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Fatigue improvement of welded elements by ultrasonic impact treatment

Poboljšanje otpornosti na zamor zavarenih elemenata primenom obrade ultrazvučnim udarom

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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 UIT/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 UIT/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 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 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 results of fatigue testing of large-scale welded specimens in as-welded condition and after application of UIT/UP are considered in this paper. It is shown that UIT/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.

Rezime

Ultrazvučna obrada udarom (Ultrasonic impact treatment – UIT) predstavlja relativno novi obećavajući metod poboljšanja zamornog veka zavarenih elemenata i konstrukcija. U većini industrijskih primena, ovaj proces je poznat po imenu ultrazvučno ojačavanje (Ultrasonic peening - UP).

Poboljšavajući efekat UIT/UP metod postiže pre svega rasterećivanjem zaostalih napona i ubacivanjem pritisnih napona na površinski sloj materijala. Sekundarni faktori pri poboljšavanju otpornosti na zamor primenom ove metode se ogledaju u smanjenju koncentracije napona oko linije stapanja, kao i poboljšanje mehaničkih osobina površinskog sloja materijala. Ispitivanje zamora zavarenih epruveta je pokazalo da je UIT/UP najefikasniji vid obrade u poređenju sa tradicionalnim tehnikama poput brušenja, TIG-prevalaka, termičke obrade, čekićanja i primene LTT elektroda. Razvijeni računarski sistem za UIT/UP je uspešno primenjen na povećanje zamornog veka i otpornost na koroziju zavarenih elemenata, eliminisanje distorzija prouzrokovanih zavarivanjem i drugim tehnološkim procesima, smanjenje zaostalih napona, kao i povećanje tvrdoće površinskog sloja materijala.

U ovom radu su prikazani rezultati ispitivnja zamorom, zavarenih uzoraka velikih dimenzija u zavarenom stanju i nakon primene UIT/UP. Pokazano je da je primena UIT/UP tehnike efikasna i ekonomična za povećanje zamorne čvrstoće zavarenih elemenata od materijala različite čvrstoće. Ovi rezultati takođe pokazuju izrazitu tendenciju povećanja zamorne čvrstoće zavarenih elemenata nakon primene process UP posebno sa porastom mehaničkih osobina tretiranih materijala.



1. Introduction

The UIT/UP technique is based on the combined effect of high frequency impacts of special strikers and ultrasonic oscillations in treated material [1, 2]. 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 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 [3]. The basic system for UIT/UP treatment (total weight - 11 kg) includes an ultrasonic transducer, a generator and a laptop (optional item) with software for optimum application of UIT/UP - maximum possible increase in fatigue life of welded elements with minimum cost, labour and power consumption. In general, the basic UIT/UP system shown in Fig. 1 could be used for treatment of weld toe or welds and base metal also if necessary.

1. Uvod

UIT/UP tehnika je zasnovana na kombinovanom uticaju visokofrekventnih udara koji se vrše posebnim čekićima i ultrazvučnih oscilacija na obrađivanom materijalu [1, 2]. Poboľšavajući efekat UIT/UP metod postiže pre svega rasterećivanjem zaostalih zatezних napona i ubacivanjem pritisnih napona na površinskom sloju materijala, i u nešto manjoj meri zahvaljujući smanjivanju koncentracije napona oko linija stapanja zavarneog spoja i poboljšanju mehaničkih osobina površinskog sloja materijala [3]. Osnovni sistem za UIT/UP obradu, ukupne težine 11 kg, se sastoji od ultrazvučnog pretvarača, generatora i laptopa sa softverom koji omogućava optimalnu primenu UIT/UP metode – kako bi se ostvarilo maksimalno produženje zamornog veka zavarenih elemenata uz minimalne troškove, napor i potrošnju struje. Uopšteno, osnovni UIT/UP sistem prikazan na slici 1 se može koristiti i za obradu zavarenih spojeva ili osnovnog materijala, po potrebi.

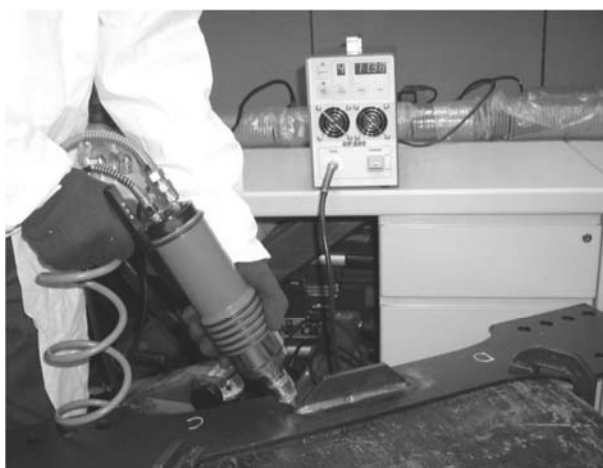


Figure 1. Ultrasonic impact treatment (UIT/UP) of welded sample for fatigue testing
Slika 1. Obrada ultrazvučnim udarom (UTI/UP) zavarene epruvete za ispitivanje zamorom

Fatigue testing of welded specimens showed that 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.

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. At that time and later, a number of different tools based on using freely movable strikers were developed for impact treatment of materials and welded elements by using pneumatic [4,5] and ultrasonic [6-12] 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

Ispitivanje zamorom zavarenih epruveta je pokazao da je UIT/UP najefikasnija metoda obrade u poređenju sa prethodno pominjanim tradicionalnim metodama (brušenje, TIG-prevlake, itd.).

2. Principi i tehnologija UIT/UP

2.1 Pokretni čekići

UIT/UP oprema je zasnovana na dobro poznatom tehničkom rešenju iz četrdesetih godina prošlog veka, koje je koristilo radne glave sa čekićima koji su mogli slobodno da se pomeraju, za potrebe čekićanja. Tada, a i kasnije, razvijen je veliki broj alata zasnovanih na primeni pokretnih čekića za potrebe obrade materijala i zavarenih elemenata primenom pneumatske [4, 5] i ultrazvučne opreme [6 - 12]. Obrada udarom je efikasnija u slučaju kada čekići nisu povezani sa vrhom pokretača, već mogu da se slobodno kreću između pokretača i radnog



treated material. The tools for impact treatment of materials and welded elements with the freely movable strikers (12 on Fig. 2a and 21 on Fig. 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.

komada. Alati za obradu udarom materijala i zavarenih elemenata sa pokretnim čekićima (12 na slici 2a i 21 na slici 2b), koji su montirani na držač, su prikazani na slici 2. U slučaju takozvane posredne veze između elementa i čekića, dovoljna je sila od svega 30 – 50 N za obradu materijala.

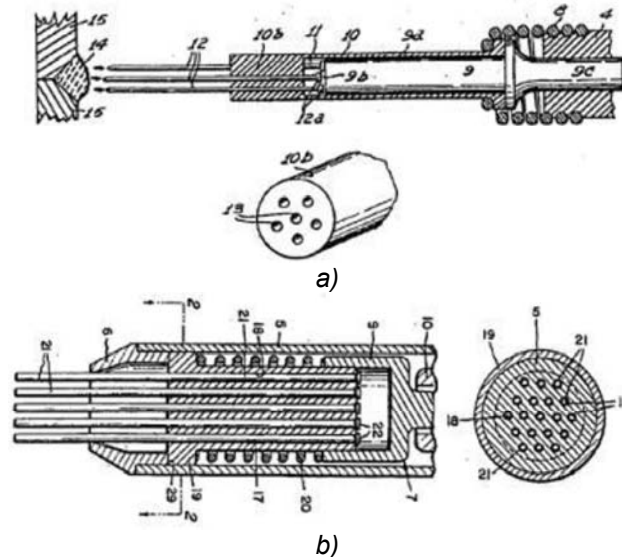


Figure 2. Sectional view through tools with freely movable strikers for surface impact treatment: a – described in [4], b – described in [5]

Slika 2. Poprečni presek alata sa pokretnim čekićima za površinsku obradu udarom: a – opisan u [4], b – opisan u [5].

Fig. 3 shows a standard set of easy replaceable working heads with freely movable strikers for different applications of UIT/UP.

Na slici 3 je prikazan standardan komplet lako zamenljivih radnih glava sa pokretnim čekićima za različite primene UIT/UP metode.



Figure 3. A set of interchangeable working heads for UIT/UP [1]

Slika 3. Komplet zamenljivih radnih glava za UIT/UP [1].

2.2 Ultrasonic Impact and Effects of Ultrasound

During the ultrasonic impact treatment, the striker oscillates in the small gap between the end of the ultrasonic transducer and the treated specimen, impacting the treated area [6-9]. 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

2.2 Ultrazvučni udar i efekti

Tokom obrade ultrazvučnim udarom, čekić osciluje u malom zazoru između kraja ultrazvučnog pretvarača i radnog komada, pri čemu udara u obrađivanu površinu [6 - 9]. Ovakva vrsta visokofrekventnog kretanja/udara u kombinaciji sa visokofrekventnim oscilacijama koje se javljaju u obrađivanom materijalu se najčešće naziva ultrazvučni udar. Ultrazvuk može imati veliki broj različitih uticaja na metale, od kojih se najčešće



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 [13].

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 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 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 (Fig. 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.

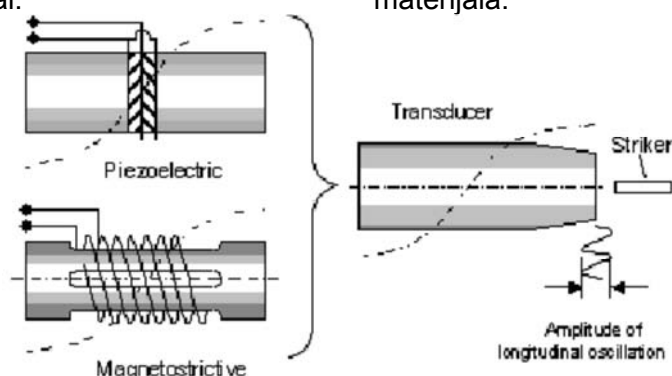


Figure 4. Schematic view of transducers for UIT/UP using piezoelectric and magnetostrictive approaches
Slika 4. Šematski prikaz pretvarača za UIT/UP primenom peizelektrične i magnetostruktivne tehnologije.

razmatraju: zvučno omekšavanje, zvučno ojačavanje, zvučno zagrevanje, itd. U slučaju prvog (omekšavanje, koje je takođe poznato pod imenom zvučno-plastični efekat), delovanje zvuka smanjuje nivo napona koji su neophodni za plastičnu deformaciju. Uopšteno, uticaj ultrazvuka na mehaničko ponašanje materijala se može uporediti sa zagrevanjem. Razlika je u tome što se zvučno omekšavanje dešava još dok je metal izložen dejstvu ultrazvuka. Takođe, ultrazvučni talasi sa relativno niskom amplitudom ne ostavljaju zaostale uticaje na fizičke osobine nakon što izloženost zvučnim dejstvima prestane [13].

2.3 Tehnologija i oprema za UIT/UP

Ultrazvučnu pretvarač osciluje sa visokom frekvencijom, najčešće u rasponu od 20 do 30 kHz. Ultrazvučni pretvarač može biti zasnovan ili na piezoelektričnoj ili magnetostruktivnoj tehnologiji. Bez obzira na izbor tehnologije, izlazi iz pretvarača će uvek oscilovati, najčešće sa amplitudama od 20-40 mm. Tokom ovih oscilacija, vrh pretvarača će udarati čekić(e) u različitim fazama ciklusa oscilacije. Čekić(i) će, kao posledica toga, udarati u obrađivanu površinu. Ovi udari će proizvesti plastičnu deformaciju u površinskom sloju. Kada se ovakvi udari ponavljaju i po hiljadu puta u sekundi, u kombinaciji sa visokofrekventnim oscilacijama koje su indukovane u obrađivanom materijalu, dolazi do pojave niza povoljnih efekata zahvaljujući primeni UIT/UP.

Postoje dva opšta tipa ultrazvučnih pretvarača koji se koriste za UIT/UP: magnetostruktivni i piezoelektrični. Oba postižu isti efekat pretvaranja naizmenične električne energije u oscilujuću mehaničku energiju, ali na malo drugačiji način, slika 4. U slučaju magnetostruktivnih pretvarača, naizmenična struja iz ultrazvučnog generatora se prvo pretvara u naizmenično magnetno polje, pomoću žičanog kalema. Naizmenično magnetno polje se onda koristi kako bi se indukovale mehaničke vibracije sa ultrazvučnim frekvencijama u rezonantnim trakama magnetostruktivnog materijala.



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 watercooling. 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 basic UIT/UP system that is based on piezoceramic transducer is shown in Fig. 1.

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 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 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 UIT/UP is shown on Fig. 5 with the attained distribution of the stresses after the UIT/UP. The description of the UIT/UP benefits is presented in Tab. 1.

Magnetostruktivni pretvarači su generalno manje efikasni od piezoelektričnih. Ovo je pre svega zbog toga što ovi pretvarači zahtevaju dvostruko pretvaranje energije – iz električne u magnetnu, i obrnuto. Pri svakom od ovih pretvaranja se gubi deo efikasnosti. Efekti magnetnog histerezisa takođe umanjuju efikasnost ovakvih pretvarača, a pored toga im je neophodno i prinudno hlađenje vodom.

Piezoelektrični pretvarači pretvaraju naizmeničnu električnu energiju direktno u mehaničku energiju zahvaljujući piezoelektričnom efektu. Današnji piezoelektrični pretvarači koriste jače, efikasnije i stabilnije keramičke materijale, koji mogu da rade i pod opterećenjem, na različitim temperaturama, čime je poboljšana njihova pouzdanost i smanjena potrošnja energije do 60%. Usled visoke energetske efikasnosti piezoelektričnih pretvarača, efekat povećanja zamornog veka primenom UIT/UP je maltene isti kao i kod magnetostruktivnih pretvarača, uz značajno manji utrošak energije. Osnovni UIT/UP sistem zasnovan na piezoelektričnim pretvaračima je prikazan na slici 1.

UIT/UP predstavlja veoma efikasan način rasterećenja opasnih zaostalih zatezних napona uvođenjem pritisnih zaostalih napona u površinski sloj delova i zavarenih elemenata. Mehanizam preraspodele zaostalih napona je u najvećoj meri vezan za dva faktora. Pri visokofrekventnom udarnom opterećenju, oscilacije složenog spektra frekvencija će se prostirati kroz obrađivani materijal. Priroda ovog spektra zavisi od frekvencije ultrazvučnog pretvarača, mase, količine i oblika čekića, kao i od geometrije radnog komada. Ove oscilacije za posledicu imaju smanjenje zaostalih napona koji se javljaju nakon zavarivanja. Drugi, važniji faktor, bar sa stanovišta otpornosti na zamor, predstavlja plastična deformacija površinskog sloja, čime se u materijal uvode korisni pritisni naponi.

Pri poboljšanju zamornog veka, povoljni uticaju se najviše ostvaruju uvođenjem pritisnih zaostalih napona u površinske slojeve metala i legure, smanjenjem zaostalih napona oko linije stapanja i poboljšanjem mehaničkih osobina površinskog sloja materijala. Šematski prikaz poprečnog preseka materijala/dela koji je poboljšan primenom UIT/UP je prikazan na slici 5, sa novo dobijenom raspodelom napona. Prednosti primene UIT/UP su predstavljane u tabeli 1.

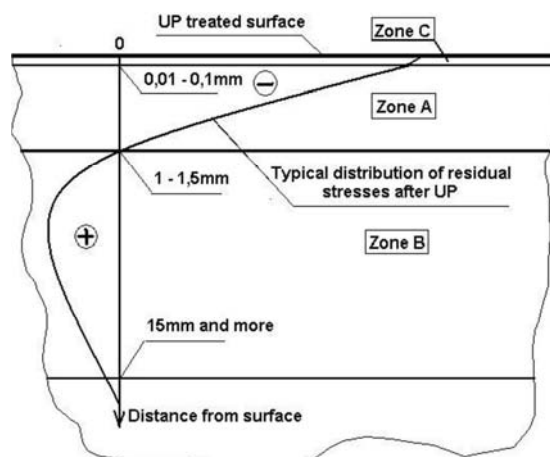


Figure 5. Schematic view of the cross section of material/part improved by Ultrasonic Peening [1]
Slika 5. Šematski prikaz poprečnog preseka materijala/dela poboljšanog primenom UIT/UP [1]

Table 1. Zones of Material/Part Improved by UIT/UP (see Figure 5 for illustration of the zones) [1]
Tabela 1. Zone u materijalu/delu koje su poboljšane primenom UIT/TP (prikazane na slici 5) [1]

Zona	Opis	Penetracija(udaljenost od površine),mm	Poboljšane osobine
A	Zona plastične deformacije i pritisnih zaostalih napona	1-1,5 mm	Otpornost na zamor, koroziju, habanje, krivljenje
B	Zona relaksacija zaostalih napona usled zavarivanja	Od 15 mm naviše	Krivljenje, otpornost na rast prsline
C	Zona nano-kristalizacije (koja može nastati pri određeniim uslovima)	0,01-0,1 mm	Otpornost na koroziju, habanje, zamor na povišenim temperaturama

Fig. 6 illustrates the concept of the fatigue life improvement of welded elements by UIT/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 of welded elements. The produced by UIT/UP so-called “groove” in different types of welded elements is shown in Fig. 7 and 8.

Na slici 6 je ilustrovan koncept produženja zamornog veka zavarenih elemanta primenom UIT/UP metode. U slučaju zavarenih delova, dovoljno je obraditi samo liniju stapanja, odnosno zonu prelaska sa osnovnog materijala na zavareni spoj, kako bi se postiglo značajno produženje zamornog veka ovakvih elemenata. Na slikama 7 i 8 su prikazani takozvani „žlebovi“ proizvedeni primenom UIT/UP metode.

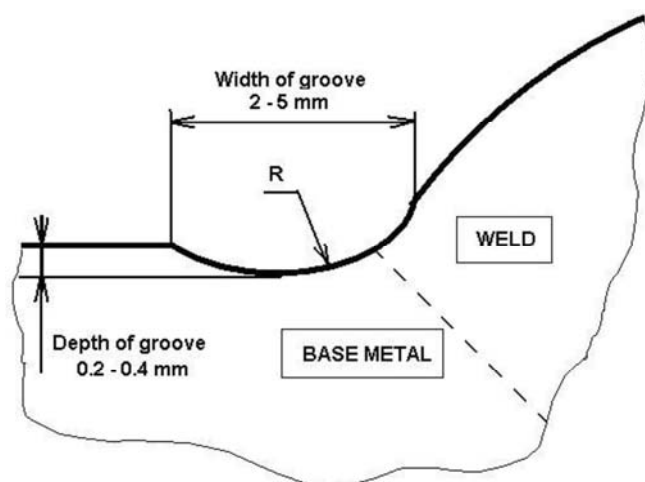


Figure 6. Profile of weld toe improved by Ultrasonic Peening [1]
Slika 6. Profil linije stapanja obrađene ultrazvučnim ojačavanjem [1].



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

Slika 7. Izgled sučeonog zavarenog spoja nakon zavarivanja (levo) i nakon što je urađen UP (desno)



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

Slika 8. Izgled ugaonog zavarenog spoja nakon zavarivanja (levo) i nakon što je obrađen UP (desno)

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 [2]. Fig. 9 shows the photo published in [2] of the “groove” that was produced by ultrasonic impact treatment of the end of welded stiffener that is critical from the fatigue point of view of the considered welded element.

Potrebno je napomenuti da je pristup koji se zasniva samo na obradi linije stapanja, kojim se dobija takozvani „žleb“ primenom UIT/UP metode, kao i njegoova velika efikasnost pri povećanju otpornosti na zamor zavarenih elemenata prvo su opisana u literaturi 1989. godine [2]. Na slici 9 se može videti fotografija žleba iz literature [2], proizvedenog obradom ultrazvučnim udarom kraja zavarenog ukrućenja, koji predstavlja kritično mesto sa stanovišta zamora posmatranog zavarenog elementa.

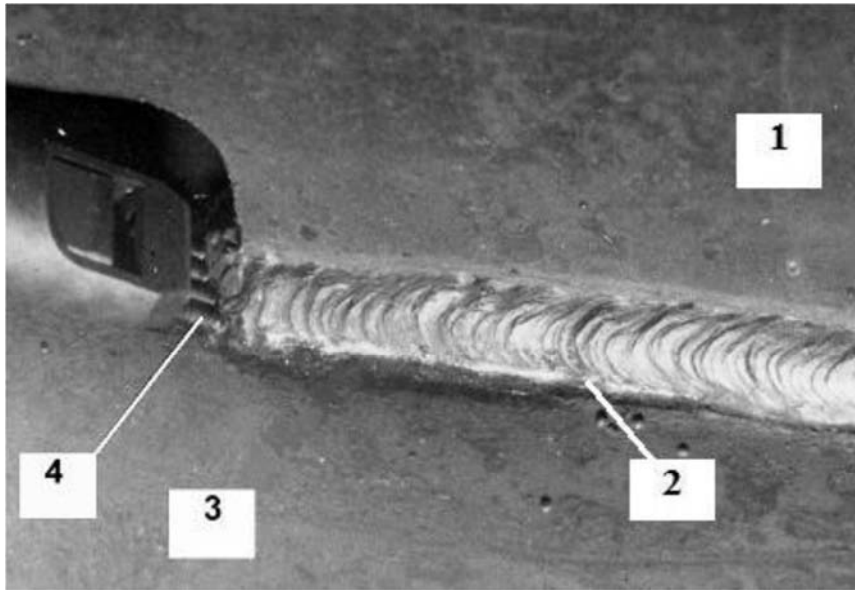


Figure 9. Photo of the “groove” produced by ultrasonic impact treatment of the end of welded stiffener published in 1989 [2]: 1 – welded stiffener, 2 – “groove” produced by UIT/UP, 3 - base plate, 4 – strikers of UIT tool

Slika 9. Fotografija „žleba“ porizvedenog obradom ultrazvučnim udarom kraja zavarenog ukrucenja, iz rada objavljenog 1989. [2]; 1 – ukrucenje, 2 – “žleb” proizveden primenom UIT/UP, 3 – osnovni materijal, 4 – čekići UIT alata.

3. Effectiveness of UIT/UP in Fatigue Improvement

The large-scale welded specimens were fatigue tested in as-welded conditions and after UIT/UP. Investigated materials - steels and aluminium alloys of different strength. Some results of fatigue testing are presented below.

3.1. 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 [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 Fig. 10.

3. Efikasnost UIT/UP pri poboljšanju otpornosti na zamor

Zavarene epruvete velikih dimenzija su ispitivane na zamor neposredno nakon zavarivanja, kao i nakon što su obrađene primenom UIT/UP. Ispitivani materijali su obuhvatali čelike i legure aluminijuma različitih mehaničkih osobina. U daljem tekstu su prikazani rezultati nekih od ovih ispitivanja.

3.1 Čelik povišene čvrstoće (granica tečenja 960 MPa)

Četiri serije epruveta su ispitivane na zamor kako bi se ocenila efikasnost UIT/UP metode na produženje zamornog veka zavarenih elemenata od čelika povišene čvrstoće, sa granicom tečenja od 960 MPa [14]. Epruvete za ispitivanje na zamor, urađene sa sledećim dimenzijama – širina 50 mm i debljina 6 mm – sa podužnim nenosećim ugaonim zavarima, kao što je prikazano na slici 10.

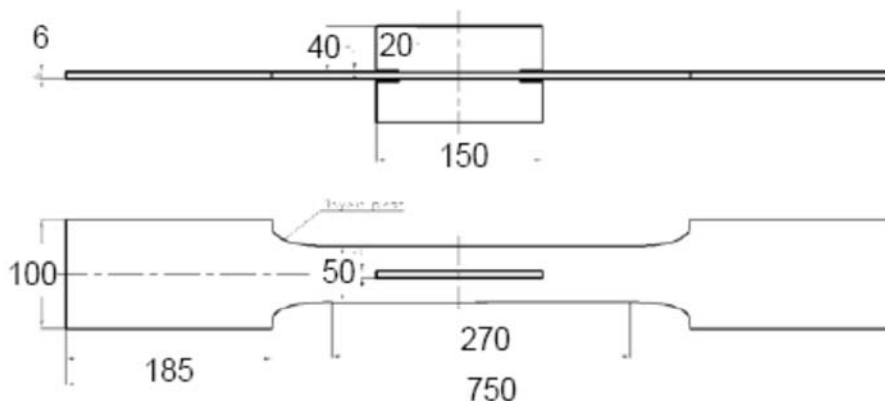


Figure 10. Specimen geometry for fatigue testing of 960 MPa yield strength steel welded elements [14]

Slika 10. Geometrija epruveta za ispitivanje zamora, izrađenih od čelika sa granicom tečenja od 960 MPa [14].



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 Fig. 11.

As can be seen from Fig. 11, 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.

Ispitivanje je izvršeno pod konstantnim amplitudnim naponom sa odnosom napona $R = -1$. Sve epruvete uzete iz neobrađenog zavarenog spoja su pukle u oblasti linije stapanja na kraju podužnih ukrucenja. Što se obrađenih epruveta tiče, ispitivanje je izvršeno sa konstantnim amplitudnim naponom, uz različite režime otkaza. Rezultati ovog ispitivanja na zamor su prikazani na slici 11.

Kao što se može videti sa ove slike, obrada primenom UIT/UP sa opremom koja radi na principu piezoelektričnog pretvarača (sistem UP-600) je proizvela najveće poboljšanje u zamornom ponašanju posmatranog zavarenog elementa za slučaj čelika povišene čvrstoće ($R_e = 960$ MPa), u poređenju sa drugim metodama, uključujući ultrazvučno ojačavanje pomoću magnetostruktivnih pretvarača, kao i LTT elektrode.

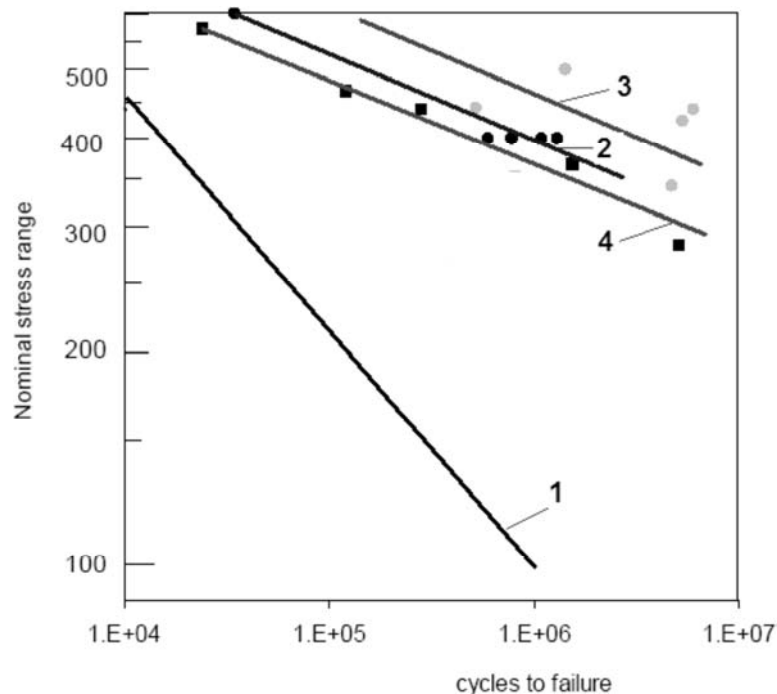


Figure 11. Fatigue test results for 960 MPa yield strength steel welded specimens [14]: 1- in as-welded condition, 2 and 3 - after UIT/UP based on using magnetostrictive and piezoelectric system transducers respectively, 4- after application of LTT electrodes

Slika 11. Rezultati ispitivanja zamora epruveta od čelika povišene čvrstoće [14]: 1-neobrađeno stanje nakon zavarivanja, 2 i 3-nakon obrade primenom UIT/UP magnetorestriktivnim i piezoelektričnim pretvaračima, respektivno, 4-nakon primene LTT elektroda.

3.2. Fatigue crack repair by welding

The UIT/UP could also be effectively used during the weld repair of fatigue cracks. Figure 12 shows the drawing of a large-scale welded specimen containing a non-load carrying longitudinal attachments designed for fatigue testing [15]. 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 with and without application of UIT/UP.

3.2 Reparatura zamornih prslina zavarivanjem

UIT/UP se takođe može efikasno koristiti tokom reparaturnog navarivanja zamornih prslina. Na slici 12 je prikazan crtež epruvete velikih dimenzija koja sadrži i nenoseći podužni priključak, koji služi za ispitivanje zamora [15]. Mehaničke osobine materijala koji je posmatran u ovom slučaju su – granica tečenja od 360 MPa, zatezna čvrstoća od 420 MPa. Ove epruvete su ispitane nakon zavarivanja, kao i nakon reparaturnog navarivanja, sa i bez primene UIT/UP.

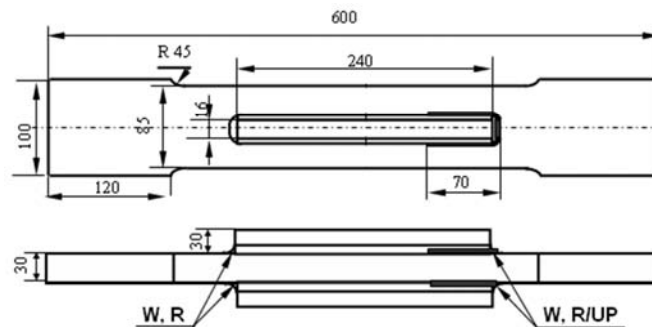


Figure 12. Drawings of welded specimens for fatigue testing at different conditions [15]: W – as-welded condition; R – fatigue crack repair by welding; R/UP – fatigue crack repair by welding and UIT/UP

Slika 12. Crteži zavarenih epruveta za ispitivanje na zamor u različitim uslovima [15]: W – nakon zavarivanja, R – nakon reparaturnog navarivanja zamorne prslina, R/UP – nakon reparaturnog navarivanja zamorne prslina i primene 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 Fig. 13.

Zavarene epruvete su ispitane pri odnosu napona $R = 0$, uz različite vrednosti maksimalnih napona. Frekvencija ispitivanja je iznosila 5 Hz. Ispitivanje zamora je zaustavljeno i broj ciklusa je zabeležen u trenutku kad je površinska zamorna prslina dostigla dužinu od 20 mm. Nakon toga je prslina reparirana i nastavljeno je sa ispitivanjem zamora. Određen broj epruveta je također podvrgnutu UIT/UP obradi nakon reparaure. Linija stapanja „novog“ zavarenog spoja je obrađena na ovaj način. Rezultati zamornih ispitivanja zavarenih epruveta u uslovima nakon zavarivanja, kao i nakon reparaure zamornih prslina su prikazani na slici 13.

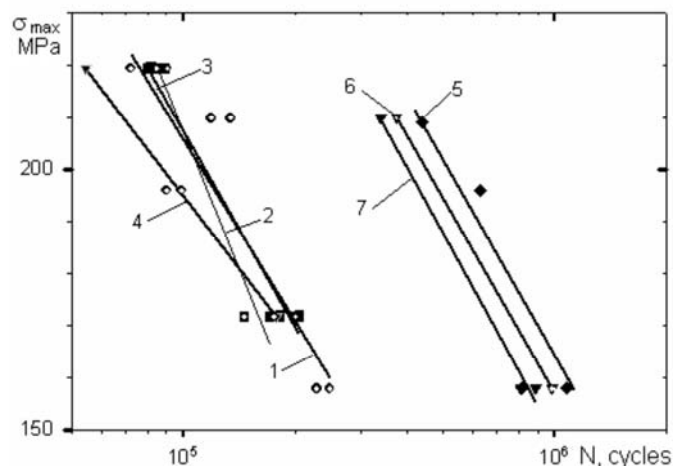


Figure 13. Results of fatigue testing of welded elements [15]: 1 - aswelded condition, 2, 3 and 4 – after first, second and third weld repair, 5, 6 and 7 - after first, second and third weld repair with application of UIT/UP

Slika 13. Rezultati ispitivanja na zamor zavarenih elemenata [15]: 1- nakon zavarivanja, 2, 3 i 4 - nakon prve, druge i treće reparaure zavarenog spoja; 5, 6 i 7 - nakon prve, druge i treće reparaure sa UIT/UP obradom

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 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

Ispitivanje na zamor ovih epruveta je pokazalo da je zavarivanje povratilo izvornu zamornu čvrstoću zavarenih elemenata, kao što je bila neposredno nakon što je zavarivanje izvršeno. Drugo i treće reparaturno navarivanje je ostvarilo praktično isti rezultat u pogledu otpornosti na zamor.

Primena UIT/UP nakon reparaturnog navarivanja je produžila zamorni vek 3-4 puta. Praktično isti značajan porast zamornog veka je primećen i pri drugoj i trećoj reparaturi ovih zavarenih spojeva.



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.

4. Industrial application of UIT/UP

As was demonstrated, 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 for rehabilitation and weld repair of parts and welded elements. The areas/industries where the UIT/UP was applied successfully include: Railway and Highway Bridges, Construction Equipment, Shipbuilding, Mining, Automotive and Aerospace. Fig. 14 illustrates three examples of UIT/UP industrial application. In first case the UIT/UP was applied for fatigue life improvement of welded elements of a highway bridge, in second case - as a final stage of fatigue crack repair in heavy mining equipment, in third – for prevention of initiation and propagation of fatigue and corrosion cracking of large aluminum welded panels.

Prikazani rezultati, kao i mnogi drugi vezani za ispitivanje na zamor, zavrenih epruveta od čelika i aluminijumskih legura, su pokazali da se primenom UIT/UP postiže značajno povećanje zamornog veka svih zavarenih spojeva i materijala, kao i da je ova metoda najefikasniji vid obrade u pogledu poboljšanja zavarneih spojeva, u poređenju sa tradicionalnijim pristupima.

4. Industrijska primena UIT/UP

Kao što je prethodno prikazano, UIT/UP se može efektivno prieniti na poboljšanje zamornog veka tokom proizvodnje, obnove i reparature zavarenih elemenata i konstrukcija. UIT/UP tehnologija i oprema su uspešno primnjene u različitim industrijskim projektima obnove i reparature delova i zavarenih elemenata. Industrijske oblasti u kojima je ova metoda uspešno primenjena obuhvatile su: železnicu i mostove, građevinsku opremu, brodogradnju, rudarstvo, autoindustriju i vazduhoplovstvo.

Na slici 14 su prikazana tri primera industrijske primene UIT/UP. U prvom slučaju je korišćena za produženje zamornog veka zavarenih elemenata mosta na autoputu, u drugom slučaju se odnosila na reparaturno navarivanje zamornih prslina kod teške rudarske opreme, i u trećem slučaju je korišćena za sprečavanje nastanka i rasta prslina usled zamora i korozije u zavarenim pločama od aluminijuma.

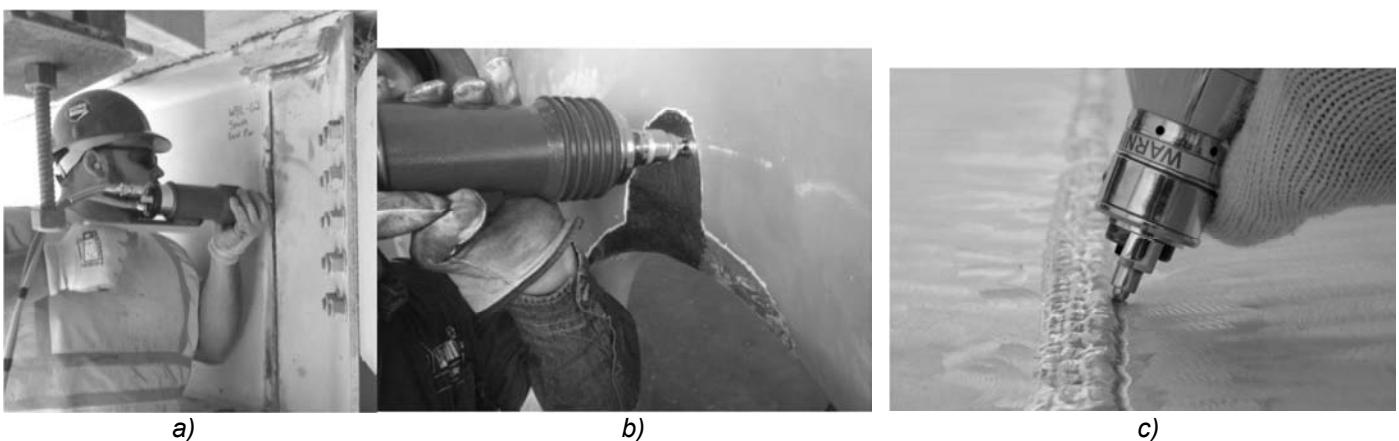


Figure 14. Industrial application of UIT/UP: a) fatigue improvement of welded elements of a highway bridge, b) final stage of fatigue crack repair in heavy mining equipment and c) for prevention of fatigue and corrosion cracking of large aluminium welded panels

Slika 14. Industrijska primena UIT/UP postupka: a) poboljšanje otpornosti na zamor zavarenih elemenata mosta na autoputu, b) finalna obrada reparaturnog navarivanje zamornih prslina kod teške rudarske opreme i c) primena za prevenciju na zamor i koroziju na zavarenim pločama od aluminijuma



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