Fatigue Improvement of Welded Elements and Structures by Ultrasonic Impact Treatment

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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 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 the surface layers of the material. The fatigue testing of welded specimens showed that the UIT/UP is the most efficient improvement treatment when compared with such traditional techniques as grinding, TIG-dressing, heat treatment, hammer peening, shot peening, application of LTT electrodes [1,11,12].

The UIT/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 - 9 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 [6,10,13]. 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.

The most recent design of the UIT/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 UIT/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.

Figure 1. Using of basic UP system for fatigue life improvement of tubular welded joint

The developed technology and computerized complex for UIT/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 and Stamping Equipment, Shipbuilding, Mining, Automotive and Aerospace to name a few.

The paper presents the description of the technology and equipment for UIT/UP and examples of their application for fatigue life improvement during the manufacturing, rehabilitation and repair of welded elements and structures.

Basic Principles, Technology and Equipment for UIT/UP

Freely Movable Strikers

The equipment for UIT/UP is based on known from the 40's of last century technical solutions of working heads for hammer peening. At that time and later, a number of different multi-striker working heads were developed for impact treatments of parts and welded elements by using mostly pneumatic driven 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 treated material [14-15]. Figure 2 shows a set of working heads for different applications of UP. The working head could be easily replaced, if necessary.

Figure 2. Set of the changeable working heads

Ultrasonic Impact and Effects of Ultrasound

The UIT/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]. 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 treated specimen, impacting the treated area. This kind of high frequency movements/impacts in the combination with high frequency oscillation 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. [17]. In the first of these (acoustic softening that is also known as acousto-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 of the 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 [17].

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 be oscillating, typically with amplitude of 20 – 40 μm. During the oscillations, the transducer tip will impact the striker at different stages in the oscillation cycle. The striker(s) impacts 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 the combination with high frequency oscillation induced in the treated material result in a number of beneficial effects of UIT/UP.

The UIT/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.

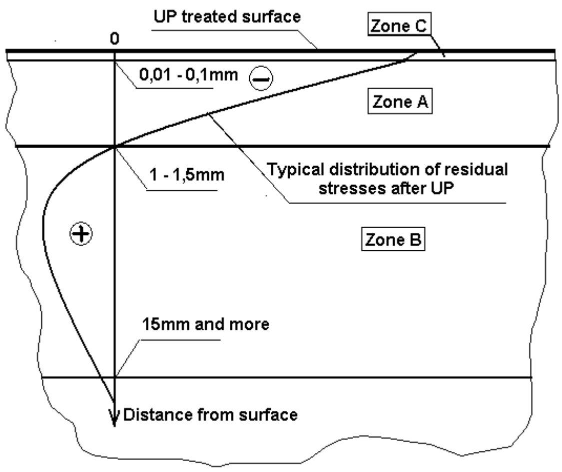

Figure 3. Schematic view of the cross section of material/part improved by Ultrasonic Peening

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	Penetration (distance from surface), mm	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 (could be produced at certain conditions)	0,01 – 0,1 mm	Corrosion, wear, fatigue at elevated temperature

Figure 4 illustrate 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 on Figure 5, characterized by certain geometrical parameters is produced by UP [2,3,6,7].

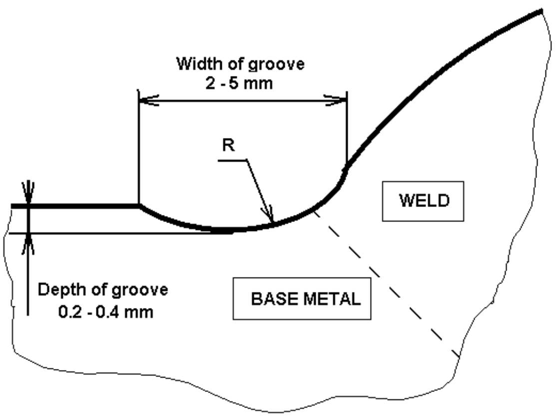

Figure 4. Profile of weld toe improved by Ultrasonic Peening

There are two general types of ultrasonic transducers which can be used for UIT/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 UIT/UP needs forced water-cooling.

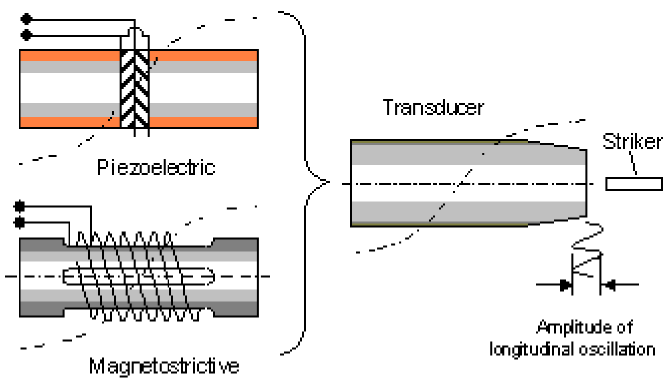

Figure 6. Schematic view of transducer for UIT/UP

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 300-500 Watts [6,11,12]. A UIT/UP system that is based on piezoceramic transducer is shown in Figure 1.

Application of UIT/UP for Fatigue Improvement

The UP could be effectively applied for fatigue life improvement during manufacturing, rehabilitation and repair of welded elements and structures [6-10,18].

Manufacturing and Rehabilitation

Three series of large-scale welded samples 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 general view of welded sample for fatigue testing is shown of Figure 7.

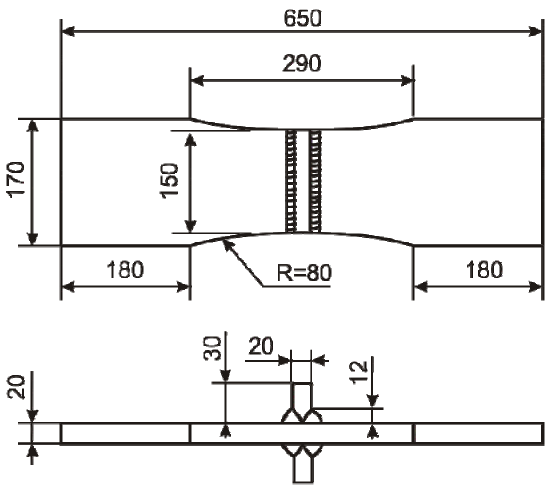

Figure 7. The general view of welded sample for fatigue testing

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.

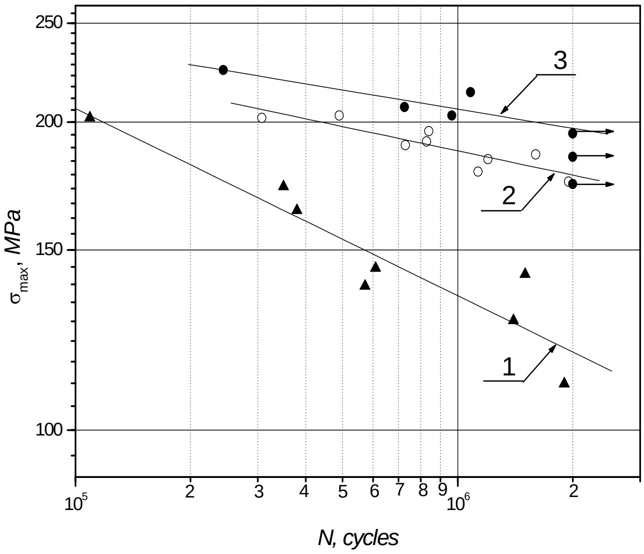

Figure 8. Fatigue curves of welded elements (transverse non-load-carrying attachment):
1 – in as welded condition, 2 – UP was applied before fatigue testing, 3 – UP was applied after fatigue loading with the number of cycles corresponding to 50% of expected fatigue life of samples in as-welded condition.

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. 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.

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 [7,18].

Figure 9 shows the drawings of large-scale welded specimens (600x100x30mm) containing non-load carrying longitudinal attachments for fatigue testing [18]. These specimens were tested in as-welded condition and after weld repair with and without application of UP.

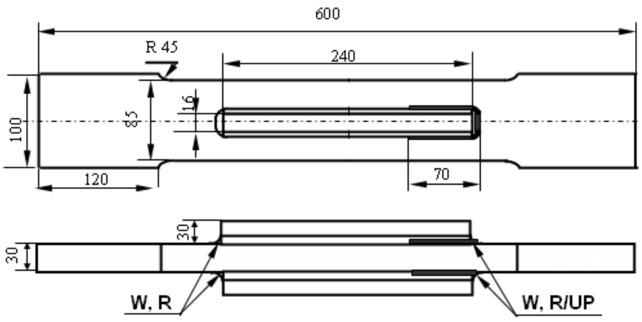

Figure 9. Drawings of welded specimens for fatigue testing at different conditions:
W – as-welded condition; R - repair by gouging and welding;
R/UP – repair by gouging, welding and UP

The cyclic testing conditions were zero-to-tension stress cycle (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 "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 on Figure 10.

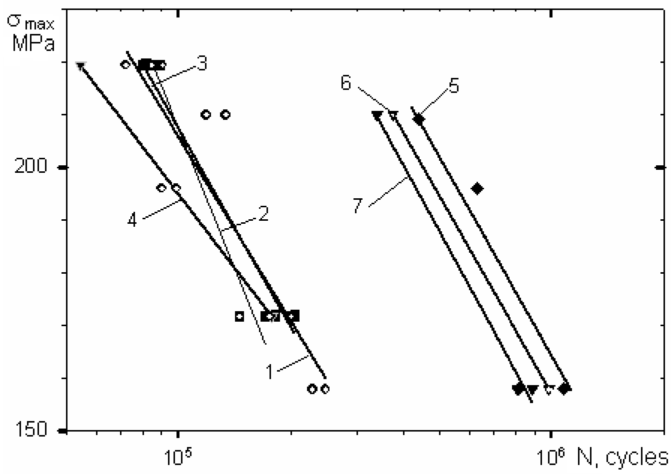

Figure 10. Results of fatigue testing of welded elements:
1 - as-welded condition, 2, 3 and 4 – after first, second and third weld repair, 5, 6 and 7 - after first, second and third weld repair with application of UP

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.

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.

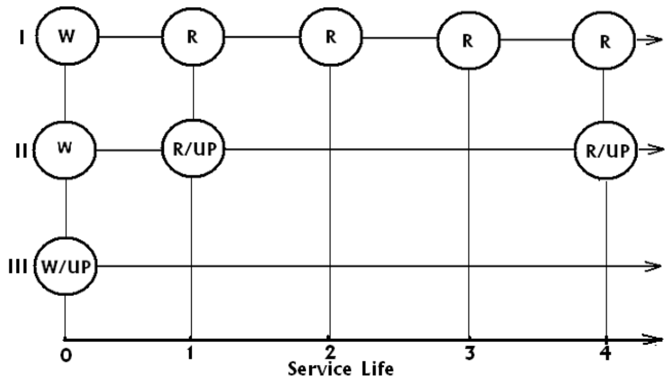

Figure 11. Diagram showing the endurance of welded element:
I - fatigue crack is repaired by gouging and welding,
II - fatigue crack is repaired by gouging, welding and UP,
III – UP is applied before/during the first phase of service life,
W – as-welded condition,
R - repair by gouging and welding,
R/UP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

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 12.

Figure 12. Application of UP for rehabilitation and repair of welded elements of mining equipment

Summary

Ultrasonic Impact Treatment (UIT) or Ultrasonic Peening (UP) is a promising technique for fatigue life improvement and could be efficiently used for manufacturing, rehabilitation and repair of welded elements and structures. 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, shot peening or application of LTT electrodes. The developed computerized complex for Ultrasonic Peening (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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