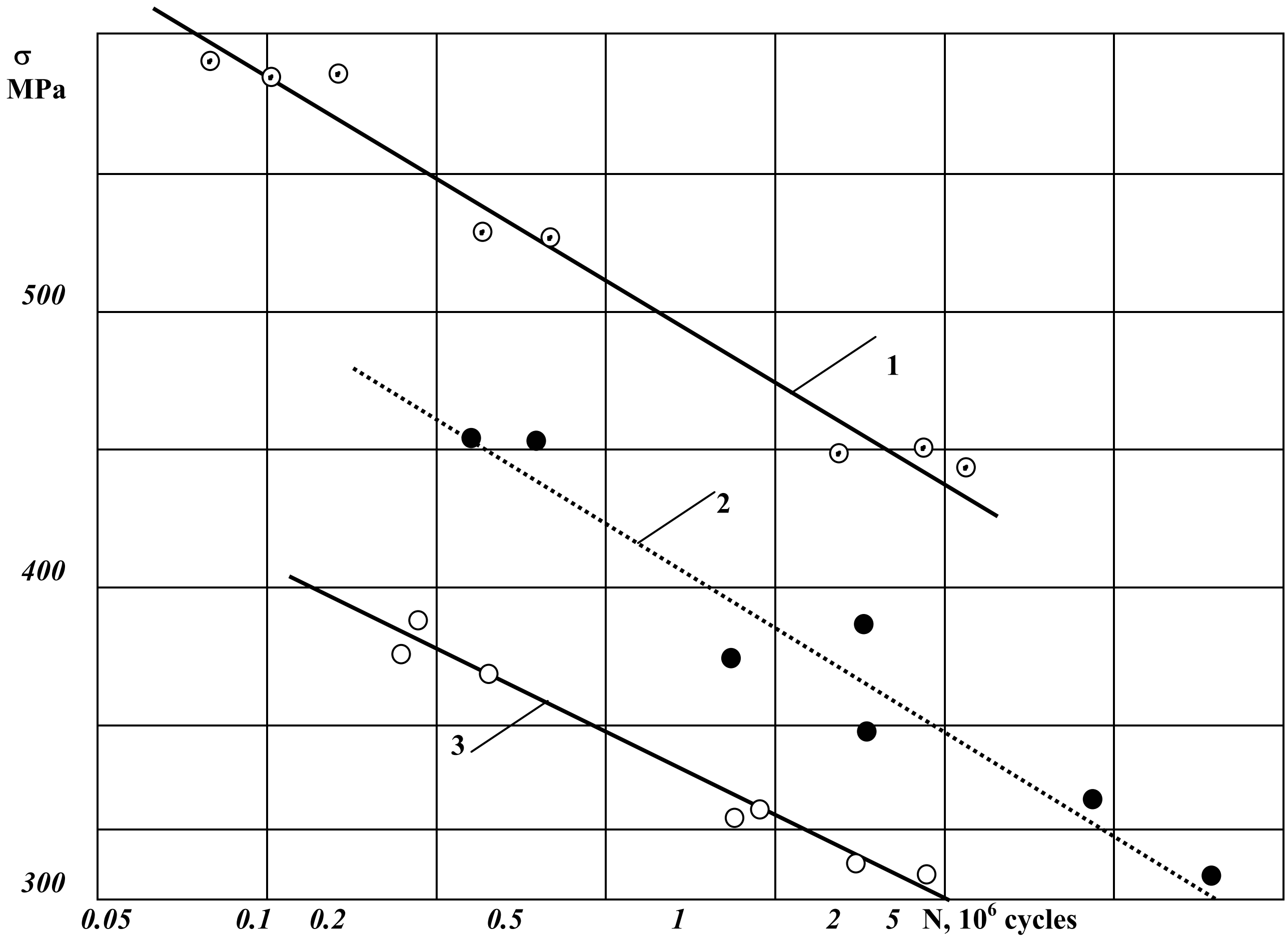
Fig. 9 Samples of Werlded Joints

Some samples illustrated in Fig. 9a were kept in initial stage. Other samples illustrated in Fig. 9b were exposed to UIT. After UIT, matting boundaries of 3.25 and 20 mm in radius were observed on the treated surface.

3. Experimental Results [33]

The samples in initial state were tested under conditions of harmonic loading at a room temperature (Fatigue Curve 2, Fig. 10) with DSO-2 (ДСО-2) device and under conditions of ramp loading at the temperature of -60^{0}C (Fatigue Curve 3, Fig. 10) with DSO-1 (ДСО-1). Repeated loading of samples was performed under cross bending with the following stress ratio: R=0.56.

The length of a crack developed on a sample surface equal to 20 mm was taken as the fracture criterion.



1 - after UIT (Fig. 8b.,); ramp loading at -60^{0}C;
2; 3 - in an initial state (Fig. 8a); harmonic loading at a room temperature and ramp loading at -60^{0}C respectively.

Fig. 10 Fatigue strength of a T-joint of 09G2-grade steel at loading with stress ratio R=0.56

Fatigue curve equations and fatigue limits on the basis of 2×10^6 loading cycles are tabulated in Table 1.

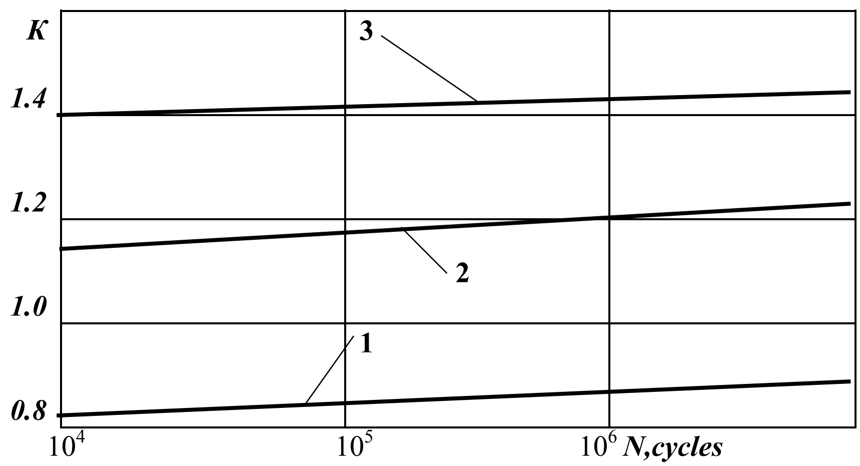
Table 1 **Fatigue strength of a T-joint of 09G2S-grade steel in relation with its conditions and test conditions**

Conditions of a welded joint	Test conditions	Fatigue curve equation	MPa	K
			2×10^6 cycles	
Initial state	Harmonic loading at room temperature	$\sigma = 986 - 99.3 \times \lg N$	360	
	Ramp loading at -60^{0}C	$\sigma_{ut} = 794.7 - 77.6 \times \lg N$	306	0,85
UIT	Ramp loading at -60^{0}C	$\sigma_{out} = 1{,}107 - 106.7 \times \lg N$	435	1,21

The testing of samples in initial state demonstrated that their fatigue strength under ramp loading conditions at -60^{0}C is less than under conditions of harmonic loading at room temperature. The impact of ramp loading-low temperature mode was assessed with the help of the following coefficient:

$$\hat{E}_{óò} = \frac{\sigma_{óò}}{\sigma} = \frac{10{,}241 - \lg N}{12{,}706 - 1{,}281\lg N}, \qquad (1)$$

where, σ_{ut} и σ - fatigue limits under ramp loading and at low temperature and under harmonic loading at a room temperature respectively. This function is illustrated by curve 1 on Fig. 11. The tests proved that within the studied endurance range fatigue strength of a T-joint of 09G2S-grade steel is less under conditions of ramp loading at -60^{0}C than under harmonic loading conditions at a room temperature.



1 *- coefficient of ramp loading and low temperature K_{ym} influence upon fatigue strength of a T-joint in an initial state;*
2 *- coefficient of UIT, ramp loading, and low temperature K_{oym} influence;*
3 *- coefficient of UIT influence K_0 upon T-joint fatigue strength under conditions of ramp loading at -60^{0}C.*

Fig. 11 Relations of coefficient of test conditions and UIT influence upon 09G2S-grade steel T-joint fatigue strength with cyclic endurance

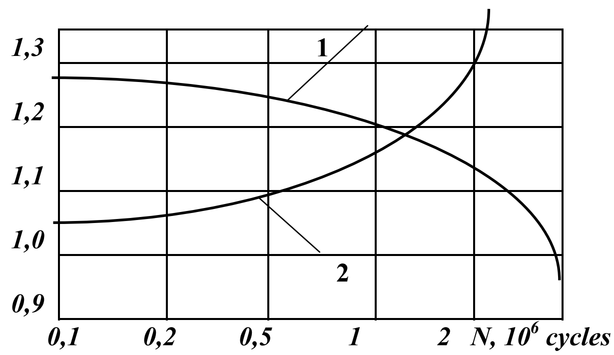
The results of testing samples exposed to UIT under conditions of ramp loading at -60^{0}C are illustrated by curve 1 on Fig. 9. The equation of fatigue curve 1 and fatigue limits on the basis of 2×10^6 cycles are tabulated in Table 1. The effect of UIT, ramp loading, and low temperature was assessed according to the following coefficient:

$$K_{oym} = \frac{\sigma_{oym}}{\sigma} = \frac{11{,}148 - 1{,}0745 - \lg N}{9{,}93 - \lg N}, \qquad (2)$$

where: σ_{oym} - fatigue limit of a welded joint under conditions of ramp loading at -60^{0}C , σ - fatigue limit of a welded joint in its initial state under harmonic loading and room temperature conditions. The change of this coefficient from the test base ***lgN*** is illustrated by curve 2 on Fig. 10. Experimental data show that within the studied endurance range fatigue strength of a T-joint of 09G2S-grade steel exposed to UIT under conditions of ramp loading at -60^{0}C is 20% higher than that of the same joint in its initial state under conditions of harmonic loading at a room temperature. UIT influence only under ramp loading at low temperature can be evaluated according to the following coefficient:

$$K_{o} = \frac{\sigma_{oym}}{\sigma_{ym}} = \frac{14{,}265 - 1{,}375 \times \lg N}{10{,}241 - \lg N}, \qquad (3)$$

The dependency of this coefficient upon ***lgN*** is illustrated by curve 3 on Fig. 11. It is seen that UIT allows for over than 40% increase in fatigue strength of a T-joint of 09Г2С-grade steel under conditions of ramp loading at -60^{0}C.



1, 2 - K_0 at cyclic endurance according to ultimate crack length criterion and micro-crack development respectively

Fig. 12 Relations of coefficient of K_0 burst treatment upon fatigue strength of 09G2S-grade steel butt joint under ramp loading

Comparison of graphs shown on figures 11 and 12 shows that within the studied endurance limit UIT allows for more stable increase in fatigue strength of a welded joint as compared to the burst treatment [18].

4. Conclusion

Based on this as well as on the analysis of efficiency of other techniques for treatment of welded joints (mechanical treatment of a butt joint, i.e. cleaning of weld reinforcement flush with the base metal surface, argon-arc welding of a T-joint) it can be concluded that Ultrasonic Impact Treatment is the most efficient method for increase in fatigue strength of welded joints under conditions of ramp loading and low temperature. Therefore, the UIT strengthening of welded joints is recommended to increase the durability of welded structures of machines and vehicles operating in regions with cold climate [33].

G. CONCLUSIONS

1. UIT is the post-weld method resulting in a complex technological effect involving improvement of quality and reliability of welded joints.

2. UIT provides high efficiency of the process, reduction in residual welding stress, compensation of residual welding deformation, formation of favorable compressive stress, increase in corrosion-fatigue strength of welded joints under conditions of ramp loading and low temperatures.

3. Technical and resource characteristics of UIT allow for wide application of this method in production of welded structures.

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