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PREVENT CRACKING IN DEPOSITION OF CARBON STEEL ON INCONEL 625

SPREČAVANJE NASTANKA PRSLINA PRI NANOŠENJU UGLJENIČNOG ČELIKA NA INCONEL 625

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Ključne reči: *Granica zrna tipa II, martenzit, naprezanje na granici stapanja, pritisni naponi, razblaživanje, rafinacija zrna, migracija ugljenika, PWHT*

Key words: *Type II grain boundary, Martensite, Stress at fusion boundary, Compressive stresses, Dilution, Grain refining, Carbon migration, PWHT*

Abstract
Welding procedure of clad steel including deposition of carbon steel on nickel base alloy usually gives unaccepted mechanical properties. Cracks were formed along type II boundary in nickel base alloy pass and a martensitic layer was formed in carbon steel pass. In this paper, cracks along type II boundary were prevented by lowering the martensitic start temperature (T_{Ms}) of the martensitic layer. Decreasing of T_{Ms} was obtained by two methods: *Dilution method* and *Grain refining method*. Three levels of T_{Ms} (approximately 350, 200, and 50°C) are obtained. The results showed that: cracks along type II boundary were prevented at T_{Ms} lower than 200°C; however type II boundary itself was prevented at T_{Ms} lower than 50°C. Also post weld heat treatment was necessary to achieve accepted impact properties.

Rezime
Tehnologija zavarivanja platiranog čelika, uključujući nanošenje ugljeničnog čelika na leguru nikla, obično daje neprihvatljiva mehanička svojstva. Prsline su formirane duž granice tipa II u prolazu od legure nikla i formiran je martenzitni sloj u prolazu od ugljeničnog čelika. U ovom radu, prsline duž granice tipa II su sprečene smanjenjem martenzit start temperature (T_{Ms}) martenzitnog sloja. Smanjenje T_{Ms} je postignuto na dva načina: metodom razblaživanja i metodom rafinacije zrna. Dobijena su tri nivoa T_{Ms} (približno 350, 200 i 50°C). Rezultati su pokazali da su: prsline duž granice tipa II bile sprečene kod T_{Ms} nižih od 200°C; međutim, sama granica tipa II bila je sprečena kod TM niže od 50°C. Takođe je bila potrebna toplotna obrada nakon zavarivanja da bi se postigle prihvatljive karakteristike udarnih osobina.

1. Introduction

Welding of carbon steel pipes (X65) cladded by nickel base alloy (Inconel 625) are usually being welded by AWS A5.14- ERNiCrMo3 filler metal. A trial was attempted to weld first and second passes by AWS A5.14- ERNiCrMo3 and subsequent passes by AWS A5.1 E7018. Unaccepted mechanical properties were resulted due to creation of cracks along type II boundary and formation of martensitic layer in carbon steel deposit [1]. In the present paper an unconventional idea was developed to prevent cracking along type II boundary. This idea is illustrated schematically in Fig1, where martensite which formed in carbon steel pass (3rd pass) was induced compressive

1. Uvod

Zavarivanje cevi od ugljeničnog čelika (X 65) pLatirane legurom na bazi nikla (Inconel 625) obično se zavaruju dodatnim materijalom prema AWS A5.14- ERNiCrMo3. Pokušano je da se koristi za prvi i drugi prolaz AWS A5.14-ERNiCrMo3 a naredni prolazi sa AWS A5.1 - E7018. Neprihvatljiva mehanička svojstva nastala su zbog stvaranja prslina duž granice tipa II i formiranja martenzitnog sloja u nanetom sloju ugljeničnog čelika [1]. U ovom radu je razvijena nekonvencionalna ideja za sprečavanje prslina duž granice tipa II. Ova ideja je šematski ilustrovana na slici 1, gde je martenzit koji je nastao u prolazu ugljeničnog čelika (treći prolaz) izazvan pritisnim stresses on 2^{nd} inconel pass; hence cracks were prevented. It must be mentioned that the idea of promoting martensitic formation in welds was considered a departure from conventional thinking [2]. But in the present work martensite would be beneficial if lower martensite start temperature was achieved. Lowering martensite start temperature (T_{Ms}) means that more compressive stresses were induced at surrounding passes i.e. transformation induced compressive stresses generation [2-4]. T_{Ms} can be controlled by chemical composition and by grain size [5-7].

Two methods were used to reduce T_{Ms} of the 3rd pass. The first one was described as "Dilution Method". In this method, dilution level was increased by increasing the welding current. This means that more alloying elements (mainly Ni and Cr) would transfer from the 2nd pass (Inconel) to the 3rd pass (carbon steel). These alloying elements will increase the hardenability and decrease T_{Ms}. The second method was described as "Grain Refining Method". In this method T_{Ms} decreased by decreasing grain size of the 3rd pass. The composition of the 3rd pass was similar to martensitic stainless steel [1]. Thus, tempering is necessary to provide the required notch toughness [8]. The post weld heat treatment (PWHT) was applied for welds free cracks.

naprezanjima na drugom prolazu od inkonela; stoga su sprečene prsline. Mora se napomenuti da je ideja promovisanja stvaranja martenzita u zavarenim spojevima, smatrana odstupanjem od konvencionalnog razmišljanja [2]. Ali u sadašnjem radu, martenzit bi bio koristan ako bi se postigla niža martenzit start temperatura. Spuštanje matrenzit start temperature martenzita (T_{Ms}) znači da su u okolnim prolazima izazvana veća pritisna naprezanja, tj. stvaranje pritisnih naprezanja izazvanih transformacijom [2-4]. T_{Ms} se mogu kontrolisati hemijskim sastavom i veličinom zrna [5-7].

Dve metode su korišćene za smanjenje T_{Ms} trećeg prolaza. Prva je opisana kao "Metoda razblaživanja". U ovoj metodi, nivo razređenja je povećan povećanjem struje zavarivanja. To znači da bi više legirajućih elemenata (uglavnom Ni i Cr) prelazilo iz 2.og prolaza (Inconel) u 3. prolaz (ugljenični čelik). Ovi legirajući elementi će povećati tvrdoću i smanjenje T_{Ms}. Druga metoda je opisana kao "Metoda rafinacije zrna". U ovoj metodi T_{Ms} je smanjen smanjenjem veličine zrna 3-eg prolaza. Sastav 3.eg prolaza je bio sličan martenzitnom nerđajućem čeliku [1]. Prema tome, otpuštanje je neophodno da bi se obezbedila zahtevana udarna žilavost [8]. Toplotna obrada nakon zavarivanja (PWHT) primenjena je kod šavova bez prslina.

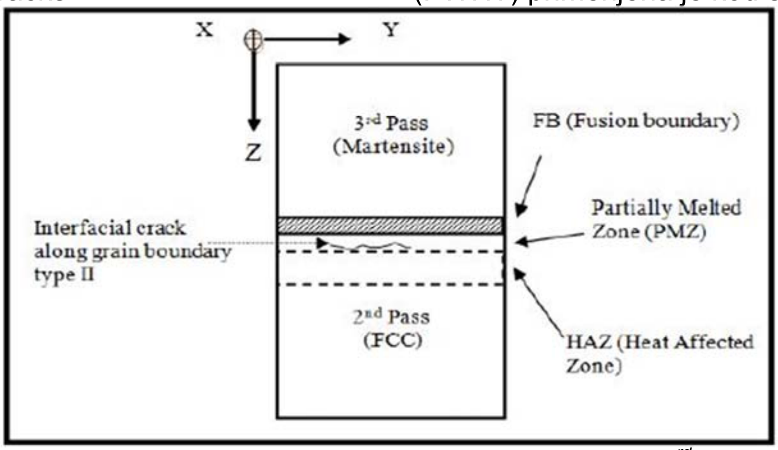

Fig 1. *Schematic diagram illustrated the idea of using martensite which formed in 3rd pass to prevent crack along type II boundary in 2nd pass: "X" longitudinal, "Y" transverse and "Z" through thickness*

Slika 1. *Šematski dijagram ilustruje ideju upotrebe martenzita koji je nastao u 3. prolazu da bi se sprečila prslina duž granice tipa II u drugom prolazu: "X" podužno, "I" poprečno i "Z" kroz debljinu*

2. Experimental procedure

2.1. Welding and Material

Base metal was API 5L Grade X-65 pipe steel with 305 mm diameter, 21.4 mm thickness and cladded with 2 mm thickness of inconel 625. Filler metals used in this study were AWS A5.14 ERNiCrMo3 and AWS A5.1E7018. The test coupon pipes were fabricated with full penetration single groove butt joint with 60 degrees included angles. Welding was done using flat position "1G". As shown in Table1, gas tungsten arc welding (GTAW) process with

2. Eksperiment

2.1. Zavarivanje i materijal

Osnovni materijal je cev od API 5L X-65 čelika prečnika 305 mm, debljine 21,4 mm i platirana slojem debljine 2 mm od inkonela 625. Koriščeni dodatni materijali u ovom istraživanju bili su AWS A5.14 - ERNiCrMo3 i AWS A5.1 - E7018. Ispitne cevi su proizvedene sučeonim spojem sa potpunim uvarivanjem, jednostranim žljebovima sa uglovima od 60 stepeni. Zavarivanje je obavljeno u položaju "1G". Kao što je prikazano u Tabeli 1, korišćen je

pure argon shielding gas was used to weld first and second passes using AWS A5.14- ERNiCrMo3 filler metal. The heat inputs of the 1st and 2nd passes were lowered as possible (about 0.9KJ/mm) to minimize dilution.
Table 1 shows that: two methods were used to weld the 3rd pass. The first one was described as "*Dilution Method*". In this method; the 3rd pass was welded by shielded metal arc welding (SMAW) process using AWS A5.1 E7018. Three levels of dilution were achieved by using three cases of heat input (about1.2, 1.4 and 2.0 KJ/mm). The second method was described as "*Grain Refining Method*". In this method, the 3rd pass was welded by flux cored arc welding (FCAW) process using E70T-4. The subsequent passes of the two methods were welded by SMAW using AWS A5.1 E7018. The welding variables were listed and illustrated in Table1.

TIG postupak zavarivanja (GTAW) sa čistim argonom kao zaštitnim gasom za zavarivanje prvog i drugog prolaza pomoću AWS A5.14-ERNiCrMo3. Unos toplote prvog i drugog prolaza je smanjen što je više moguće (oko 0.9KJ / mm) da bi se smanjilo razblaživanje.
Tabela 1 pokazuje da su dve metode korišćene za zavarivanje 3. prolaza. Prva je opisana kao "Metoda razblaživanja". U ovoj metodi; treći prolaz je izveden ručnim elektrolučnim postupkom zavarivanja (SMAW) pomoću AWS A5.1 - E7018. Tri nivoa razređenja postignuta su korišćenjem tri slučaja unosa toplote (oko 1,2, 1,4 i 2,0 KJ / mm). Druga metoda je opisana kao "Metoda rafinacije zrna". U ovoj metodi, treći prolaz je zavaren postupkom zavarivanja punjenim žicama (FCAW) korištenjem E70T-4. Sledeći prolazi dve metode su zavareni SMAW postupkom pomoću AWS A5.1- E7018. Promenljive zavarivanja su navedene i ilustrovane u Tabeli 1.

Welding Process	Electrode		Pass	Travel Speed (mm/sec)	Current (amp)	Voltage (V)	Heat Input (KJ/mm) ± 25%	Others
	Type	Diameter (mm)						
GTAW	AWS A5.14-ERNiCrMo3	2	1st	0.8	110	9	0.92	(1)
			2nd	1.2	150	10	0.93	
Dilution Method								
Case I								
SMAW	AWS A5.1 E7018	2.4	3rd	1.4	95	22.5	1.2	(2)
			Filling	1.4	95	22.5	1.2	
			Cap	1.4	95	22.5	1.2	
Case II								
SMAW	AWS A5.1 E7018	2.4	3rd	1.4	110	22.5	1.4	(2)
			Filling	1.4	110	22.5	1.4	
			Cap	1.4	110	22.5	1.4	
Case III								
SMAW	AWS A5.1 E7018	2.4	3rd	1.4	150	24	2	(2)
			Filling	1.4	150	24	2	
			Cap	1.4	150	24	2	
Grain Refining Method								
FCAW-S	E70T-4	1.6	3rd	4.7	280	27	1.3	(3)
SMAW	AWS A5.1 E7018	2.4	Filling	1.4	95	22.5	1.2	(2)
			Cap	1.4	95	22.5	1.2	

Table1. *Welding variables*

(1) Inter pass temperature was about (115±5)°C

(2) Inter pass temperature was about (200°C±5)

(3) Feed rate = 87mm/s & Tip to work distance = 20 mm

Tabela 1. *Promenljive zavarivanja*

(1) Međuslojna temperatura je oko (115±5)°C

(2) Međuslojna temperatura je oko (200°C±5)

(3) Brzina dodavanja = 87mm/s i rastojanje vrh-radni komad = 20 mm

2.2. Post Weld Heat Treatment

Tempering was proceeded at 720°C and 3 hours holding time. Tempering was applied only for crack free welds.

2.3. Microstructural Characterization

Specimens were cut and prepared for mechanical tests in accordance with ASME-Section IX, where tensile, impact and bend test are required. The specimens for impact test were prepared from cap and root (including the 3rd pass). Microstructural characterization was performed using optical metallography and scanning electron microscope. Because of the wide range of compositions and microstructures, a number of chemical etchants were used. Nital (2 mL HNO_3 and 98 mL ethanol) was used to reveal martensitic structure; Vilella's reagent (5 mL HCl, 1 gram picric acid, and 100 mL ethanol) was used to reveal grains of martensite. Mixed acids (equal parts of HCL, HNO3, and acetic acids) were used to reveal grain boundaries of nickel base alloy. Microhardness across transition region was measured using diamond pyramid indenter in conjunction with both 10 and 100 gram loads.

2.4. Determination of Martensite Start Temperature (T_{Ms}) for the 3rd Pass

In this investigation, T_{Ms} was calculated using empirical equations. For dilution method, Gooch equation (Eq.1) [9] was used. This equation is usually used for martensitic stainless. However, for grain refining method; Lee equation (Eq. 2) [10] was used. This equation considers the effects of chemical composition and austenite grain size on martensite start temperature.

2.2. Termička obrada posle zavarivanja

Otpuštanje je obavljeno na 720°C i 3 sata zadržavanja. Otpuštanje je primenjeno samo za zavarene spojeve.

2.3. Mikrostrukturna karakterizacija

Uzorci su isečeni i pripremljeni za mehanička ispitivanja u skladu sa ASME-Deo IX, gde su potrebni zatezni, udarni i savojni testovi. Uzorci za udarnu žilavost pripremljeni su iz vrha/pokrivni zavar) i korena (uključujući i treći prolaz). Mikrostrukturna karakterizacija je izvedena optičkom mikroskopijom i skenirajućim elektronskim mikroskopom. Zbog širokog spektra sastava i mikrostruktura, korišćen je veliki broj sredstava za nagrizanje. Nital (2 mL HNO3 i 98 mL etanol) je korišćen za otkrivanje martenzitne strukture; Vilela reagens (5 mL HCl, 1 gram pikrinske kiseline i 100 mL etanola) korišćen je za otkrivanje zrna martenzita. Mešane kiseline (jednaki delovi HCl, HNO_3 i sirćetne kiseline) su korišćene za otkrivanje granica zrna legure na bazi nikla. Mikrotvrdoća duž prelaznog područja je merena korišćenjem dijamantske piramide u kombinaciji sa opterećenjem od 10 i 100 grama.

2.4. Određivanje martenzit start temperature (T_{Ms}) trećeg prolaza

U ovom istraživanju, T_{MS} je izračunat pomoću empirijskih jednačina. Za metodu razređivanja korištena je Gooch-ova jednačina (Jedn.1) [9]. Ova jednačina se obično koristi za martenzitne nerđajuće čelike. Međutim, za metodu rafinacije zrna; korišćena je Li –ova jednačina (jednačina 2) [10]. Ova jednačina uzima u obzir efekte hemijskog sastava i veličine zrna austenita na martenzit start temperaturu.

$$Ms\ (°C) = 540 - (497C\% + 6.3Mn\% + 36.3Ni\% + 10.8Cr\% + 46.6Mo\ \%) \quad \textbf{(Eq. 1)}$$

$$Ms\ (°C) = 402 - 797C + 14.4Mn + 15.3Si - 31.1Ni + 345.6Cr + 434.6Mo + (59.6C + 3.8Ni - 41Cr - 53.8Mo).G \quad \textbf{(Eq. 2)}$$

Where G is the ASTM austenite grain size and elements in weight fraction

Typical EDX detector was used to measure chemical composition of the 3rd pass. But this detector can detect a limited range of X-ray energies so light elements (Z<10) such as carbon, nitrogen cannot be measured accurately. To overcome this problem; in the present work; estimated complete chemical composition was determined using back calculation methodology as follows:

1. Major alloying elements such as Fe, Ni and Cr were determined by EDX analysis. Then dilution levels of major elements were calculated using Eq. 3 [6].

Tipični EDX detektor je korišćen za merenje hemijskog sastava 3. prolaza. Ali ovaj detektor može da otkrije ograničen opseg energije rendgenskih zraka tako da se laki elementi (Z <10), kao što je ugljenik, azot ne mogu precizno meriti. Kako bi se prevazišao ovaj problem; u ovom radu; procenjeni potpuni hemijski sastav je određen korišćenjem povratne metodologije izračunavanja kako sledi:

1. Glavni legirajući elementi kao što su Fe, Ni i Cr određeni su EDX analizom. Zatim su nivoi razređenja glavnih elemenata izračunati korišćenjem jed. 3 [6].

$$D = (C_w - C_f)/(C_b - C_f) \quad \textbf{(Eq. 3)}$$

Where D is the dilution, C w, C f and C b are the concentration of each element in weld metal, filler metal, and base metal respectively.

2. Average dilution level (Dav) of the major alloying elements was determined.

3. Eq.4 was used to calculate the concentrations of other alloying elements.

$$C_w = [(C_b - C_f) * D_{av}] + C_f \qquad \textbf{(Eq. 4)}$$

3. Results and discussion

3.1. Effect of T_{Ms} value on type II grain boundary conditions

It is accepted that grain boundary type II worked as a weak line which easy cracked [11, 12]. In the present work martensitic transformation which formed in 3rd pass was used to produce compressive stresses on 2nd pass, hence tensile stresses were reduced and cracks were prevented. Because of elastic modulus increase with decreasing of metal temperature; the amount of compressive stresses generated from martensitic transformation increased with decreasing of T_{Ms} [13, 14].

Because of quantitative measurements of stresses at type II grain boundary are hard to conduct, a qualitative method was used to give an indication about stress level. This technique was proceeded by observing any cracks near the fusion boundary i.e. observation of cracks means high tensile stresses. Thus an approach of the relation between T_{Ms} values of the 3rd pass and stresses level at fusion boundary was built. Depending on this methodology effective levels of T_{Ms} were approximately determined as the following:

a) Case I of Dilution Method: As shown in Table 1; heat input was about 1.2 KJ/mm which gave 6.5% average dilution. Mechanical properties are shown in Table 2, 3 and 4, where unaccepted results of side bend test and notch impact toughness are noted. Table5 shows that T_{Ms} for the fusion zone of the 3rd pass equaled to 354°C. Fig2 reveals the cracks along type II boundary. This means that at 354°C; the created compressive stresses were not sufficient to overcome the tensile stresses, hence crack was occurred.

b) Case II of Dilution Method: As shown in Table 1; heat input was about 1.4 KJ/mm which gave 13.5% average dilution. Mechanical properties are shown in Tables 2, 3 and 4. As shown in Table5, T_{Ms} for the fusion zone of the 3rd pass equaled to 197°C. Fig.3 shows type II grain boundary appeared without any interfacial cracks. This means that at 197°C, the created compressive stresses were sufficient to overcome the most of

gde je D razblaženje, C $_w$, C $_f$ i C $_b$ su koncentracije svakog elementa u metalu šava, dodatnom materijalu i osnovnom materijalu.

2. Određen je prosečan nivo razređivanja (Dav) glavnih legirajućih elemenata.

3. Jedn. 4 je korišćena za izračunavanje koncentracija drugih legirajućih elemenata.

Rezultati i diskusija

3.1. Uticaj vrednosti T_{Ms} na uslove granice zrna tipa II

Prihvaćeno je da je granica zrna tipa II radila kao slaba linija koja lako puca [11, 12]. U sadašnjem radu korišćena je martenzitna transformacija nastala u 3. prolazu da bi se proizvele pritisna naprezanja na 2. prolazu, pa su smanjeni zatezni naponi i sprečene su prsline. Zbog toga što se modul elastičnosti povećava sa smanjenjem temperature metala; količina pritisnih napona stvorena martenzitnom transformacijom, povećana je sa smanjenjem T_{Ms} [13, 14]

Zato što je kvantitativno merenje naprezanja na granici zrna tipa II teško sprovesti, upotrebljena je kvalitativna metoda da se dobije indikacija o nivou napona. Ova tehnika je nastavljena posmatranjem bilo kakvih prslina u blizini granice stapanja, tj. posmatranje prslina znači visoka zatezna naprezanja. Tako je izgrađen pristup odnosu između vrednosti T_{Ms} trećeg prolaza i nivoa naprezanja na granici stapanja. U zavisnosti od ove metodologije, efektivni nivoi T_{Ms} su približno određeni na sledeći način:

a) Slučaj I metode razređivanja: Kao što je prikazano u tabeli 1; unos toplote je bio oko 1,2 KJ / mm, što je dalo prosečno razređenje od 6,5%. Mehaničke osobine su prikazane u tabelama 2, 3 i 4, gde su zabeleženi neprihvactljivi rezultati ispitivanja bočnog savijanja i udarne žilavosti. Tabela 5 pokazuje da T_{Ms} za zonu stapanja trećeg prolaza iznosi 354oC. Slika 2 otkriva prsline duž granice tipa II. To znači da na 354°C; stvorena pritisna naprezanja nisu bila dovoljna za prevazilaženje naprezanja na istezanje, pa je došlo do pucanja**.**

b) Slučaj II metode razblaživanja: Kao što je prikazano u tabeli 1; unos toplote je bio oko 1.4 KJ / mm što je dalo 13.5% prosečnog razblaženja. Mehaničke osobine su prikazane u tabelama 2, 3 i 4. Kao što je prikazano u tabeli 5, T_{Ms} za zonu stapanja trećeg prolaza iznosio je 197°C. Na slici 3 prikazana je granica zrna tipa II bez ikakvih međupovršinskih prslina. To znači da su na 197°C stvorene pritisna naprezanja bila dovoljne za prevazilaženje većine zateznih naprezanja i tensile stresses and cracks were prevented. This observation 3. reflects the resulted accepted side bend test and improved notch toughness (Table 3, and 4 respectively).

sprečene su prsline. Ovo zapažanje odražava prihvaćeni test bočnog savijanja i poboljšanu udarnu žilavost (Tabela 3 i 4).

Method		Ultimate Tensile Stress (N/mm^2) Zatezna čvrstoća	Failure Location Mesto preloma	Comment Komentar
Dilution Razređenje	Case I	641	W.M/ metal šava	Acceptable
		669	W.M	Acceptable/ prihvatljivo
	Case II	645.33	W.M	Acceptable
		656.6	W.M	Acceptable
	Case III	649.74	W.M	Acceptable
		669.34	W.M	Acceptable
Grain Refining Rafinacija zrna		668.36	W.M	Acceptable
		664.44	W.M	Acceptable

Table 2. *Tensile test results in as weld conditions*
Tabela 2. *Rezultati ispitivanja zatezanjem u uslovima zavarivanja*

Specimen No. Epruveta br.	Dilution Method Metoda razređivanja			Grain Refining Method Metoda rafinacije zrna
	Case I Slučaj I	Case II	Case III	
1	Rejected Odbačen	Accepted Prihvaćen	Rejected	Accepted
2	Rejected	Accepted	Rejected	Accepted
3	Rejected	Accepted	Rejected	Accepted
4	Rejected	Accepted	Rejected	Accepted

Table 3. *Guided side bend test results in as weld conditions*
Tabela 2. *Rezultati ispitivanja bočnog savijanja u uslovima zavavanja*

Position	WM			FL			FL+2			FL+5		
	1	2	3	1	2	3	1	2	3	1	2	3
Dilution Method												
Case I												
Cap	69	60	94	110	50	65	140	115	125	118	117	106
Root	10	12	10	95	110	85	140	145	150	165	160	155
Case II												
Cap	64	55	89	105	45	60	135	110	120	113	112	101
Root	19	23	23	91	106	81	136	141	146	161	156	151
Case III												
Cap	52	43	77	93	33	48	123	98	108	101	100	89
Root	2	11	13	78	93	68	123	128	133	148	143	138
Grain Refining Method												
Cap	100	53	86	130	105	109	105	97	96	70	79	103
Root	23	26	22	92	90	76	127	143	141	150	148	144

Table 4. *Notch impact toughness results (Joule) at 0^{0}C for as welded conditions*
Tabela 4. *Rezultati ispitivanja udarne žilavosti (Džul) na 0^{0}C u uslovima zavarivanja*

**WM: weld metal/ metal šava* ** FL: Fusion Line Linija stapanja* **FL+2: Fusion Line+2mm *FL+5: Fusion Line +5mm Linija stapanja*

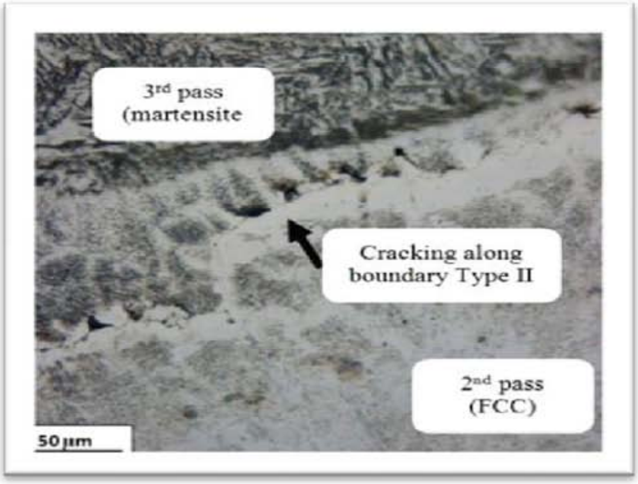

Fig.2 Case I of dilution method: Interfacial cracks are running along grain boundary type II.
Sl.2. Slučaj I metode razređenja:međufazne prsline se prostiru duž granica zrna tipa II

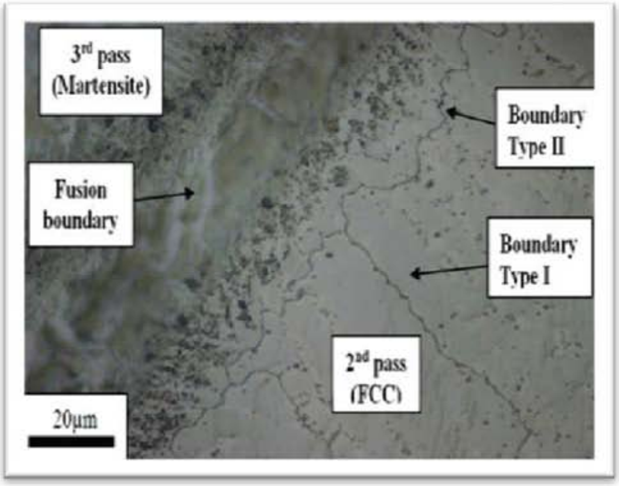

Fig. 3 Case II of dilution method: Grain boundary type II appeared without cracks
Sl. 3. Slučaj I metode razređenja: Granica zrna tipa libez prslina

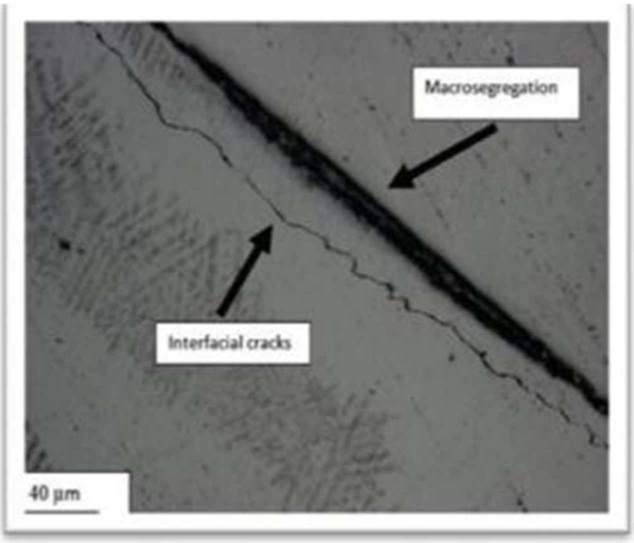

Fig. 4 Case III of dilution method: Parts from filler are forces inside the 2nd pass forming martensitic island inside with cracks
Sl.4. Slučaj III metode razređenja: Delovi dod. materijala su sile unutar 2.og prolaza koje stvaraju ostrva martenzita sa prslinama

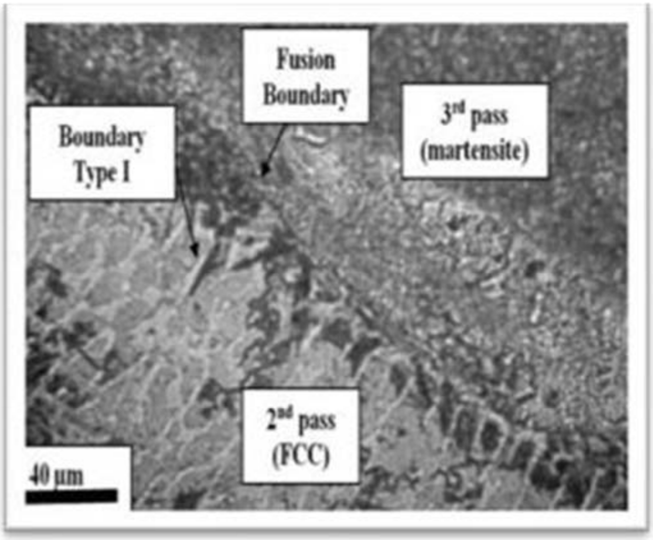

Fig.5 Case III of dilution method: Type II boundary disappeared and cellular structure continued until fusion boundary
Sl. 5. Slučaj III metode razređivanja: Tip II granica je nestala i ćelijska struktura nastavlja do granice stapanja

c) Case III of Dilution Method: As shown in Table 1; heat input was about 2 KJ/mm; giving 20.22% average dilution. This heat input is considered relatively high heat. Mechanical properties are shown in Table 2, 3 and 4, where unaccepted results of side bend and notch impact toughness tests are noted. Fig.4 reveals microstructure near fusion boundary where planar solidification region and type II grain boundary are not found i.e. cellular structure continued until fusion boundary. Depending on Nelson et al. work [15, 16], the tensile stress which worked as a driving force for type II boundary formation, was nil. Table 5 shows that T_{Ms} for fusion zone of the 3rd pass was 48 °C.

c) Slučaj III metode razblaživanja: Kao što je prikazano u tabeli 1; unos toplote je bio oko 2 KJ/mm; dajući 20.22% prosečnog razblaženja. Ovaj unos toplote se smatra relativno visokom toplotom. Mehaničke osobine su prikazane u tabelama 2, 3 i 4, gde su zabeleženi neprihvatljivi rezultati ispitivanja bočnog savijanja i udarne žilavosti. Slika 4 otkriva mikrostrukturu blizu granice stapanja, gde nije pronađena ravanska oblast očvršćavanja i granica zrna tipa II, tj. ćelijska struktura se nastavlja sve do granice stapanja. U zavisnosti od rada Nelsona i dr. [15, 16], zatezni napon koji je služio kao pogonska sila za formiranje granica tipa II, bio je nula. Tabela 5 pokazuje da su T_{Ms} za zonu

Based on these results, it can be concluded that: at T_{Ms} equal or lower than 48°C the generated compressive stresses at fusion boundary were sufficient to overcome all tensile stresses so type II boundary itself disappeared.

stapanja trećeg prolaza 48°C. Na osnovu ovih rezultata može se zaključiti da: kod T_{MS}-a jednakih ili nižih od 48°C stvorena pritisna naprezanja na granici stapanja su bila dovoljna da se prevladaju sva zatezna naprezanja pa je i sama granica tipa II nestala.

Element (%)	Base Metal X65	Filler Metals			Dilution Method				Grain Refined Method
		AWS A5.1 E7018	AWS A5.14-ERNiCrMo3	E70T-4	Case I	Case II	Case III		
							WM	Islands	
Ni	0.011	0.03	64.6	0.02	3.02	6.32	9.46	3.94	4.72
Cr	0.011	0.00	21.7	0.00	1.12	2.29	3.42	1.46	1.74
Fe	Bal	Bal	0.6	Bal	93.44	88.28	83.32	91.95	89.94
Mo	0.228	0.15	8.9	0.00	0.47	0.97	1.46	0.6	0.73
Nb	0.008	0.00	3.5	0.00	0.21	0.43	0.65	0.27	0.32
C	0.007	0.07	0.08	0.23	0.07	0.07	0.08	0.07	0.22
Mn	1.4	1.05	0.00	0.5	1.02	1.00	0.97	1.02	0.52
Si	0.22	0.55	0.1	0.28	0.55	0.54	0.54	0.55	0.30
P	0.01	0.016	0.00	0.011	0.02	0.02	0.02	0.02	0.03
S	0.005	0.01	0.00	0.003	0.01	0.01	0.01	0.01	0.01
Al	0.008	0.01	0.00	1.5	0.02	0.04	0.06	0.03	1.38
Ti	0.1	0.001	0.00	0.01	0.02	0.04	0.06	0.03	0.04
Co	0.00	0.00	1.00	0.00	0.05	0.11	0.16	0.07	0.08
T_{MS} °C					354	197	48	310	56

Table 5. *Chemical analyses of base metal, filler metal and estimated chemical analyses and T_{Ms} of the weld metal*
Tabela 5. *Hemijski sastav osnovnog i dodatnog materijala i procenjene hemijske analize i T_{Ms} metala šava*

However a plan view of 2nd pass is illustrated in Fig.5, where parts from filler metal are observed. Parts from filler metals were forced inside the 2nd inconel pass and solidified giving martensitic islands. Microhardness of these regions was ranged from 497 to 522 HV. These results are supported by SEM and EDX analyses in Fig.6 where iron percentage was about 92%. These islands were obtained as a result of using high welding current [17, 18]. As shown in Fig.7 cracked type II boundary is observed parallel to theses filler metal islands. Table5, T_{Ms} of martensitic islands within 2nd pass is 310°C. This means that: at 310°C compressive stresses were very low compared with tensile stresses so cracking occurred.

Although type II boundary near fusion boundary were prevented, formation of filler metal martensitic islands with cracks within 2nd inconel pass leaded to poor impact toughness and unaccepted side bend results. These results are given in Table3 and Table 4 respectively.

Međutim, planski pogled na 2. prolaz je ilustrovan na slici 5, gde se posmatraju delovi dodatnog materijala. Delovi dodatnog materijala bili su prisiljeni da uđu u prolaz 2. od inkonela i očvrsnu stvarajuí martenzitna ostrva. Mikrotvrdoća ovih regiona kretala se od 497 do 522 HV. Ovi rezultati su podržani SEM i EDX analizama na slici 6, gde je procenat železa bio oko 92%. Ova ostrva su dobijena korišćenjem visoke struje zavarivanja [17, 18]. Kao što je prikazano na slici 7, granica tipa II sa prslinama se posmatra paralelno sa ovim ostrvcima dodatnog materijala. Tabela 5, T_{Ms} na martenzitskim ostrvima unutar 2. prolaza je 310°C. To znači da su pri 310°C pritisna naprezanja bila vrlo niska u poređenju sa zateznim naprezanjima pa je došlo do pucanja.

Iako su granice tipa II u blizini granice stapanja bile sprečene, formiranje martenzitnih ostrva od dodatnog materijala sa prslinama u prolazu 2. od inconela dovelo je do loše udarne žilavosti i neprihvatljivih rezultata bočnog savijanja. Ovi rezultati su dati u Tabeli 3 i Tabeli 4.

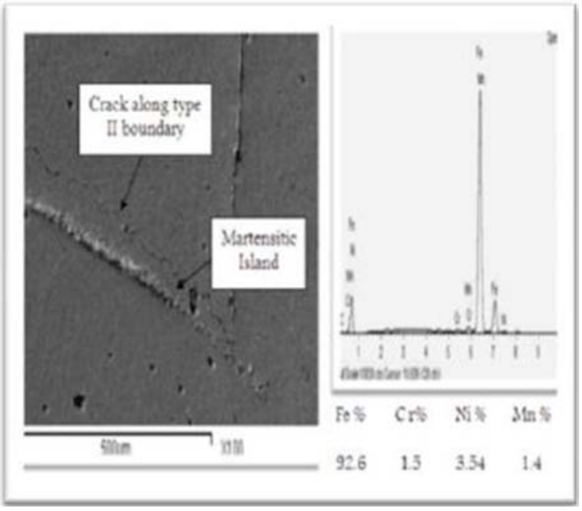

Fig.6 *Case III of dilution method - SEM and EDX for filler metal islands within the 2nd inconel pass*
Sl. 6. *Slučaj III metode razređenja- SEM i EDX za ostvca dodatnog materijala unutar 2. Prolaza od inkonela*

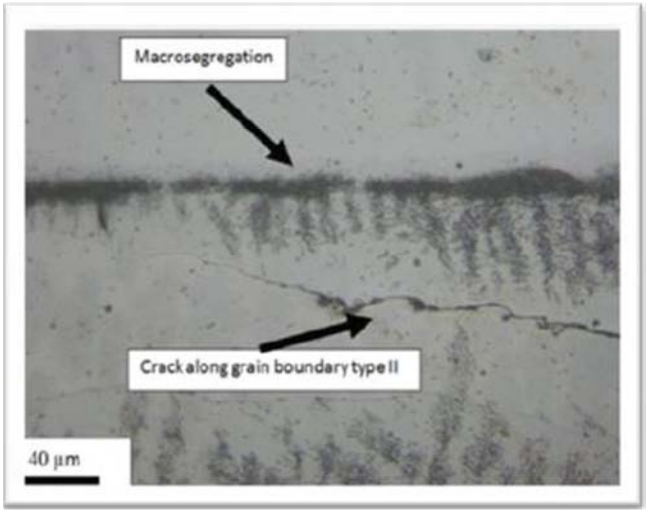

Fig.7 *Case III of dilution method-cracked type II boundary parallel to filler metal islands within the 2nd inconel pass*
Sl. 7. *Slučaj III metode razređenja- Tip II granice sa prslinama paralelna sa ostrvima dodatnog materijala unutar 2. prolaza od inkonela*

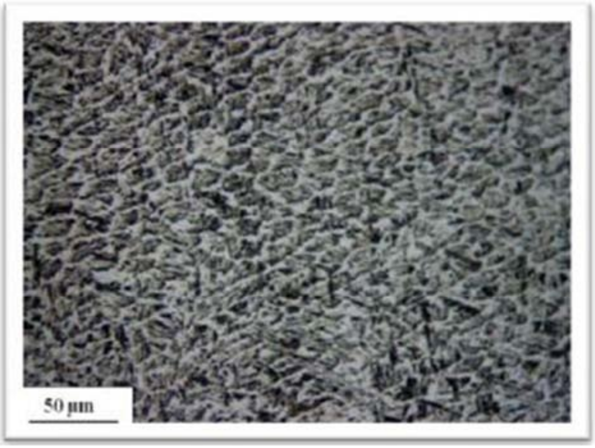

Fig.8 *Grain Refined Method - Prior austenite grains of 3rd pass; etched with Vilella's reagent*
Sl.8. *Metoda rafinacije zrna* **–** *prethodna austenitna zrna 3. eg prolaza; nagrizeno Vilela reagensom*

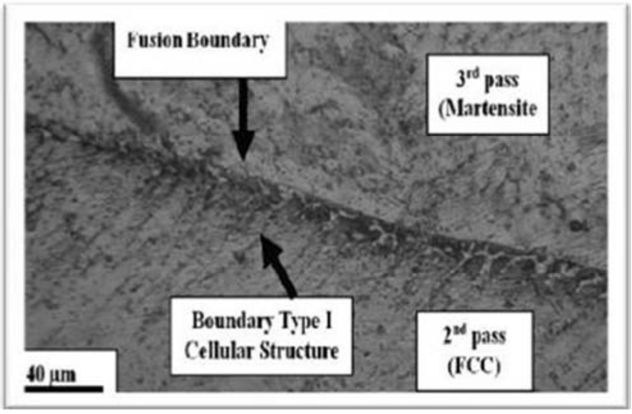

Fig.9 *Grain refining method: Type II boundary disappeared and cellular structure continued until fusion boundary*
Sl. 9. *Slučaj III metode razređenja- Granica tipa II je nestala i ćelijska struktura se nastavila do granice stapanja*

d) Grain Refining Method: The effect of austenitic grain size on T_{Ms} was studded by several researchers [19- 21]. One argument is that a refinement of the austenite grain size leads to the Hall–Petch strengthening of austenite, thereby making it difficult for martensite to form [22]. Grain refinement of the 3rd pass was achieved by using E70T-4 which acted as a source of aluminium oxide and aluminium nitride. Aluminium nitrides and aluminium oxides which may be considered as non-metallic inclusions and impair mechanical properties were used here as nucleation sites causing grain refining. Fig. 8 shows the prior austenite grains of the 3rd pass which is martensite. Grain size was measured using Method –ASTM E112 giving intercept ASTM grain size

d) Metoda rafinacije zrna: Uticaj veličine austenitnih zrna na T_{Ms} ispitivalo je nekoliko istraživača [19-21]. Jedan argument je da rafinacija veličine zrna austenita dovodi do Hall-Petchovog ojačavanja austenita, što otežava formiranje martenzita [22]. Rafinacija zrna trećeg prolaza postignuto je korišćenjem E70T-4 koji je služio kao izvor aluminijum oksida i aluminijum nitrida. Aluminijum-nitridi i aluminijum-oksidi koji se mogu smatrati nemetalnim uključcima i umanjuju mehanička svojstva su ovde korišćeni kao mesta nukleacije, što dovodi do rafinacije zrna. Slika 8 prikazuje prethodna austenitna zrna 3. prolaza koji je martenzit. Veličina zrna je merena korišćenjem metode presretanja - ASTM E112 koji govori da je ASTM broj zrna jednak 12.

Kao što je prikazano u tabeli 5, T_{Ms} trećeg prolaza je 56°C, koji je izračunat pomoću Lee-ove number equals to 12 .

As shown in Table5, T_{Ms} of the 3rd pass is 56°C, which was calculated using Lee equation. Fig. 9 shows that planer solidification region and type II grain boundary are disappeared where cellular structure is continued until fusion boundary. This means that: at 56oC compressive stresses created at fusion boundary were sufficient to overcome all tensile stresses so type II boundary itself disappeared. Preventing formation of type II boundary was reflected on mechanical properties of weld metal, where accepted side bend test results and improved notch toughness (23 Joule 0°C) are noted in Table3 and Table4 respectively.

3.2. Effect of Post Weld Heat Treatment

It well known that the accepted notch toughness of carbon steel at 0°C is 27 Joule [22]. However, in as welded conditions, unaccepted notch toughness at 0°C was resulted as shown in Table2. Thus in order to obtain accepted notch toughness, tempering was necessary. Tempering was proceeded at 720°C for 3hr holding time. Based on the results taken from as welded conditions, tempering was applied only for crack free cases (case II of dilution method and grain refining method). The results of mechanical properties are represented in Table 6.

Fig.10a and Fig.11a give a plan view for fusion boundary between 2nd and 3 rd pass for case II dilution and grain refined methods respectively. Tempered martensite was noted in the 3rd pass and dark etched region was found at the interface Fig.10b and Fig.11b where highly localized hardness peak was noted.

jednačine. Na slici 9 je vidljivo da ravanska oblast očvršćavanja i granica zrna tipa II nestaju tamo gde se ćelijska struktura nastavlja do granice stapanja. To znači da su pri 56°C, pritisna naprezanja stvorena na granici stapanja, bila dovoljna da se prevladaju sva zatezna naprezanja pa je i sama granica tipa II nestala. Sprečavanje formiranja granice tipa II odrazilo se na mehaničke osobine metala šava, gde su prihvatljivi rezultati ispitivanja bočnim savijanjem i poboljšana udarna žilavost (23 džula 0°C) navedeni u Tabeli 3 i Tabeli 4, respektivno.

3.2. Uticaj termičke obrade posle zavarivanja

Dobro je poznato da je prihvatljiva žilavost ugljeničnog čelika na 0°C od 27 J [22]. Međutim, u uslovima zavarivanja, dobijena je neprihvatljiva udarna žilavost na 0°C, kao što je prikazano u Tabeli 2. Tako je, da bi se dobila prihvatljiva žilavost, bilo potrebno otpuštanje. Otpuštanje je sprovedeno na 720°C tokom 3 sata. Na osnovu rezultata dobijenih iz zavarenih uslova, otpuštanje je primenjeno samo za slučajeve bez prslina (slučaj II metoda razblaživanja i metoda rafinacije zrna). Rezultati mehaničkih svojstava prikazani su u tabeli 6.

Slika 10a i Sl.11a daju prikaz granice stapanja između 2. i 3. prolaza za metode II razređivanja i metode rafinacije zrna. U trećem prolazu zabeležen je otpušteni martenzit, a na međupovršini sl.10b i sl.11b nađen je tamno nagrižen region gde je zabeležen lokalizovani visoki pik tvrdoće.

Method	*Ultimate Unit Stress Zatezna čvrstoća (N/mm2)*	*Side strana Bend Savijanje*	*Impact Toughness at Root (including interface between 2nd and 3rd Pass) (Joule at 0°C) Udarna žilavost u korenu (uključujući međupovršinu između 2, i 3, sloja) (Džul na 0°C)*
As welded condition Uslovi zavarivanja			
Increased Dilution Povećano ratređenje	*654*	*Accepted Prihvatljivo*	*22*
Grain Refining Rafinacija zrna	*680*	*Accepted Prihvatljivo*	*23*
As tempered condition Uslovi otpuštanja			
Increased Dilution Povećano ratređenje	*649*	*Accepted Prihvatljivo*	*43*
Grain Refining Rafinacija zrna	*663*	*Accepted Prihvatljivo*	*30*

Table 6. *Average results of mechanical properties for increased dilution case II and grain refined methods in as weld and tempered conditions*

Tabela 6. *Srednje vrednosti mehaničkih osobina kod slučaja II povećanog razređivanja i metode rafinisanog zrna u uslovima zavarivanja i otpuštanja*

As documented in literatures **[23-26]**, this dark layer was enriched carbide layer which formed due to carbon migration from ferrite side to austenite side. This layer was clearly observed in grain refining method than dilution method due to difference of carbon content (0.22% and 0.07% respectively). The effect of this layer on notch toughness is also noted in **Table 6**. For case II of dilution method; notch toughness increased from 22 to 43Joule (as welded and tempered condition respectively). However for grain refining method notch toughness increased only from 23 to 30Joule (as welded and tempered condition respectively).

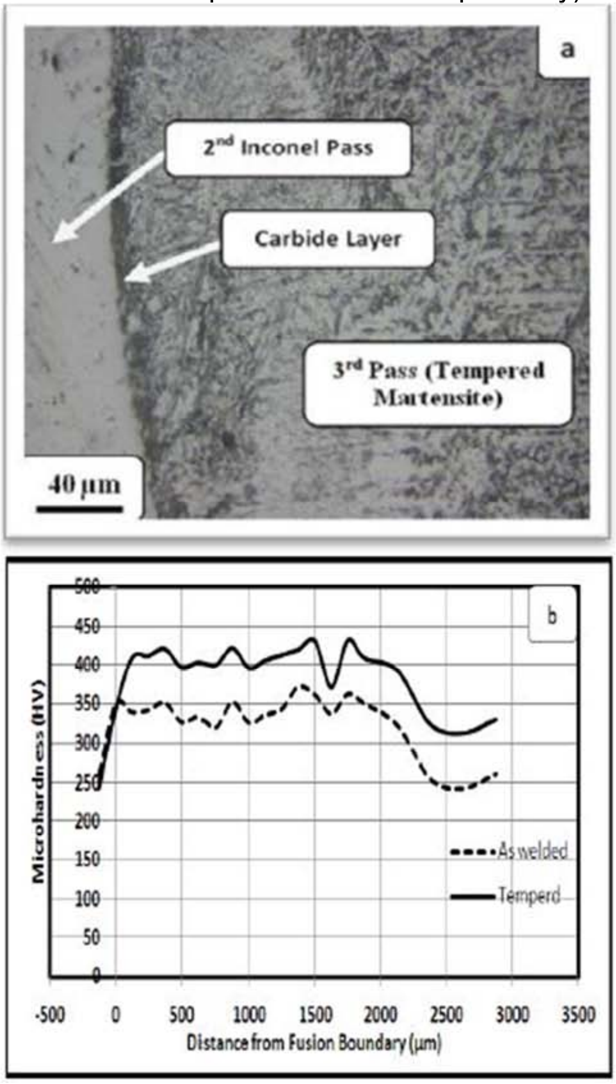

Fig. 10 *Case II of Dilution Method*
a)- Microstructure b)- Microhardness
Sl. 10. *Slučaj II metode razređivanja*
a)- Mikrostruktura b)- Mikrotvrdoća

4. Conclusions

Based on the results and discussion presented in this investigation, T_{Ms} of the 3rd pass was considered the controlling factor that determines the conditions of stresses at type II boundary. Three levels of T_{Ms} of the 3rd pass can be obtained:

Kao što je dokumentovano u literaturi [23-26], ovaj tamni sloj je obogaćen karbidnim slojem koji je nastao usled migracije ugljenika sa feritne na austenitnu stranu. Ovaj sloj je jasnije uočen metodom rafinacije zrna nego metodom razređivanja zbog razlike u sadržaju ugljenika (0,22% i 0,07%). Efekat ovog sloja na žilavost je takođe naveden u tabeli 6. Za slučaj II metode razblaživanja; žilavost je povećana sa 22 na 43 J (kao zavareni i otpušteni uslovi). Međutim, za metode rafinacije, udarna žilavost povećala se samo sa 23 na 30 J (kao zavareni i otpušteni uslovi).

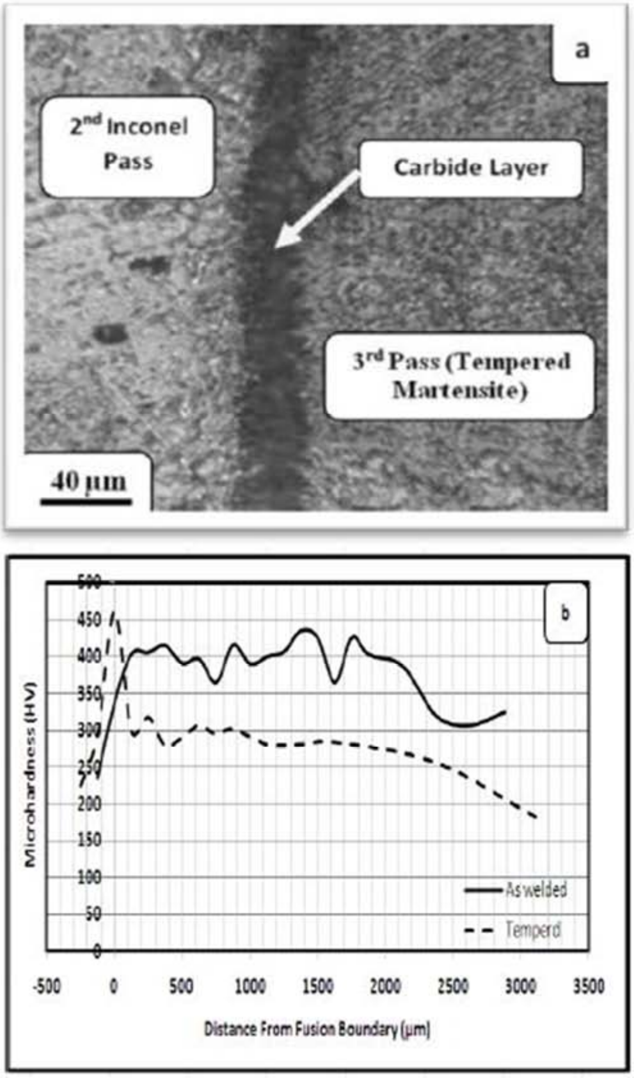

Fig. 11 *Grain Refining Method*
a)- Microstructure b)- Microhardness
Sl.11. *Metoda rafinacije zrna*
a)- Mikrostruktura b)- Mikrotvrdoća

4. Zaključci

Na osnovu rezultata i diskusije prikazane u ovom istraživanju, T_{Ms} trećeg prolaza se smatra kontrolnim faktorom koji određuje uslove naprezanja na granici tipa II. Moguće je dobiti tri nivoa T_{Ms} trećeg prolaza:

1- At T_{Ms} ≥ 300°C, lower compressive stresses are generated from martensitic transformation in the 3rd pass. So high tensile stresses are residue causing cracking along type II boundary.
2- At T_{Ms} ≈ 200°C, relatively high compressive stresses are generated from martensitic transformation in the 3rd pass. The net stresses which resulted at fusion boundary are tensile but with low magnitude value. These low tensile stresses work as a driving force for type II boundary formation and are not sufficient to cause cracking.
3- At T_{Ms} ≈ 50°C, high compressive stresses are generated from martensitic transformation in the 3rd pass. In this case, all tensile stresses are compensated. Therefore the driving force for formation of type II boundary is nil hence, type II boundary itself is not created.
4- PWHT is necessary to achieve accepted impact strength (i.e. higher than 27Joule at 0°C). Thus mechanical properties are accepted only when cracks are inhabited and PWHT is applied.

1- Pri T_{Ms} ≥ 300°C, manja pritisna naprezanja se generišu od martenzitne transformacije u 3. prolazu. Tako zaostala visoka zatezna naprezanja izazivaju pucanje duž granice tipa II.
2 - Pri T_{Ms} ≈ 200°C, relativno visoka pritisna naprezanja nastaju od martenzitne transformacije u 3. prolazu. Mreža naprezanja koja su rezultovala na granici stapanja su zatezna, ali sa malom veličinom. Ova niska zatezna naprezanja funkcionišu kao pokretačka sila za formiranje granica tipa II i nisu dovoljna da izazovu pucanje.
3 – Pri T_{Ms} ≈ 50°C, visoka pritisna naprezanja se generišu iz martenzitne transformacije u 3. prolazu. U ovom slučaju, sva zatezna naprezanja se kompenziraju. Stoga je pogonska sila za formiranje granice tipa II nula, te tako ni sama granica tipa II, nije stvorena.
4 – PWHT(Termička obrada posle zavarivanja) je neophodna da bi se postigla prihvatljiva udarna žilavost (tj. veća od 27 J na 0°C). Tako se mehanička svojstva prihvataju samo kada su prsline izbegnute i primenjuje se PWHT.

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