



Su-Kil Park ^{1,a}, Young-Ho Cho ^{1,b}, Chun-Ho Jee ^{1,c}, Namhyun Kang ^{2,d}

Effect of boron and manganese on hot crack resistance and toughness for flux cored arc weldments of 550 MPa grade tensile strength

Uticaj bora i mangana na otpornost ka toplim prslinama i žilavost elektrolučno zavarenih spojeva punjenom elektrodnom žicom čelika klase zatezne čvrstoće od 550 MPa

Originalni naučni rad / Original scientific paper

Rad je u izvornom obliku objavljen u okviru 72. IIV godišnje Skupštine i međunarodne konferencije održane u Bratislavi-Slovačka 07-12. Jula 2019

Rad primljen / Paper received:

Decembar 2020.

Prevod izvornog rada na srpski jezik: A. Mitrašinić

Adresa autora / Author's address:

¹ Welding Research Dep't, Hyundai Heavy Industries Co., Ltd., Ulsan, Republic of Korea

² Department of Materials Science & Engineering, Pusan National University, Busan, Republic of Korea

^a psk2011@hhi.co.kr,

^b choyh@hhi.co.kr,

^c jee1005@hhi.co.kr,

^d nhkang@pusan.ac.kr

Keywords: hot crack resistance, low temperature toughness, self-restraint testing, boron, manganese

Ključne reči: otpornost na tople prsline, žilavost pri niskim temperaturama, ispitivanje zavarljivosti, bor, mangan

Rezime

Abstract

The hot crack resistance and mechanical properties of flux cored arc (FCA) welds were investigated with three kinds of welding consumables having different boron (B) and manganese (Mn) contents for high strength carbon steel. The hot crack resistance measured from self-restraint testing strongly depended on the amount of B in the welding consumable. Welding consumable with higher B contents resulted in longer total crack length and an increased number of cracks. Boron was intensely detected near the grain boundary of the weld centerline by secondary ion mass spectrometry (SIMS) analysis, and precipitated with boron carbide ($\text{Fe}_{23}(\text{C},\text{B})_6$), as analyzed by transmission electron microscopy (TEM). This promoted hot crack propagation in the high strength carbon steel welds.

Otpornost ka stvaranju toplih prslina i mehaničke osobine elektrolučno zavarenih spojeva sa punjenim elektrodnom žicama (FCA) je ispitivano sa tri vrste žica sa različitim količinama bora (B) i mangana (Mn) za zavarivanje ugljeničnog čelika visoke čvrstoće. Otpornost ka toplim prslinama je merena primenom testova zavarljivosti, i jako je zavisila od količine B u upotrebljenom dodatnom materijalu za zavarivanje. Punjene elektrodne žice za zavarivanje sa većim sadržajem B rezultirale su varovima sa povećanim brojem i većom dužinom prslina. Bor je intenzivno detektovan uz granice zrna duž središnje linije vara i određivan je metodom sekundarne jonske masene spektrometrije (SIMS). On se taložio u obliku bor-karbida ($\text{Fe}_{23}(\text{C}, \text{B})_6$), što je utvrđeno transmissionom elektronskom mikroskopijom (TEM).

However, removing B from the welding consumable decreased the low temperature toughness for root and face weld metal due to the growth of Ferrite Side Plate (FSP) in comparison with welding consumables having more B or Mn contents. The addition of Mn in the weld metal suppressed the formation of FSP and increased the low temperature toughness. Therefore, the minimization of B and the supplement of Mn

To je podstaklo dalje širenje toplih prslina u varovima ugljeničnog čelika visoke čvrstoće. Međutim, uklanjanjem bora iz dodatnog materijala smanjivala se žilavost na niskim temperaturama korenog i pokrivnog metala vara, zbog rasta feritnih lamela. Međutim, u poređenju sa upotrebljenim punjenim elektrodnom žicama koje sadrže B ili Mn, uklanjanjem B iz punjenih elektrodnih žica, smanjila se žilavost na niskim temperaturama osnovnog i površinskog metala vara zbog rasta bočnih feritnih



successfully achieved hot crack resistance and low temperature toughness for high strength carbon steel welds of 550 MPa tensile strength.

1. Introduction

Hot cracking occurs when sensitive microstructure for cracking and tensile stress due to shrinkage and external restraint of the weld at high temperature exceeding 300 °C during or immediately after welding is encountered.

The main cause of hot cracking is known as the austenite matrix of the face-centered cubic (FCC) crystal structure having a low solubility of phosphorus (P) and sulfur (S), and austenitic stainless steels and high alloy steels such as nickel alloys have been focused on hot cracking [1].

The purpose of this study is to evaluate the effect of boron (B) contents for hot cracking on Flux Cored Arc (FCA) weld metal for high strength carbon steel. Especially, the change of mechanical properties according to the content of boron was examined to prevent hot cracking and to secure mechanical properties by adjustment of chemical composition such as manganese (Mn).

2. Materials and experimental procedures

2.1 Base metal and welding condition

The base metal used in this study is high strength carbon steel (Grade: AH36) manufactured by Thermo-Mechanically Controlled Process (TMCP). FCA welding was performed using three kinds of welding consumables having the similar chemical composition including 0.04 wt.% C except for boron and manganese contents in the AWS Class. E81T1-K2C grade (A: 1.02% Mn - 42 ppm B, B: 1.02% Mn, - 1 ppm B, and C: 1.46% Mn - 2 ppm B).

Welding consumable B removed boron from welding consumable A, and welding consumable C increased manganese content in welding consumable B to 1.46 wt.%. Hot cracking and mechanical properties were evaluated according to the differences in boron and manganese content.

The hot crack resistance testing was performed with specimen having 400 mm wide and 600 mm long as shown in Fig. 1, and were subjected to grooving with a length of 400 mm and two

lamella. Dodavanje Mn u metal šava potisnulo je stvaranje feritnih lamela i povećalo je žilavost pri niskim temperaturama. Dakle, minimiziranjem količine B i dodavanjem Mn uspešno je povećana otpornost na tople prsline i žilavost na niskim temperaturama zavarenih spojeva ugljeničnih čelika visoke čvrstoće klase zatezne čvrstoće od 550 MPa.

1. Uvod

Tople prsline nastaju tokom ili neposredno posle zavarivanja kod mikrostruktura osetljivih na stvaranje prsline i zbog zateznih napona, usled skupljanja i spoljašnjih ograničenja zavarenog spoja. na temperaturama višim od 300 °C

Glavni uzročnik stvaranja toplih prsline je niska rastvorljivost fosfora (P) i sumpora (S) u austenitnoj osnovi površinski orijentisanih kristalnih struktura (FCC). Takođe, austenitni nerđajući i visokolegirani čelici kao što su legure nikla imaju nisku otpornost ka toplim prslinama [1].

Svrha ove studije je procena uticaja sadržaja bora (B) na otpornost na stvaranje toplih prsline elektrolyučno zavarenih spojeva punjenim elektrodnim žicama (FCA) kod ugljeničnih čelika klase zatezne čvrstoće od 550 MPa. Posebno je ispitana promena mehaničkih osobina u odnosu na sadržaj bora kako bi se sprečile tople prsline, i prilagođavanje hemijskog sastava manganom (Mn) radi osiguranja mehaničkih osobina.

2. Materijali i eksperimentalni postupci

2.1 Osnovni metal i uslovi zavarivanja

Osnovni metal koji se koristi u ovoj studiji je ugljenični čelik visoke čvrstoće (klase: AH36) proizveden procesom Thermo Mechanical Controlled Process (TMCP). Elektrolyučno zavarivanje punjenim elektrodnim žicama (FCA) je izvedeno upotrebom tri vrste materijala za zavarivanje sa 0,04 tež% C i različitim koncentracijama bora i mangana u AVS klasi. E81T1 -K2C razred (A: 1,02% Mn - 42 ppm B, B: 1,02% Mn, - 1 ppm B, i C: 1,46% Mn - 2 ppm B).

Upotrebljeni dodatni materijal za zavarivanje je B je sa uklonjenim borom iz materijala A, a upotrebljeni dodatni materijal za zavarivanje C imao je povećani sadržaj mangana u materijalu za zavarivanje B na 1,46 mas.%. Otpornost na tople prsline i mehanička svojstva ocenjivana su prema razlikama u sadržaju bora i mangana.

Ispitivanje otpornosti na tople prsline izvedeno je na uzorcima širine 400 mm i dužine 600 mm, kao što je prikazano na slici 1, i formirani su šavovi



conditions of low current (220 A) and high current (280 A) respectively.

dužine 400 mm, primenom niske (220 A) i visoke struje (280 A), respektivno.

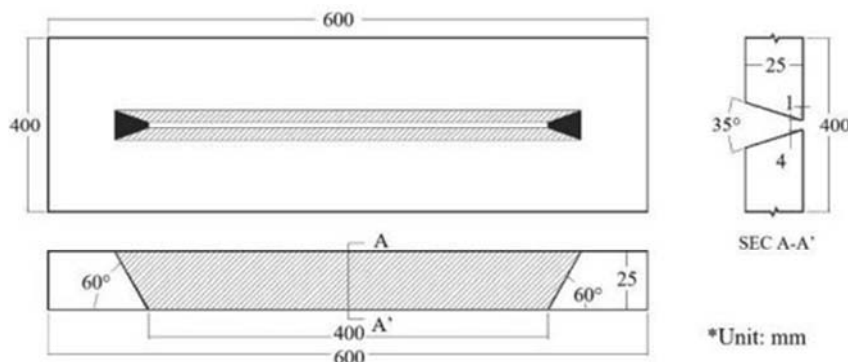


Figure 1. Specimen geometry for hot crack resistance testing

Slika 1. Geometrija uzorka za ispitivanje otpornosti na tople prsline

Further, additional specimens were prepared on the same base metal with the hot crack resistance testing specimen to confirm the change of mechanical properties according to the adjusted chemical composition.

Tab. 1 shows the bead sequence and detailed welding conditions for the evaluation of hot crack resistance and mechanical properties.

Dalje, dodatni uzorci su pripremljeni na istom osnovnom metalu sa uzorkom za ispitivanje otpornosti na tople prsline kako bi se potvrdila promena mehaničkih osobina u skladu sa prilagođenim hemijskim sastavom.

Tabela 1 prikazuje redosled i detaljne uslove zavarivanja radi procene otpornosti na tople prsline i mehaničkih osobina.

Table 1. Welding conditions to check hot crack resistance and mechanical properties (Welding position: 1G)

Tabela 1. Uslovi zavarivanja radi procene otpornosti na tople prsline i mehaničke osobine (položaj zavarivanja: 1G)

	Redosled zavarivanja	Uslovi zavarivanja				
		Prolaz Br.	Struja, (A)	Napon, (V)	Brzina kretanja (CPM)	Unos toplote, (kJ/cm)
Otpornost na tople prsline		1	220	27	17,0	21.0
		1	280	31	24,8	21.0
Mehaničke osobine		1	220	26	11,4	30.1
		2-5	300-330	32-34	19,2- 22,4	30.1

2.2 Hot crack resistance and mechanical testing

The specimens for the evaluation of hot crack resistance were subjected to liquid penetrant testing as shown in Fig. 2 to determine the crack length and the number of cracks visually confirmed.

Also, all weld metal tensile test, hardness test and impact test were carried out on the specimens for evaluation of mechanical properties. As shown in Fig. 3, the impact test was separated into root and face weld metal and carried out in 1 set of three specimens at each area.

2.2 Otpornost na tople prsline i ispitivanje mehaničkih osobina

Uzorci za procenu otpornosti na tople prsline podvrgnuti su ispitivanju penetrantima kao što je prikazano na slici 2, da bi se odredila dužina prsline i vizuelno potvrdio broj prsline.

Takođe, sva ispitivanja zatezanjem metala šava, ispitivanje tvrdoće i ispitivanje energije udara, izvršeno je radi procene mehaničkih svojstava. Kao što je prikazano na slici 3, ispitivanje enegije udara je razdvojeno na koren i lice metala šava i izvedeno je u setu od tri uzorka za svako područje.

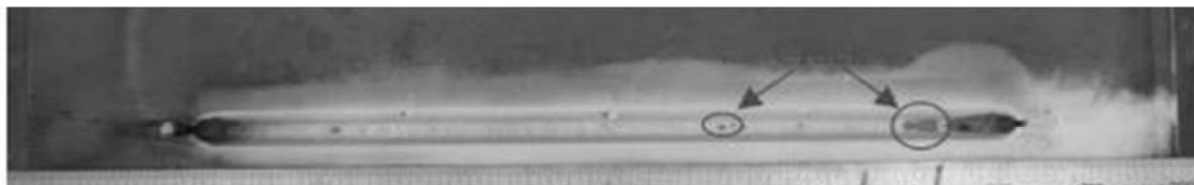


Figure 2. Top surface of hot crack testing specimens after liquid penetrant testing

Slika 2. Lice šava uzoraka za ispitivanje na otpornost na tople prsline nakon ispitivanja penetrantima

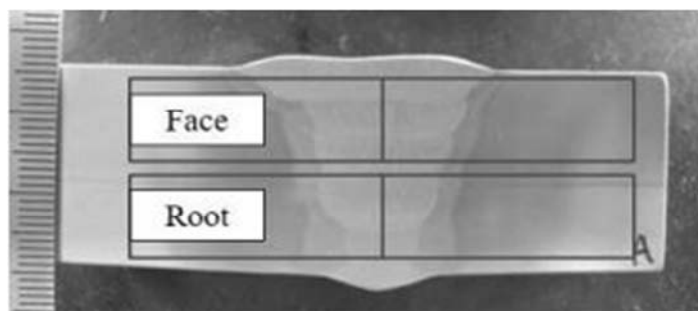


Figure 3. Location of impact-testing specimens

Slika 3. Položaj uzoraka za ispitivanje energije udara

2.3 Metallurgical analysis

The crack type was analyzed by Scanning Electron Microscopy (SEM) through analysis of fracture surface. Secondary ion mass spectrometry (SIMS) was used to analyze boron content added in small quantities in tens of ppm [2]. And, the specimens were prepared by Focused Ion Beam (FIB) and analyzed by Transmission Electron Microscopy (TEM).

Chemical compositions were analyzed by Optical Emission Spectroscopy (OES) in order to investigate the change of composition and mechanical properties for weld metal by dilution with base metal.

3. Results and discussion

3.1 Hot cracking behaviour by boron and manganese content

Fig. 4a and 4b show the results of the liquid penetrant testing at the low current (220 A) and high current (280 A) conditions respectively. The cracks for low current conditions were observed in the longitudinal direction of the weld line only for the welding consumable A having a boron content of 42 ppm. The cracks occurred in all welding consumables under high current conditions, but the total crack length was longest and the number of cracks was largest in case of welding consumable A having a boron content of 42 ppm. And, welding consumable B removed boron showed the shortest crack length and the smallest number of cracks under high current conditions.

2.3 Metalurška analiza

Tip prsline je analiziran skenirajućom elektronskom mikroskopijom (SEM) analizom površine loma. Sekundarna jonska masena spektrometrija (SIMS) korišćena je za analizu sadržaja Bora koji se dodaje u malim količinama, u desetinama ppm [2]. Uzorci su pripremljeni fokusiranim jonskim snopom (FIB) i analizirani transmisijom elektronskom mikroskopijom (TEM).

Hemijski sastavi su analizirani optičkom emisionom spektroskopijom (OES) kako bi se ispitala promena sastava i mehaničkih osobina metala šava razblaživanjem sa osnovnim metalom.

3. Rezultati i diskusija

3.1 Otpornost na tople prsline u zavisnosti od sadržaja bora i mangana

Na slikama 4a i 4b prikazani su rezultati ispitivanja penetrantima u uslovima niske (220 A) i visoke struje zavarivanja (280 A). Prsline nastale u uslovima niske struje su uočene u uzdužnom pravcu linije zavarivanja samo za materijal A sa sadržajem bora od 42 ppm. Do stvaranja prsline je došlo u svim dodatnim materijalima za zavarivanje u uslovima visokih struja, a ukupna dužina prsline bila najduža, a broj prsline najveći u slučaju dodatnog materijala za zavarivanje A sa sadržajem bora od 42 ppm. Dodatni materijal B je sa uklonjenim borom je pokazao najkraću dužinu prsline i najmanji broj prsline u uslovima visokih struja.

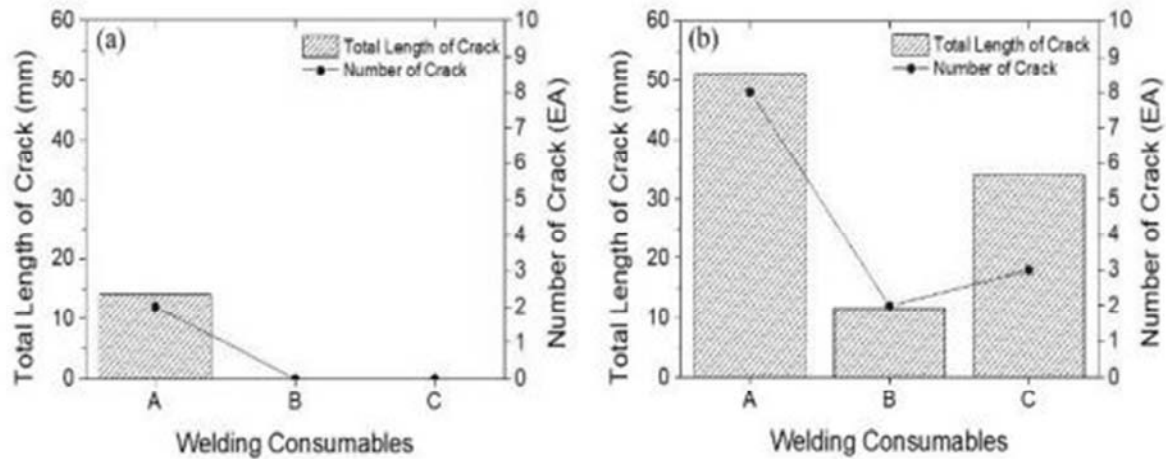


Figure 4. Total crack length and number of cracks after liquid penetrant testing for the welds produced at (a) low current and (b) high current

Slika 4. Ukupna dužina prslina i njihov broj nakon ispitivanja pentrantima za zavarene spojeve proizvedene pri (a) niskoj i (b) visokoj struji.

Fig. 5 is an optical microscope photograph for the cross section of the weld metal occurred cracking along the length of the weld line in the specimen welded at high current (280 A) with welding consumable A having high boron content.

Slika 5 je fotografija sa optičkog mikroskopa za poprečni presek šava gde je pucanje nastalo duž linija zvarivanja u uzorku zavarenom visokom strujom (280 A) sa dodatnim materijalom A sa visokim sadržajem bora.

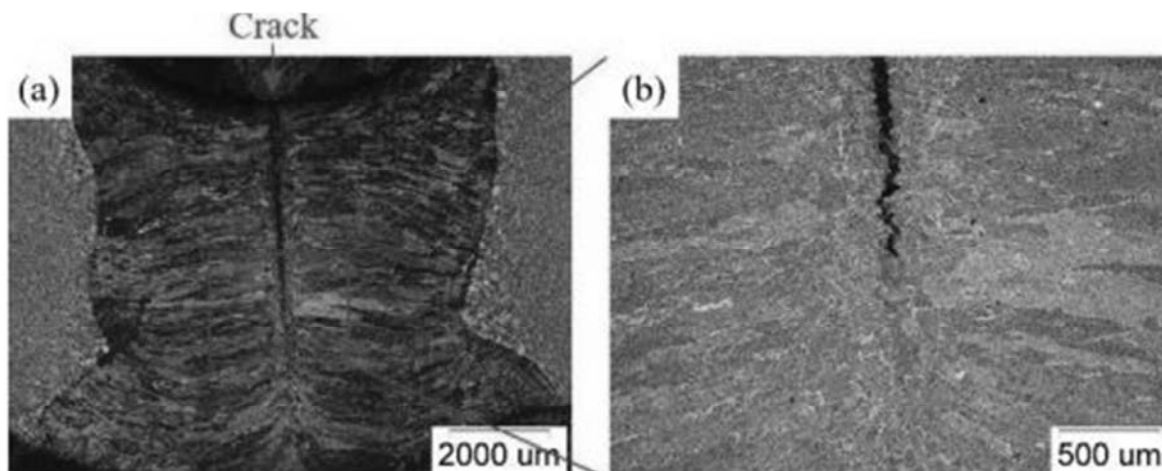


Figure 5. Cross section of hot crack specimens produced by weld metal A and high current (280 A): (a) weld cross section and (b) enlarged view of hot crack observed in the weld centerline

Slika 5. Poprečni presek toplih prslina u uzorku koji je zavaren dodatnim metalom A i visokom strujom (280 A): (a) presek vara i (b) uvećan prikaz tople prsline uočene u središnjoj liniji šava

As shown in Fig. 5a, the crack was observed in the depth direction at the weld metal centerline, which is the final solidification point where the dendritic microstructures grown on the solid-liquid interface meet.

Kao što je prikazano na slici 5a, uočena je prslina u dubini središnje linije šava, što je poslednja tačka očvršćavanja gde se susreću dendritne mikrostrukture nastale na granici čvrsto/tečno.

Fig. 6 is a SEM image of the fracture surface for crack of the welded joint under the same condition. The liquid phase was solidified and the generated columnar dendrites were observed, which is judged to be typical hot cracking.

Slika 6. je SEM slika površine loma zavarenog pod istim uslovima. Tečna faza je očvrstnula i uočeni su stubasti dendriti, za koje je procenjeno da su tipični za tople prsline.

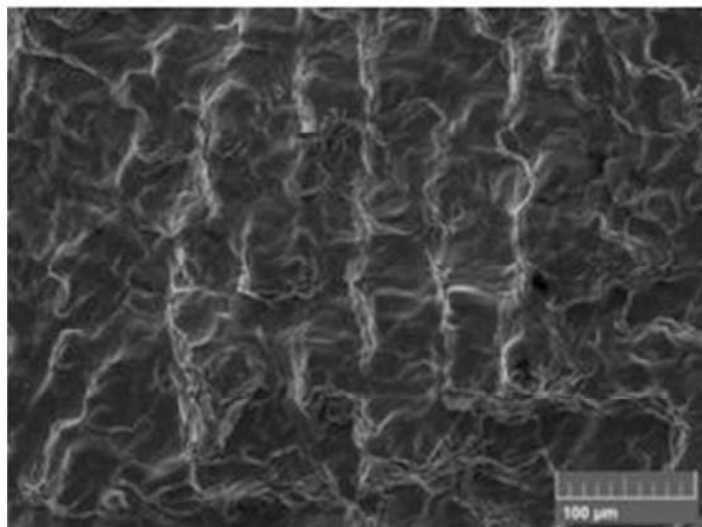


Figure 6. SEM micrograph of fractured surface for the hot crack specimens produced by weld metal A and high current (280 A)

Slika 6. SEM mikrografija snimljene površine loma sa toplim prslinama kod uzoraka zavarenih dodatnim metalom A sa visokom strujom zavarivanja (280 A)

3.2 Hot cracking mechanism by boron and manganese content

Fig. 7 is an SEM image of the microcracks directly connected to the end (Fig. 7a) and the side (Fig. 7b) of hot crack for welding consumable A, where only the hot crack occurred under the low current (220 A) condition. SIMS was performed for the chemical composition analysis at the position closest to the end of hot crack (Yellow square in Fig. 7a).

3.2 Mehanizam nastajanja toplih prslina u zavisnosti od sadržaja bora i mangana

Slika 7 je SEM izgled mikropsline direktno povezane sa krajem (Slika 7a) i bočnom stranom (Slika 7b) tople prslina nastale zavarivanjem dodatnim materijalom A, gde je topla prslina nastala samo u uslovima niske struje (220 A). SIMS analiza hemijskog sastava je izvršena na položaju najbližem kraju tople prslina (svetli kvadrat na slici 7a).

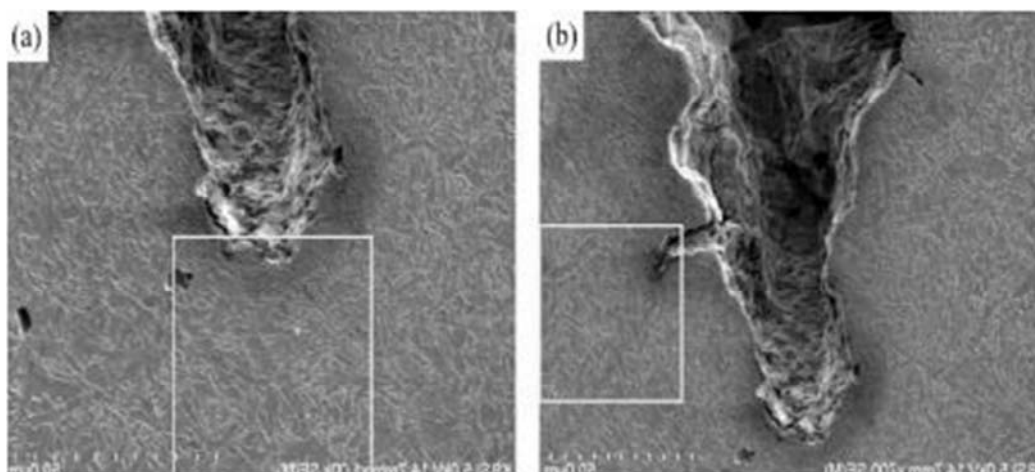


Figure 7. Location of SIMS analysis for the hot crack produced by welding consumable A and low current (220 A): (a) the end of hot crack and (b) the side of hot crack

Slika 7. Položaj SIMS analize za toplu prslinu nastalu zavarivanjem dodatnim materijalom A niskom strujom (220 A): (a) kraj i (b) strana tople prslina

Fig. 8 shows the mapping of boron, carbon, nitrogen and iron, and the results of line scan for the direction of 1 → 2 in mapping of boron and iron components. At the end of hot crack, boron (Fig. 8a) was concentrated and distributed around the

Slika 8. prikazuje mapiranje sadržaja bora, ugljenika, azota i železa i rezultate linijskog skeniranja za pravac 1 → 2 za komponente bora i železa. Bor (slika 8a) je koncentrovan na kraju tople prslina i raspoređen oko prslina. Ugljenik



crack. The carbon (Fig. 8b) and nitrogen (Fig. 8c) were also concentrated at the end of hot crack, similar to the position of boron, and segregated around the cracks. As a result of the line analysis, the degree of boron segregation was high at the end of hot crack, and iron showed uniform composition distribution.

Therefore, it is assumed that precipitates such as boron carbide ($\text{Fe}_{23}(\text{C},\text{B})_6$) formed by combining boron with carbon and iron or boron nitride (BN) produced by bonding with nitrogen are concentrated at the end of hot crack [3-5].

(slika 8b) i azot (slika 8c) su takođe segregirani oko prslina i koncentrisani na njihovim krajevima, slično položaju bora. Kao rezultat linijske analize, stepen segregacije bora bio je visok na kraju tople prsline, a železo je pokazalo ravnomernu raspodelu sastava.

Stoga se pretpostavlja da se talozi poput bor-karbida ($\text{Fe}_{23}(\text{C}, \text{B})_6$) nastali spajanjem bora sa ugljenikom i železom ili bor - nitridom (BN) i da se koncentrišu na krajevima toplih prslina [3-5].

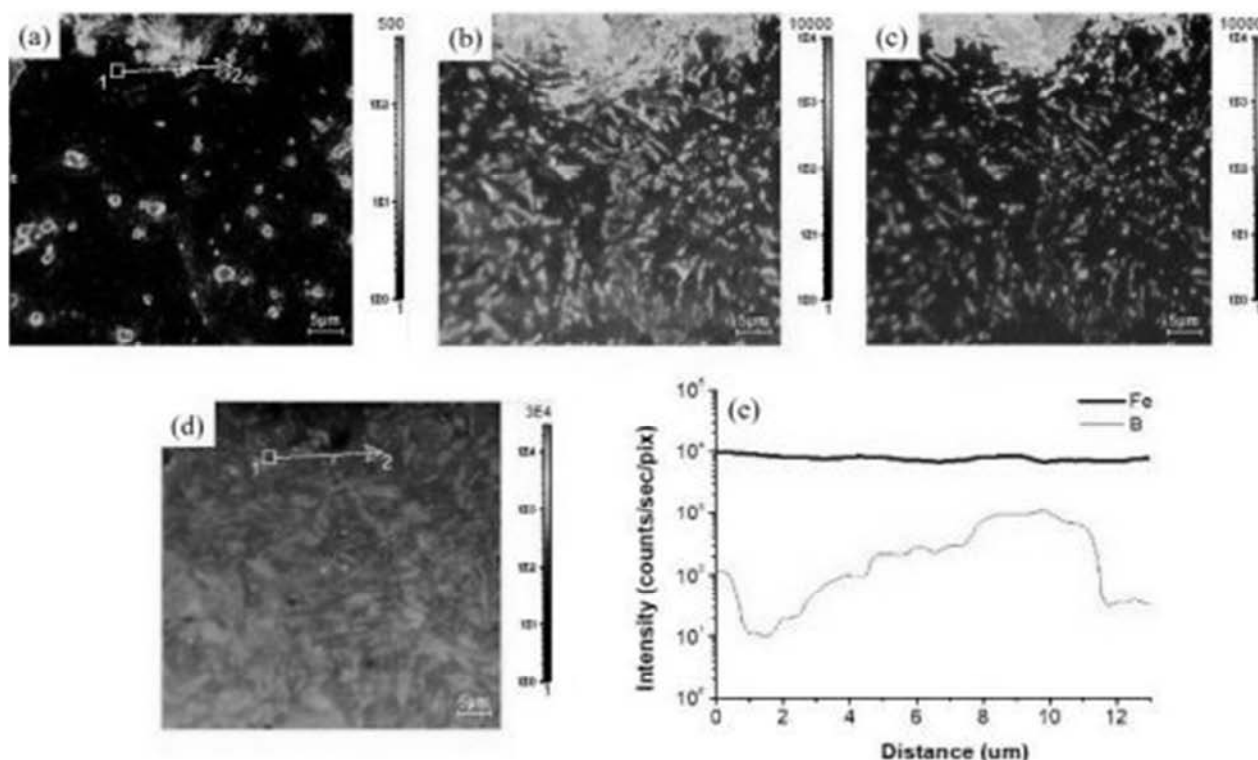


Figure 8. Concentration maps measured by SIMS for the end of hot crack produced by welding consumable A and low current 220 A: (a) boron, (b) carbon, (c) nitrogen, (d) Fe elements and (e) line scan profiles starting from position 1 to 2 indicated in (a, d)

Slika 8. Mape koncentracije merene SIMS-om na kraju tople prsline nastale zavarivanjem dodatnim materijalom A, niskom strujom od 220 A: elementi (a) bor, (b) ugljenik, (c) azot, (d) Fe i (e) linijski profili skeniranja koji počinje od položaja 1 do položaja 2 naznačenih u (a, d)

Based on the results of SIMS, a specimen for TEM analysis was prepared using FIB at the area (Red square in Fig. 9a) judged as precipitates in the grain boundaries closest to the microcrack at the side of hot crack to confirm the kind of precipitate formed by the combination of boron with other elements.

Fig. 9b-9d are the results of analysis of the respective TEM diffraction patterns at positions 1-3 of Fig. 9a, all of which are identified as M_{23}C_6 type carbides.

Na osnovu rezultata SIMS-a, uzorak za TEM analizu pripremljen je pomoću FIB-a na području (crni kvadrat na slici 9a) sa pretpostavkom da je talog u granicama zrna najbliži do mikroprslina na strani tople prsline da bi se potvrdilo da je ta vrsta taloga nastala kombinovanjem bora sa drugim elementima.

Slike 9b-9d prikazuju rezultate analize odgovarajućih obrazaca difrakcije TEM-a na pozicijama 1-3 na slici 9a, koji su svi identifikovani kao karbidi tipa M_{23}C_6 .

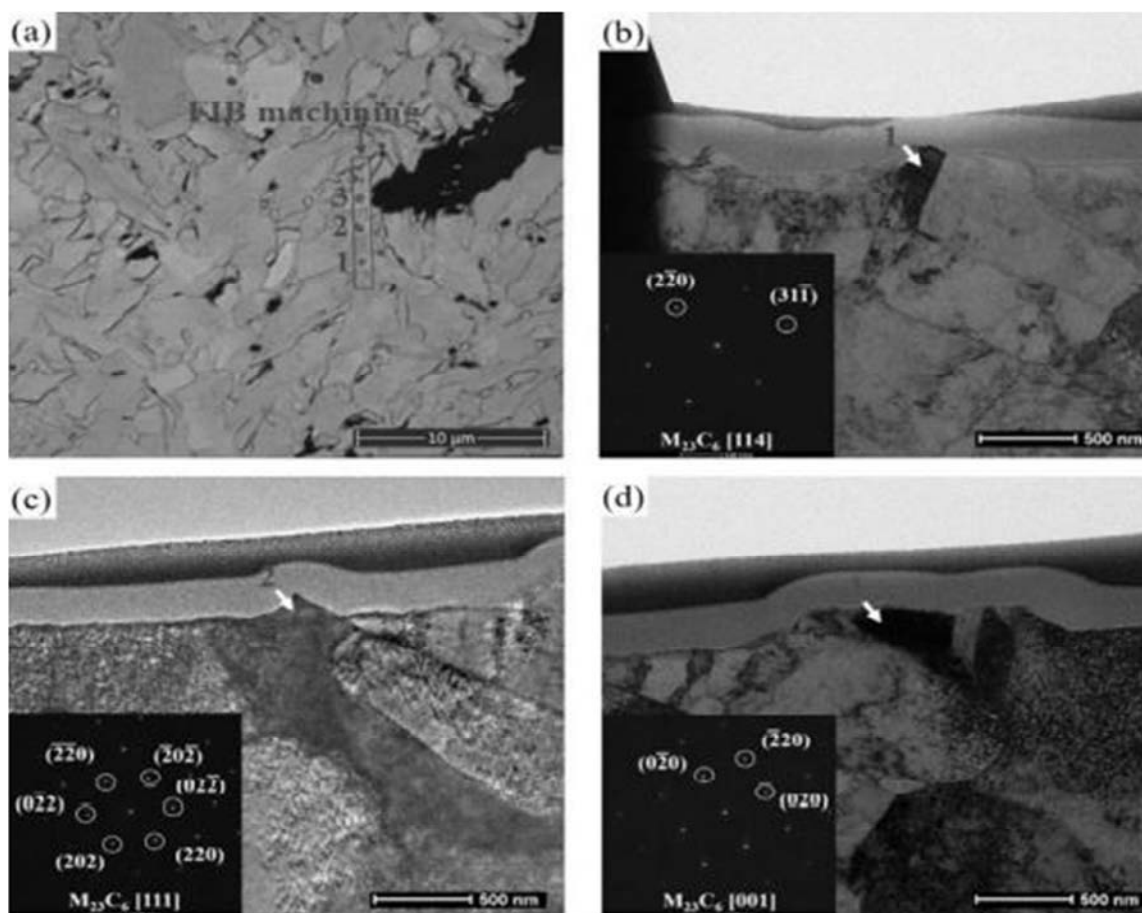


Figure 9. TEM micrographs for the side of hot crack produced by welding consumable A and low current (220 A): (a) location of FIB machining, (b) bright field image and diffraction pattern for No. 1 precipitate, (c) bright field image and diffraction pattern for No. 2 precipitate and (d) bright field image and diffraction pattern for No. 3 precipitate

Slika 9. TEM mikrofografije na strani tople prsline nastale zavarivanjem dodatnim materijalom A sa niskom strujom (220 A): (a) mesto FIB obrade, (b) slika svetlog polja i difrakcioni uzorak za talog br. 1, (c) slika svetlog polja i difrakcioni uzorak za talog br. 2 i (d) slika svetlog polja i difrakcioni obrazac za talog br. 3

The results of the quantitative analysis by Energy Dispersive X-ray Spectroscopy (EDS) at the same position are as shown in Tab. 2. As a result of the atomic percent analysis, carbon and boron exist in the precipitates 1-3. Therefore, the precipitates are boron carbides ($\text{Fe}_{23}(\text{C}, \text{B})_6$).

Rezultati kvantitativne analize pomoću energetske disperzione rentgenske spektroskopije (EDS) u istoj tački su prikazani u Tabeli 2. Kao rezultat atomske procentualne analize, ugljenik i bor postoje u talozima 1-3. Zbog toga su to bor-karbidni talozi ($\text{Fe}_{23}(\text{C}, \text{B})_6$).

Table 2. Chemical composition of precipitates measured by TEM/EDS

Tabela 2. Hemijski sastav taloga meren pomoću TEM/EDS-a

Br.	Sadržaj	Element				
		CK	Fe K	NK	BK	Ukupno
1	tež.%	3.2	95.7	0.0	1.1	100.0
	at.%	12.6	82.4	0.0	5.0	100.0
2	tež.%	1.8	97.2	0.0	1.0	100.0
	at.%	7.5	87.9	0.0	4.6	100.0
3	tež.%	1.9	97.1	0.1	0.9	100.0
	at.%	7.8	87.6	0.4	4.2	100.0



3.3 Mechanical properties and microstructure by boron and manganese contents

The tensile properties of the multi-layered welds according to the alloying elements are shown in Fig. 10a. Welding consumable A containing boron and welding consumable C having increased manganese content showed high yield and tensile strength and welding consumable B having a relatively low content of boron and manganese showed the lowest strength value. However, the welding consumables A-C satisfied both the minimum yield strength of 470 MPa and the tensile strength of 550-690 MPa required by the AWS Class E81T1-K2C of AWS A5.29.

Fig. 10b shows the Vickers hardness values for the weld metals as the minimum and maximum values. All of the welding consumables have a hardness lower than the maximum 350 HV10 required by the Society and satisfy acceptance criteria. The hardness value of the welding consumable C having a high manganese content is about 20 HV10 higher than the welding consumables A and B.

The hardness of welding consumable C is considered to be the highest because of the effect of increasing hardenability with increasing manganese content when comparing welding consumables B and C having the same chemical composition except for manganese.

3.3 Mehanička svojstva i mikrostrukture u zavisnosti od sadržaju bora i mangana

Zatezne karakteristike višeprolaznih varova na osnovu legirajućih elemenata prikazane su na Slici 10a. Dodatni materijal A koji sadrži bor i materijal C sa povećanim sadržajem mangana pokazali su visoke vrednosti za granicu tečenja i zateznu čvrstoću. Dodatni materijal B sa relativno niskim sadržajem bora i mangana pokazao je najnižu vrednost čvrstoće. Međutim, dodatni materijali A-C su zadovoljili oba zahtevana kriterijuma za klasu E81T1-K2C iz grupe AWS A5.29, i minimalnu granicu tečenja od 470 MPa i zateznu čvrstoću od 550-690 MPa.

Slika 10b prikazuje vrednosti Vickers-ove tvrdoće za zavarene spojeve kao minimalne i maksimalne vrednosti. Svi dodatni materijali za zavarivanje imaju tvrdoću manju od zahtevanih maksimalnih 350 HV10 i zadovoljavaju kriterijume prihvatljivosti. Vrednost tvrdoće dodatnog materijala za zavarivanje C sa visokim sadržajem mangana je za oko 20 HV10 veća od materijala A i B.

Kada se porede dodatni materijali B i C koji imaju isti hemijski sastav osim mangana, smatra se da je tvrdoća materijala C veća zbog efekta povećanja čvrstoće sa povećanjem sadržaja mangana.

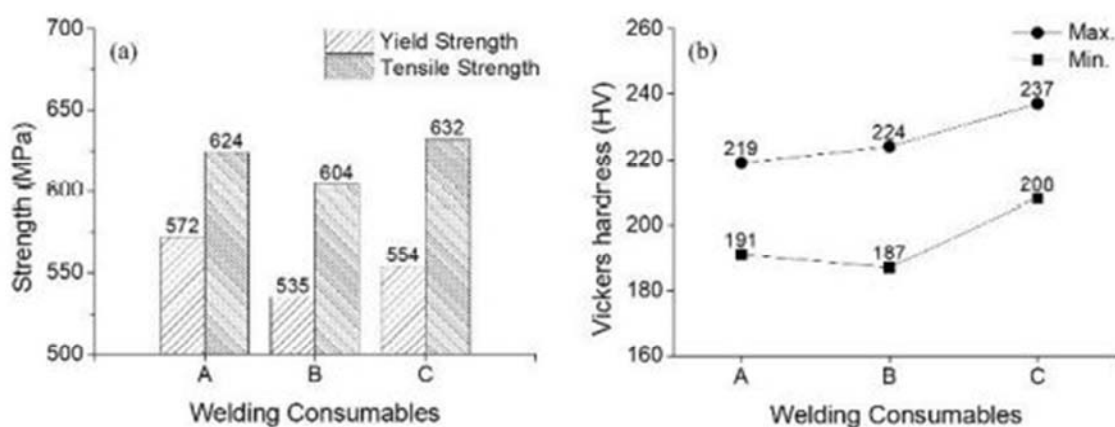


Figure 10. Mechanical properties for the welds produced by various welding consumables: (a) yield and tensile strengths and (b) Vickers hardness

Slika 10. Mehanička svojstva zavarenih spojeva koji su zavareni različitim dodatnim materijalima za: (a) granica tečenja i zatezna čvrstoća i (b) Vickers -ova tvrdoća

Fig. 11 shows the impact test results measured at -20 °C for each welding consumable. The impact test results of the face weld metal showed good impact value of 98 J or more in all the welding consumables, but the welding consumable B had a

Slika 11. prikazuje rezultate ispitivanja energije udara merenih na -20 °C za svaki dodatni materijal. Rezultati ispitivanja energije udara sa lica metala šava pokazali su dobru vrednost energije udara od 98 J ili više kod svih dodatnih materijala, ali je materijal B imao veliko odstupanje sa



large deviation with a minimum value of 85 J and a maximum value of 112 J.

In addition, the impact test results for the root weld metal showed the lowest value of average 22 J for welding consumable B compared to welding consumable A and C.

minimalnom vrednošću od 85 J i maksimalnom vrednošću od 112 J.

Osim toga, rezultati ispitivanja energije udara korena metala šava pokazali su najnižu vrednost od prosečno 22 J za dodatni materijal B u poređenju sa materijalom A i C.

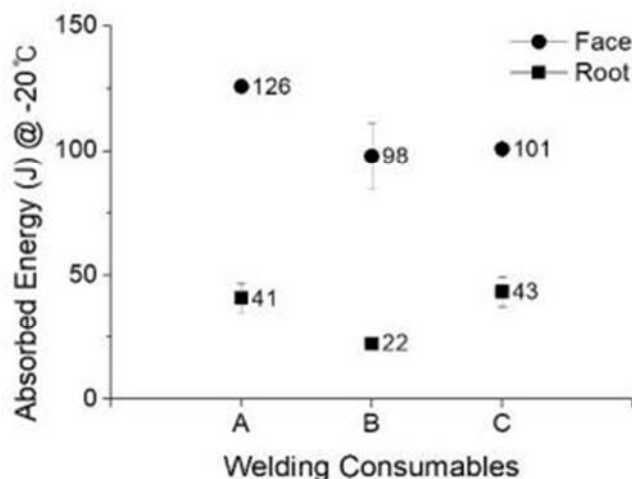


Figure 11. Impact toughness measured at -20 °C for various welding consumables

Slika 11. Energija udara merena pri -20 °C za različite dodatne materijale

Chemical compositions were analyzed to determine the causes of low toughness at low temperature on the root weld metal. The results are shown in Tab. 3.

The carbon content of the welding consumables was 0.04 wt.%, but the carbon content of the weld metal increased to 0.07-0.08 wt.% by dilution with the base metal. The boron content of the weld metal A was similar to that of the welding consumable A. The boron content of the weld metal B and C was higher than that of the welding consumables but the boron content was considerably lower than that of the weld metal A. The manganese content of the weld metals remained similar to the chemical composition of the welding consumables.

Hemijski sastavi su analizirani da bi se utvrdili uzroci niske žilavosti pri niskim temperaturama u korenu zavarenog spoja. Rezultati su prikazani u Tabeli 3.

Sadržaj ugljenika u dodatnom materijalu je bio 0,04 tež.% ali je sadržaj ugljenika povećan na 0,07-0,08 tež.% usled mešanja sa osnovnim metalom. Sadržaj bora u metalu šava koji je zavaren dodatnim materijalom A bio je sličan sadržaju samog dodatnog materijala A. Sadržaj bora u metalu šava B i C bio je veći od sadržaja u dodatnom materijalu, ali je sadržaj bora bio znatno niži nego u metalu šava kod A. Sadržaj mangana u metalima šavova je ostao sličan hemijskom sastavu dodatnih materijala.

Table 3. Chemical composition of root weld metal (wt.%)

Tabela 3. Hemijski sastav korena metala šava (tež.%)

ID	C	Si	Mn	P	S	Ti	B
A, ppm	0,07	0,40	1,03	0,013	0,006	0,06	46
B, ppm	0,08	0,45	1,07	0,013	0,006	0,06	8
C, ppm	0,08	0,44	1,44	0,013	0,006	0,06	10

Fig. 12 is a representative microstructure analyzed by optical microscope (OM) on the root weld metal. Welding consumable A and C were

Slika 12. je tipična mikrostruktura analizirana optičkim mikroskopom (OM) korena šava. Dodatni materijali A i C su se uglavnom sastojali od mainly



composed of acicular ferrite (AF) and grain boundary ferrite (GBF). However, in the welding consumable B, not only AF and GBF but also ferrite side plates (FSP) were observed.

igličastog ferita (AF) i ferita na granici zrna (GBF). Međutim, u dodatnom materijalu B, nisu primećene samo AF i GBF već i feritne lamele (FSP).

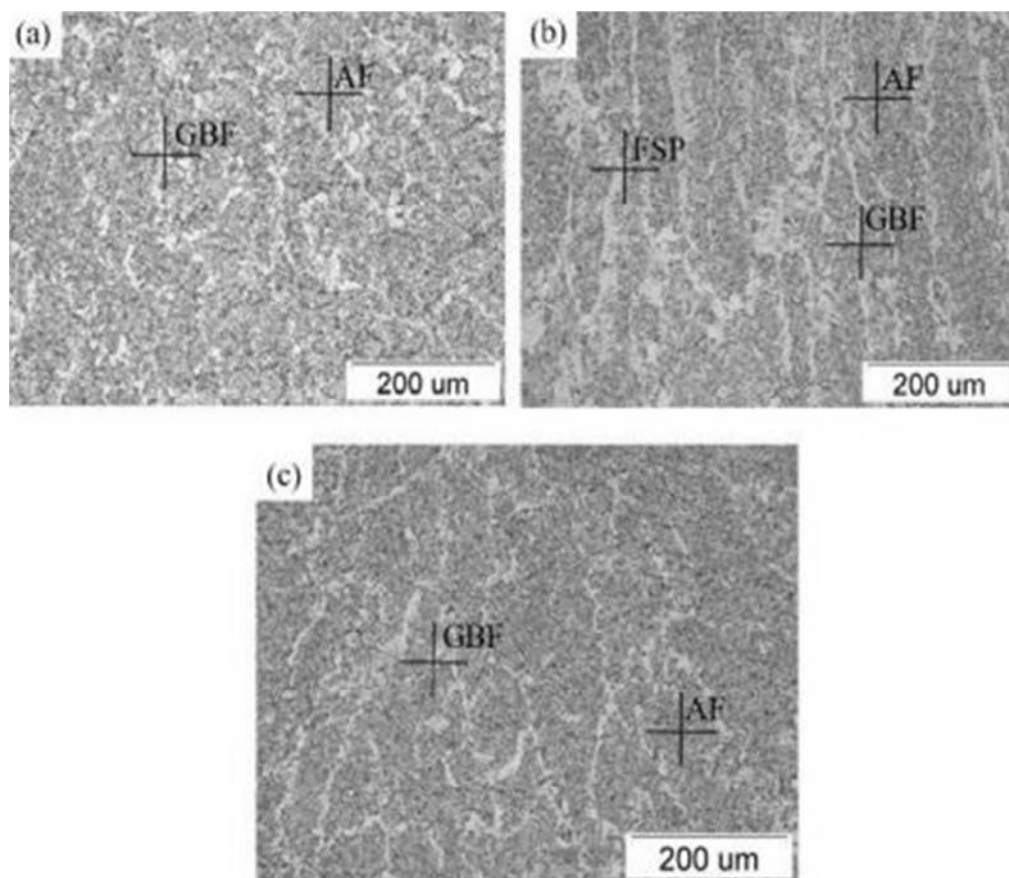


Figure 12. Microstructure for root weld metal produced from various welding consumables: (a) ID-A, (b) ID-B, (c) ID-C (GBF : Grain Boundary Ferrite, AF : Acicular Ferrite, FSP : Ferrite Side Plate)

Slika 12. Mikrostruktura korena metala šava formirana različitim materijalima za zavarivanje: (a) ID-A, (b) ID-B, (c) ID-C (GBF: Ferit na granici zrna, AF: Igličasti ferit, FSP: lamelarni ferit)

Fig. 13 is a representative microstructure analyzed by OM and SEM on the face weld metal. The face weld metal is a microstructure for the final weld bead that is not affected by reheating from the subsequent weld pass relative to the microstructure of the root weld metal.

Welding consumable B was relatively large in size of FSP and produced a large amount of FSP. The results of impact test at the low temperature for the face weld metal can be explained by more AF and few GBF and FSP on the microstructure of welding consumable A than the welding consumable C. In addition, the SEM image of high magnification for the face weld metal as shown in Fig. 13d-13f can easily distinguish that the size of the GBF for the welding consumable B is larger than that of the welding consumable A and C.

Slika 13. je tipična mikrostruktura analizirana OM-om i SEM-om na licu metala šava. Metal lica šava je mikrostruktura za završni prolaz na koji ne utiče ponovno zagrevanje u odnosu na mikrostrukturu korenog dela metala šava.

Dodatni materijal B je imalo veliku količinu lamelarnog ferita i relativno krupne lamele ferita. Rezultati ispitivanja energije udara na niskoj temperaturi metala lica šava mogu se objasniti sa većom količinom igličastog ferita, nešto ferita na granici zrna i lamelarnog ferita u mikrostrukturi dodatnog materijala A nego kod dodatnog materijala C. Osim toga, sa SEM slika pri velikom uvećanja lica metala šava, kao što je prikazano na slikama 13d-13f, lako se može uočiti da je veličina GBF-a kod dodatnog materijala B veća nego kod dodatnih materijala A i C.

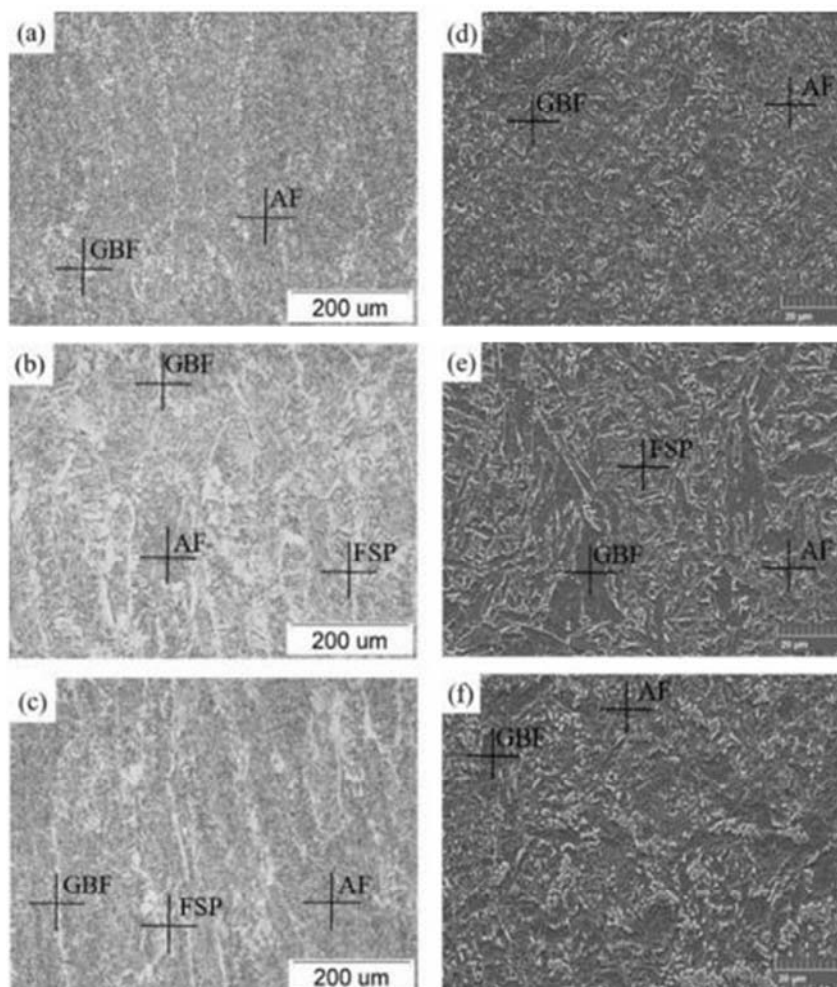


Figure 13. Microstructure for face weld metal produced from various welding consumables: (a) OM image for ID-A, (b) OM image for ID-B, (c) OM image for ID-C, (d) SEM image for ID-A, (e) SEM image for ID-B and (f) SEM image for ID-C

Slika 13. Mikrostruktura lica metala šava formirana različitim dodatnim materijalima: (a) OM slika za ID-A, (b) OM slika za ID-B, (c) OM slika za ID-C, (d) SEM slika za ID-A, (e) SEM slika za ID-B i (f) SEM slika za ID-C

Therefore, the welding consumable B having a reduced boron content in order to reduce the hot cracking has unstable impact toughness in the face weld metal and has low impact toughness in the root weld metal. This problem can be solved by the increase of manganese content because it accelerates AF formation and inhibits FSP formation, and supplement impact toughness of welding consumable C [6].

4. Conclusions

In order to investigate the effect of boron and manganese on the hot crack resistance and low temperature impact toughness of FCA weld metal for high strength carbon steel, the self-restraint test after single pass welding and mechanical properties and microstructure after multi-layer welding were analyzed and the following conclusions were obtained.

Stoga, dodatni materijal B u kojem je smanjen sadržaj bora radi umanjavanja toplih prslina ima nestabilnu udarnu žilavost na licu metala šava i ima nisku udarnu žilavost u korenu šava. Ovaj problem se može rešiti povećanjem sadržaja mangana jer to ubrzava stvaranje igličastog ferita i inhibira stvaranje lamelnog ferita i povećava udarnu žilavost dodatnog materijala C [6].

4. Zaključci

U cilju ispitivanja uticaja bora i mangana na otpornost na stvaranje toplih prslina i niskotemperaturnu udarnu žilavost elektrodočno zavarenih spojeva ugljeničnih čelika visoke čvrstoće sa punjenim elektrodnom žicama (FCA), vršeni su jednoprolazni testovi zavarljivosti, a mehaničke osobine i mikrostrukture nakon više prolaznih zavarivanja su analizirane i dobijeni su sledeći zaključci.



In the self-restraint test, FCA weld metal by welding consumable B and C with reduced boron content did not undergo hot cracking under low current (220 A) and low speed (17.0 CPM) welding conditions. However, hot cracking occurred at high current (280 A) and high speed (24.8 CPM) welding conditions even when boron-reduced welding consumables were used, and the length and number of hot cracks decreased compared to welding consumable A with high boron content.

The hot cracking propagated along the grain boundaries of the weld centerline where the liquid phase finally existed during solidification.

According to SIMS analysis, the boron concentration around the hot crack was confirmed. It was found through TEM analysis that boron was bound to iron and carbon in the process of cooling at high temperature and existed as a precipitate of $Fe_{23}(C,B)_6$ in grain boundaries at room temperature.

Welding consumable B with reduced boron content was increased in nonuniformity according to low temperature impact value due to FSP growth. Welding consumable C with increased manganese content was able to secure low temperature toughness by suppressing FSP formation.

The high strength carbon steel welds of 550 MPa-grade tensile strength prevent hot cracking through minimization of boron content and secured low temperature toughness by increase of manganese content at the same time.

References / Literatura

[1] S. Kou, *Welding Metallurgy*, 2nd ed., pp. 279-280, John Wiley & Sons, New Jersey (2003).

[2] H. U. Hong, I. S. Kim, B. G. Choi, Y. S. Yoo and C. Y. Jo, *Met. Mater. Trans.* 43, 173 (2012).

[3] H. Tamehiro, M. Murata, R. Habu and M. Nagumo, *Trans. ISIJ* 27, 128 (1987)

Kod testova zavarljivosti, u metalu šava koji je dobijen dodatnim materijalima B i C koji su imali smanjeni sadržaj bora, nisu otkrivene tople prsline pri niskim strujama (220 A) i niskim brzinama zavarivanja (17,0 CPM). Međutim, došlo je do pojave toplih prsline pri visokim strujama (280 A) i velikim brzinama zavarivanja (24,8 CPM), čak i kada su korišćeni dodatni materijali za zavarivanje sa smanjenom količinom bora. Dužina i broj toplih prsline je manji nego kada se koristio dodatni materijal A sa visokim sadržajem bora.

Tople prsline su se širile duž granica zrna centralne linije spoja gde tečna faza poslednja očvrćava.

Prema SIMS analizi, potvrđena je koncentracija bora oko toplih prsline. TEM analizom je utvrđeno da se bor vezao za železo i ugljenik tokom procesa hlađenja sa visokih temperatura i na sobnoj temperaturi se izdvojio kao talog $Fe_{23}(C,B)_6$ na granicama zrna.

Usled rasta lamelnog ferita i na osnovu niskotemperaturne udarne žilavosti, dodatni materijal B sa smanjenim sadržajem bora, ima uvećanu neujednačenost osobina. Dodatni materijal C sa povećanim sadržajem mangana je obezbedio niskotemperaturnu žilavost suzbijanjem stvaranja lamelnog ferita.

Kod zavarenih spojeva od ugljeničnog čelika visoke zatezne čvrstoće od 550 MPa, sprečavanje pojave toplih prsline postiže se minimiziranjem sadržaja bora, a u isto vreme obezbeđuje se niskotemperaturna žilavost povećanjem sadržaja mangana.

[4] Y. S. Choi, S.J. Kim, I. M. Park, K. W. Kwon and I. S. Yoo, *Met. Mater.* 3, 121 (1997).

[5] D. J. Mun, E. J. Shin, Y. W. Choi, J. S. Lee and Y. M. Koo, *Mater. Sci. Eng. A* 545, 224 (2012).

[6] Z. Zhang and R. A. Farrar, *Weld. J.* 77, 195-s (1997).