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Fatigue Improvement of Welded Elements by Ultrasonic Impact Treatment

30 Years of Practical Application

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1. Introduction

The development of the Ultrasonic Impact Treatment (UIT) technology was a logical continuation of the work done before directed on the investigation and further development of known techniques for surface plastic deformation such as shot peening, hammer peening, needle peening [1]. Originally the UIT technology was developed in 70-s and 80-s of last century in former Soviet Union with the purpose to strengthen the pressure hulls of submarines. The goal was to develop technology that is more efficient, faster and more comfortable for operators then existing improvement treatments of welded elements and structures. During the different stages of its development the UIT process was also known as "ultrasonic treatment", "ultrasonic impact technique/technology/treatment/peening". In many industrial applications the UIT process is known as ultrasonic peening (UP).

The UIT/UP technique is based on the combined effect of high frequency impacts of special strikers and ultrasonic oscillations in treated material. The beneficial effect of UIT/UP is achieved mainly by relieving of harmful tensile residual stresses and introducing compressive residual stresses into surface layers of material and also on smaller scale by decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of the surface layers of the material [2]. The basic system for UIT/UP treatment includes an ultrasonic transducer and generator. The basic UIT/UP system shown in Figure 1 could be used for treatment of weld toe or welds and base metal also if necessary.

Figure 1. Ultrasonic impact treatment (UIT/UP) of welded elements of a highway bridge

At the end of the 80-s of last century it was studied and proposed the principle to treat only the weld toe zone of welded elements and produce so-called "groove" by UIT/UP. In fact this "groove" is a quite shallow imprint with the depth of typically 0,2-0,4 mm. It was shown also that efficiency of UIT/UP in fatigue improvement of welded elements is the same or even higher when the “groove” approach is applied in comparison with the case when larger area is treated including weld, heat affected zone and adjusted base metal. The “groove” approach as an efficient way to apply UIT/UP for fatigue life improvement of welded elements for the first time described in literature in 1989 [3]. The parameters of “groove” described in [2] are practically the same that are recommended at present for effective fatigue improvement of welded joints [4].

The UIT/UP technology was introduced to the IIW community in 90-s of the last century [5-7]. After that dozens of IIW Documents describing mainly efficiency of UIT/UP in fatigue improvement of welded elements were presented and disscused at IIW Commission XIII “Fatigue of welded components and structures “.

This document summarises the 30 years of UIT/UP practical application. The UIT/UP technology and equipment, efficiency and examples of industrial applications are described.

2. Principles and Technology of UIT/UP

2.1 Freely Movable Strikers

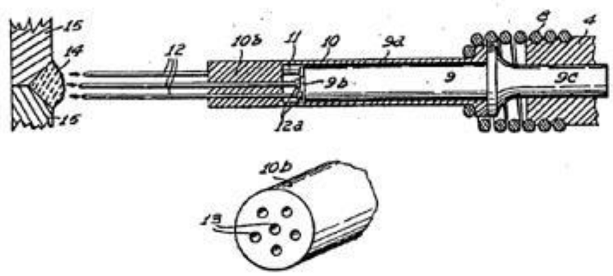
The UIT/UP equipment is based on known from the 40’s of last century technical solutions of using working heads with freely movable strikers for hammer peening [8]. During 60-s and 70-s of last century a number of different tools based on using freely movable strikers were developed for impact treatment of materials and welded elements by using pneumatic [9] and ultrasonic [10-16] equipment. The more effective impact treatment is provided when the strikers are not connected to the tip of actuator but could move freely between the actuator and the treated material. Pneumatic tools for impact treatment of materials and welded elements with the freely movable strikers (12 on Figure 2a and 21 on Figure 2b) that are mounted in a holder are shown in Figure 2. In the case of so-called intermediate element-striker(s) a force of only 30 - 50 N is required for treatment of materials.

Figure 3 shows a standard set of easy replaceable working heads with freely movable strikers for different applications of UIT/UP that are used in present.

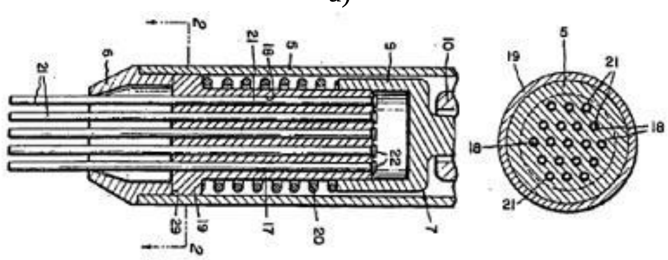
2.2 Ultrasonic Impact and Effects of Ultrasound

During the UIT/UP, the striker oscillates in the small gap between the end of the ultrasonic transducer and the surface of material, impacting the treated area. 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 level of 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 [18].



a)



b)

Figure 2. Sectional view through pneumatic tools with freely movable strikers for surface impact treatment: a – described in [8], b – described in [9]

Figure 3. A standard set of interchangeable working heads with freely movable strikers for different applications of UIT/UP [17]

2.3 Technology and Equipment for UIT/UP

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 mm. 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 impacts results in plastic deformation of the surface layers of the material. These impacts, repeated from few 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 UIT/UP.

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 4). 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.

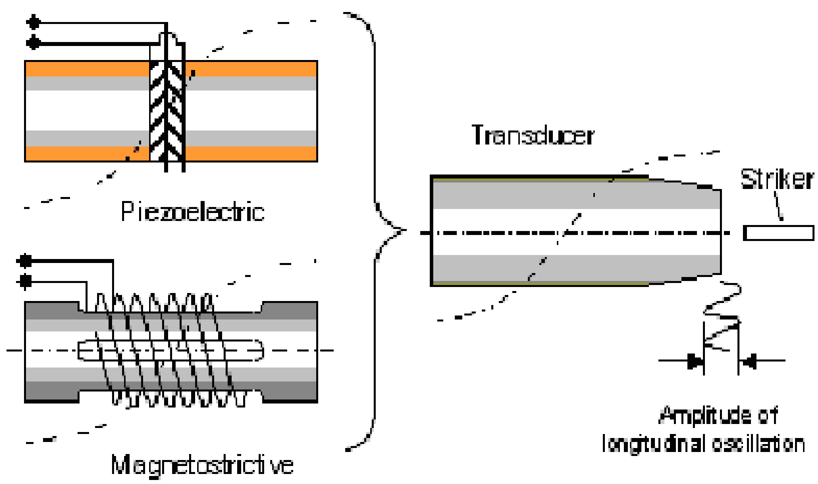


Figure 4. Schematic view of ultrasonic transducers for UIT/UP using piezoelectric and magnetostrictive approaches

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.

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 UIT/UP is practically the same by using of the magnetostrictive transducer with less power consumption. A UIT/UP system that is based on using of piezoceramic transducer is shown in Figure 5.

Figure 5. UIT/UP system that is based on using of piezoceramic transducer

2.4 Mechanism of Fatigue Improvement by 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 of welded elements, is the surface plastic deformation that leads to introduction of the beneficial compressive residual stresses in surface layers of material.

In the fatigue improvement, the beneficial effect is achieved mainly by introducing of the compressive residual stresses into surface layers of material [2], also 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 UIT/UP is shown on Figure 6 with the attained distribution of the residual stresses after the UIT/UP. The description of the UIT/UP benefits is presented in Table 1.

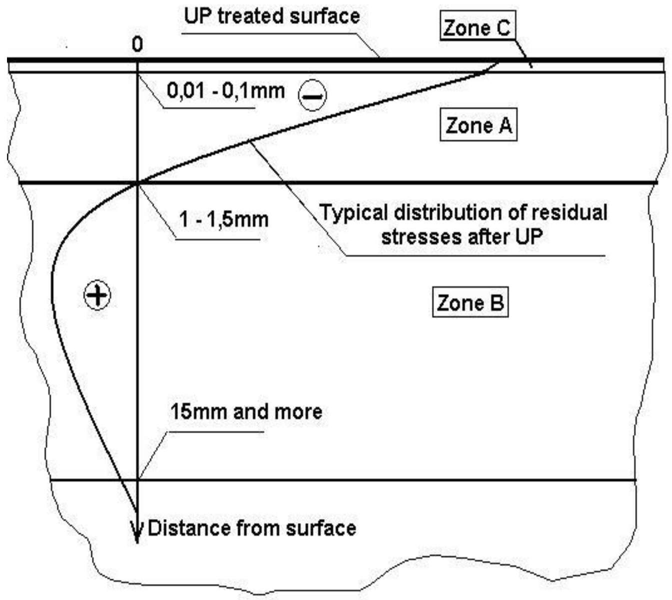


Figure 6. Schematic view of the cross section of material/part improved by UIT/UPUltrasonic Peening [19]

Table 1. Zones of Material/Part Improved by UIT/UP (see Figure 5 for an illustration of the zones) [19]

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 7 illustrates the concept of the fatigue life improvement of welded elements by UIT/UP. In the 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 of welded elements. Produced by UIT/UP so-called “groove” along the weld toe in different types of welded elements is shown in Figures 8 and 9.

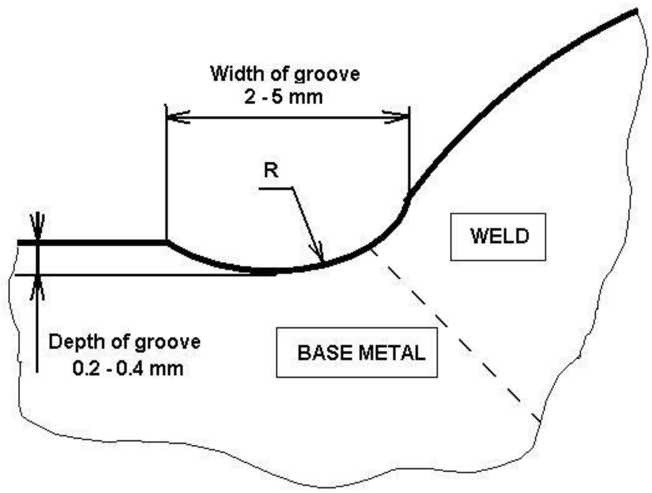


Figure 7. Profile of weld toe improved by Ultrasonic Peening [19]

Figure 8. The view of the butt welds in as-welded condition (left side sample)
and after application of UIT/UP (right side sample)

It should be noted that the principle to treat only the weld toe zone and to produce so-called "groove" by UIT/UP and high efficiency of this approach for fatigue improvement of welded elements was for the first time described in literature in 1989 [3]. In fact this "groove" is a profile of a quite shallow imprint from the action of UIT/UP with the depth of typically 0,2-0,4 mm. Figure 10 shows the photo published in [3] of the "groove" that was produced by UIT/UP of the end of welded stiffener that is critical from the fatigue point of view of the considered welded element.

Figure 9. The view of the fillet welds in as-welded condition (left side sample) and after application of UIT/UP (right side sample)

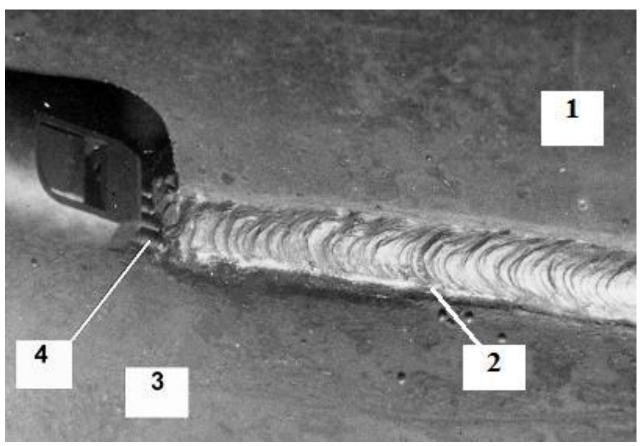


Figure 10. Photo of the "groove" produced by ultrasonic impact treatment of the end of welded stiffener published in 1989 [3]: 1 – welded stiffener, 2 – "groove" produced by UIT/UP, 3 - base plate, 4 – strikers of UIT tool

3. Effectiveness of UIT/UP in Fatigue Improvement

A large number of different large-scale welded specimens were fatigue tested in as-welded conditions and after application of UIT/UP. Investigated materials - steels and aluminium alloys of different strength. The process of UIT/UP of one of the welded samples for fatigue testing shown on Figure 11. Some results of fatigue testing are presented below.

Figure 11. The process of UIT/UP of welded sample for fatigue testing

3.1. Effectiveness of UIT/UP applied after welding and after 50% of expected fatigue life of welded elements

Three series of welded samples were subjected to fatigue testing to evaluate the effectiveness of UIT/UP application to the existing welded structures [20]:

1 – in as welded condition,
2 – UIT/UP was applied before fatigue testing,
3 – UIT/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.

The general view of welded sample for fatigue testing is shown in Figure 12.

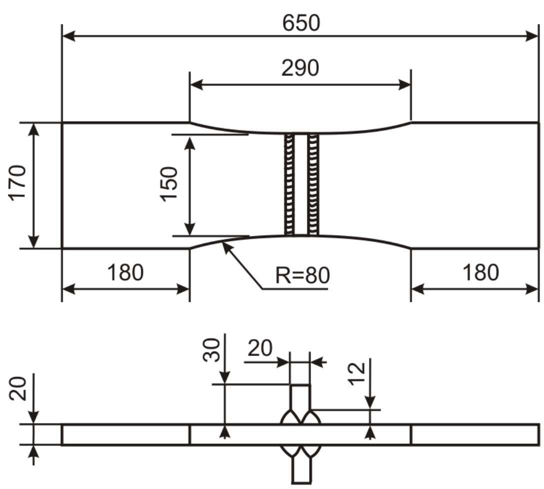


Figure 12. The general view of welded sample for fatigue testing

The data on mechanical properties of base material are presented in Table 2.

Table 2.The mechanical properties of base material

σ_y, *MPa*	σ_u, *MPa*	δ, *%*	ψ, *%*
260	465	37,6	63

All welded samples were tested at stress ratio R=0. The results of the fatigue testing are presented on Figure 13.

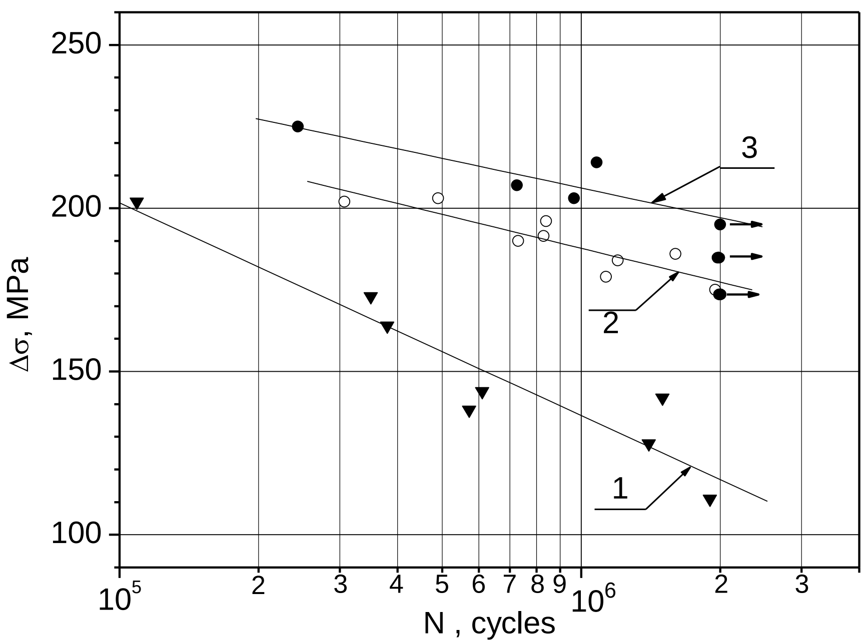


Figure 13. Fatigue curves of welded samples (transverse non-load-carrying attachment) [20]:
1 – in as welded condition, 2 – UIT/UP was applied before fatigue testing,
3 – UIT/UP was applied after fatigue loading with the number of cycles corresponding to 50% of expected fatigue life of samples in as-welded condition

As can be seen from Figure 13, the UIT/UP caused a significant increase in fatigue strength of the considered welded element for both series of UIT/UP treated samples. The increase in limit stress range (at $N=2\cdot10^6$ cycles) of welded samples is 53% (from 118 MPa to 180 MPa) for UIT/UP treated samples before fatigue loading and 67% (from 118 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. Also, on average, the UIT/UP caused 4-6 times increase in fatigue life of welded samples depending on the level of applied loading.

The higher increase of fatigue life of UIT/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 UIT/UP in comparison with the fatigue curve #2.

3.2. 960 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 960 MPa yield strength steel [21]. 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.

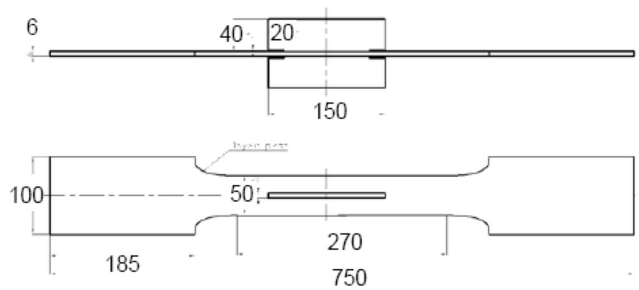


Figure 14. Specimen geometry for fatigue testing of 960 MPa yield strength steel welded elements [21]

The testing has been conducted under constant amplitude using stress ratio 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 15.

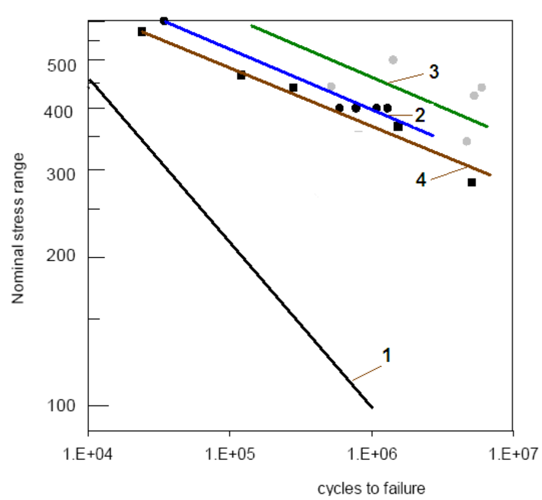


Figure 15. Fatigue test results for 960 MPa yield strength steel welded specimens [21]: 1- in as-welded condition, 2 and 3 - after UIT/UP based on using magnetostrictive and piezoelectric system transducers respectively, 4- after application of LTT electrodes

As can be seen from Figure 15, the UIT/UP treatment with an instrument based on piezoelectric transducer (UP-600 system) 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 as well as LTT electrodes during welding.

3.3. Fatigue crack repair by welding

The UIT/UP could also be effectively used during the weld repair of fatigue cracks. Figure 16 shows the drawing of a large-scale welded specimen containing a non-load carrying longitudinal attachments designed for fatigue testing [22]. Mechanical properties of considered material: yield strength – 360 MPa, ultimate strength – 420 MPa. These specimens were tested in as-welded condition and after weld repair of fatigue crack with and without application of UIT/UP.

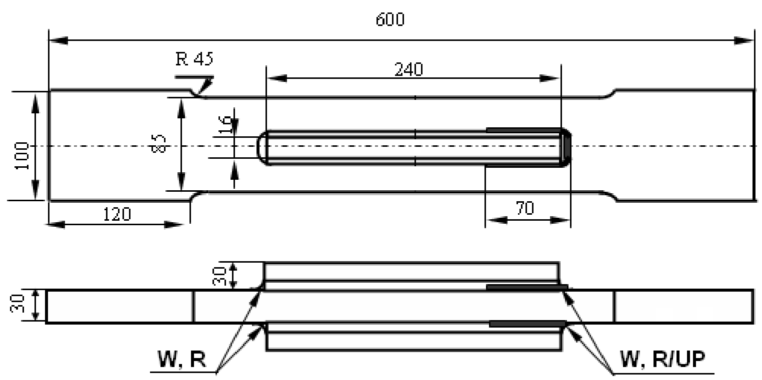


Figure 16. Drawings of welded specimens for fatigue testing at different conditions [22]: W – as-welded condition; R – fatigue crack repair by welding; R/UP – fatigue crack repair by welding and UIT/UP

The welded specimens were tested at stress ratio R=0 with different levels 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. After that the fatigue crack was repaired by gouging and welding and the fatigue test was continued. After weld repair, a number of samples were also subjected to UIT/UP. The weld toe of the “new” weld was UIT/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 17.

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.

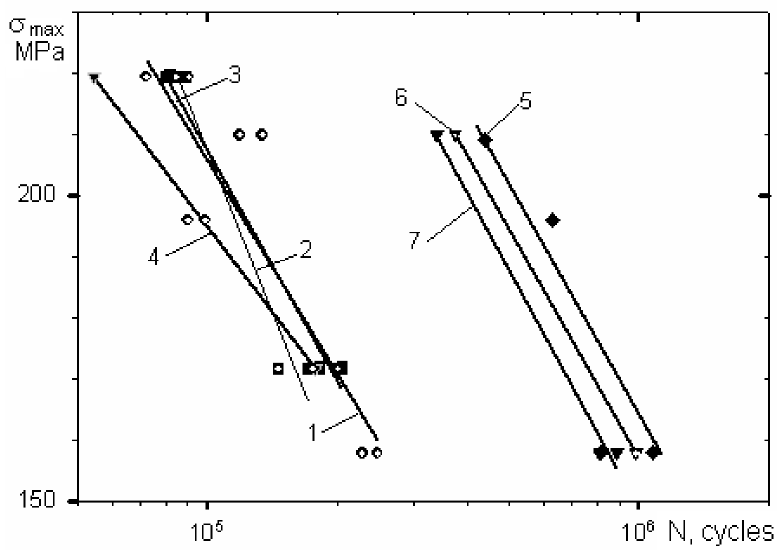


Figure 17. Results of fatigue testing of welded elements [22]: 1 - as-welded condition, 2, 3 and 4 – after the first, second and third weld repair, 5, 6 and 7 - after the first, second and third weld repair with application of UIT/UP

The application of UIT/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.

These and other numerous results of fatigue testing of welded specimens made from steels and aluminium alloys showed that the UIT/UP provided significant increase in fatigue performance of all considered types of welded joints and materials and that the UIT/UP is the most efficient improvement treatment as compared with traditional techniques such as grinding, TIG-dressing, heat treatment, shot peening, and hammer peening application of LTT electrodes.

In cases where there are no experimental data on fatigue life improvement by UIT/UP for a certain material, the type of welded elements and the conditions of cyclic loading, the benefit factor that is described in IIW recommendations on fatigue life improvement of welded elements including UIT/UP [23] could be applied to determine the expected increase of fatigue strength of welded elements.

4. Industrial application of UIT/UP

Introducing the so-called “groove” approach in application of UIT/UP for fatigue improvement of welded elements at the end of last century [2,3] made attractive the usage of UIT/UP in commercial applications. The “groove” approach significantly increases the speed of treatment, simplifies the quality control and makes it easier for operators to perform the UIT/UP.

Among the advantages of using of UIT/UP system (shown on Figures 1, 5 and 11) in industrial applications one can mention the following:

- High (highest) efficiency
- Quick (treatment speed of ~ 0.4 m of weld/min)
- Improved design of tool for operation in different positions including upper position
- Considerably reduced vibrations and noise levels, easier in use than hammer peening
- Deeper penetration (depth of plastic deformation)
- Computer controllable
- Robotic line - ready
- Lighter with no need in forced water-cooling as compared with similar magnetostrictive systems.

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

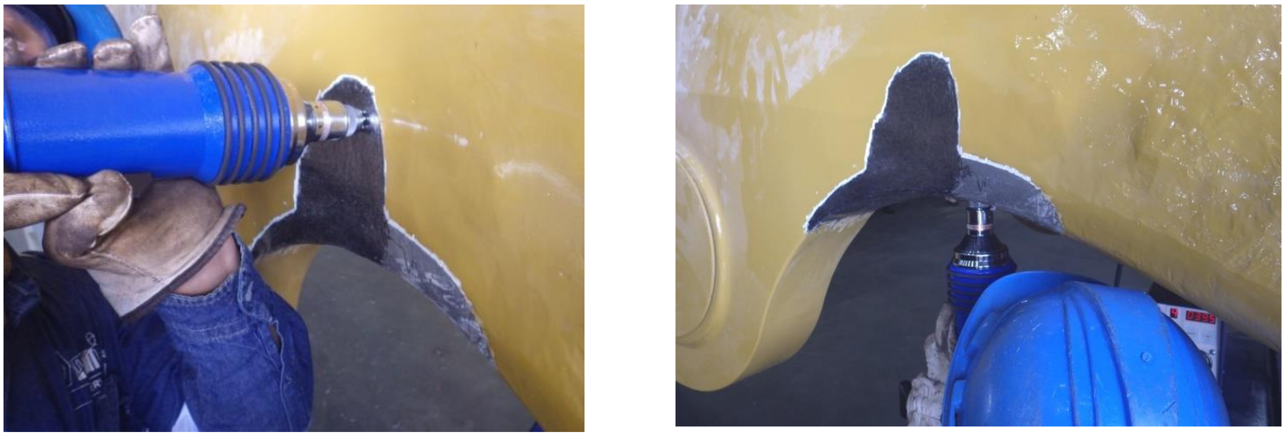
A few examples of UIT/UP industrial application are illustrated below. In the first case the UIT/UP was applied for fatigue life improvement of a highway bridge. Figure 18a shows the process of UIT/UP of one of the welded elements of a highway bridge and Figure 18b shows the location of the zones of treatment that are marked in white.

a)

b)

Figure 18. The process of UIT/UP in upper position of tool of one of the welded elements of a highway bridge (a) and the zones of treatment that are marked in white (b)

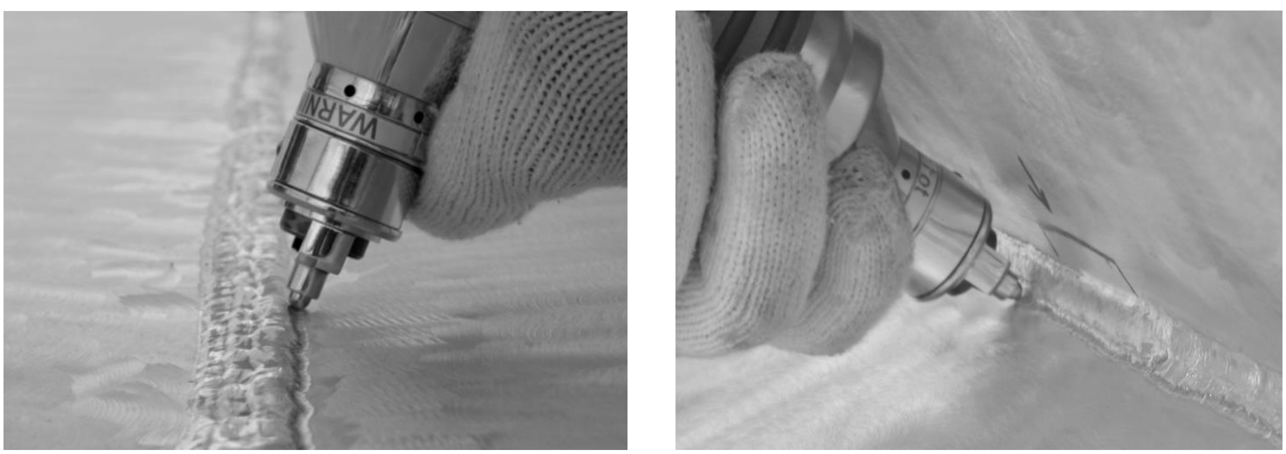
The second example is a using of UIT/UP as a final stage of fatigue crack repair of heavy mining equipment for preventing of the origination of fatigue cracks at the same location again in the future. Figure 19 shows the process of UIT/UP of the zone of fatigue crack repair both in horizontal and upper position of a tool.



a) b)

Figure 19. Application of UIT/UP at a final stage of fatigue crack repair of heavy mining equipment for preventing of the origination of fatigue cracks: a) horizontal position of a tool, b) upper position of a tool

Third example is an application of UIT/UP for prevention of initiation and propagation of fatigue and corrosion cracking of large aluminum welded panels containing both butt and fillet welds (Figure 20).



a) b)

Figure 20. The process of UIT/UP of butt weld (a) and fillet weld (b) for prevention of initiation and propagation of fatigue and corrosion cracking of large aluminum welded panels

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