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Increasing Fatigue Strength of Welded Joints by Ultrasonic Impact Treatment

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ABSTRACT

The Ultrasonic Impact Treatment (UIT) is one of the new and promising processes 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 UIT/UP is achieved mainly by relieving of harmful tensile residual stresses and introducing of compressive residual stresses into surface layers of a material, decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of the surface layers of the material. The UIT/UP technique is based on the combined effect of high frequency impacts of special strikers and ultrasonic oscillations in treated material. The fatigue testing of welded specimens showed that the UIT/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 UIT/UP was successfully applied for increasing of 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 areas/industries where the UIT/UP process was applied successfully include: Railway and Highway Bridges, Construction Equipment, Shipbuilding, Mining, Automotive and Aerospace.

Keywords: *Welded Joint, Fatigue Strength, Ultrasonic Impact Treatment, Ultrasonic Peening, Residual Stresses, Stress Concentration*

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1. Introduction

The ultrasonic impact treatment (UIT) is one of the new and promising processes for fatigue life improvement of welded elements and structures [1-5]. In most industrial applications this process is also known as ultrasonic peening (UP) [6-10]. The beneficial effect of 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 the 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, 11, 12].

The UP technique is based on the combined effect of high frequency impacts of special strikers and ultrasonic oscillations in treated material. 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 1 could be used for treatment of weld toe or welds and larger surface areas if necessary.

Figure 1. Basic Ultrasonic Peening system for fatigue life improvement of welded elements and structures

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.

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, parameters of cyclic loading and other factors. For effective application of the 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.

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.

2. Principles, Technology, Equipment for UP

2.1. Freely Movable Strikers

The UP equipment is based on known from the 40's of last century technical solutions of using working heads with freely movable strikers for hammer peening. At that time and later, a number of different working heads were developed for impact treatment of materials and welded elements by using pneumatic [13, 14] and ultrasonic [15-18] equipment. The effective impact treatment is provided when the strikers are not connected to the tip of actuator but are located 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.

Figure 2. A set of interchangeable working heads for UP

2.2. Ultrasonic Impact and Effects of Ultrasound

The UP technique is based on the combined effect of the 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 [15-18]. 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 [19].

2.3. 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 oscillation induced in the treated material result in a number of beneficial effects of UP.

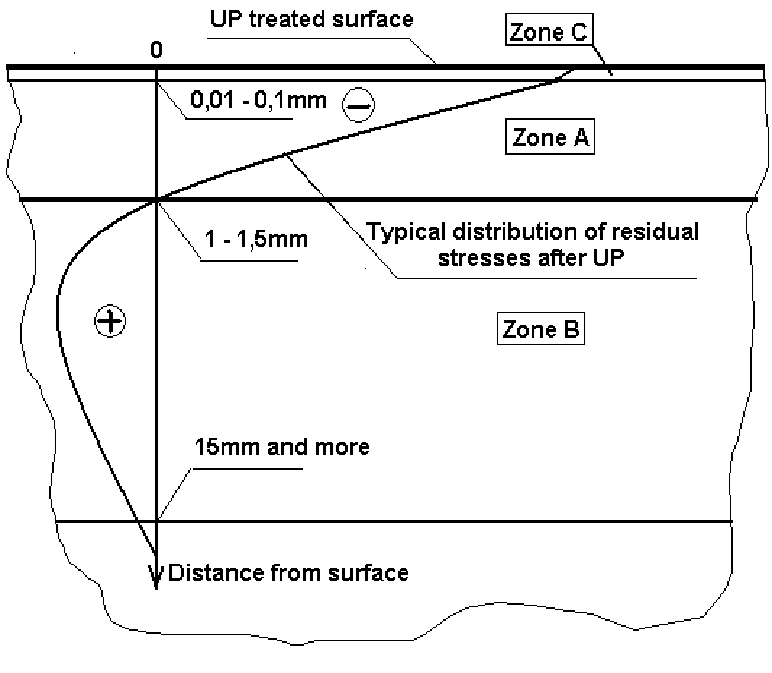

Figure 3. Schematic view of the cross section of material/part improved by Ultrasonic Peening

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 on Figure 3 with the attained distribution of the stresses after the UP. The description of the UP benefits is presented in Table 1.

Table 1. Zones of Material/Part Improved by Ultrasonic Peening
(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

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 so-called groove, shown also in Figures 4 and 5, characterized by certain geometrical parameters is produced by UP [2, 3, 6, 7].

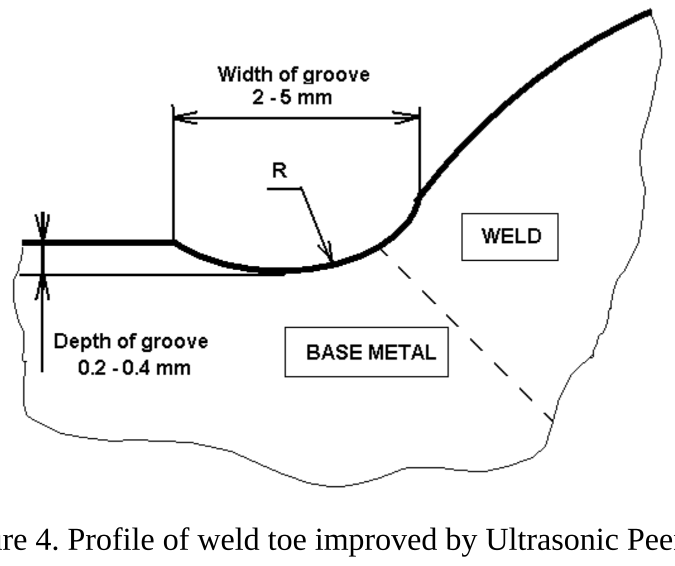

Figure 4. Profile of weld toe improved by Ultrasonic Peening

There are two general types of ultrasonic transducers which can be used for UP: magnetostrictive and piezoelectric. Both accomplish the same task of converting alternating electrical energy to oscillating mechanical energy but do it in a different way (Figure 6). In magnetostrictive transducer the alternating electrical energy from the ultrasonic generator is first converted into an alternating magnetic field through the use of a wire coil. The alternating magnetic field is then used to induce mechanical vibrations at ultrasonic frequency in resonant strips of magnetostrictive material.

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

Magnetostrictive transducers are generally less efficient than the piezoelectric ones. This is due primarily to the fact that the magnetostrictive transducer requires a dual energy conversion from electrical to magnetic and then from magnetic to mechanical. Some efficiency is lost in each conversion. Magnetic hysteresis effects also detract from the efficiency of the magnetostrictive transducer. In addition, the magnetostrictive transducer for UP needs forced water-cooling.

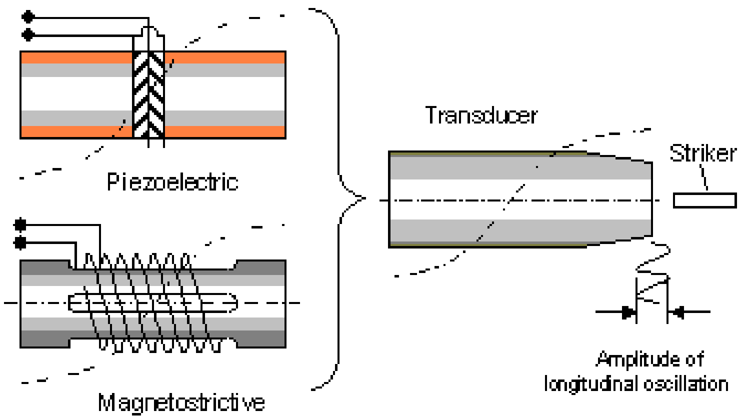

Figure 6. Schematic view of transducers for UIT/UP using piezoelectric and magnetostrictive approaches

Piezoelectric transducers convert the alternating electrical energy directly to mechanical energy through the piezoelectric effect. Today's piezoelectric transducers incorporate stronger, more efficient and highly stable ceramic piezoelectric materials, which can operate under the temperature and stress conditions, making them reliable and allowing to reduce the energy costs for operation by as much as 60%. Due to the high energy efficiency of piezoelectric transducers, the effect in fatigue life improvement by UP is practically the same by using of the magnetostrictive transducer with power consumption of 1000 Watts and piezoceramic transducers with power consumption of only 300-600 Watts [5, 6, 11]. A basic UP system that is based on piezoceramic transducer is shown in Figure 1.

3. 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 [5-10, 20].

3.1. Manufacturing and Rehabilitation

Three series of large-scale welded samples, designed as shown in Figure 7, 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 [7].

The results of fatigue testing of large-scale welded samples imitating the transverse non-load-carrying attachments with UP applied to specimens in as-welded condition and also after 50% of expected fatigue life are presented in Figure 8.

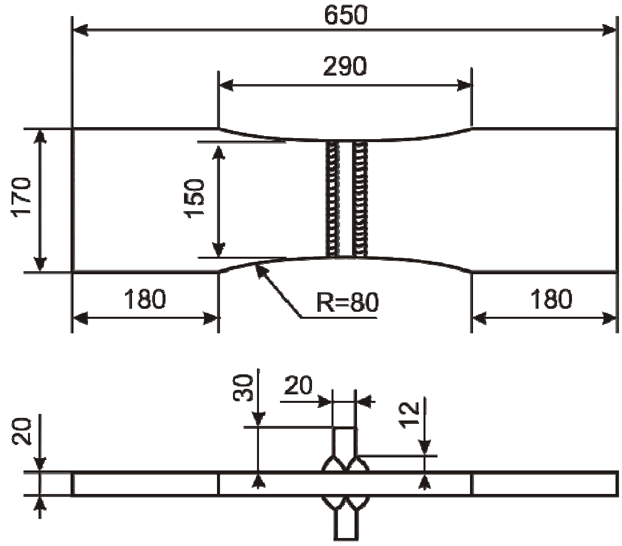

Figure 7. The general view of welded sample for fatigue testing

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 $N=2\cdot10^6$ 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. The 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 and/or "healing" of fatigue damaged material by UP in comparison with the fatigue curve #2.

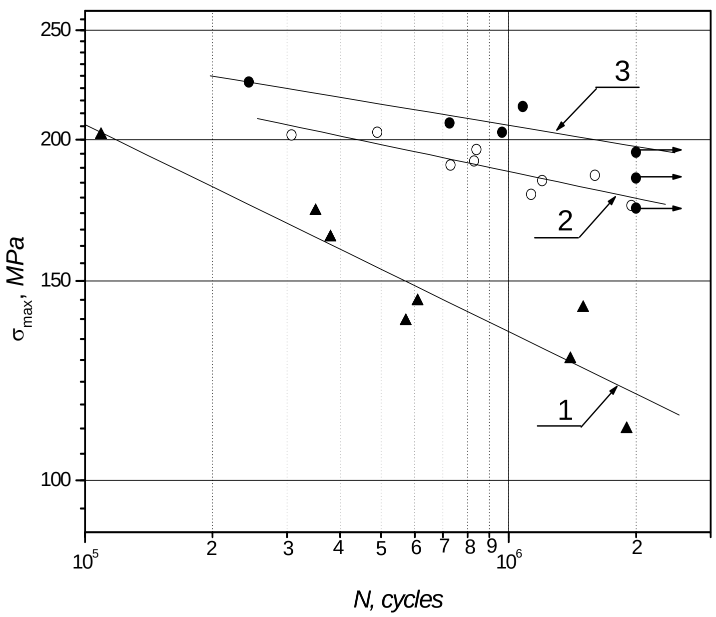

Figure 8. Fatigue curves of welded elements (transverse non-load-carrying attachment): 1 – in as welded condition, 2 – UP was applied before fatigue testing, 3 – UP was applied after fatigue loading with the number of cycles corresponding to 50% of expected fatigue life of samples in as-welded condition

3.2. Weld Repair

In this paper the rehabilitation is considered as a prevention of possible fatigue cracks initiation 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, 20].

Figure 9 shows the drawing of a large-scale welded specimen containing non-load carrying longitudinal attachments designed for fatigue testing [20]. Such specimens were tested in as-welded condition and after weld repair with and without application of UP.

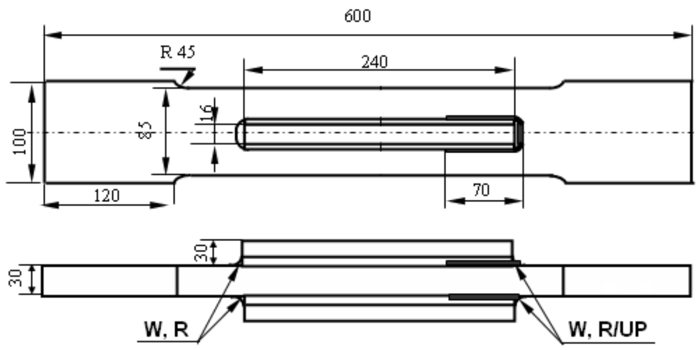

Figure 9. Drawings of welded specimens for fatigue testing at different conditions: W – as-welded condition; R - repair by gouging and welding; R/UP – repair by gouging, welding and UP

The testing conditions were zero-to-tension stress cycles (R=0) with different level of maximum stresses. 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 10.

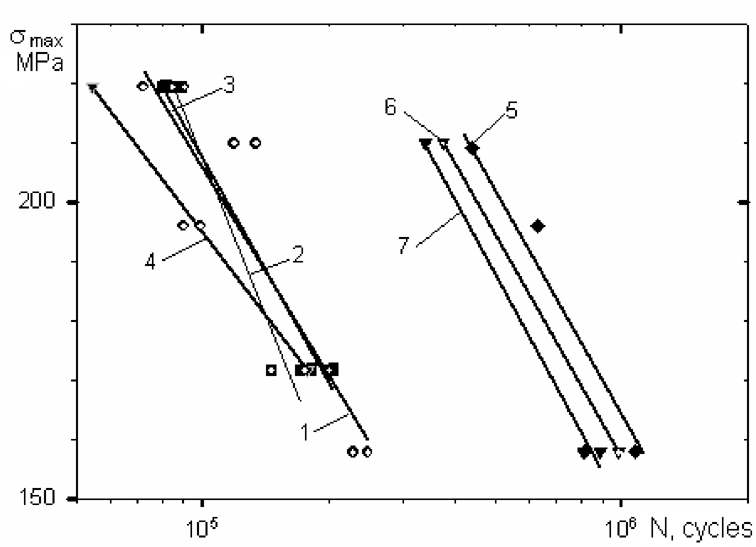

Figure 10. Results of fatigue testing of welded elements:
1 - as-welded condition, 2, 3 and 4 – after first, second and third weld repair, 5, 6 and 7 - after first, second and third weld repair with application of UP

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.

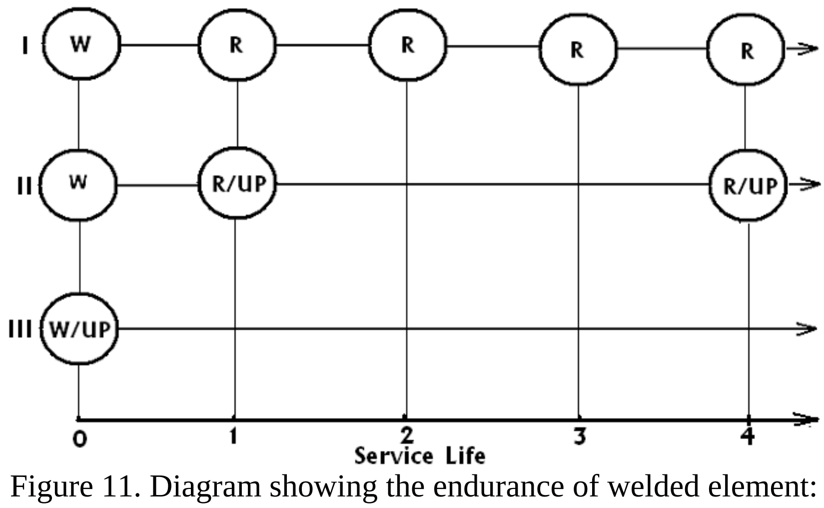

Figure 11. Diagram showing the endurance of welded element:
I - fatigue crack is repaired by gouging and welding,
II - fatigue crack is repaired by gouging, welding and UP,
III – UP is applied before/during the first phase of service life,
W – as-welded condition, R - repair by gouging and welding,
R/UP – 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 11. 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.11 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.11, the benefit from application of UP for weld repair and rehabilitation of welded elements is obvious.

4. Ultrasonic Peening of HSS Welded Elements

4.1. 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 [11]. 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 12.

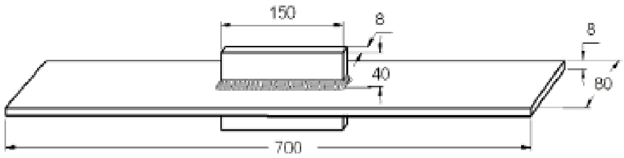

Figure 12. Welded specimen for fatigue testing of 350 and 700 MPa yield strength steel welded elements [11]

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 13.

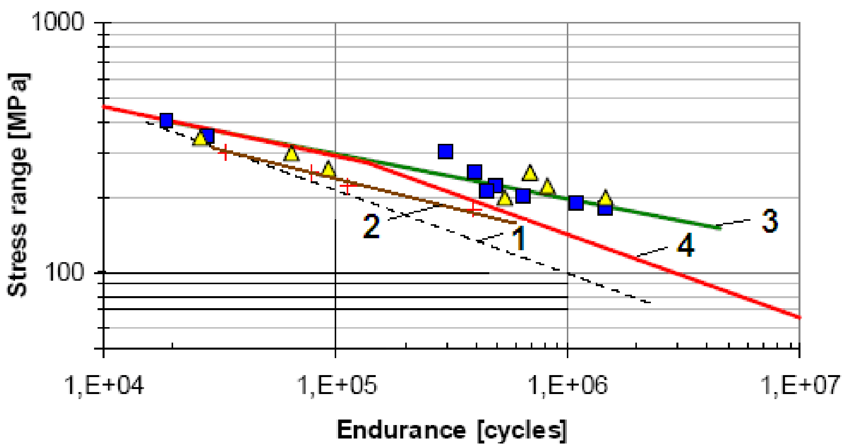

Figure 13. Fatigue test results for 350 and 700 MPa yield strength steel welded specimens [11]: 1- in as-welded condition350 MPa and 700 MPa yield strength steels,
2 - after UIT 350 MPa yield strength steel,
3- after UIT/UP 350 MPa and 700 MPa yield strength steels, 4- FAT 112 design curve

As can be seen from Figure 13, 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% in comparison with as-welded condition. At the same time, the TIG-dressing provided 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 [11]

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

4.2. 960 MPa yield strength steel

Also, 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 960 MPa yield strength steel [12]. 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 14.

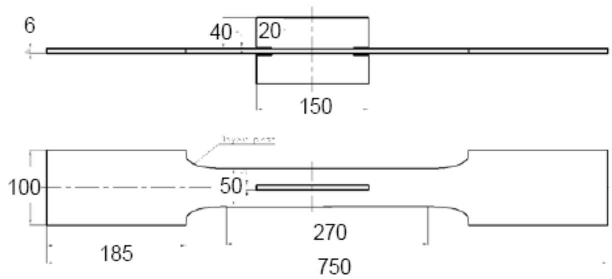

Figure 14. Specimen geometry for fatigue testing of 960 MPa yield strength steel welded elements [12]

These 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 welds tested using constant amplitude loading, a variety of other failure modes were observed. The results of fatigue testing are presented in Figure 15.

As can be seen from Figure 15, the UIT/UP based on using and 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.

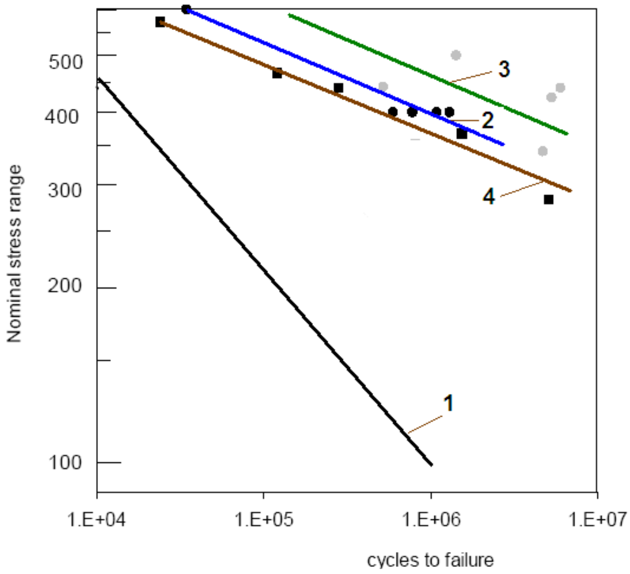

Figure 15. Fatigue test results for 960 MPa yield strength steel welded specimens [12]: 1- in as-welded condition, 2 and 3 - after UIT/UP based on using magnetostrictive and piezoelectric transducers, 4- after application of LTT electrodes

5. 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 16. Around 300 meters of welds, critical from fatigue point of view, were UP treated to provide improved fatigue performance of large grinding mills.

Figure 16. Application of UP for rehabilitation of welded elements of a large grinding mill

Based on the fatigue data and the solution described in [7], 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. The stages of preparation for UP treatment of the bridge and the process of UP treatment of one of the welded vertical stiffeners are shown in Figures 17 and 18. More than two thousand and five hundred welded details of the bridge structure that were considered to be fatigue critical were UP treated.

Figure 17. Ultrasonic Peening of a welded bridge: preparation for UP treatment
(two UP systems/lifts)

Figure 18. Ultrasonic Peening of a welded bridge: UP of the end of one of welded vertical stiffeners

6. 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 traditional techniques such as grinding, TIG-dressing, heat treatment, hammer peening, shot peening or 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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