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Residual stress management: recent advances in engineering methods for non-destructive measurement and beneficial redistribution of residual stresses

Kontrolisanje zaostalih napona: razvoj najnovijih inženjerskih metoda za merenje bez razaranja i povoljnu preraspodelu zaostalih napona

CONTINUED FROM PREVIOUS ISSUE
Part 2

NASTAVAK IZ PREDHODNOG BROJA
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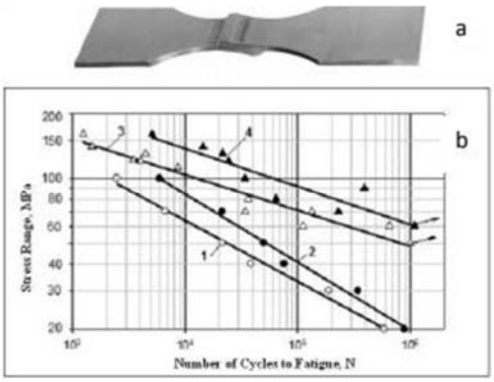

Figure 14. *Sample of overlap welded joint of 3 mm thick 6061-T6 aluminium alloy after application of UP* ***(a)*** *and fatigue curves of overlap welds of 3mm-thick 6061-T6 aluminium alloy* ***(b):*** *1 and 2–as-welded condition with 6 mm and 15 mm overlap respectively; 3 and 4–UIT/UP treated with 6 mm and 15 mm overlap respectively*

Slika 14. *Epruveta preklopnog zavarenog spoja debljine 3 mm od aluminijumske legure 6061-T6, nakon primene UP* ***(a)*** *zamorne krive preklopnog spoja od 3 mm;* ***(b)*** *1 i 2-preklopi od 6 i 15 mm u izvornom stanju; 3 i 4-UIT/UP obrađene epruvete sa preklopima od 6 i 15 mm, respektivno*

Specimens were subjected to axial loading at R=0 until complete specimen failure.The results of fatigue testing of the overlap welds prepared from 3mm-thick 6061-T6 aluminium alloy are illustrated in Fig. 14b.

As can be seen from Fig. 14b, the data for both overlap welds of 3mm-thick 6061-T6 aluminium alloy that were treated by UP are located considerably higher (lines 3 and 4 in Fig. 14b) then the data of “as-welded” samples (lines 1 and 2 in Fig. 14b). At 10,000 cycles of fatigue, an increase in the stress range was achieved by a factor of ~2 for overlap size of 6 mm and a factor of ~2.3 for the 15 mm overlap. At the same time, the number of cycles to fatigue increased ~ 6 times for the 6 mm overlap, and ~10 times for the 15 mm overlap.

In a different study, the influence of the ultrasonic peening treatment was evaluated for 5083 type aluminium alloy samples welded in two different configurations as shown in Fig. 15 and using different welding processes.

Epruvete su jednoosno opterećene pri odnosu napona R=0, do potpunog loma epruvete. Rezultati ispitivanja zamora zavarenih spojeva sa preklopom, napravljenih od 6061-T6 legure debljine 3 mm su prikazani na Slici 14b.

Kao što se može videti sa Slike 14b, podaci za oba preklopna spoja od legure 6061-T6, debljine 3 mm, koja je obrađena ultrazvučnim sačmarenjem (linije 3 i 4 na Slici 14b) se nalaze značajno iznad podataka dobijenih za epruvete u početnom stanju (linije 1 i 2 na slici 14b). Pri broju zamornih ciklusa od 10,000, faktor uvećanja napona koji je dostignut za preklapanje od 6 mm je iznosio ~2, dok je za preklapanje od 15 mm iznosio ~2.3. Istovremeno, broj zamornih ciklusa se povećao ~6 puta za preklop od 6 mm, i ~10 puta za preklop od 15 mm.

Druga studija se bavila uticajem ultravzučnog sačmarenja na aluminijumsku leguru 5083, pri čemu su korišćene epruvete sa dve različite konfiguracije, koje se mogu videti na Slici 15. U ovoj studiji su korišćeni različiti postupci zavarivanja.

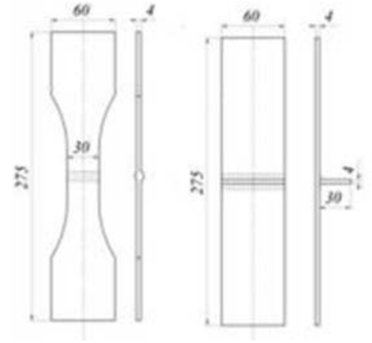

__Figure 15.__ Drawings of welded specimens in butt-weld and T-joint configurations

__Slika 15.__ Crteži zavarenih epruveta sa sučeonom i ugaonom konfiguracijom

The results of fatigue testing of these samples, using axial loading and R=0, in "as-welded" condition and after UP treatment are shown in Fig. 16. As can be seen from Fig. 16, the data for samples welded in both configurations that were treated by UP are located considerably higher then the data of "as-welded" samples.

Rezultati ispitivanja zamora za ove epruvete, pri jednoosnom opterećenju i R=0, u početnom stanju, kao i nakon obrade UP, su prikazani na Slici 16. Kao što se može videti sa slike, vrednosti za obrađene epruvete su daleko iznad vrednosti za epruvete u početnom stanju.

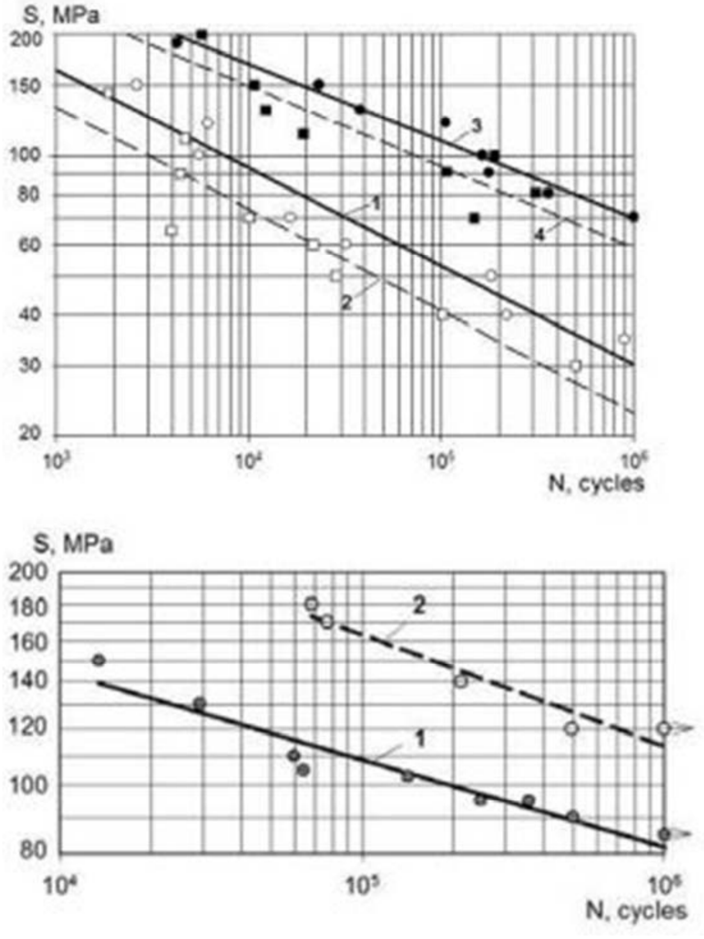

__Figure 16.__ Results of fatigue testing of samples made from 5083 alloy. __a)__ butt- welded (as in Fig. 16a): 1, 2- in as-welded condition; 3, 4- after UP. 1, 3 – technology of welding A; 2, 4 – technology of welding B; __b)__ T-joint weld (as in Fig. 16b): 1- in as-welded condition; 2 - after UP

__Slika 16.__ Rezultati zamornih ispitivanja epruveta od legure 5083. __a)__ sučeoni spoj (kao na slici 16a); 1,2 – početno stanje; 3,4 – nakon UP; 1,3 – tehnologija zavarivanja A; 2,4 – tehnologija zavarivanja B; __b)__ T-spoj (kao na slici 16b): 1 – početno stanje; 2 – nakon UP

At 10,000 cycles of fatigue, a ~54% increase in the stress range was achieved for the butt-welded samples and 30% for the T-joint samples. The fatigue life was also increase considerably, i.e. the number of cycles to fatigue increased ~ 12 times for both welded configurations.

4.4 Ultrasonic Underwater Peening (UUP) of Welded Structures

An ultrasonic peening system was designed and built for applications under water [29], [30]. The system (Fig. 17) looks similar to the basic UP systems shown in Fig. 10, but actually is very different in design.

Pri broju ciklusa od 10.000, postognuto je povećanje opsega napona od ~54% u slučaju sučeonih, i ~30% u slučaju T-spojeva. Zamorni vek je takođe značajno produžen, odnosno broj ciklusa je povećan ~12 puta za obe konfiguracije.

4.4 Podvodno ultrazvučno sačmarenje (Ultrasonic Underwater Peening – UUP) zavarenih konstrukcija

Sistem ultrazvučnog sačmarenja razvijen za primenu pod vodom [29, 30] je prikazan na slici 17 i izgleda slično kao i klasičan UP sistem prikazan na Slici 10, iako je zapravo veoma drugačije konstruisan.

Figure 17. *The ultrasonic system UltraPeen for underwater ultrasonic peening (UUP)*

Slika 17.*Sistem za ultrazvučno sačmarenje UltraPeen za podvodnu primenu*

Specially selected anti-corrosion materials were used in the design of the underwater UP instrument. The length of the cable connecting the peening gun to the generator can be adjusted to allow for treatments underwater at depths up to 30 meters or, if required, with certain modifications, even deeper. Acoustic pump principle is used in the originally developed system for water cooling of the transducer. The developed UP system allows for improvement treatments at four different power levels and is using replaceable working heads that come in various configurations with variable numbers of pins, depending on the application. Fig. 18 shows the process of underwater welding (Fig. 18a) followed by ultrasonic peening using the UUP system in manual treatment by an operator (Fig. 18b).The system was also operated in an automated mode, without the help from an operator.

Posebno odabrani antikorozivni materijali su korišćeni pri izradi instrumenata za podvodno ultrazvučno sačmarenje. Dužina kablova koji povezuju pištolj sa generatorom se može prilagoditi radu pod vodom na dubini do 30 metara, ili po potrebi i sa određenim modifikacijama, za još veće dubine. Princip akustične pumpe je primenjen na ovaj sistem kako bi se omogućilo vodeno hlađenje sonde. Ovako razvijen UP sistem omogućava poboljšanje u četiri različita nivoa snage i koristi zamenljive radne glave koje postoje u velikom broj različitih konfiguracija sa promenljivim brojem pinova, u zavisnosti od primene. Slika 18 prikazuje proces podvodnog zavarivanja (Slika 18a), praćen ultrazvučnim sačmarenjem primenom UUIP sistema, od strane operatera (Slika 18b). Ovaj sistem takođe može da radi u automatskom režimu, bez pomoći operatera.

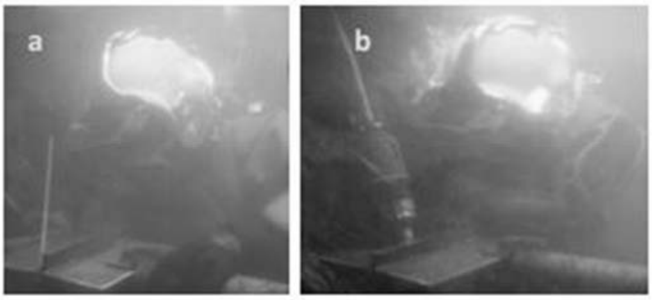

Figure 18. *The process of underwater ultrasonic peening using UltraPeen system. a) underwater welding process; b) Manual UP treatment of the welded sample by an operator;*

Slika 18. *Proces podvodnog ultrazvučnog sačmarenja primenom UltraPeen sistema. a) podvodno zavarivanje; b) ručna UP obrada zavarenog dela od strane operatera;*

To evaluate the efficiency of the new UltraPeen® technology and equipment for underwater ultrasonic peening (UUP) of welded elements, a study was conducted in which thirty four large-scale welded samples were produced (Fig. 19a) and fatigue tested after underwater UP treatment.

Kako bi se ocenila efikasnost nove UltraPeen® tehnologije i opreme za podvodno ultrazvučno sačmarenje, sprovedena je studija u okviru koje su napravljena 34 velika zavarena uzorka (Slika 19a), koji su ispitani na zamor nakon podvodnog ultrazvučnog sačmarenja.

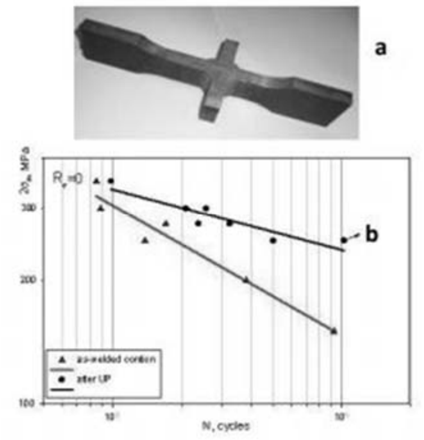

Figure 19. *Results of fatigue testing of samples welded and UP treated under water. a) Example of a non-load caring fillet sample prepared by underwater welding and following underwater UP treatment used in fatigue testing b) Results of fatigue testing of large metal samples in as-welded condition (triangles) and after the UUP treatment (solid circles).*

Slika 19. *Rezultati ispitivanja na zamor zavarenih uzoraka koji su obrađeni ultrazvučnim sačmarenjem pod vodom. a) primer nenosećeg ugaonog spoja pripremljenog podvodnim zavarivanjem nakon kojeg je sledila obrada pomoću UUP, za potrebe ispitivanja zamora b) rezultati ispitivanja na zamor velikih metalnih uzoraka u početnom stanu (trouglovi) i nakon UUP obrade (puni krugovi).*

Half of these samples were welded in open air and another half – underwater (Fig. 18a). Then, 50% of the samples from both batches were subjected to UUP (Fig. 18b) and all samples were fatigue tested. The results of the fatigue testing (Fig. 19b) had shown that the UUP provides significant fatigue improvement of welded elements, similar to what is observed for UP in air. The fatigue life of welded samples increased under the action of UUP 4-5 times depending on the level of applied stresses.

Polovina ovih uzoraka je zavarena na otvorenom, a druga polovina pod vodom (Slika 18a). Nakon toga, 50% uzoraka iz obe ture su podvrgnute obradi UUP metodom (Slika 18b), pri čemu su svi uzorci ispitani na zamor. Rezultati isptivanja zamora (Slika 19b) su pokazali da UUP obezbeđuje značajno poboljšanje zavarenih elemenata u pogledu otpornosi na zamor, slično kao što je uočeno kod ultrazvučnog sačmarenja na otvorenom. Zamorni vek zavarenih uzoraka je na ovaj način produžen 4-5 puta, u zavisnosti od nivoa delujućih napona.

Summary

In summary, it is safe to say that the concept of residual stress management is helping welders and the welding community to fully understand the effect of residual stresses by addressing major aspects of residual stresses in welds and welded structures. When the elements of the RSM are used together, the optimum performance of welded structures can be achieved.

The effect of residual stresses on material properties like fatigue, fracture, corrosion resistance and dimensional stability can be considerable and they, therefore, should be taken into account during design, fatigue assessment and manufacturing of parts and welded elements.

Substantial technological progress was made in the non-destructive measurement of applied and residual stresses by ultrasonic method. The UltraMARS-7 system incorporates new software and new functional capabilities, allowing evaluate the bulk, average through thickness stresses as well as the subsurface and surface stress changes. In addition it allows also evaluating the thickness of the materials and their Young modulus and Poisson ratio. The residual and applied stresses can be measured, calculated and their distribution displayed on the screen of the UltraMARS-7 instrument as continuous curves, with the option of transferring the data onto an USB device for further processing. The developed advanced ultrasonic method for non-destructive measurement of stresses and based on it portable instrument were used successfully in laboratory and field conditions for non-destructive measurement of applied and residual stresses in real parts and structural elements.

The ultrasonic peening technology was also matured with new models of the instrumentation for air and underwater treatments being developed and successfully demonstrated. The UP technology was successfully applied in construction industry, shipbuilding, railway and highway bridges, nuclear reactors, aerospace industry, oil and gas engineering and in other areas during manufacturing, in service inspection and repair of welded elements and structures.

Zaključci

Na kraju se može sa sigurnošću zaključiti da koncept kontrolisanja zaostalih napona pomaže zavarivačima da u potpunosti razumeju uticaj zaostalih napona u zavarenim spojevima i konstrukcijama. Kada se elementi RSM koriste istovremeno, može se ostvariti optimalno fukncionisanje zavarenih konstrukcija.

Uticaj zaostalih napona na osobine materijala, poput zamora, sklonosti ka lomu, otpornosti na koroziju i stabilnosti dimenzija može biti značajan i stoga se oni moraju uzeti u obzir tokom projektovanja, ocene zamornog veka i proizvodnje delova i zavarenih elemenata.

Značajan tehnološki napredak je načinjen u oblasti merenja metodama bez razaranja delujućih i zaostalih napona pomoću ultrazvuka. UltraMARS-7 sistem koristi novi softver i nove funkcije koje omogućavaju merenje prosečnog napona kroz celu debljinu, kao i na i pod površinom. Pored toga je takođe moguće oceniti debljinu materijala i njegov modul elastičnosti i Poasonov koeficijent. Delujući i zaostali naponi se mogu izmeriti, proračunati i prikazati na monitoru uređaja UltraMARS-7 u obliku neprekidnih kriva, sa opcijom prebacivanja podataka na USB uređaj za potrebe dalje obrade. Razvijene napredne ultrazvučne metode za merenje bez razaranja zasnovane na prenosivim uređajima su uspešno primenjene u laboratorijskim i terenskim uslovima za merenje delujućih i zaostalih napona u stvarnim delovima i konstrukcijama.

Tehnologija ultrazvučnog sačmarenja je takođe „sazrela“ sa primenom novih modela uređaja za obradu na vazduhu i pod vodom, koji su sa uspehom razvijeni i primenjeni u te svrhe. UP tehnologija je uspešno primenjena u građevinskoj industriji, brodogradnji, zatim u izradi železnice i mostova, nuklearnih reaktora, avioindustriji, naftnoj industriji i mnogim drugim oblastima, pri kontroli i reparaciji zavarenih elemenata i konstrukcija.

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