M Consonni, D J Abson, TWI Ltd

INVESTIGATION OF WELD REPAIR WITHOUT POST-WELD HEAT TREATMENT FOR P91

ISTRAŽIVANJE REPARATURE ZAVARENOG SPOJA BEZ NAKNADNE TERMIČKE OBRADE NA ČELIKU P91

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Abstract

Post-weld heat treatment (PWHT) is generally required for any grade 91 steel fabrication before entering service, as well as after any repair welding. However, this may sometimes be impractical or not cost-effective. A review of current welding practice for grade 91 showed that, whilst welding is relatively well established, there is a lack of published literature and proven procedures for non standard operations, such as weld repair without PWHT. By applying a microstructural refinement criterion (temper bead), SMAW and GTAW weld repairs of grade 91 steel without PWHT have been investigated. Metallographic examination and hardness testing were carried out to evaluate the degree of HAZ refinement and tempering, respectively. For both welding processes, a good level of refinement was produced, but only limited tempering was achieved. Recommendations are provided for the development of weld repair procedures based on an alternative criterion to that explored in this present project

Rezime

Naknadna termička obrada (TOPZ) se generalno zahteva kod bilo kojeg čelika klase P91pre uključivanja u eksploataciju, kao i posle svakog reparaturnog zavarivanja. Međutim, to može biti nepraktično ili neisplativo. Pregled sadašnje zavarivačke prakse za klasu 91 je pokazao, da je zavarivanje relativno dobro ustanovljeno, dok postoji nedostatak publikovane literature i odobrenih procedura za nestandardne operacije, kao što je reparaturno zavarivanje bez TOPZ. Primenom kriterijuma mikrostrukturne rafinacije (zavar za otpuštanje), podvrgnuti su reparirani zavareni spojevi klase 91 bez TOPZ postupcima MIG i TIG. Radi ocene stepena rafinacije i otpuštanja sprovedena su metalografska ispitivanja i merenje tvrdoće. Za oba postupka zavarivanja, postignut je dobar nivo rafinacije, ali samo ograničeno otpuštanje. Obezbeđene su preporuke za razvoj procedura reparaturnog zavarivanja zasnovane na nekom alternativnom kriterijumu.

Introduction

Grade 91 steel (also referred to as P91 in the pipe form, EN designation X10CrMoVNb 9-1) is widely used in fossil fuel power stations, where it has found application in new build and, particularly for headers in existing power plants, to replace lower alloy steel counterparts. The 9% chromium content and the incorporation of vanadium and niobium as alloying elements have effected a substantial improvement in creep strength compared to the

Uvod

Čelik klase 91 (poznat i kao P91 u obliku cevi, EN oznaka X10CrMoVNb 9-1) se naširoko koristi u elektranama na fosilna goriva, gde je našao primenu u novogradnji, a posebno za kolektore u postojećim elektranama, za zamenu niže legiranih čelika. Sadržaj hroma od 9% i ugrađivanje vanadijuma i niobijuma kao legirajućih elemenata su proizveli značajan napredak u otpornosti na puzanje u odnosu na manje Cr-Mo klase (npr klasa lesser alloyed Cr-Mo grades (*e.g.* grade 22), and has allowed designers to provide for an increase in steam temperature from around 540 to 580°C or even 600°C. The higher alloy content has also ensured that the microstructure of the parent steel (and the HAZ of any weld) will be martensitic for all likely cooling rates. Moreover, the hardness of such as formed martensite is typically > 400HV. In the light of the high creep resistance of the steel, the hardness decreases only slowly during tempering or PWHT, as shown in *Figure 1*.

22), te je dizajnerima dozvoljeno da povećavaju temperaturu pare od oko 540-580°C ili čak 600°C. Veći sadržaj legirajućih elemenata je takođe osigurao da mikrostruktura osnovnog materijala-čelika (i ZUT i šav) bude martenzitna za sve brzine hlađenja. Osim toga, tvrdoća, tako nastalog martenzita je obično >400HV. U svetlu visoke otpornost na puzanje čelika, tvrdoća se blago smanjuje tokom otpuštanja ili TOPZ (termičke obrade posle zavarivanja), kao što je prikazano na slici 1.

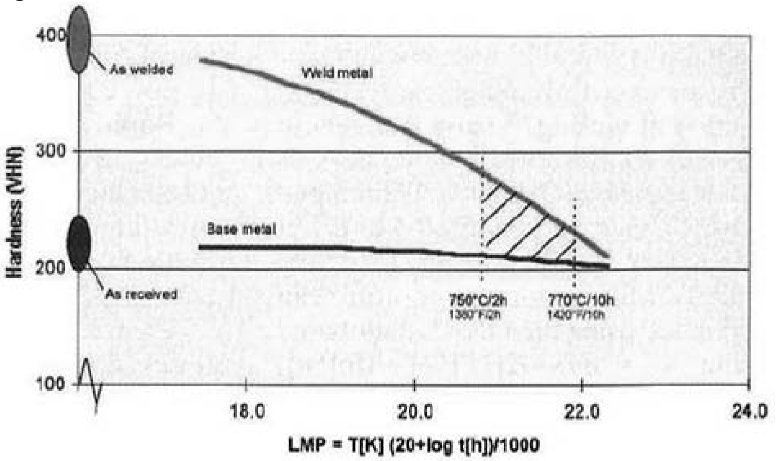


Figure 1. *Trend of hardness as function of the Larson Miller parameter.*[1] *Reproduced by permission of the American Welding Society. The coarse-grain HAZ hardness will be similar to that of the weld metal.*

Sl. 1. *Trend vrednosti tvrdoće kao funkcije Larson Miller—ovog parametra.*[1] *Reprodukovano uz dozvolu American Welding Society. Tvrdoća grubozrnog ZUT biće slična onoj za metal šava*

PWHT is generally required for any grade 91 steel fabrication before entering service, to relieve residual stresses, to reduce weld metal and HAZ hardness, and to improve toughness. For the same reasons, after any repair welding there is an expectation, and currently a requirement, that a PWHT is carried out. However, since PWHT may be difficult to perform and often not cost effective, depending on the location and accessibility of the weld repair, a procedure that allows its omission is desirable, and controlled deposition welding procedures (also referred to as 'temper bead' or 'cold repair' procedures) have been devised for C-Mn steel and for the lower alloy steels in creep service. Although at least one study has demonstrated that some HAZ softening can be affected by careful bead placement [2], industry standards currently do not allow this approach for grade 91 steel components.

Following a review of the available literature on weld repair of grade 91 without PWHT, summarized below, this project investigated the possibility of carrying out non-PWHT weld repairs employing the controlled deposition approach, with some variation in electrode diameter being explored.

TOPZ je generalno potrebna za bilo koju klasu čelika 91 pri izradi i pre uvođenja u eksploataciju, za smanjenje zaostalih napona, kako bi se smanjila tvrdoća metala šava i ZUT, i radi poboljšanja žilavosti. Iz istog razloga, nakon svake popravke zavarivanjem postoji očekivanje, a trenutno je zahtev, da se obavlja TOPZ. Međutim, budući da se TOPZ teško izvodi i često nije isplativa, zavisno od lokacije i pristupačnosti šavu koji se reparira, postupak koji omogućava njeno izostavljanje je poželjan, i procedure kontrolisanog polaganja zavara (poznata i kao 'zavar za otpuštanje–tehnološki zavar' ili procedura 'reparatura na hladno') su osmišljene za C-Mn čelike i za manje legirane čelike u uslovima puzanja. Iako je barem jedna studija pokazala da sena izvesno omekšavanje ZUT može uticati pažljivim postavljanjem zavara [2], industrijski standardi trenutno ne dozvoljavaju ovaj pristup za klasu 91 čeličnih komponenata.

Nakon pregleda dostupne literature o reparaturnom zavarivanju klase 91 bez TOPZ, sumarno datoj ispod, ovaj projekat je istraživao mogućnost obavljanja reparature šava bez TOPZ korišćenjem pristupa kontrolisanog polaganja zavara uz neke varijacije u prečniku elektroda koje se koriste.

Low heat input levels were used, as this gives not only a reasonably small coarse-grain HAZ grain size but it also restricts the width of the thermally-damaged region at or beyond the edge of the fine-grain HAZ, which is generally the creep-weak region in a welded joint subjected to cross-weld stress. The preliminary trials reported here represent the first stage in exploring whether repair welding of grade 91 steel without a subsequent PWHT is possible; if progress is to be made, further extensive welding trials and testing will be required, including investigating HAZ toughness and cross-weld creep strength.

Literature review

Repair using Ni-based consumables

Mitchell and Brett [3] published a review of cold weld repair procedures that have been successfully applied to repairs made to type IV cracking in 2¼Cr1Mo¼V steels with Ni-based consumables. The main advantages identified by Mitchell and Brett when repairing with Ni-alloys are:

Lower risk of hydrogen cracking due to the face-centred cubic (FCC) lattice in weld metal.

Higher fracture toughness of the weld metal compared with weld metal with matching composition and initially lower residual stress.

However, major drawbacks have been identified as well, such as:

Addition of a 'dissimilar metal transition' joint in the repaired component.

Issues with NDE and slow relaxation of the residual stresses developed during repair.

Use of ferritic consumables

The use of ferritic consumables has grown in popularity over recent years. For 2¼Cr1Mo steels, both manual metal arc and flux cored arc welding procedures have been applied. However, for the modified 9Cr1Mo¼V steels manual metal arc (SMAW) welding has generally been selected.

A few examples of repairs of Grade 91 using matching (or near matching) consumables have been published. Storesund and Samuelson [4] indicate that a repair in a grade 91 steam line after 118,000 hours service was only subjected to 23,000 hours further service until a crack developed in the HAZ at the outside of the pipe, which was post weld heat treated. These repair welds had a consistently higher hardness than the original, service aged weld. This particular case considered repair of fabrication flaws, rather than the repair of service degradation such as type IV cracking.

Korišćeni su mali nivoi unete toplote, jer to daje, ne samo razumno malu grubozrnu ZUT, već isto tako ograničava širinu termički oštećene regije u ili izvan ivica finozrne ZUT, koja se generalno javlja u regijamau groženim puzanjem zavarenog spoja koji je podvrgnut poprečnim naponima usled zavarivanja. Prema preliminarnim pokušajima, koji su saopšteni ovde, oni predstavljaju prvu fazu u istraživanju da li je moguća popravka zavarivanjem klase čelika 91 bez naknadne TOPZ; ako se napravi napredak, biće potrebna dalja opsežna zavarivanja i ispitivanje, uključujući i istraživanje žilavosti ZUT i granice puzanja poprečnog šava.

Pregled literature

Reparatura dodatnim materijalom na bazi nikla

Mitchell i Brett [3] su objavili pregled procedura reparaturnog zavarivanja na hladno koje se uspešno primenjuje na popravkama prslina tipa IV na čelicima 2¼Cr1Mo¼V dodatnim materijalom na bazi Ni. Glavne prednosti koje su identifikovali Mitchell i Brett pri reparaturi sa Ni-legurama su:

Manji rizik od vodoničnih prslina zbog površinski centrirane kubne rešetke (FCC) u metalu šava.

Veća lomna žilavost metala šava u odnosu na metal šava sa odgovarajućim sastavom i inicijalno manji zaostali naponi.

Međutim, glavni nedostaci su identifikovani, kao što su:

Dodatak spoja 'prelaz različitih metala' u repariranu komponentu.

Problemi sa IBR i spora relaksacija zaostalih napona stvorenih tokom popravke.

Korišćenje feritnih dodatnih materijala

Korišćenje feritnih dodatnih materijala je postalo popularno poslednjih godina. Za 2¼Cr1Mo čelike, primenjuju se i ručno elektrolučno zavarivanje i punjena žica. Međutim, za modifikovani 9Cr1Mo¼V čelike, uglavnom je odabrano ručno elektrolučno (REL).

Nekoliko primera reparature čelika klase 91 koristeći odgovarajući (ili blizu odgovarajućeg) dodatni materijal je objavljeno. Storesund i Samuelson [4] ukazuju na to da je reparatura parovoda od čelika klase 91 nakon 118.000 sati rada bila podvrgnuta daljem radu od samo 23.000 sati dok se prslina razvila u ZUT na spoljašnjoj strani cevi, koja je bila podvrgnuta termičkoj obradi posle zavarivanja. Ovi reparirani šavovi imaju sistematično veću tvrdoću od originala, šava koji je ostario tokom rada. Ovaj konkretni slučaj se odnosi na reparaturu nedostatka tokom izrade, a ne reparaturu degradacije tokom rada kao što su prsline tipa IV.

With regard to repairing service degradation flaws, it is recommended that the entire weld is cut out (including HAZ) and re-welded, as the damage accumulation in the creep weak type IV region is likely to be aggravated by the residual stresses associated with any repair. The use of grade 91 matching consumables for such repairs produces welds with have a better creep resistance compared with the parent material which is service-aged. This may aggravate further type IV cracking in the HAZ created by the weld repair.

Vekeman and Huysmans [2] proposed using less alloyed consumables as an alternative to matching the parent material. The rationale behind this is the attempt to match the creep resistance of the service-aged base material. As residual stress relaxation is a 'creep-like' mechanism, less creep resistant weld metal will allow a somewhat greater degree of relaxation of such stresses. A modified T24 filler metal with Nb alloying was used. The authors established that gas backing would be needed, so standard 2¼Cr filler metal was used for the root pass to eliminate the excessive oxidation of the weld bead. The weld repair was performed successfully. However, care needed to be taken with the deposition sequence to ensure that the maximum hardness measured in the HAZ was less than 400HV (to avoid stress corrosion cracking in the absence of PWHT), and it was observed that restrictions on the service temperature (limited to 540-580°C) may be required to avoid reheat cracking during service. At the time of writing this report, there is no evidence of components repaired with the above procedures being put in service.

Experimental approach

Summary

Two welding processes were selected for the investigation of weld repair procedures without PWHT: shielded metal arc welding (SMAW) and mechanised (machine) gas tungsten arc welding (GTAW). Both processes are allowed by clause IWA-4620 of Section XI of the ASME B&PV Code for in-service temper bead repairs of base materials classified as P-No 1, 3, 12A, 12B or 12C, which do not include grade 91 (P-No 5B). It should be noted that the GTAW process is only allowed by ASME B&PV Section XI if 'automatic' or 'machine' using cold wire feed.

For both processes multi-layer welded pads were deposited on service-aged P91 pipe material with 15 mm thickness to simulate weld repairs. The welding parameters for each layer were selected in order to maximise the refinement of the HAZ associated with subsequent welding layers, by

Što se tiče reparature oštećenja usled degradacije tokom rada, preporučuje se da se celi šav iseče (uključujući ZUT) i ponovo zavari, jer će akumulacija oštećenja u regiji oštećenja usled puzanja tipa IV verovatno biti povećana zaostalim naponima vezanim za bilo kakvu reparaturu. Upotreba dodatnog podudarnog materijala klase 91 za takve reparature daje bolju otpornost na puzanje u poređenju sa osnovnim materijalom koji je ostario tokom rada. To može dalje da pogorša prsline tipa IV u ZUT stvorenoj reparaturom šava.

Vekeman and Huismans [2] predložili su korišćenje manje legiranog dodatnog materijala kao alternativu podudaranju sa osnovnim materijalom. Obrazloženje je pokušaj da odgovara otpornosti na puzanje osnovnog materijala koji je ostario tokom rada. Za relaksaciju zaostalih napona koristi se mehanizam 'puzanje-poput', metal šava manje otpornosti na puzanje omogućiće donekle veći stepen relaksacije takvih naprezanja. Korišćen je modifikovan T24 dodatni materijal legiran sa Nb. Autori su utvrdili da će biti potrebna gasna podloška, pa je korišćen standardni 2¼Cr dodatni materijal za koreni prolaz da bi eliminisao prekomernu oksidaciju zavara. Reparatura šava je uspešno izvedena. Međutim, potrebna je velika pažnja pri nanošenju da se osigura da maksimalna tvrdoća u ZUT bude manje od 400HV (da bi se izbegle prsline usled naponske korozije u odsustvu TOPZ), a uočeno je da se ograničenje radne temperature (ograničeno do 540-580°C) može zahtevati radi izbegavanja prslina usled ponovnog zagrevanja tokom rada. U vreme pisanja ovog izveštaja, nema dokaza o repariranim komponentama, navedenim postupcima.

Eksperimentalni pristup

Kratki pregled

Odabrana su dva postupka zavarivanja za istraživanje procedura reparature zavarenog spoja bez TOPZ: ručno elektrolučno zavarivanje (REL) i mehanizovano (mašinsko) zavarivanje u zaštiti gasa (TIG). Oba postupka su dozvoljena klauzulom IWA-4620 Sekcije XI ASME B & PV pravila za reparaturu u toku rada zavarom za otpuštanje, osnovnih materijala svrstanih kao P-No 1, 3, 12A, 12B ili 12C, koji ne uključuju klasu 91 (P-No 5B). Treba napomenuti da je postupak TIG dopušten samo po ASME B&PV sekcija XI ako se koristi 'automatsko' ili 'mašinsko' dodavanje.

Za oba postupka, naneti su višeslojni šavovi na čelik P91 koji je ostario tokom rada u obliku cevi debljine 15 mm za simulaciju reparature šava. Parametri zavarivanja za svaki sloj su odabrani kako bi se povećala rafinacija ZUT povezana sa kasnijim zavarivanjem slojeva, koristeći kriterijum using the two-layer refinement criterion suggested by Alberry: [5] R ≤ C ≤ P where P is the maximum fusion boundary depth (first bead), C is the sum of maximum fusion boundary depth + average layer height (first bead) and R is the maximum depth of the refining zone (second bead). A schematic representation of this criterion is shown in *Figure 2.*

rafinacije preko dva sloja koji je predložio Alberry: [5] R ≤ C ≤ P gde je P maksimalna dubina granice stapanja (prvi zavar), C je suma maksimalnih dubina granica stpanja + prosečna visina sloja (prvi zavar) i R je maksimalna dubina zone rafinacije (drugi zavar). Shematski prikaz ovog kriterijuma je prikazan na slici 2.

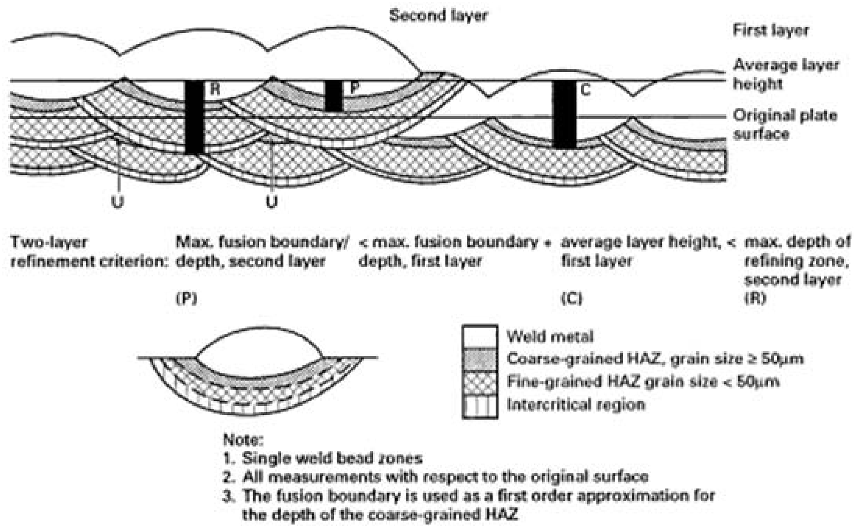


Figure 2. *Two-layer refinement parameters* [6]
Sl. 2. *Parametri rafinacije u dva sloja* [6]

In addition, it was expected that the deposition of subsequent welding layers would affect some tempering of the HAZ associated with the first layer. The weld repair procedures were then tested by metallographic examination and hardness testing, to evaluate the degree of refinement and tempering obtained, respectively.

Osim toga, očekivano je bilo da nanošenje naknadnih zavarenih slojeva može uticati na otpuštanje ZUT od prvog sloja. Postupci reparature zavarenog spoja su potom proverene metalografskim ispitivanjem i ispitivanjem tvrdoće, za procenu stepena postignute rafinacije i otpuštanja.

Manufacture of weld repair samples SMAW.

For the SMAW welding tests, two-layer welded pads were produced, using different combinations of electrode sizes and heating cycles between the first and second layer. The welding parameters and electrode sizes were based on the work carried out on cold weld repairs of C-Mn steels, [6] which in turn used Alberry's refinement criterion, and were subsequently adjusted to suit the high Cr consumables being used.
Test weld W01 was welded using Ø3.2 and 4.0 mm (1/8 and 5/32 in) electrodes for the first and second layer, respectively. Test weld W03 was welded using Ø2.5 and 4.0 mm (3/32 and 5/32 in) electrodes for the first and second layer, respectively. A 'cascade' sequence was applied, with the second layer deposited on a smaller area, to allow sectioning of single and double-layer configurations. All welds were carried out in the vertical-up welding position; with a minimum

Izrada uzoraka iz repariranog zavarenog spoja REL

Za testove REL zavarivanje, dva sloja zavarene jastučići su proizvedeni, koristeći različite kombinacije veličina elektroda i ciklusa grejanje između prvog i drugog sloja. Parametri zavarivanja i veličine elektroda su bile zasnovane na radu koji se obavlja popravkom C-Mn čelika hladnim zavarivanjem, [6] koji zauzvrat koristi kriterijum profinjenosti Alberry, a kasnije su prilagođeni korišćenju potrošnih materijala sa visokim Cr.
Ispitni šav W01 je zavaren elektrodama za prvi i drugi sloj Ø3.2 i 4.0 mm (1/8 i 5/32 in). Ispitni šav W03 je zavaren elektrodama za prvi i drugi sloj ø2,5 i 4.0 mm (3/32 i 5/32 in). Primenjenaje „kaskadna“ sekvenca, a drugi sloj je nanet na manju površinu, kako bi se omogućilo razdvajanje jednosnojnih i dvoslojnih konfiguracija. Svi šavovi su izvedeni u položaju zavarivanja vertikalno na gore; sa minimalnom temperaturompredgrevanja od 200°C (oko 390°F), a maksimalna međuslojna preheat temperature of 200°C (approximately

390°F) and a maximum interpass temperature of 250°C (approximately 480°F). The SMAW electrical variables are summarised in *Table 1*.

temperatura od 250°C (oko 480°F). Promenljive električne karakteristike za REL su date u tabeli 1.

Ispitni šav Test weld	Prečnik L1 ø, mm	Jačina struje i, A	Napon V	Dužina ROL mm	Uneta količina toplote AE, kJ/mm	Prečnik L2 ø, mm	Jačina struje i, A	Napon V	Dužina ROL mm	Uneta količina toplote AE, kJ/mm
W01	3.2	100	22	150	0.5-0.6	4	112	22	100	0.9-1.1
W03	2.5	75	21	150	0.5	4	125	22		1.6

Table 1. *As-recorded MMA welding parameters, the corresponding welded pads are shown in Figures 3 and 4.*
Tabela 1. *Parametri zavarivanja koji su snimljeni za REL, odgovarajući zavareni šavovi su prikazani na slikama 3 i 4.*
Notes to Table 1: L= layer number and electrode size, i=welding current, V= voltage, ROL= run-out length assuming a 50mm end stub for 350mm-long stick electrodes, AE=arc energy.
Napomene za tabelu 1: L = broj sloja i veličine elektroda, i = struja zavarivanja, V = napon, ROL = izvedena dužina uzimajući u obzir 50mm za odbačeni kraj 350mm dugačke elektrode, AE = energija luka

Welding was carried out using AWS A5.5 E8015-B8 electrodes, matching the composition of Grade 9. The purpose of these tests was to verify the effect of the selected welding procedures on HAZ microstructure and hardness, it was not considered necessary to use consumables matching Grade 91. In addition, type 'B8' consumables have a lower resistance to creep than type B9. These were considered suitable for evaluating repairs on Grade 91 in the service aged condition, *i.e.* with a somewhat reduced creep strength compared with the as-fabricated condition. After welding, the test pads were not subjected to PWHT.

Mechanised GTAW.

GTAW repair using the temperbead (or 'half bead') approach have been developed by Alberry et al [5] and Gandy et al [7] for ASME SA 508 Class 2 steel for application in the nuclear sector. In particular, Gandy et al developed a three-layer procedure, using the same parameters for all layers. Bead on plate (BoP) tests, which are not detailed in this paper, were carried out to determine the optimum welding parameters. The BoP trials were assessed according to the refinement criterion (*Formula (1)* and *Figure 2*) and one set of welding parameters was selected (table 2). Subsequently, in accordance with the abovementioned three-layer procedure, a weld pad (W15) was obtained using the same parameters for all layers. Metallographic specimens were then obtained from three cross-sections, identified as W15-1, 2 and 3, to compare the effect of the subsequent layers on the base metal via visual examination and hardness testing.
AWS SFA A5.28 ER 80S-B8 with Ø1.2 mm (0.045 in) was used, matching the composition of Grade 9 rather than Grade 91, see discussion above. The TOPTIG^{TM} variant of the GTAW

Zavarivanje je izvedeno korištenjem AWS A5.5 E8015-B8 elektrode, koja odgovara sastavu klase 9. Svrha ovih ispitivanja je bila da se proveri učinak odabranih postupaka zavarivanja na mikrostrukturu ZUT i tvrdoću, nije smatrano potrebnim da se koristi dodatni materijal koji odgovara klasi 91. Osim toga, tip "B8" dodatni materijali imaju manju otpornost na puzanje nego tipa B9. Oni su smatrani pogodnim za ocenjivanje reparature na klasi 91 u starenom stanju posle rada, t.j. sa nešto smanjenom granicom puzanja u odnosu na stanje posle izrade. Nakon zavarivanja, ispitne podloge nisu bile izložene TOPZ.

Mehanizovani TIG

Reparatura TIG postupkom korišćenjem zavara za žarenje (ili 'pola zavara') razvili su Alberri i dr. [5] i Gandi i dr. [7] za čelik prema ASME SA 508 klasa 2 za primenu u nuklearnom sektoru. Konkretno, Gandi i dr. su razvili proceduru sa tri sloja, koristeći iste parametre za sve slojeve.
Testovi zavara na ploči (Bop), koji nisu navedeni u ovom radu, sprovedeni su radi određivanja optimalnih parametara zavarivanja. Probe Bop su ocenjivane prema kriterijumu rafinacije (Formula (1) i Slika 2) i odabran je jedan skup parametara zavarivanja (tabela 2). Nakon toga, u skladu sa pomenutom procedurom troslojnog zavarivanja, šav (W15) je dobijen korišćenjem istih parametara za sve slojeve. Metalografski uzorci su zatim dobijen iz tri preseka, koji su identifikovani kao W15-1, 2 i 3, radi upoređenja efekta narednih slojeva na osnovni materijal putem vizuelno i merenjem tvrdoće.
Korišćen je, prema AWS A5.28 SFA dodatni materijal, ER 80S-B8 prečnika Ø1.2 mm (0.045 in) koji se poklapa sa sastavom klase 9 pre nego sa klasom 91, videti diskusiju gore. Varijanta TIG

process was used [8], as this generally allows a smoother HAZ profile for the first layer, compared with standard GTAW welding, hence increasing the possibility of a consistent refinement and tempering of the HAZ itself, when the second and third layer are deposited.

postupka, TOPTIG^{TM} [8] je korišćena, jer generalno omogućava glatkiji profil ZUT za prvi sloj, u poređenju sa standardnim TIG zavarivanjem, stoga povećava mogućnost stalne rafinacije i otpuštanja samog ZUT, kada se nanose drugi i treći sloj.

Jačina struje A	**Napon V**	**Brzina zavarivanja TS, mm/min**	**Brzina dodavanja žice WFS, mm/min**	**Uneta količina toplote AE, kJ/mm**
200	11	250	1500	0.53

Table 2 *GTAW welding parameters*
Tabela 2. *Parametri TIG zavarivanja*

Notes to Table 2: i=welding current, V= voltage, TS=travel speed, WFS=wire feed speed, AE=arc energy, this corresponds to 'heat input' values according to the ASME terminology.

Napomene za tabelu 2: : i=struja zavarivanja, V= napon, TS=brzina zavarivanja, WFS=brzina dodavanja žice, AE=energija luka, što odgovara vrednosti 'unete toplote' prema ASME terminologiji

Results
SMAW

Figure 3 shows photomacrographs of the sections taken from test weld W01 (Ø3.2/4.0 mm). The sections taken from test weld W03 (Ø2.5/4.0 mm) are shown in Figure 4. The above mentioned figures indicate that if the combination Ø2.5/4.0mm electrode is used for the first/second layer, the latter penetrates through the thickness of the first layer and a new untempered and unrefined HAZ is formed. On the other hand, if the combination Ø3.2/4.0 mm electrode is used, the outer regions of the HAZ produced by the second layer appear to overlap with that produced by the first, hence providing the condition for refinement.

Rezultati
REL

Slika 3 prikazuje sliku makrostrukture tih preseka uzetih iz ispitnog šava W01 (Ø3.2/4.0 mm). Preseci uzeti iz šava W03 (Ø2.5/4.0 mm) su prikazani na slici 4. Gore navedeni podaci ukazuju da, ukoliko se kombinacija Ø2.5/4.0 mm elektroda koristi za prvi / drugi sloj, zadnja prodire kroz debljinu prvog sloja i stvara novu neotpuštenu i nerafiniranu ZUT. Sa druge strane, ako se koristi kombinacija Ø3.2/4.0 mm elektroda, spoljašnji regioni ZUT dobijeni drugim slojem koji preklapa onaj dobijen prvim slojem, time obezbeđujući uslov za rafinaciju.

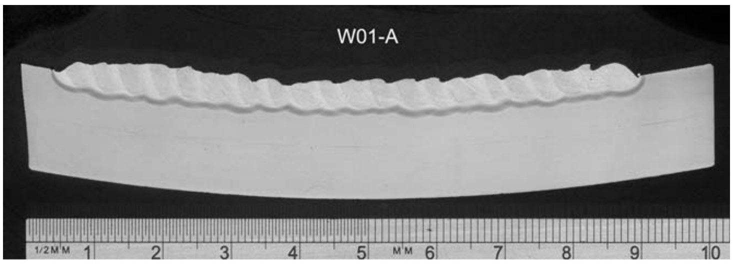
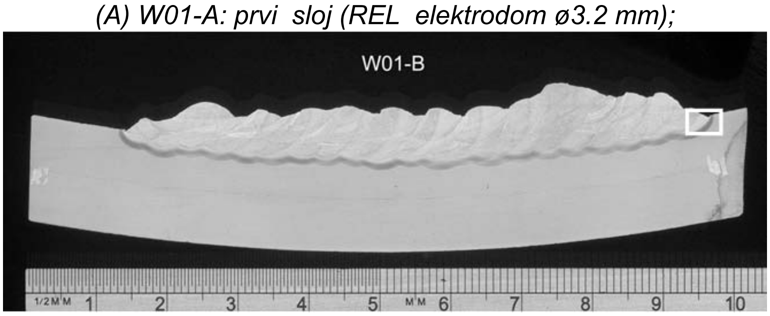


Figure 3. *Macrosections taken through test weld W01. Scale ruler shown:*
(a) W01-A: first layer appearance (SMAW electrode ø3.2 mm);
Slika 3. *Makropreseci uzeti iz ispitnog šava W01. Lenjir sa skalom pokazuje:*
(A) W01-A: prvi sloj (REL elektrodom ø3.2 mm);



(b) W01-B: appearance after second layer (SMAW electrode ø4.0 mm)
(b) W01-B: izgled nakon drugog sloja (REL elektrodom ø4.0 mm)

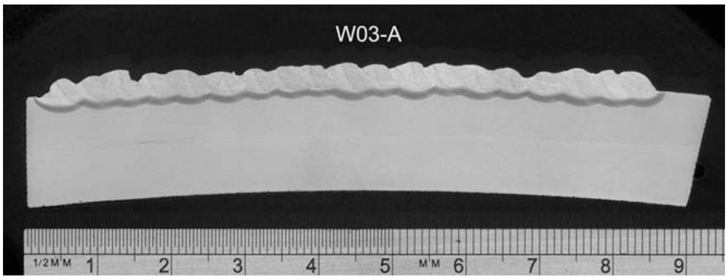
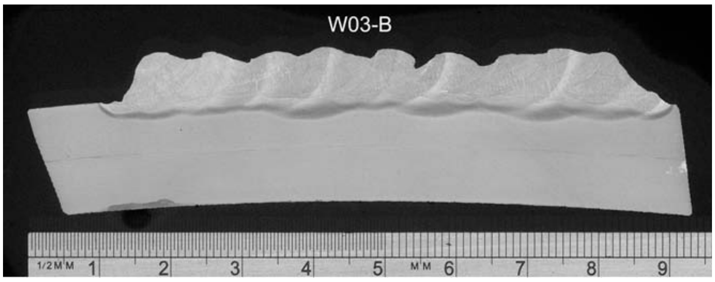


Figure 4. *Macrosections taken through the samples relating to test weld W03. Scale ruler shown:*
(a) W03-A: first layer appearance, showing fairly even HAZ (SMAW electrode ø2.5 mm);
Slika 4. *Makropresci uzeti iz uzoraka vezanih za ispitni šav W03. Lenjir sa skalom pokazuje:*
(a) W03-A: izgled prvog sloja, prikazuje vidljivu ZUT (REL elektrodom ø2.5 mm);



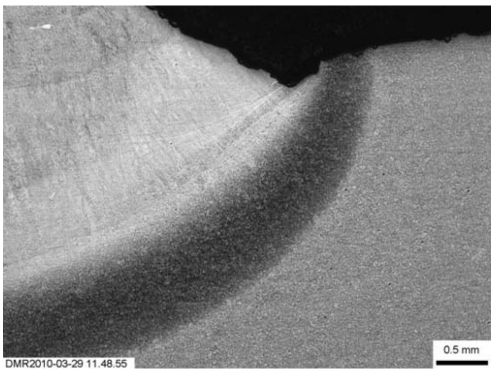
(b) W03-B: appearance after second layer, showing elimination of original HAZ and formation of a new HAZ resulting from the higher heat input (SMAW electrode ø4.0 mm).
(b) W03-B: izgled posle drugog sloja, prikazuje eliminaciju originalne ZUT i stvaranje nove ZUT što je rezultat vešeg unosa toplote (REL elektrodom ø4.0 mm).

The irregular profiles shown in *Figures 3* and *4* are explained by the imposition of welding parameters and heat input levels that are outside the usual ranges for the consumables being used. It should also be noted that at this stage, the primary purpose of the test welds was to determine the effect of different combinations of electrode size and electrical parameters on the HAZ microstructure, hence limited emphasis was put on obtaining a smooth weld pad profile.

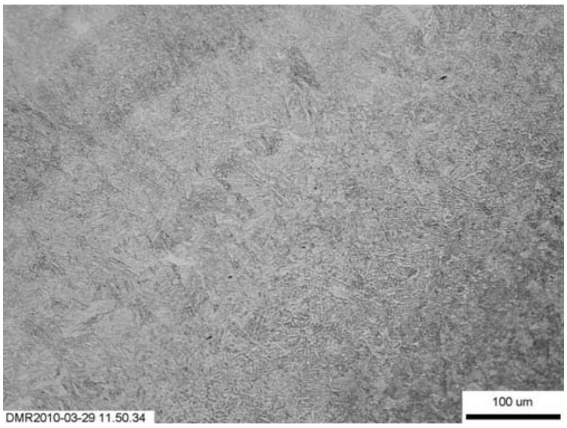
The Ø2.5/4.0 mm combination was discarded based on the photomacrographs. Subsequent metallographic examination was limited to test weld W01 (Ø3.2/4.0 mm). *Figure 5* shows the effect of the bead placement and temper bead technique on the HAZ. Good refinement of the HAZ was obtained.

Neregularni profili prikazani na slikama 3 i 4 objašnjavaju se parametrima zavarivanja i nivoom unete toplote koji su izvan uobičajenog opsega za potrošne materijale koji se koriste. Takođe, treba napomenuti da je u ovoj fazi, primarna svrha ispitnih šavova bio da se utvrdi uticaj različitih kombinacija veličina elektroda i električnih parametara na mikrostrukture ZUT, stoga je ograničen akcenat stavljen na dobijanje glatkog profila šava.

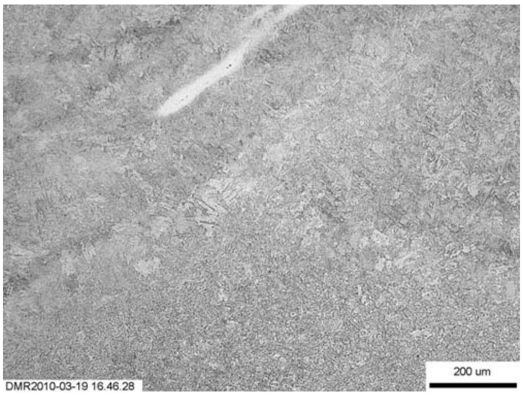
Kombinacija Ø2.5/4.0 mm je odbačena na osnovu makrofotografije. Naknadno metalografsko ispitivanje je ograničeno na ispitivanje šava W01 (Ø3.2/4.0 mm). Slika 5 pokazuje efekat mesta i tehnike izvođenja zavara na ZUT. Postignuta je dobra rafinacija ZUT.



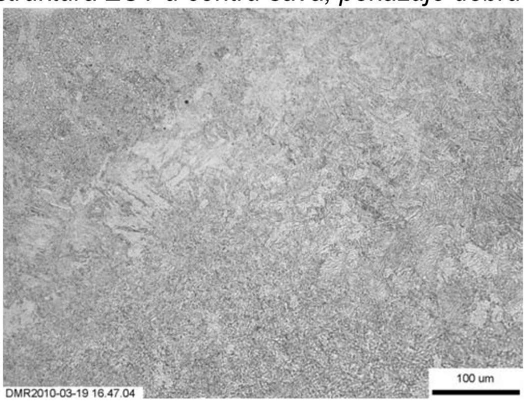
Detail of the weld and HAZ microstructures resulting from test weld W01 (Figure 3) Magnification indicated by micron marker:
(a) Microstructure at one end of the weld pad (see Figure 3), showing limited refinement;
Detalj šava i mikrostruktura ZUT iz ispitnog šava W01 (slika 3) Uvećanje označeno oznakom mikrona:
(a) Mikrostruktura na jednom kraju šava (videti sliku 3), pokazuje ograničenu rafinaciju;



(b) Detail of Figure 5a, showing a predominantly martensitic microstructure;
(b) Detalj sa slike 5a, pokazuje uglavnom martenzitnu mikrostrukturu;



(c) Microstructure of the HAZ at the centre of the weld, showing good refinement;
(c) Mikrostruktura ZUT u centru šava, pokazuje dobru rafinaciju



(d) Detail of Figure 5c, showing tempered martensite microstructure.
(d) Detalj sa slike 5c, pokazuje otpuštenu martenzitnu mikrostrukturu.

Hardness measured in the HAZ of specimen W01 ranged between 329-435HV_5 (average 385HV_5) and 258-420HV_5 (average 360 HV_5) after deposition of one and two layers, respectively, against 224-229 HV_5 for the parent metal.

Izmerene vrednosti tvrdoće ZUT na uzorku W01su u opsegu 329-435HV_5 (srednja vrednost 385HV_5) i 258-420HV_5 (srednja vrednost 360 HV_5).

GTAW

Figure 6 shows the degree of overlap between the HAZs of the three welding layers in test weld W15. In particular, *Figure 6b* shows that the HAZ associated with the second layer consistently overlapped that of the first layer, whereas, due to the variation in layer thickness, the HAZ produced by the third layer appears to have extended over the fusion line only in a few positions (*Figure 6c*).

TIG

Slika 6 prikazuje stepen preklapanja između ZUT-ova tri zavarena sloja na ispitnom šavu W15. Konkretno, slika 6b pokazuje da je ZUT vezan za drugi sloj dosledno preklopljen onim iz prvog sloja, dok zbog varijacija u debljini sloja, ZUT dobijen trećim slojem se nastavlja preko linije stapanja samo u nekoliko pozicije (slika 6c).

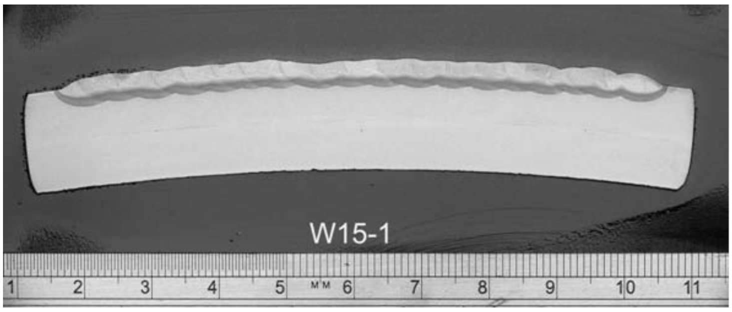
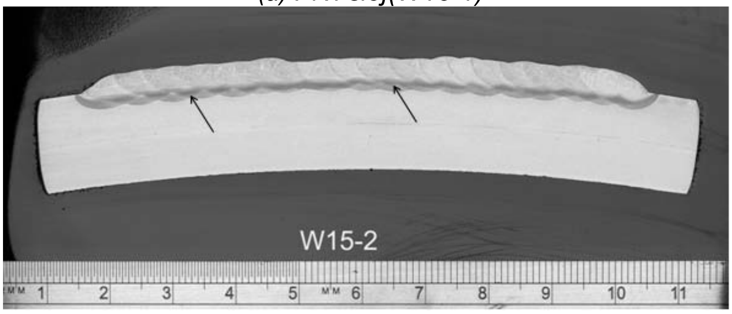
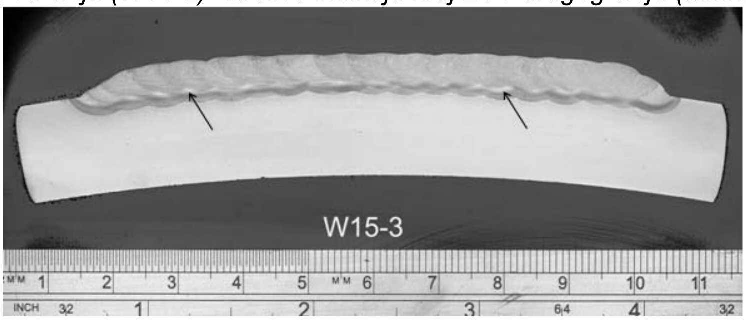


Figure 6.*Macrosections taken through the samples relating to test weld W15. Scale ruler shown:*
(a) First layer (W15-1);
Slika 6. *Makropresci uzeti iz uzoraka vezanih za ispitni šav W15. Lenjir sa skalom pokazuje:*
(a) Prvi sloj(W15-1)



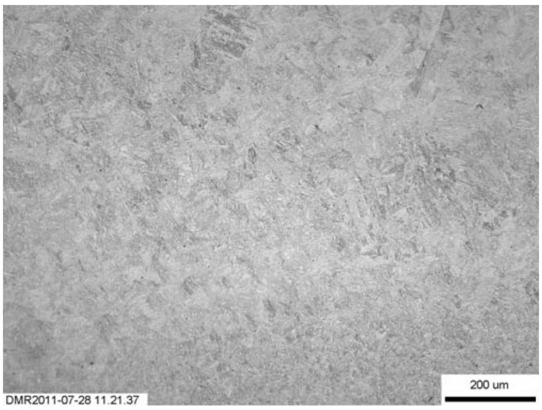
Two layers (W15-2) - arrows indicate the limit of the 2nd layer HAZ (darker);
(b)Dva sloja (W15-2)- strelice indikuju kraj ZUT drugog sloja (tamnije);



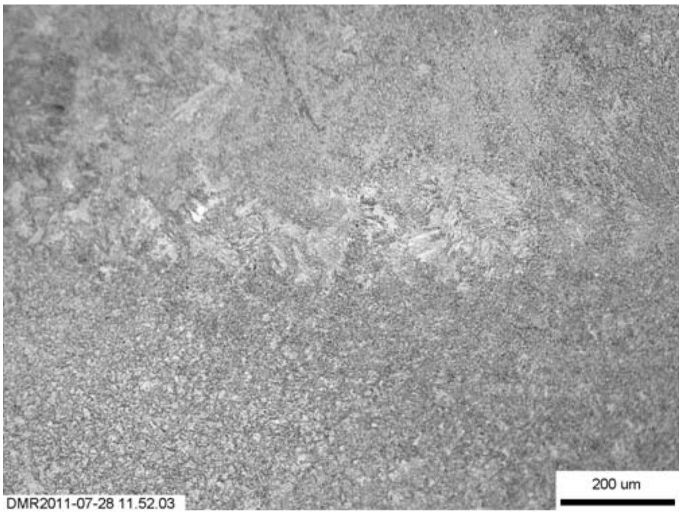
(b) Three layers (W15-3) - arrows indicate the limit of the 3rd layer HAZ (lighter).
(c)Tri sloja (W15-3)- strelice indikuju kraj ZUT trećeg sloja (svetlije);

Figure 7 shows the degree of HAZ refinement obtained when depositing two and three layers (*Figure 7b* and *c*, respectively), compared with the HAZ produced by the deposition of a single layer (*Figure 7a*).

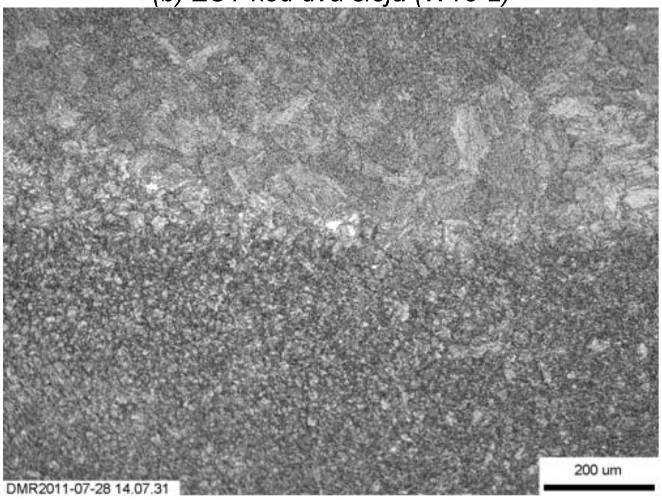
Slika 7 pokazuje stepen rafinacije ZUT dobijen kada se nanose dva ili tri sloja (slika 7b i c) u poređenju sa ZUT dobijen nanošenjem jednog sloja (slika 7a)



Detail of the weld and HAZ microstructures resulting from test weld W15 (GTAW). Magnification indicated by micron marker:
(a) HAZ associated with a single layer (W15-1);
Detalj šava i mikrostrukture ZUT kod ispitnog šava W15 (TIG). Uvećanje prikazano oznakom mikrona:
(A) ZUT kod jednog sloja (W15-1);



(b) HAZ associated with two layers (W15-2).
(b) ZUT kod dva sloja (W15-2)



(a) HAZ following the deposition of the third layer (W15-3).
(d) ZUT koji prati naonešenje trećeg sloja (W15-3)

The HAZ hardness associated with a single layer ranged from 391 to 473HV5, and averaged 430HV5. After the deposition of a second layer, the HAZ hardness ranged from 374 to 453HV5 and the average value slightly decreased to 423HV5. The values measured after the deposition of the third layer varied between 312 and 466HV5 with an average of 391HV5. This indicated that, whilst the third layer did not contribute to the refinement of the HAZ, it had a measurable effect on HAZ tempering.

Tvrdoća ZUT vezana sa jedan sloj je od 391 do 473HV5, i prosečno 430HV5. Nakon nanošenja drugog sloja, tvrdoća ZUT je od 374 do 453HV5 a prosečna vrednost neznatno opada na 423HV5. Vrednosti merene nakon nanošenja trećeg sloja variraju između 312 i 466HV5 sa prosekom od 391HV5. To ukazuje da, iako treći sloj nije doprineo rafinaciji ZUT, ima merljive efekte na otpuštanje ZUT.

Discussion

The review of current welding practice for grade 91 showed that whilst conventional welding and repair procedure are relatively established and can be reliably assessed, there is a lack of published literature and proven procedures for non-standard operations, such as welding without PWHT, which are highly desirable in a variety of fabrication and maintenance scenarios.

Diskusija

Pregled sadašnje prakse zavarivanja klase 91 pokazuje da iako je konvencionalno zavarivanje i procedura popravke relativno uspostavljeno i mogu se pouzdano proceniti, postoji nedostatak literature i proverenih procedure za nestandardne operacije, kao što je zavarivanje bez TOPZ (PWHT), što je veoma poželjno kod različitih izrada i scenarija održavanja.

In this respect, the experimental results showed that, if a refinement criterion previously applied to C-Mn steels, is applied to investigate the possibility to repair grade 91 components without PWHT, a substantial degree of HAZ refinement can be obtained for both the SMAW and GTAW processes. However, the tempering produced by such approach in the HAZ cannot be considered significant for SMAW, with an average hardness drop of approximately 25HV5. On the other hand, when GTAW was applied, a moderate degree of tempering was obtained, with a hardness reduction of 40HV5 after the deposition of three weld layers. It should however be noted that grade 91, being resistant to creep damage, is intrinsically resistant to tempering.

The wide range of hardness values observed indicated the range of maximum temperatures experienced in the HAZ regions with the lowest hardness values, corresponding to the areas that had been more effectively tempered by the heat cycle induced by the subsequent layers. This confirms that the depth of penetration of the second and following welding layers, as well as their associated HAZ, must be made more uniform, if consistent tempering is to be obtained.

Conclusions

No procedures for 'cold' weld repairs of P91 components are available in the public domain, which have been successfully employed in-service.

SMAW and GTAW weld repair procedures for grade 91 without PWHT were investigated by applying a refinement criterion.

A combination of SMAW electrodes with diameters 3.2 mm (1/8 in, first layer) and 4.0 mm (5/32 in, second layer) produced some refinement, but only limited tempering occurred in the HAZ.

A three-layer GTAW repair procedure provided a higher degree of microstructural refinement, with limited tempering.

Recommendations

If weld repair procedures for grade 91 without PWHT are to be developed, the investigation of a controlled deposition procedure, based on a shallower penetration by the second layer than that explored in this present project, is recommended to achieve maximum tempering rather than maximum refinement.

In order to assess the performance of such repair procedures for in service applications, extensive welding trials and testing are required, including investigating HAZ toughness and cross-weld creep strength.

U tom smislu, eksperimentalni rezultati su pokazali da, ukoliko se primenjuje kriterijum rafinacije, prethodno primenjivan za C-Mn čelike, radi ispitivanja mogućnosti za popravku komponenti od klase 91 bez TOPZ (PWHT), značajan stepen rafinacije ZUT se može postići REL i TIG postupcima zavarivanja. Međutim, otpuštanje postignuto ovakvim pristupom u ZUT ne može se smatrati značajnim za REL, sa prosečnim padom tvrdoće od oko 25HV5. S druge strane, kada je primenjen TIG, umereni stepen otpuštanja je postignut, smanjenjem tvrdoće 40HV5 nakon nanošenja tri sloja. Međutim, treba napomenuti da je klasa 91, otporna na puzanje, suštinski otporna na otpuštanje.

Širok raspon vrednosti tvrdoće koji je uočen, ukazuje na opseg maksimalnih temperatura u ZUT regionima sa najnižim vrednostima tvrdoće, odgovara područjima koja su efikasnije otpuštena, toplotnim ciklusima izazvanim narednim slojevima. Ovo potvrđuje da dubina prodiranja drugog i narednih slojeva zavarivanja, kao i njihove ZUT, moraju biti uniformnije, ako se želi postići dosledno otpuštanje.

Zaključci

Nema procedure za 'hladno' reparaturno zavarivanje komponenti od P91 koje su javno dostupne, a da su bile uspešno korišćene u eksploataciji.

Postupci REL i TIG za reparaturu kod klase 91 bez TOPZ (PWHT) su ispitivani primenom kriterijuma rafinacije.

Kombinacija REL elektroda prečnika 3.2 mm (1/8 in, prvi sloj) i 4.0 mm (5/32 in, drugi sloj) proizvela je donekle rafinaciju, ali se u ZUT desilo samo ograničeno otpuštanje.

Postupak TIG reparaturnog zavarivanja u tri sloja obezbeđuje viši stepen mikrostrukturne rafinacije, sa ograničenim otpuštanjem.

Preporuke

Ako se postupci popravke zavarivanjem bez TOPZ za klasu 91 budu razvijali, istraživanje procedure kontrolisanog nanošenja, na osnovu plićeg prodora drugim slojem, koja su korišćena u sadašnjem projektu, preporučuje se da se postigne maksimalno otpuštanje, a ne maksimalna rafinacija.

U cilju procene učinka takvih procedura popravke za tokom ekspolatacije, obavezne su opsežne studije zavarivanja i ispitivanje, uključujući istraživanje žilavost ZUT i granicu puzanja po preseku šava.

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Air-Liquide, 2012: www.airliquidewelding.cz/file/otherelement/pj/new%20toptig%202386z18473.pdf

MIŠLJENJE (KOMENTAR)

o knjizi **"Termičko sečenje metala"**, autor Milan Dragića Milovanović, u izdanju "Slovensko društvo za neporušitvene preiskave", Ljubljana, 2016. g.

Pročitali smo knjigu i pogledali priloženi CD (knjiga u proširenom elektronskom izdanju) i zaključili da je uložen veliki trud.
Knjiga obuhvata razne načine rezanja plazmom i laserom, a pored toga (mada nije tema naslova) opisane su i tehnike zavarivanja plazmom i laserom, MIG/MAG, pa sve do elektrootporskog zavarivanja zavrtnjeva i bolcni (nemački "Bolzenschweissen").
Uočeni su nedostaci vezani za standardizovanu terminologiju iz ove oblasti (tiče se i samog naslova, gde bi umesto izraza "sečenje" trebalo da stoji izraz "rezanje"). Takođe i najveći broj tabela i legendi ispod slika nisu na srpskom jeziku, već, pretežno, na nemačkom jeziku. Ako čitaocu to ne smeta, a dobro zna nemački jezik, u knjizi može da nađe niz interesantnih podataka iz oblastzi rezanja plazmom i laserom, a i iz oblasti pomenutih tehnika zavarivanja.
Knjiga obiluje propagandnim materijalom raznih proizvđača opreme za rezanje i zavarivanje (nažalost i taj tekst je uglavnom na nemačkom jeziku), pa i to može da bude interesntno nekom ko traži rešenje za svoj problem iz pomenute tematike.
Ko je zainteresovan za ovakvu publikaciju, moguće ju je nabaviti direktno od autora.

Komentar dao: Martinovski Vlado, dipl. inž. maš.