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MIKROPRSLINE U ZUT SPOJEVA FINOZRNIH ČELIKA ZAVARENIH U ZAŠTITI CO_2

MICROCRACKS IN HAZ OF FINEGRAINED STEEL, WELDED IN CO_2 SHIELDING

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Ključne reči
- finozrni čelik
- zavarivanje u zaštiti CO_2
- specifikacija tehnologije zavarivanja (WPS)
- zona uticaja toplote
- mikroprslina

IZVOD

Specifikacija tehnologije zavarivanja (WPS) je zahtevana za proizvodnju cisterni od normalizovanog finozrnog mikrolegiranog čelika i nerđajućeg čelika za prevoz tečnog CO_2. Za zavarivanje ovih čelika namenjenih radu na niskim temperaturama izabran je MAG postupak. Prototip rezervoara je ispitan probnim pritiskom od 26 bar. Ispitivanja bez razaranja (IBR) koja su usledila nakon probnog ispitivanja, otkrila su mikroprsline, uglavnom raspoređene u zoni uticaja toplote finozrnog čelika. Da bi se utvrdilo poreklo i uzrok inicijacije prslina, izvedena su mehanička ispitivanja i mikrografska analiza. Dobijeni rezultati su diskutovani i predložena verzija poboljšane WPS je prikazana u ovom radu.

Keywords
- fine grain steel
- CO_2 shielded welding
- welding procedure specification (WPS)
- heat-affected-zone
- microcrack

ABSTRACT

Welding procedure specification (WPS) has been required for manufacturing of storage tanks of normalized fine grain microalloyed steel and of stainless steel for liquefied CO_2 gas transport. MAG procedure has been selected for welding of these steels for low temperature application. Storage tank prototype had been tested by proof pressure 26 bar. Following non-destructive testing (NDT) revealed microcracks, mainly distributed in the heat-affected-zone of fine grain steel. In order to identify the origin and cause of their initiation, mechanical tests and micrography analysis has been performed. Obtained results are discussed and proposed version of improved WPS is presented in the paper.

UVOD

Novorazvijene cisterne za prevoz tečnog CO_2 projektovane su od finozrnog mikrolegiranog čelika namenjenog za rad na niskim temperaturama za omotač i danca, a nerđajući čelik je korišćen za izradu prirubnica i priključaka. Karakteristike cisterne date su u tab. 1.

Tabela 1. Karakteristike cisterne za prevoz tečnog CO_2

Zapremina, m^3	21
Ukupna dužina, mm	9 975
Unutrašnji prečnik, mm	1700
Materijal	Mikrolegirani čelik P355NL2
Debljina zida omotača, mm	10
Debljina zida poklopca, mm	12
Radna temperatura, ^oC	-40 ±3
Najveći radni pritisak, bar	19,5
Ispitni pritisak, bar	26
Klasa posude JUS EN E2 151	II

Imajući na umu razvoj proizvodnje novih cisterni zahtevana je izrada prototipa za proveru konstrukcije. To je uslovilo i obezbeđenje kvaliteta zavarenih spojeva specifikacijom tehnologije zavarivanja (WPS), za koju je potrebno izabrati postupak zavarivanja, izraditi uzorke i izvesti ispitivanja prema standardima .

INTRODUCTION

New developed storage tanks for liquefied CO_2 gas transportation has been designed with fine grain microalloyed steel for low temperature application for shell and lids, and stainless steel has been used for flanges and connections. Storage tank specification is given in Table 1.

Table 1. Storage tank specification for liquefied CO_2 transport

Volume, m^3	21
Total length, mm	9 975
Inner diameter, mm	1700
Material	Microalloyed steel P355NL2
Shell wall thickness, mm	10
Lid wall thickness, mm	12
Operating temperature, ^oC	-40 ±3
Maximum operating pressure, bar	19.5
Proof test pressure, bar	26
Pressure vessel class JUS EN E2 151	II

Having in mind the development of new storage tank production, the manufacturing of prototype is required for design verification. For that, quality assurance of welded joints is required by welding procedure specification (WPS), for which it is necessary to select welding procedure, produce samples and perform testing according standards.

SPECIFIKACIJA ZAHTEVA ZA ZAVARENE SPOJEVE I REZULTATI ISPITIVANJA

U preliminarnom zavarivanju nije bilo problema sa nerđajućim čelikom. Uspešno je izvedeno TIG zavarivanje delova od nerđajućeg čelika, kao i delova od nerđajućeg čelika sa delovima od konstrukcijskog čelika. Međutim, zavarivanje konstrukcijskog čelika, za koje je izabran MAG postupak zavarivanja u zaštiti mešavine gasa 82% Ar + 18%CO_2, zahtevalo je detaljnu analizu i prethodnu specifikaciju postupka zavarivanja (pWPS) prema EN 288.

Hemijski sastav izabranog normalizovanog finozrnog čelika TSt E355 prema DIN 17102 (P355NL2) dat je u tab. 2, a njegove mehaničke osobine prikazane su u tab. 3.

2. Hemijski sastav TSt E355 čelika

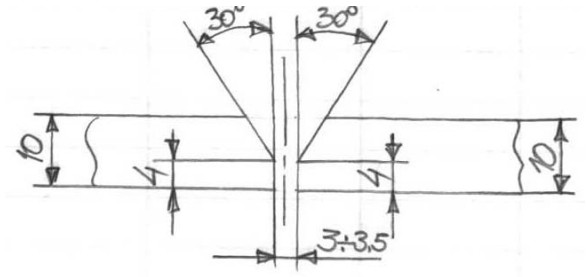
Element	C	Mn	Si
Sadržaj, %	0.17	1.36	0.31

P	S	Al	Ni	Cr	Mo	Cu	Nb	N_2
0.015	0.006	0.020	0.051	0.07	0.02	0.10	0.026	0.0074

Tabela 3. Mehaničke osobine TSt E355 čelika

Čelik	Napon tečenja	Zatezna čvrstoća	Izduženje	Žilavost, J, na
	MPa	MPa	%	-50°C
TSt E355	503	597	252	26 - 42

Konstrukcija karakterističnog podužnog i kružnog sučeono zavarenog spoja omotača, izabrana za pWPS, prikazana je na sl. 1.



Slika 1. Konstrukcija sučeono zavarenog spoja

Za posude pod pritiskom klase II (JUS EN E2 151) i nivo kvaliteta prema JUS ISO 5817, propisan je način kontrole, dat u tab. 4.

Tabela 4. Nivo kvaliteta prema JUS ISO 5817 i specifikacija postupaka kontrole

	Podužni zavari	Kružni zavari	Priključci i prstenovi
Nivo kvaliteta JUS ISO 5817	B	C	C
Vizuelna kontrola, %	100	100	100
Dimenziona kontrola, %	100	100	100
Kontrola penetrantima, %	100	100	100
Kontrola agnetofluksom, %	100	100	
Ultrazvučna kontrola, %	100	100	

Za zavarivanje podužnih i kružnih šavova konstrukcijskog čelika izabran je postupak 135 jednosmernom strujom na + polu (DC+), MAG, u zaštiti mešavine gasa M2.1 EN 439 (82% Ar + 18 % CO_2), i puna žica OK AUTROD 13.26 (AWS A5.28-79 ER 80S-G), ϕ 1,2 mm.

SPECIFIED WELDED JOINTS REQUIREMENTS AND TEST RESULTS

In preliminary welding no problem had been met with stainless steel. The TIG welding of stainless steel parts, as well as stainless steel parts and structural steel parts was successful. However, welding of structural steel, for which gas-shielded metal arc welding procedure with gas-mixture 82% Ar + 18%CO_2 (MAG) is selected, requiring detailed analysis and preliminary welding procedure specification (pWPS) according to EN 288.

Chemical composition of selected normalized fine grain steel TSt E355 according DIN 17102 (P355NL2) is given in Table 2, and its mechanical properties presented in Table 3.

Table 2. Chemical composition of TSt E355 steel

Element	C	Mn	Si
Content, %	0.17	1.36	0.31

P	S	Al	Ni	Cr	Mo	Cu	Nb	N_2
0.015	0.006	0.020	0.051	0.07	0.02	0.10	0.026	0.0074

Table 3. Mechanical properties of TSt E355 steel

Steel	Yield strength	Tensile strength	Elongation	Toughness, J, at
	MPa	MPa	%	-50°C
TSt E355	503	597	252	26 - 42

Typical butt welded joint design of longitudinal and circular welds on the shell, selected for pWPS, is presented in Fig. 1.

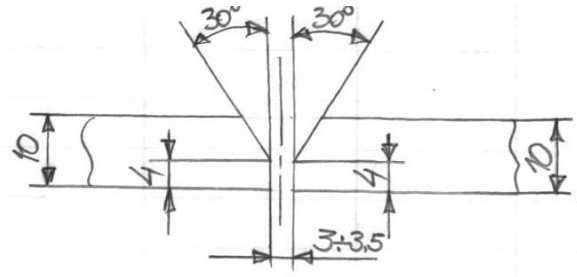


Figure 1 The design of butt welded joint

Respecting class II of pressure vessel (JUS EN E2 151) and quality level after JUS ISO 5817, necessary inspection procedure is required, as listed in Table 4.

Table 4. Quality levels after JUS ISO 5817 and inspection procedure specification

	Longitudinal welds	Circular welds	Connections and rings
Quality level JUS ISO 5817	B	C	C
Visual inspection, %	100	100	100
Dimension control, %	100	100	100
Dye penetrant control, %	100	100	100
Control by magnetoflux,%	100	100	
Ultrasonic inspection, %	100	100	

For welding of longitudinal and circular joints of structural steel procedure 135 is selected, using direct current on + pole (DC+), MAG, shielded by M2.1 EN 439 gas mixture (82% Ar + 18%CO_2), and solid wire OK AUTROD 13.26 (AWS A5.28-79 ER 80S-G), ϕ 1.2 mm.

Hemijski sastav i mehani;ke karakteristike žice su dati u tab. 5. Protok gasa je 10-14 l/min. Propisana temperatura predgrevanja i međuprolaza je T_p = 100 - 120°C.

Tabela 5. Puna žica
OK AUTROD 13.26 (AWS A5.28-79 ER 80S-G)
a. Hemijski sastav

Element	C	Mn	Si	Ni	Cu
Sadržaj, %	0.10	1.4	0.8	0.8	0.3

b. Mehaničke karakteristike

Napon tečenja	Zatezna čvrstoća	Izduženje pri lomu	Udarna žilavost J, na	
MPa	MPa	%	20°C	-40°C
504	625	26	140	90

Da bi se odredio unos toplote za najbolje rezultate [1], urađena je prethodna specifikacija tehnologije zavarivanja (pWPS) sa sledećim vrednostima unete toplote:

- 16/2 WPS: 5,55 – 7,05 kJ/ cm
- 23/2 WPS: 5,25 – 11,75 kJ/ cm
- 303/1 WPS i 302/1 WPS: 8,25 – 13,85 kJ/ cm

Parametri režima zavarivanja dati su u tab. 6. Prihvaćen redosled zavarivanja i izgled zavarenog spoja za položaj PA prikazani su na sl. 2.

Tabela 6. Parametri režima zavarivanja

Prolaz	Struja, A	Napon, V	Uneta toplota, kJ/cm
16/2 WPS			
1	120-140	17-19	6,25
2	100-120	17-19	5,55
3	100-120	17-19	6,45
4	120-140	17-19	7,05
5	100-120	17-19	5,75
23/2 WPS			
1	100-110	16-18	5,25
2	120-140	18-20	7,75
3	150-180	18-20	8,75
4	160-180	20-22	11,05
5	150-170	20-22	11,75
302/1 WPS			
1	120-140	18-20	8,25
2	150-170	20-22	8,75
3	160-180	20-22	9,65
4	180-200	20-22	12,45
5	180-200	20-22	13,75
303/1 WPS			
1	120-140	18-20	8,35
2	140-160	20-22	9,45
3	180-200	20-22	11,65
4	180-200	20-22	12,75
5	200-220	20-22	13,85

Rezultati ispitivanja zatezanjem bili su u okviru očekivanih vrednosti i nisu pokazivali veće rasipanje.

Radi ocene kvaliteta izvedenog zavarivanja izmerena je tvrdoća po preseku zavarenog spoja u tri nivoa, kao što je prikazano na sl. 2. Položaji merenja 1 do 5 se odnose na osnovni metal sa leve strane spoja (sl. 2), u ZUT se nalaze položaji 6 do 10 sa leve strane i položaji 16 do 20 sa desne strane, a položaji 11 do 15 su u metalu šava.

Wire chemical composition and mechanical properties are given in Table 5. Shielding gas flow is 10-14 l/min. Prescribed preheating and interpass temperatures are T_p= 100 - 120°C.

Table 5. Solid wire
OK AUTROD 13.26 (AWS A5.28-79 ER 80S-G)
a. Chemical composition

Element	C	Mn	Si	Ni	Cu
Content, %	0.10	1.4	0.8	0.8	0.3

b. Mechanical properties

Yield strength	Tensile strength	Elongation at fracture	Impact toughness, J, at	
MPa	MPa	%	20°C	-40°C
504	625	26	140	90

In order to specify heat input for best welding results [1], following heat input values for preliminary welding procedure specification (pWPS) had been selected:

- 16/2 WPS: 5.55 – 7.05 kJ/ cm
- 23/2 WPS: 5.25 – 11.75 kJ/ cm
- 303/1 WPS and 302/1 WPS: 8.25 – 13.85 kJ/ cm

Welding regime parameters are given in Table 6. Accepted welding sequence and welded joint form for welding position PA are presented in Fig. 2.

Table 7. Welding regime parameters

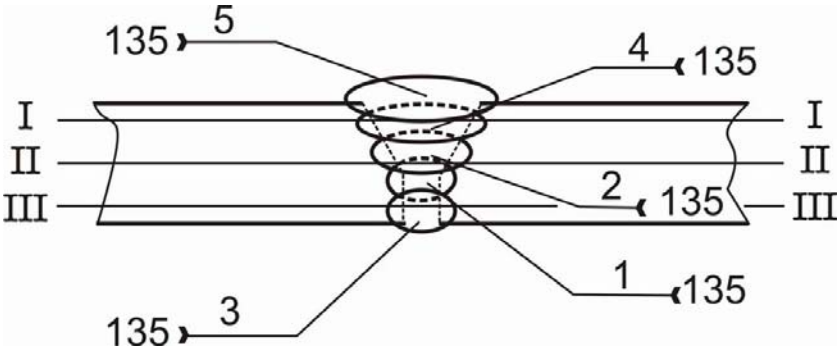
Run	Current, A	Voltage,V	Heat input, kJ/cm
16/2 WPS			
1	120-140	17-19	6.25
2	100-120	17-19	5.55
3	100-120	17-19	6.45
4	120-140	17-19	7.05
5	100-120	17-19	5.75
23/2 WPS			
1	100-110	16-18	5.25
2	120-140	18-20	7.75
3	150-180	18-20	8.75
4	160-180	20-22	11.05
5	150-170	20-22	11.75
302/1 WPS			
1	120-140	18-20	8.25
2	150-170	20-22	8.75
3	160-180	20-22	9.65
4	180-200	20-22	12.45
5	180-200	20-22	13.75
303/1 WPS			
1	120-140	18-20	8.35
2	140-160	20-22	9.45
3	180-200	20-22	11.65
4	180-200	20-22	12.75
5	200-220	20-22	13.85

Mechanical test results had been in the frame of expected values.

For the evaluation of performed welding quality, hardness across welded joint dad been meausred in three levels, as presented in Fig. 2. Positions 1 to 5 reffer to base metal on the lifet side of the joint (Fig. 2), in the HAZ are located positions 6 to 10 on the left side and positions 16 to 20 on the right side, and positions 11 to 15 are in weld metal.

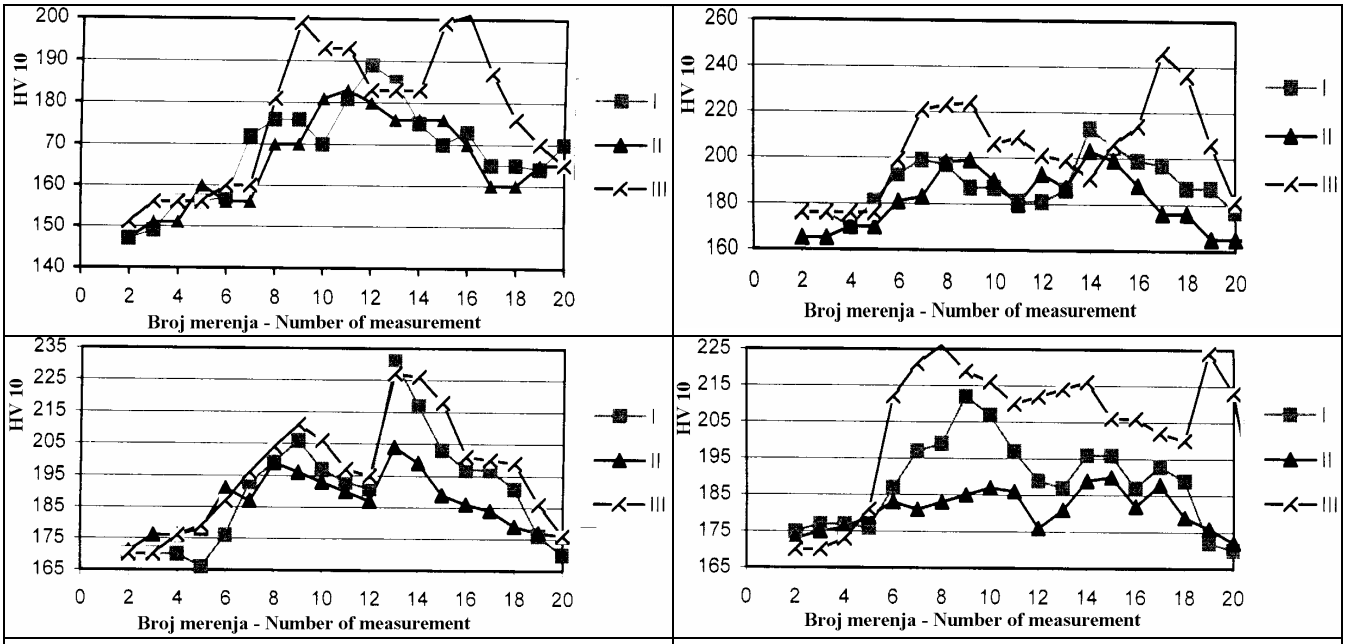
Načelno, vrednosti tvrdoće ispod 240 HV 10, koje su ovde izmerene (sl. 3) se mogu smatrati prihvatljivim. Iz raspodele tvrdoće se vidi da jedino kod uzorka 16/2 WPS u metalu šava i ZUT nije premašena vrednost od 200 HV10, što ukazuje da u tom slučaju ne treba očekivati krta područja u zavarenom spoju. Zbog toga je verovatna niska prelazna temperatura krtosti, pa i prihvatljivo ponašanje zavarenog spoja na -50°C, što treba dokazati ispitivanjem udarne žilavosti. Na preostala tri uzorka je u ZUT lokalno izmerena viša tvrdoća, koja na nekim mestima dostiže vrednost 240 HV10. Na tim mestima se može ocekivati viša prelazna temperatura krtosti, a ne može se isključiti postojanje krtih područja, odnosno krto ponašanje na -50°C. Ravnomernija raspodela tvrdoće u sloju II posledica je efekta otpuštanja čelika zagrevanjem pri narednim prolazima zavarivanja.

In general, hardness values bellow 240 HV 10, measured here (Fig. 3) can be considered as acceptable. It is clear from hardness distribution that only for sample 16/2 WPS the value 200 HV 10 is not exceeded in weld metal and in HAZ, indicating that in this case brittle regions in welded joint are not expected. For that low nil ductility transition temperature is probable, as well as acceptable behaviour of welded joint at -50°C, that should prove by impact toughness testing. On additional three samples higher hardness is localy measured in HAZ, reaching in som pointsthe value of 240 HV10. In these points higher transition temperature can be expected, and the existance of brittle regions can not be excluded, e.g. brittle behaviour at -50°C. More regular hardness distribution in level II is a consequence of relaxation effect of heating in next welding passes.



Slika 2. Presek zavarenog spoja za položaj zavarivanja PA

Figure 2 Welded joint cross-section for welding position PA



Slika 3. Raspodela tvrdoće u zavarenom spoju
a. 16/2 WPS; b. 23/2 WPS; c. 302/1 WPS; d. 303/1

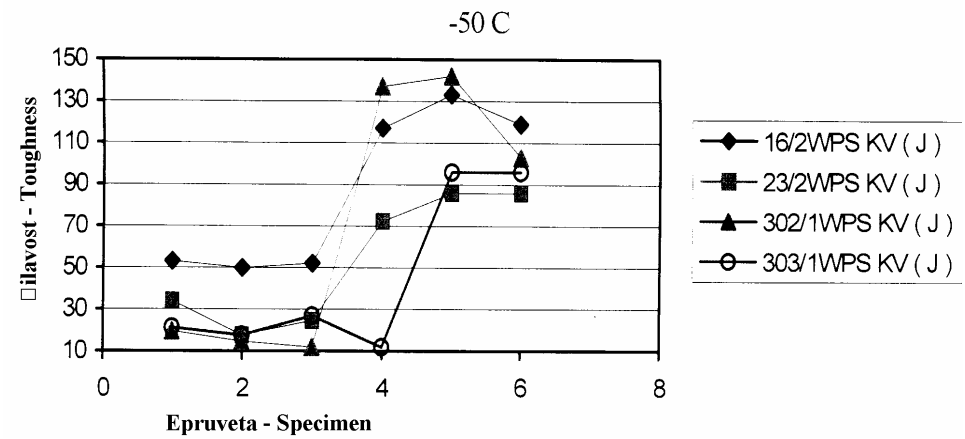
Figure 3. Hardness distribution in welded joint
a. 16/2 WPS; b. 23/2 WPS; c. 302/1 WPS; d. 303/1

Rezultati udarnog ispitivanja po Šarpiju epruveta sa V zarezom za sve četiri uzorka su prikazani na sl. 4. Vrednosti energije udara za zarez u ZUT su vrlo male. Jedino za uzorke 16/2 WPS se ove vrednosti mogu prihvatiti, dok je za ostale uzorke udarna žilavost nedovoljna [2,3,4].

The results of Charpy impact testing of V notched specimens for all four samples are presented in Fig. 4. The values of impact energy are very low for notch in HAZ. Only for samples 16/2 WPS the values are acceptable, but for other samples impact energy is not satisfactory [2,3,4].

Imajući u vidu namenu cisterni, za čiju proizvodnju se razvija tehnologija zavarivanja i WPS, zahtevano je i ispitivanje udarne žilavosti po Šarpiju na -50°C. Rezultati ispitivanja su za sva četiri uzorka prikazani na sl. 4 (epruvete 1 do 3 - V zarez u ZUT, epruvete 4 do 6 - V zarez u metalu šava). Jasno je da je udarna energija epruveta sa zarezom u ZUT manja od uobičajeno zahtevanih 27 J za tri uzorka izrađenih sa većom unetom toplotom, a da se može prihvatiti samo za uzorke 16/2 WPS, gde iznosi oko 50 J. To je bio razlog što je postupak 16/2 WPS izabran za izradu prototipa. Treba napomenuti da je vizuelnim pregledom i ultrazvučnim ispitivanjem otkrivena prslina na uzorku 23/2 WPS, ali razlog njenog nastajanja nije detaljnije analiziran jer je za izradu prototipa usvojena tehnologija zavarivanja prema specifikaciji 16/2 WPS.

Having in mind the use of storage tanks, for which production welding technology and WPS are developed, Charpy impact test at -50°C is required. Test results for all four samples are presented in Fig. 4 (specimens 1 to 3 - V notch in HAZ, specimens 4 to 6 - V notch in weld metal). It is clear that impact energy of specimens with V notch in HAZ is lower than normally required 27 J for three samples produced with higher heat input, and that can only be accepted for sample 16/2 WPS, when it is about 50 J. For that, the procedure 16/2 WPS has been selected for prototype manufacturing. It is to mention that crack had been detected by visual examination and by ultrasonic testing on 23/2 WPS sample, but the reason for its occurence did not examined in detail, since welding technology according specification 16/2 WPS is accepted for prototype manufacturing.



Slika 4. Vrednosti udarne žilavosti na -50°C: epruvete 1 – 3, V zarez u ZUT, epruvete 4 – 6, V zarez u metalu šava

Figure 4 Impact toughness values at -50°C:specimens 1 – 3, V notch in HAZ , specimens 4 – 6, V notch in weld metal

IZRADA PROTOTIPA CISTERNE

Pre izrade prototipa cisterne, zavarivači su atestirani prema JUS EN 287. Prototip je izrađen u u normalnim uslovima u radionici, na sobnoj temperaturi, uz nadzor inženjera zavarivanje i primljen posle kontrole izvedene prema specfikaciji (tab. 4), u kojoj su vizuelnim pregledom i ultrazvučnim ispitivanjem otkrivene male greške, ali veličine dopuštene za nivo kvaliteta B.

Primljeni prototip je pripremljen za ispitivanje vodenim pritiskom. Prema specifikaciji, datoj u tab. 1, zahteva se probni pritisak 26 bara. Kontrolom posle ispitivanja probnim pritiskom je utvrđeno da postoje male prsline, koje nisu otkrivene pri kontroli posle izrade. Da bi se problem pojave prslina rešio, zahtevana su dodatna ispitivanja mikrostrukture, koja su izvedena svetlosnom mikroskopijom.

Pojava ovih prslina je pripisana velikoj unetoj toploti pri zavarivanju, kada je nadzor od strane inženjera zavarivanja bio nedovoljan. Nađene prsline su otklonjene brušenjem, do najveće dubine od 5 mm. Ponovno zavarivanje je izvedeno prema postupku 16/2 WPS, ali sada uz striktni nadzor inženjera zavarivanja. Ultrazvučnom kontrolom, izvedenom posle reparaturnog zavarivanja, nisu otkrivene rpsline u zavarenim spojevima [5].

Mikrostruktura je ispitana na izbruscima, uzetim sa sva četiri uzorka zavarenih spojeva. Odabrani snimci mikro strukture uzorka 16/2 WPS su prikazani u tabeli (sl. 5).

MANUFACTURING OF PROTOTYPE MODEL

Before manufacturing of storage tank prototype, welders had been testes according JUS EN 287. Prototype had been produced in normal workshop condition, at room temperature, supervized by welding engineer, and accepted after inspection performed according specification (Table 4), in which small defects have been detected by visual control and ultrasonic testing, but of size allowable for quality level B.

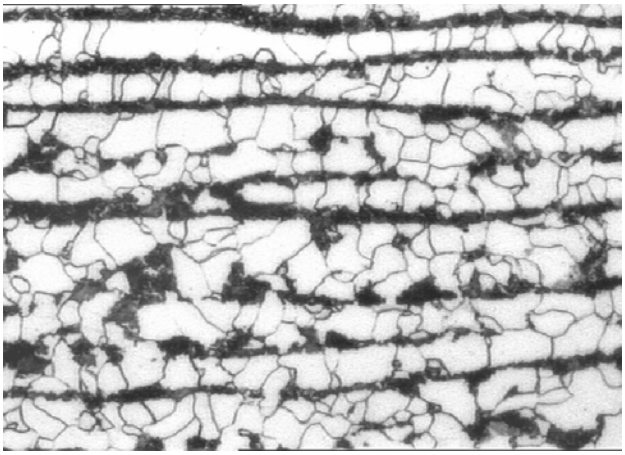
Accepted prototype was prepared for water pressure proof test. According to specification, given in Table 1, proof test of 26 bar is required. Inspection after proof test revealed the existence of cracks, not detected in inspection after manufacturing. In order to solve the problem of crack occurrence, additional testing of microstructure was required, which had been performed by light microscopy.

The occurrence of these cracks is attributed to high heat input, when supervision of welding engineer was not proper one. Detected cracks had been removed by grinding, to the maximum depth reached 5 mm. Rewelding has been performed according procedure 16/2 WPS, but now with strict supervision of welding engineer. By ultrasonic inspection, performed after repair welding, no cracks were detected in welded joints [5].

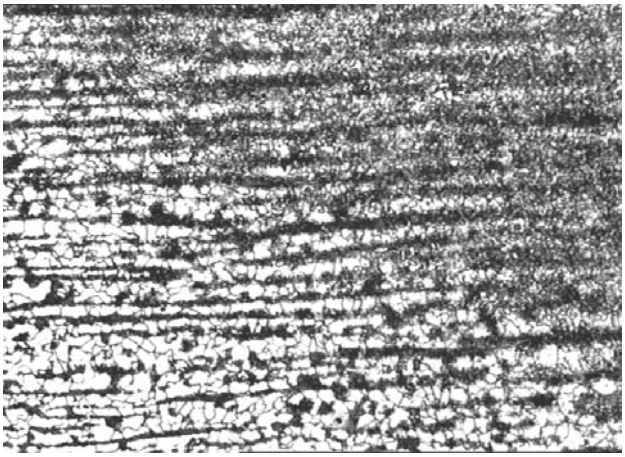
Microstructure is examined on specimens, taken from all four welded joint samples. Selected photographs of sample 16/2 WPS microstructure are presented in table (Fig. 5).

Ostala tri uzorka, izvedena sa većom unetom energijom, koje karakteriše značajno rasipanje rezultata na sl. 3. i 4, su imali sličnu mikrostrukturu u odgovarajućim područjima, pa su za ilustraciju izabrani snimci uzorka 23/2 WPS i prikazani u tabeli (sl. 6). Snimak mikrostrukture u području prsline, otkrivene u ovom uzorku, je izdvojeno prikazan.

The microstructures of other three samples, performed with higher heat input, characterized by significant scatter of results in Figs. 3 and 4, are similar, and photographs of 23/2 WPS are taken for illustration and presented in the table (Fig. 6). The photograph of microstructure in crack region, detected in this sample, is presented separately.

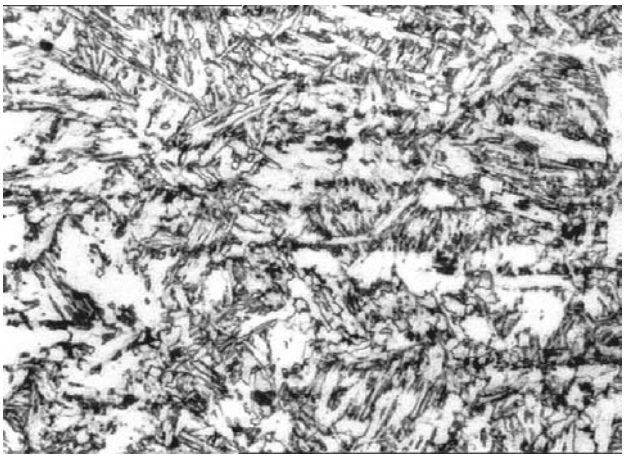


a) OM a) PM 500x



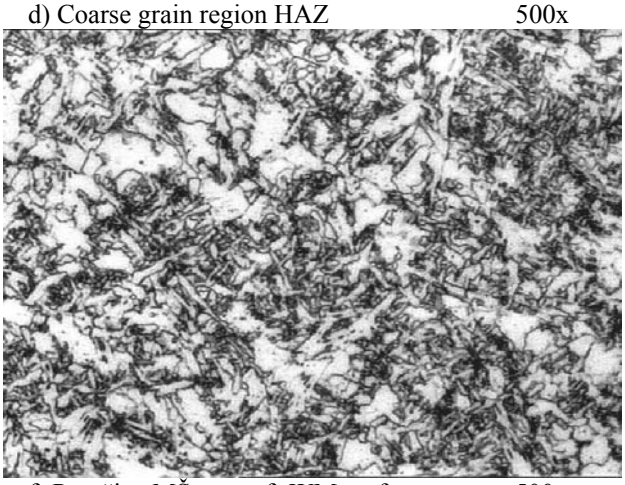
b) Sitnozrna područje OM/ZUT
b) Fine grain region PM/HAZ 200x

c) MŠ/ grubozrno područje ZUT
c) WM/ coarse grain HAZ 200x



d) Grubozrno područje ZUT
d) Coarse grain region HAZ 500x

e) Koren MŠ e) WM root 500x



f) Površina MŠ f) WM surface 500x

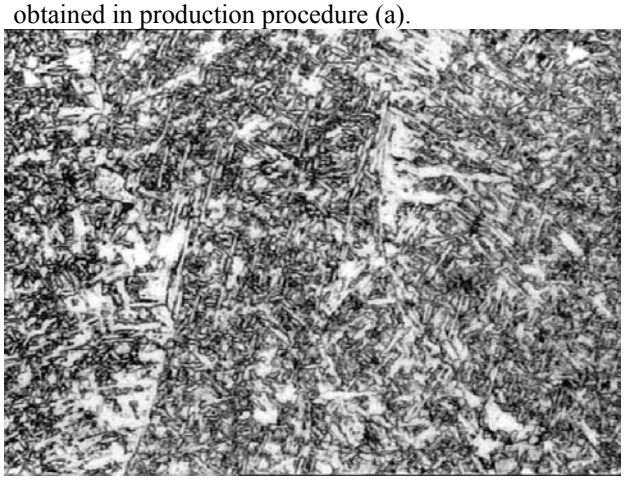
Slika 5. Mikrostrukture različitih područja zavarenog spoja, dobijene postupkom 16/2 WPS

Figure 5 Microstructures of different regions in welded joint, obtained wtih 16/2 WPS procedure

Mikrostruktura (sl. 5) svih područja zavarenog spoja uzorka 16/2 WPS je zadovoljavajuća. Struktura osnovnog metala (OM) je sitnozrna, feritno-perlitna, sa trakama uslovljenim procesom izrade (a).

Microstructure (Fig. 5) of all welded joint regions of sample 16/2 WPS is satisfactory. Macrostructure of parent metal (PM) is fine grained, ferrite - pearlite with bands, obtained in production procedure (a).

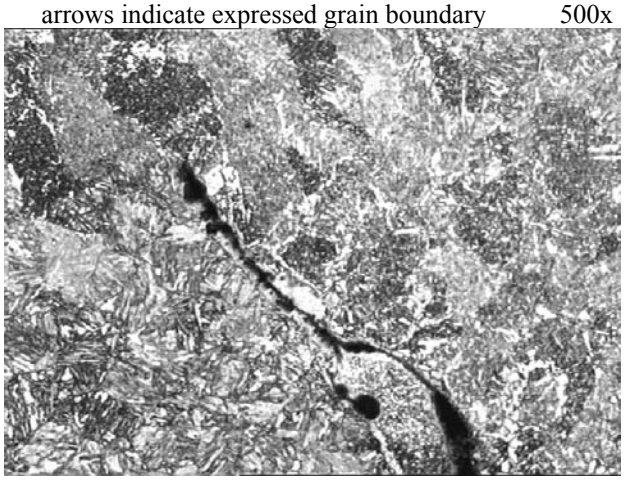
a) Koren MŠ a) WM root 500x



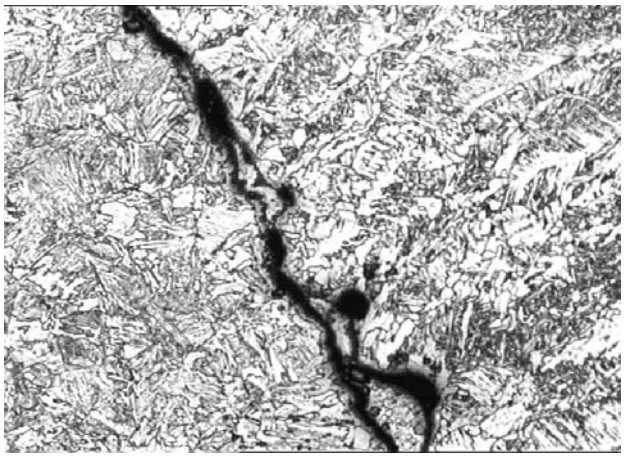
b) Površina MŠ b) WM surface 500x

c) Grubozrno područje ZUT - beintina struktura; strelice označavaju izraženu granicu zrna
c) Coarse grain region HAZ - beinitic structure; arrows indicate expressed grain boundary 500x

d) Grubozrno područje ZUT - martenzitna struktura
d) Coarse grain region HAZ - martensitic structure 500x



e) Vrh psline otkrivene na liniji stapanja; levo - ZUT, desno - MŠ
e) Tip of the crack, detected at fusion line; left - HAZ, right - WM 200x



e) Sredina psline otkrivene na liniji stapanja; levo - ZUT, desno - MŠ
e) Middle of the crack, detected at fusion line; left - HAZ, right - WM 200x

Slika 6. Mikrostrukture različitih područja zavarenog spoja, dobijene postupkom 23/2 WPS
Figure 6 Microstructures of different regions in welded joint, obtained by 23/2 WPS procedure

Na prelaznom području iz OM u ZUT nije došlo do bitnije promene mikrostrukture (sl. 5b), iako se područje prelaza jasno razaznaje. Linija stapanja ZUT i MŠ je takođe jasno izražena i deli grubozrno beinitno područje ZUT od beinitne strukture MŠ (c). Na uvećanom snimku grubozrnog područja ZUT (d) je beinitna struktura istaknuta, ali se može oceniti kao slična beintinoj strukturi u korenu MŠ (e) i na površini MŠ (f).

Mikrostruktura ZUT i MŠ dobijena pri većoj unetoj toploti (postupak 23/2 WPS, sl. 6) nije zadovoljavajuća. Microstruktura MŠ u korenu i na površini je beintitna, ali se uočava osetno krupnije zrno u poređenju sa odgovarajućom strukturom na sl. 5. U ZUT, pored beintine strukture (sl. 6c) se lokalno uspostavlja i martenzitna struktura (sl. 6d), a u oba slučaja dolazi do pojave grubog zrna, uslovljenog velikom unetom toplotom. Do pojave martenzitne strukture je moglo doći jednovremenim uticajem lokalno neravnomerno unete toplote i takođe lokalne segregacije ugljenika zbog trakaste strukture osnovnog metala. Na sl. 6c. se vidi i jasno izražena granica zrna, označena strelicama, u ZUT beinitne krupnozrne strukture. Ovako izraženim granicama zrna i lokalno martenzitnoj strukturi se može pripisati pojava prslina, otkrivenih posle probe pritiskom. To navodi na zaključak da je pri izradi prototipa, zavarivač uneo veću toplotu i time uslovio pojavu krupnozrne beinitne i martenzitne strukture, najverovatnije u periodu smanjenog nadzora. Iz izraženih granica zrna, pod velikim opterećenjem tokom ispitivanja prototipa pritiskom može se očekivati inicijacija prslina.

Otkrivena kristalizacijska prslina (sl. 6e, f) se prostire iz pore, nastale u gornjem prolazu, duž linije stapanja. Sa desne strane prsline je Vidmanštetenova struktura MŠ, a sa leve strane prsline je krupnozrna beinitna struktura ZUT (f), delimično otpuštena narednim prolazom pri zavarivanju. Pojava ove prsline je pripisana nedovoljnom nadzoru pri zavarivanju.

ZAKLJUČAK

Pravilan izbor količine unete toplote je značajan za dobijanje kvalitetnog zavarenog spoja. To je slučaj i sa zavarljivim čelikom, ovde korišćenim za izradu prototipa cisterne. Prevelika uneta toplota je dovela do neprikladne mikrostrukture zavarenog spoja, sklone pojavi prslina pod opterećenjem. Ljudski faktor je od posebnog značaja, u ovom primeru iskazan nedovoljnim nadzorom i odstupanjem od parametara propisane tehnologije pri zavarivanju, što se odrazilo na kvalitet zavarenog spoja.

There is no significant change in microstructure in transition region from PM to HAZ (Fig. 5b), although the transtion is visible. Fusion line HAZ to WM is also clearly expressed and separates HAZ coarse grained beinite region from WM beinite structure (c). In maginified photograph of HAZ coarse grained region (d) beinite structure is expressed, but it is possible to evaluate it as similar to beinite structure in WM root (e) and at WM surface (f).

Microstructure in HAZ and WM, obtained by higher heat input (procedure 23/2 WPS, Fig. 6) is not satisfactory. Microstructure in WM is beinitic, but significantly coarser grain compared to the structure in Fig. 5 is recognized. In HAZ, in addition to beinitic structure (Fig. 6c) martensitic structure is also established locally, and in both cases coarse grains are developed due to high heat input. The formation of martensitic structure is caused by simultaneous effect of locally irregular heat input and also of local carbon segregation produced due to typical band structure of parent metal. Clearly expressed grain boundary, marked by arrows in Fig. 6c, is found in HAZ of beinitic coarse grain structure. The occurrence of cracks, detected after pressure proof test, can be attributed to so expressed grain boundaries and to local martinsitic structure. This impose the conclusion that during prototype manufacturing the welder induced higher heat input, enabling the formation of coarse grained beinitic and martensitic structure, most probably when supervision had been reduced. Initiation of cracks under high load level during pressure proof test from expressed grain boundaries can be expected.

Detected crystallization crack (Fig. 6e, f) initiated from the pore, formed in upper pass, extended along fusion line. On the crack right side is Widmanstätten structure of WM, and on the left side is coarse grain beinitic structure of HAZ (f), partly tempered in next welding passes. The occurrence of this crack is attributed to missing supervision during welding.

CONCLUSION

Proper selection of heat input is of significance for welded joint quality. This is also the case with weldable steel, used here for storage tank prototype manufacturing. Excessive heat input can cause non satisfactory microstructure of welded joint, prone to crack initiation under loading. Human factor is of special importance, in this example expressed by missed supervision and incorrect parameters, different from prescribed by welding technology, that reflected to welded joint quality.

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