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FATIGUE IMPROVEMENT OF WELDED ELEMENTS AND STRUCTURES BY ULTRASONIC PEENING

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ABSTRACT

The ultrasonic impact treatment (UIT) is relatively new and promising process for fatigue life improvement of welded elements and structures. In most industrial applications this process is known as ultrasonic peening (UP). The beneficial effect of UP is achieved mainly by relieving of tensile residual stresses and introducing of compressive residual stresses into surface layers of a material. The secondary factors in fatigue improvement by UP are decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of the surface layers of the material. Fatigue testing of welded specimens showed that UP is the most efficient improvement treatment as compared with traditional techniques such as grinding, TIG-dressing, heat treatment, hammer peening and application of LTT electrodes. The developed computerized complex for UP was successfully applied for increasing the fatigue life and corrosion resistance of welded elements, elimination of distortions caused by welding and other technological processes, residual stress relieving, increasing of the hardness of the surface of materials. The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures. The areas/industries where the UP process was applied successfully include: Shipbuilding, Railway and Highway Bridges, Construction Equipment, Mining, Automotive, Aerospace. The results of fatigue testing of welded elements in as-welded condition and after application of UP are considered in this paper. It is shown that UP is the most effective and economic technique for increasing of fatigue strength of welded elements in materials of different strength. These results also show a strong tendency of increasing of fatigue strength of welded elements after application of UP with the increase in mechanical properties of the material used.

INTRODUCTION

The ultrasonic impact treatment (UIT) is one of the most efficient techniques for fatigue life improvement of welded elements and structures [1-7]. In most industrial applications this process is also known as ultrasonic peening (UP) [8-12]. The beneficial effect of UIT/UP is achieved mainly by relieving of harmful tensile residual stresses and introducing of compressive residual stresses into surface layers of materials, decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of surface layers of the material. The fatigue testing of welded specimens showed that the UP is the most efficient improvement treatment when compared with such traditional techniques as grinding, TIG-dressing, heat treatment, hammer peening, shot peening and application of LTT electrodes [1, 13, 14].



Fig.1a. Basic ultrasonic peening system for fatigue life improvement of welded elements and structures [6]

The developed system for UP treatment (total weight - 11 kg) includes an ultrasonic transducer, a generator and a laptop (optional item) with software for optimum application of UP - maximum possible increase in fatigue life of parts and welded elements with minimum cost, labor and power consumption. In general, the basic UP system shown in Figure 1a could be used for treatment of weld toe or welds and larger surface areas if necessary.

Also the special ultrasonic system was designed to perform underwater UP at the depth of up to 30 meters [26]. Figure 1b shows the process of underwater UP of welded samples in preparation for their subsequent fatigue testing.



Fig.1b. The process of underwater ultrasonic peening by using of the specially designed tool

The most recent design of the UP equipment is based on "Power on Demand" concept. Using this concept, the power and other operating parameters of the UP equipment are adjusted to produce the necessary changes in residual stresses, stress concentration and mechanical properties of the surface layers of materials to attain the maximum possible increase in fatigue life of welded elements and structures. From other side, this approach prevent the possibility to overwork the treated surface and decrease the efficiency of UP.

The effects of different improvement treatments, including the UP treatment, on the fatigue life of welded elements depend on the mechanical properties of used material, the type of welded

joints, the parameters of cyclic loading and other factors. For effective application of UP, depending on the above-mentioned factors, a software package for Optimum Application of UP was developed that is based on original predictive model. In the optimum application, a maximum possible increase in fatigue life of welded elements with minimum time/labor/cost is thought [15].

The developed technology and computerized complex for UP were successfully applied for increasing of the fatigue life of welded elements, elimination of distortions caused by welding and other technological processes, relieving of residual stress, increasing of the hardness of the surface of materials and surface nanocrystallization. The areas/industries where the UP was applied successfully include: Railway and Highway Bridges, Construction equipment, Shipbuilding, Mining, Automotive and Aerospace to name a few.

PRINCIPLES, TECHNOLOGY, EQUIPMENT FOR UP

Freely Movable Strikers

The UIT/UP equipment is based on known technical solutions from the 40's of last century of using working heads with freely movable strikers for hammer peening. At that time and later on, a number of different tools based on using freely movable strikers were developed for impact treatment of materials and welded elements by using pneumatic [16, 17] and ultrasonic [18-24] equipment. A more effective impact treatment is provided when the strikers are not connected to the tip of the actuator but could move freely between the actuator and the treated material. Figure 2 shows a standard set of easy replaceable working heads with freely movable strikers for different applications of UP.



Fig.2. A set of interchangeable working heads for UIT/UP [7]

Ultrasonic Impact and Effects of Ultrasound

The UP technique is based on the combined effect of high frequency impacts of the special strikers and ultrasonic oscillations in treated material. Some specific features of the ultrasonic impact treatment of metals are described in [16]

where it is shown that the operational frequency of the transducer and the frequency of the intermediate element-striker are not the same.

During the ultrasonic treatment, the striker oscillates in the small gap between the end of the ultrasonic transducer and the treated specimen, impacting the treated area [18-21]. This kind of high frequency movements/impacts in combination with high frequency oscillations induced in the treated material is typically called the ultrasonic impact.

There are a number of effects of ultrasound on metals that are typically considered: acoustic softening, acoustic hardening, acoustic heating, etc. In the first of these (acoustic softening that is also known as acoustic-plasticity effect), the acoustic irradiation reduces the stress necessary for plastic deformation. In general, the effect of ultrasound on the mechanical behavior could be compared with the effect of heating on a material. The difference is that acoustic softening takes place immediately when a metal is subjected to ultrasonic irradiation. Also, relatively low-amplitude ultrasonic waves leave no residual effects on the physical properties of metals after acoustic irradiation is stopped [25].

Technology and Equipment for Ultrasonic Peening

The ultrasonic transducer oscillates at a high frequency, with 20-30 kHz being typical. The ultrasonic transducer may be based on either piezoelectric or magnetostrictive technology. Whichever technology is used, the output end of the transducer will oscillate, typically with amplitude of 20 – 40 μm. During the oscillations, the transducer tip will impact the striker(s) at different stages in the oscillation cycle. The striker(s) will, in turn, impact the treated surface. The impact results in plastic deformation of the surface layers of the material. These impacts, repeated hundreds to thousands of times per second, in combination with high frequency oscillations induced in the treated material result in a number of beneficial effects of UP.

The UP is an effective way for relieving of harmful tensile residual stresses and introducing of beneficial compressive residual stresses in surface layers of parts and welded elements. The mechanism of residual stress redistribution is connected mainly with two factors. At a high-frequency impact loading, oscillations with a complex frequency mode spectrum propagate in a treated element. The nature of this spectrum depends on the frequency of ultrasonic transducer, mass, quantity and form of strikers and also on the geometry of the treated element. These oscillations lead to lowering of residual welding stresses. The second and the more important factor, at least for fatigue improvement, is surface plastic deformation that leads to introduction of the beneficial compressive residual stresses.

In the fatigue improvement, the beneficial effect is achieved mainly by introducing of the compressive residual stresses into

surface layers of metals and alloys, decrease in stress concentration in weld toe zones and the enhancement of the mechanical properties of the surface layer of the material. The schematic view of the cross section of material/part improved by UP is shown in Figure 3 with the attained distribution of the stresses after the UP. The description of the UP benefits is presented in Table 1.

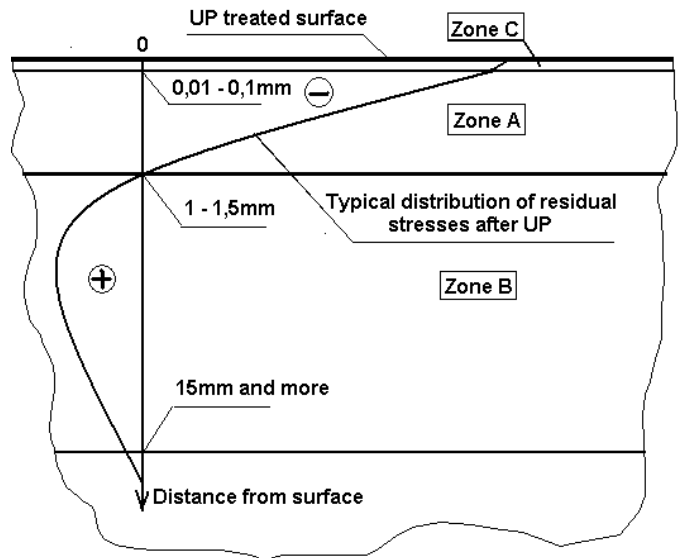


Fig.3. Schematic view of the cross section of material/part improved by Ultrasonic Peening [9]

Table 1. Zones of Material/Part Improved by Ultrasonic Peening [9] (see Figure 3 for illustration of the zones)

Zone	Description of zone	Distance from surface,	Improved characteristics
A	Zone of plastic deformation and compressive residual stresses	1 – 1.5 mm	Fatigue, corrosion, wear, distortion
B	Zone of relaxation of welding residual stresses	15 mm and more	Distortion, crack propagation
C	Zone of nanocrystallization (produced at certain conditions)	0.01 – 0.1 mm	Corrosion, wear, fatigue at elevated temperature

The most important, from the fatigue improvement point of view, is the zone A where the beneficial compressive residual stresses are induced by UP due to the plastic deformation of the surface layers of material [4]. The zone of nanocrystallization C could be produced by UP at certain conditions [27]. This

zone is characterized by a small depth of only 10-100 micrometers and does not contribute significantly to the fatigue increase of welded elements by UP. In case of surface nanocrystallization the fatigue cracks initiate under this thin layer.

Figure 4 illustrates the concept of the fatigue life improvement of welded elements by UP. In case of welded elements, it is enough to treat only the weld toe zone – the zone of transition from base metal to the weld, for a significant increase of fatigue life. The width of the zone of UP treatment is typically 2-5 mm.

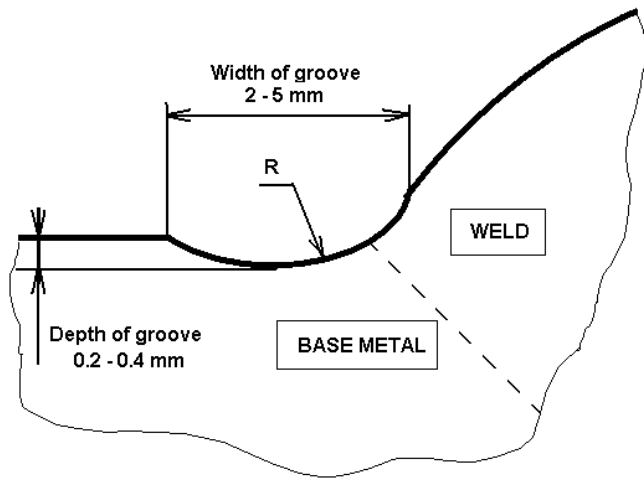


Fig.4. Profile of weld toe improved by Ultrasonic Peening [9]

A so-called groove, shown in Figures 4 and 5, characterized by certain geometrical parameters is produced by UP. This groove is a result of a surface plastic deformation of material during UP [2, 4].



Fig.5. The view of the butt welds in as-welded condition (left side sample) and after application of UP (right side sample) [7]

APPLICATION OF UP FOR FATIGUE IMPROVEMENT

The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures. Examples of all three applications will be described below.

Manufacturing and Rehabilitation

Three series of large-scale welded samples, designed as shown in Figure 6, were subjected to fatigue testing to evaluate the effectiveness of UP application to the existing welded structures: 1 – in as welded condition, 2 – UP was applied before fatigue testing, 3 – UP was applied after fatigue loading with the number of cycles corresponding to 50% of the expected fatigue life of samples in as-welded condition [9]. Material properties: yield strength – 360 MPa, ultimate strength – 420 MPa. The samples were tested at stress ratio $R=0$. Test frequency - 5 Hz.

All considered in this paper welded specimens were UP treated with the following standard parameters: speed of treatment – 0.4 meter/minute, level of amplitude of oscillation - 4, working head – one row, four pins, diameter of pin - 3mm.

The results of fatigue testing of the large-scale welded samples imitating the transverse non-load-carrying attachments (Fig. 6) with UP applied to specimens in as-welded condition and also after 50% of expected fatigue life are presented in Figure 7.

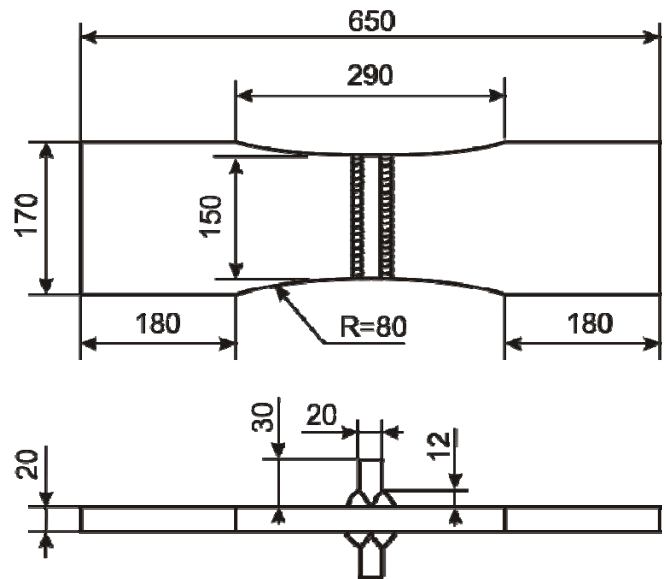


Fig.6. The general view of welded sample for fatigue testing

The UP caused a significant increase in fatigue strength of the considered welded element for both series of UP treated samples. The increase in limit stress range at $N=2 \cdot 10^6$ cycles of welded samples is 49% (from 119 MPa to 177 MPa) for UP treated samples before fatigue loading and is 66% (from 119 MPa to 197 MPa) for UP treated samples after fatigue loading,

with the number of cycles corresponding to 50% of the expected fatigue life of the samples in as-welded condition. A slightly higher increase of fatigue life of UP treated welded elements for fatigue curve #3 could be explained by a more beneficial redistribution of residual stresses by UP after cyclic loading than in as-welded condition and/or by “healing” of fatigue damaged material by recrystallization [27] during UP in comparison with the fatigue curve #2.

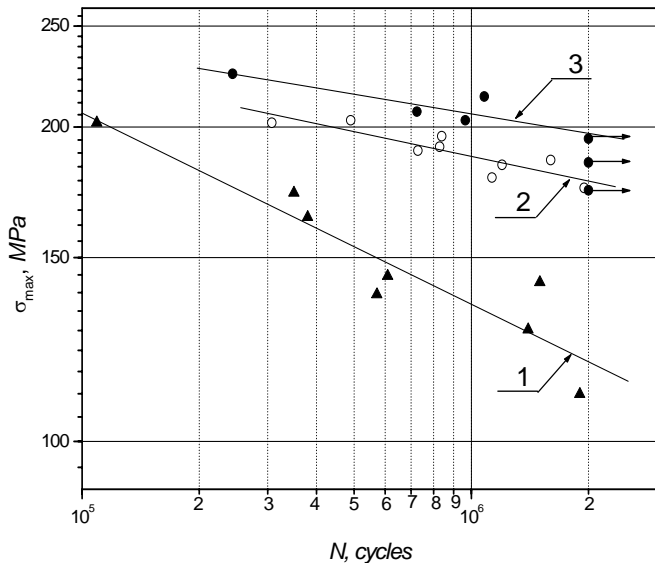


Fig.7. Fatigue curves of welded elements (transverse non-load-carrying attachment): 1 – in as welded condition, 2 – UP was applied before fatigue testing, 3 – UP was applied after fatigue loading with the number of cycles corresponding to 50% of expected fatigue life of samples in as-welded condition

Weld Repair

In this paper the rehabilitation is considered as a prevention of possible initiation of fatigue cracks in existing welded elements and structures that are in service. The UP could also be effectively used during the weld repair of fatigue cracks [7, 10].

Figure 8 shows the drawing of a large-scale welded specimen containing non-load carrying longitudinal attachments designed for fatigue testing [7]. Material properties: yield strength – 360 MPa, ultimate strength – 420 MPa. Such specimens were tested in as-welded condition and after weld repair with and without application of UP.

The testing conditions were zero-to-tension stress cycles (R=0) with different level of maximum stresses. Test frequency - 5 Hz.

The fatigue testing was stopped and the number of cycles was recorded when the length of fatigue crack on surface reached 20 mm. Then, the fatigue crack was repaired by gouging and welding and the fatigue test was continued. After repair, a

number of samples were subjected to UP. The weld toe of the “new” weld was UP treated. The results of fatigue testing of welded specimens in as-welded condition and after weld repair of fatigue cracks are presented in Figure 9.

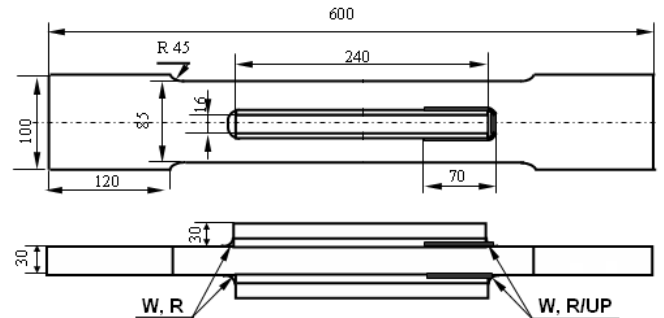


Fig.8. Drawings of welded specimens for fatigue testing at different conditions: W – as-welded condition; R - repair by gouging and welding; R/UP – repair by gouging, welding and UP

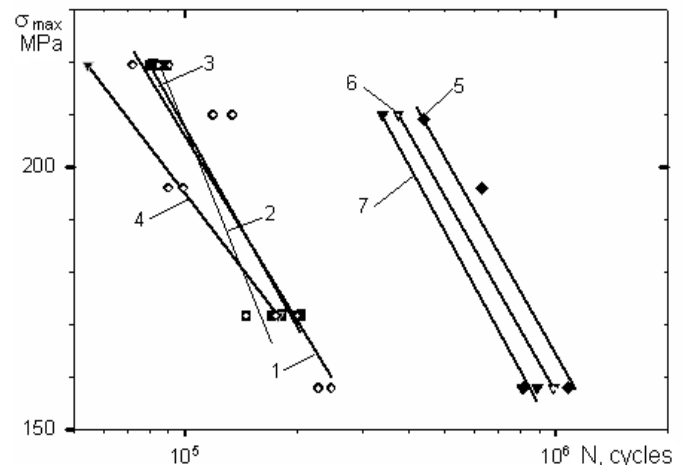


Fig.9. Results of fatigue testing of welded elements: 1 - as-welded condition, 2, 3 and 4 – after first, second and third weld repair, 5, 6 and 7 - after first, second and third weld repair with application of UP

The fatigue testing of large scale specimens showed that the repair of fatigue cracks by welding is restoring the fatigue strength of welded elements to the initial as-welded condition. Second and third repair of fatigue cracks also practically restored the fatigue life of repaired welded elements to initial as-welded condition.

The application of UP after weld repair increased the fatigue life of welded elements by 3-4 times. Practically the same significant fatigue improvement of repaired welded elements by UP is observed also after second and third repair of fatigue cracks in welded elements.

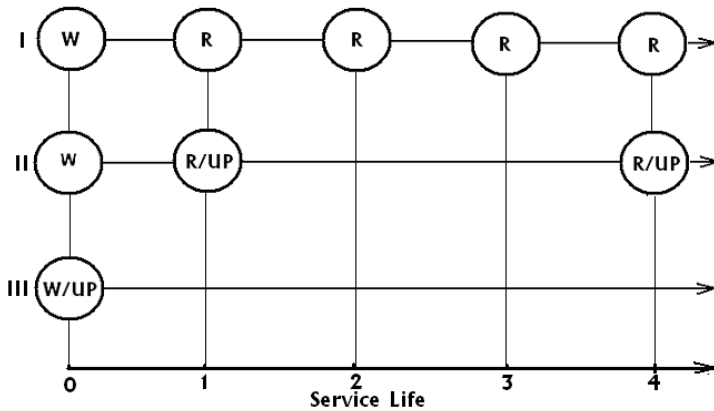


Fig.10. Diagram showing the endurance of welded elements:
 Line I - fatigue crack is repaired by gouging and welding,
 Line II - fatigue crack is repaired by gouging, welding and UP,
 Line III – UP is applied before/during the first phase of service life, W – as-welded condition, R - repair by gouging and welding, R/UP – repair by gouging, welding and UP, W/UP- welding and UP

A comparison of the efficiency of weld repair of fatigue cracks with and without application of UP is presented in Figure 10. This diagram illustrates the fatigue behavior of the same welded elements in cases when UP is not applied (I), when UP is applied after weld repair (II) and UP is applied before/during the first phase of service life (III). Here, 1 unit of service life corresponds to ~ 240,000 cycles of loading at the stress range 158 MPa and to ~ 75,000 at the stress range 220 MPa. Every circle, marked R or R/UP, in Fig.10 starting from the number 1 on service life axis indicates a fatigue fracture and a repair of the welded element. As can be seen from Fig.10, the benefit from application of UP for weld repair and rehabilitation of welded elements is obvious.

ULTRASONIC PEENING OF HSS WELDED ELEMENTS
700 MPa yield strength steel

Four series of large-scale welded samples were subjected to fatigue testing to evaluate the effectiveness of UIT/UP application for fatigue life improvement of welded elements made from 350 MPa and 700 MPa yield strength steels [13]. The fatigue specimens were designed as 80 mm wide by 8 mm thick steel plates with longitudinal non-load carrying fillet welded attachments, as shown in Figure 11.

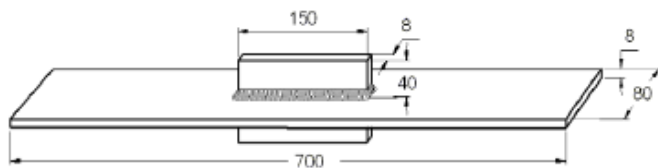


Fig.11. Welded specimen for fatigue testing of 350 and 700 MPa yield strength steel welded elements [13]

All testing has been conducted under constant amplitude axial tension in servo-hydraulic fatigue testing machines. The applied stress ratio has been $R=0.1$, with test frequencies varying from 2 to 6 Hz depending on load levels. Failure is defined to have taken place upon complete separation of the specimen. The results of fatigue testing are presented in Figure 12.

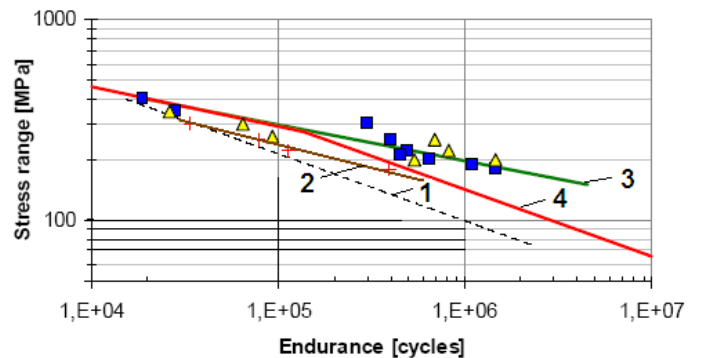


Fig.12. Fatigue test results for 350 and 700 MPa yield strength steel welded specimens [13]: 1- in as-welded condition, 350 MPa and 700 MPa yield strength steels, 2 - after UIT, 350 MPa yield strength steel, 3- after UIT/UP, 700 MPa yield strength steel, 4- FAT 112 design curve

As can be seen from Figure 12, the UIT/UP provided significant increase in fatigue performance of considered welded element for 700 MPa yield strength steel. The increase in limit stress range at 2 millions cycles of loading was 81% for welded samples treated by UIT/UP in comparison with as-welded condition, while TIG-dressing provided a 36% increase in limit stress range of welded element (see Table 2).

TABLE 2. INCREASE IN LIMIT STRESS RANGE OF WELDED ELEMENT AT 2 MILLIONS CYCLES OF LOADING [13]

S-N curve	Slope m	FAT value [MPa]	Improvement at FAT value [%]
As-welded S355 and S700	-3 (fixed)	71.3	-
UIT/UP S700	-5 (fixed)	129.4	81
Robotized TIG-dressing S700	-3 (fixed)	97.0	36.0

960 MPa yield strength steel

Four series of large-scale welded samples were subjected also to fatigue testing to evaluate the effectiveness of UIT/UP application for fatigue life improvement of welded elements made from 960 MPa yield strength steel [14]. The fatigue specimens were designed as 50 mm wide by 6 mm thick steel

plates with longitudinal non-load carrying fillet welded attachments, as shown in Figure 13.

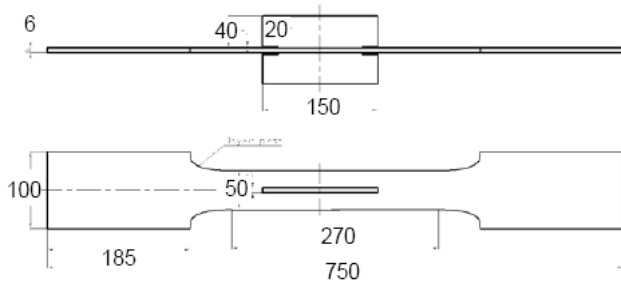


Fig.13. Specimen geometry for fatigue testing of 960 MPa yield strength steel welded elements [14]

The testing has been conducted under constant amplitude using $R = -1$. All of the as-welded specimens failed at the weld toe at the end of the longitudinal stiffeners. For the improved by UIT/UP welds, tested using constant amplitude loading, a variety of other failure modes were observed. The results of fatigue testing are presented in Figure 14.

As can be seen from Figure 14, the UIT/UP treatment with an instrument based on piezoelectric transducer provided the highest increase in fatigue performance of considered welded element for 960 MPa yield strength steel in comparison with the efficiency of application of magnetostrictive transducer and LTT electrodes.

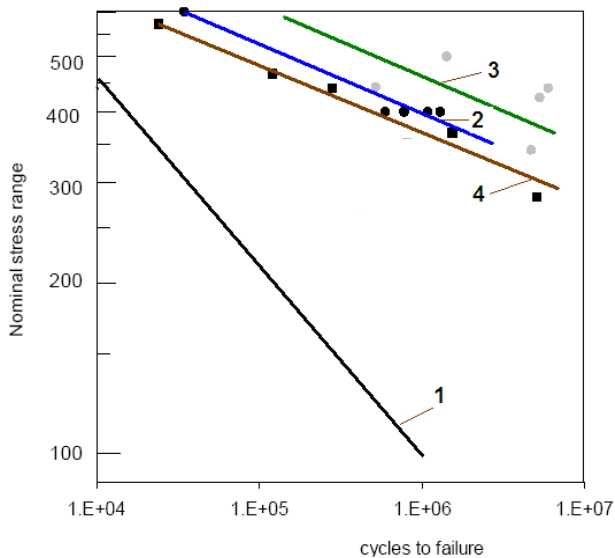


Fig.14. Fatigue test results for 960 MPa yield strength steel welded specimens [14]: 1- in as-welded condition (results of approximation of fatigue data received earlier), 2 and 3 - after UIT/UP based on using magnetostrictive and piezoelectric transducers respectively, 4- after application of LTT electrodes

INDUSTRIAL APPLICATIONS OF UP

As was demonstrated, the UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures. The UP technology and equipment were successfully applied in different industrial projects for rehabilitation and weld repair of parts and welded elements. The areas/industries where the UP was applied successfully include: Railway and Highway Bridges, Construction Equipment, Shipbuilding, Mining, Automotive and Aerospace.

An example of application of UP for repair and rehabilitation of welded elements subjected to fatigue loading in mining industry is shown in Figure 15. Around 300 meters of welds, critical from fatigue point of view, were UP treated to provide improved fatigue performance of two large grinding mills located near Labrador City, NL, Canada..



Fig.15. Application of UP for rehabilitation of welded elements of a large grinding mill

The second example is based on the fatigue data and the solution described in [10]. The UP was also applied during the rehabilitation of welded elements of a highway bridge over the Ohio River in the USA. The bridge was constructed about 30 years ago. The welded details of the bridge did not have macroscopic fatigue cracks. The motivation for application of the UP for fatigue life improvement of this bridge was the fatigue cracking in welded elements and failure of one of the spans of another bridge of approximately the same age and design. More than two thousand and five hundred welded details of the bridge structure that were considered to be fatigue critical were UP treated.

CONCLUSIONS

1. Ultrasonic Impact Treatment (UIT/UP) is a relative new and promising technique for fatigue life improvement of welded elements and structures in materials of different strength including HSS with the yield strength of 700-1000 MPa. The results of fatigue testing show a strong tendency of increasing of fatigue strength of welded elements after application of UP with the increase in mechanical properties of the material used. It allows using to a greater degree the advantages of the HSS in welded elements, subjected to fatigue loading.

2. The fatigue testing of welded specimens also showed that the UP is the most efficient improvement treatment as compared with post weld techniques such as TIG-dressing and application of LTT electrodes.

3. The developed computerized complex for UP was successfully used in different applications for increasing of the fatigue life of welded elements, elimination of distortions caused by welding and other technological processes, relieving of residual stress, increasing of the hardness of material surfaces and surface nanocrystallization. The areas/industries where the UP was applied successfully include: Railway and Highway Bridges, Mining, Construction Equipment, Shipbuilding, Automotive and Aerospace.

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