ŽELEZARSKI ZBORNIK
IZDAJAJO ŽELEZARNE JESENICE, RAVNE, ŠTORE IN METALURŠKI INŠTITUT
LETO 25 LJUBLJANA DECEMBER 1991

Vpliv varilne tehnologije in izbire dodajnega materiala na lomne lastnosti EPP zvarnega spoja na nizko ogljičnem finozrnatem jeklu

The Influence of Welding Technology and Welding Material Selection on Fracture Properties of Submerged Arc Welded, Low Carbon, Finegrained Steel Plate

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1. UVOD

Razvoj nizko ogljičnih jekel, ki so izdelana na termomehanski način ali kaljena in popuščana in ki so uporabljana v konstrukcijah z zahtevnimi obremenitvenimi pogoji, je v veliki meri spremenil varilno tehnologijo. Zaradi nizkega ogljika in nizke vsebnosti difuzijskega vodika v zvaru izdelovalci jekel ne priporočajo več predgrevanja pred varjenjem. Pri tem ni nevarnosti, da bi v TVP nastopila razpokljivost v hladnem, kar je mogoče npr. preveriti z Dürenovim in Suzuki konceptom /1, 2/.

Če navedeno prenesemo na dejanske zvarne spoje (hlajenje pod 50° C po vsakem varku in začetek varjenja brez predgrevanja), ki so zvarjeni z nizko dovedeno toploto (10—15kJ/cm), da bi zajamčili dobro žilavost v grobozrnatem predelu TVP, se lahko v raztopljenem zvaru pojavi nizka žilavost kot posledica tvorbe podolgovatih M/A strukturnih faz glede na kemično sestavo jekla in dodajnega materiala. V primeru napetostnega žarjenja pri 580° C se pojavi neugodni efekt izločevanja Fe_3C iz M/A faz, ki predstavljajo prenasičeno raztopino. Pri tem je žilavost lahko še nižja, če je staljeni zvar občutljiv na reverzibilno popuščno krhkost. V tem prispevku so obravnavane samo lastnosti raztaljenega dela zvarnega spoja.

Zaradi jasnega efekta vpliva znižanega dovoda toplote pri varjenju in zaradi zmanjšanja velikosti zrna in primarnega ferita po kristalnih mejah je bil izbran za raziskavo dodajni material z 0,4% Cr in 0,2% Mo ter z dodatkom Ti-B. Uporabljena je bila metoda elektro varjenja pod praškom - EPP. Žilavost zvara je bila ugotavljana z udarnim Charpijevim kladivom. Zareze v Charpy preizkušancih so bile locirane v kovini in korenski legi X simetričnega zvara pravokotno na debelino. Razlog za to je bilo pričakovano različno razmešanje, predvsem s stališča Nb (NB = 0,01 % v krovni legi in 0,04% v korenski legi). Preizkusi so bili opravljeni na celotni debelini zvara po metodi CTOD z upogibnimi preizkušanci, zarezanimi in utrujanimi pravokotno na debelino v sredini zvara.

Lomne površine so bile preiskane z vrstičnim elektronskim mikroskopom predvsem glede pojava in lokaci-

1. INTRODUCTION

Development of LC steels, produced on thermomechanical way or by quenching and tempering and used in constructions under sophisticated load conditions, has largely changed the welding technology.

Because of the LC and low diffusible hydrogen content in the weld, the steel producers do not recommend preheating before welding. There is no danger of cold cracking appearance in HAZ what is possible to check up with Düren and Suzuki theory for example /1, 2/ Transferring these statements into the real weldment (interpass temperatures under 50 degrees Celsius and no preheating before welding) welded with low heat input (10-15 KJ/cm) to ensure good toughness in coarse grain area of HAZ, can in the melted part of the weld cause the appearance of low toughness values as the result of oblongated M/A structural phase formation depending on the chemical composition of steel and welding material. In the case of stress relieved heating at 580 degrees Celsius there appears the undesirable effect to Fe_3C precipitation from M/A phases representing a saturated solution. The toughness values can be lowered even more if the sensitivity of the melted part of the weld on a reversible temper brittleness is present.

Because of the clear effects of low heat input at welding and reduced grain size and primary ferrite on crystal boundaries, the welding material with 0,4% Cr and 0,2% Mo and Ti-B additions was chosen in these researches. The SAW welding method was used. The weld toughness was determined by Charpy V-notch impact test. The notchess of Charpy impact specimens were located in face and root location of double V butt type weld, right angled on the thickness of the plate. The reason was in the expected uneven dilution, first of all from the Cb point of view (Cb = 0,01% in the face of the weld and 0,04% in root of the weld). Further tests were carried out on the complete weld thickness by the CTOD method on the bend type specimens notched and fatigued in the rightangled direction to the thickness in the middle of the weld.

Fractured surfaces were examined with line EM, first of all on the appearance of LBZ. Both, line EM and optical microscope were used by the examinations of microstructures in the welded joint. The presented results

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je LKP. Mikrostrukture zvara so bile preiskane z optičnim in vrstičnim elek. mikroskopom. Rezultati dokazujejo, da staljeni del zvara kljub drobnemu zrnu in nizki vsebnosti primarnega ferita po kristalnih mejah ni vedno dovolj žilav. Torej ocena struktur z optičnim mikroskopom po priporočilu IIW /3/ ni vedno zadostna za analizo in določitev vzrokov za dobro ali slabo žilavost staljenega zvara. Dodatne metode, kot npr. uporaba vrstičnega mikroskopa, lahko pokažejo dejanski vzrok za nizko ali visoko žilavost v staljenem zvaru v izhodnem in napetostno žarjenem stanju.

2. LASTNOSTI IN MIKROSTRUKTURA NIZKO OGLJIČNEGA EPP STALJENEGA ZVARA

Poznan je odnos med mikrostrukturo zvara in žilavostjo /4/. Razmešanje raztaljenega zvara v času varjenja spreminja transformacijsko kinetiko staljenega zvara, pri čemer imajo lahko vključki znaten vpliv. Gostota, velikost in porazdelitev vključkov narekujejo razvoj velikosti avstenitnih zrn po strditvi. Oksidni in drugi vključki ter koncentracija avstenitne trdne raztopine skupaj s hitrostjo ohlajevanja vplivajo na različne feritne morfologije v času premene (γ/α /5a). Puščičasti ferit se npr. pojavi v EPP zvaru, če je koncentracija O_2 višja od 450 ppm; njegova rast iz primarnega ferita na kristalni meji v zrno je intergranularna. Pri nižjih vsebnostih O_2 se pojavi več ugodnega acikularnega ferita, medtem ko nizke vsebnosti O_2 vodijo do tvorbe bainitne strukture. Poleg vsebnosti O_2 je pomembna velikost in enakomerna porazdelitev vključkov. Vključki velikosti $> 0,2\ \mu m$ bodo povzročili pospešeno tvorbo acikularnega ferita in znižali vsebnost primarnega ferita, pri čemer se povečajo primarna dendritna zrna s fino porazdeljeno intergranularno strukturo /5b/.

V času tvorbe primarnega in puščičastega ferita se preostali avstenit znatno obogati s C ter se lahko transformira v faze, ki vsebujejo zaostali avstenit in martenzit ali bainit-M/A strukturne faze. Takšno strukturo često najdemo pod izrazom ferit s sekundarno fazo. Prisotni vključki so tvorci puščičastega ferita, katerega oblika je odvisna od hitrosti ohlajevanja /6/. Višje hitrosti ohlajevanja pospešujejo tvorbo Widmanstattenskega ferita, ki ga spremlja neugodna porazdelitev M/A faz. Dodatki Nb ta fenomen še pospešujejo, kar se kaže v nižji žilavosti. Na drugi strani dodatki Ti in B izboljšajo žilavost, ker pospešujejo tvorbo acikularnega ferita, ki se pojavi na drobnih intergranularnih vključkih. Večina elementov vpliva na tvorbo in hitrost rasti puščičastega ferita. Dodatki Si in Al pospešujejo tvorbo puščičastega ferita, medtem ko jo Mn in Mo zavirata. Pretvorbo iz acikularnega ferita v ferit s sekundarno fazo, kot npr. M/A fazo, pospešujeta Cr in Mo, ki tudi povišujeta mejo plastičnosti in trdnost /7/.

3. RAZISKAVA SOČELNEGA EPP STALJENEGA ZVARA

3.1. Izbira osnovnega in dodajnega materiala

Raziskave so bile opravljene na EPP zvarnem spoju nizkoogljičnega poboljšanega jekla Niomol 390. Lastnosti osnovnega in dodajnega materiala so navedene v **tabeli 1.** Navedeni dodajni material je bil izbran, da bi poudarili razlike pri nižjem in višjem dovodu toplote zaradi njegove povišane zakaljivosti, kar je razvidno iz višjega Pcm v primerjavi z osnovnim materialom.

V predhodnih raziskavah /8/, kjer je bil uporabljen komercialni dodajni material (z 1 % Ni s Pcm = 0,149 in je bilo varjenje opravljeno prav tako brez predgrevanja, so se pojavila vidna LKP v prelomu CTOD preizkušanca v

show, that the melted part of the weld is not always tough enough in spite of fine grained coarse and low primary ferrite on crystal boudaries. Therefore, the estimation of structures with optical microscope, as it is recommended by IIW /3/, is not always sufficient enough for the analyse and determination of good or bad toughness in the melted part of the welded joint. Additional methods, as line electron microscope for example, can show the real reason for low or high toughness values in the melted part of the welded joint in as-welded or stress relieved conditions.

2. THE PROPERTIES AND MICROSTRUCTURE OF THE LOW CARBON MELTED PART OF THE SUBMERGED ARC WELDED JOINT

The relationship between microstructure and toughness of the welded joint is known /4/. Dilution of the melted part of the welded joint during welding is changing the transformation kinetic of melted weldment and the inclusions can have a significant influence on it. Density, size and distribution of inclusions do dictate the size development of austenitic grains after the solidification. Oxide and other types of inclusions and concentration of austenitic solid solution together with the cooling speed, are influencing upon different ferrite morphologies during the transformation γ/α /5a/. Acicular ferrite can appear for example in the SA welded joint, if the concentration of oxygen is higher than 450 ppm; its growth is intragranular from primary ferrite on crystal boundary into the grain. At the lower oxygen concentrations more favourable acicular ferrite appears, while low oxygen concentration lead to the formation of bainite structure.

Beside the low oxygen concentration the size and uniform distribution of inclusions is important. The inclusion sizes over $0,2\mu m$ will cause an accelerated formation of acicular ferrite and reduce the content of primary ferrite increasing at the same time the size of the dendrite grains with fine distributed intragranular structure /5b/.

During the formation of primary and acicular ferrite the remained content of austenite becomes significantly rich with carbon and can transform in phases containing residual austenite and martensite or bainite-M/A structural phases. Such structure we can often find in the expression ferrite with the second phase. Present inclusions are authors of acicular ferrite which shape depends on cooling speed /6/. Higher cooling speed accelerates the formation of Widmanstatt-ferrite accompanied by unfavourable distribution of M/A phases. The additions of Cb accelerates this phenomena what results in the lower toughness. On the other side the additions of Ti and B improve the toughness because they accelerate the formation of acicular ferrite, which appears on intragranular inclusions. The most of elements have their effect on the formation and growth speed of acicular ferrite. The additions of Si and Al accelerate the formation of arrow-shaped ferrite, while Mn and Mo retard it. The transformation from acicular ferrite to ferrite with secondary phase, as for example M/A phase, is accelerated with Cr and Mo which also increase the yield point and strength /7/.

3. RESEARCH OF THE BUTT — SA WELDED MOLTEN JOINT

3.1. The choice of the base and welding material

The researches were carried out on the SA welded, low carbon, quenched and tempered steel plate Niomol izhodnem in napetostno žarjenem stanju celo pri +20°C. Preiskave na rasterskem mikroskopu so odkrile več kot 10 % M/A strukturne faze.

Dodatek Ti-B je v tej preiskavi bil izbran z namenom preprečiti oz. znižati tvorbo primarnega ferita po kristalnih mejah in pospešiti tvorbo acikularnega ferita v strukturi staljenega zvara /9/.

Vpliv grobega zrna in primarnega ferita na žilavost staljenega zvara je bil tako z izbiro navedenega dodajnega materiala izključen. Namen preiskave je bil ugotoviti vpliv M/A faz z ozirom na njihovo sestavo (visok C), velikost, usmerjenost in gostoto na udarno in lomno žilavost v odvisnosti od hitrosti ohlajevanja in legiranosti staljenega zvara /10, 11/. Nadaljnji namen je bil ugotoviti vpliv napetostnega žarjenja na razpad M/A faz in tako na žilavost staljenega zvara.

Tabela 1: Lastnosti uporabljenih materialov

Lastnosti osnovnega materiala					
Debelina /mm/	R_e /MPa/	R_m /MPa/	σ_5 /%/	Žilavost −60°C /J/	CTODi, −40°C /mm/
30	432	528	25	198,161,149	0,51
Kemična sestava					
0,08C	0,30Si	1,11Mn	0,006S	0,015P	0,049Nb
0,08Sn	0,18Ni	0,012As	0,047Al	Pcm = 0,149	CE = 0,270
Lastnosti čistega dodajnega materiala					
EPP-dod.mat.	R_e /MPa/	R_m /MPa/	σ5 /%/	Žilavost −60°C /J/	CTOD /mm/
OP121TT Fluxocord 35.22	480	520–620	24	>50, varjeno >35, žarjeno	— —
Kemična sestava					
0,05C	0,20Si	1,2Mn	0,04Cr	0,20Mo	0,005B
Ti dod.	Pcm = 0,175	CE = 0,370			
Kemična sestava dejanskega EPP zvara					
0,05C	0,36Si	1,67Mn	0,70Cr	0,41Mo	0,025V
0,031Ti	0,023Al	0,04Sn	0,04Sb	0,006B	0,007As
0,009S	0,020P	0,022Nb			
Pcm = 0,246	CE = 0,557	O_2 = 227ppm	H_D < 2,6 ml /100 gr		

3.2. Varjenje preizkusnih plošč in priprava preizkušancev

Uporabljeno je bilo večvarkovno varjenje na simetrično pripravljenem X zvarnem žlebu. Keramični vložek je bil uporabljen z izvedbo korenskega varka. Zvarjeni sta bili dve preizkusni plošči z različnima tehnologijama, A-brez predgrevanja in B-s predgrevanjem.

Podatki o varjenju:

debelina plošče — 30 mm
predgrevanje — brez (A), 150°C (B)
vnešena toplota — 15kJ/cm
$\Delta t_{8/5}$ — 5,4s(A), 10,5s(B)
vmesna temp. — 50°C(A), 200°C(B)
pogrevanje — 200°C

*390. The properties of base and welding material are given in **Table 1.** Given welding material has been chosen for the reason to point out the differences at lower and higher heat input because of its higher quench capability, what is obvious from higher Pcm value in comparison with base material.*

In previous researches /8/, where commercial welding material (with 1% Ni) was used, with Pcm = 0,149 and where welding was also carried out without preheating, visible LBZ have appeared on fractured CTOD specimen surfaces in as-welded and stress relieved conditions even at + 20 degrees Celsius. Raster microscope examinations have determined more than 10% M/A structural phase. Ti-B addition in this research has been chosen for the reason to prevent or to reduce primary ferrite formation on crystral boundaries and to accelerate the acicular ferrite formation in the structure of molten weld /9/.

With such welding material selection the influence of coarse grain in primary ferrite on molten weld toughness was expelled. The aim of the examination was to find out the influence of M/A phases concerning their composition (high C(, size, orientation and density on fracture toughness of the molten weld depending on its cooling speed and chemical composition /10,11/. Another aim was to find the influence of stress relieving on the disintegration of M/A phases in the molten weld.

***Table 1:** Properties of material used*

Base material properties					
Thickness /mm/	*R_e /MPa/*	*R_m /MPa/*	*δ_5 /%/*	*Toughness −60°C /J/*	*CTODI, −40°C /mm/*
30	*432*	*528*	*25*	*198,161,149*	*0,51*
Chemical composition					
0,08C	*0,30Si*	*1,11Mn*	*0,006S*	*0,015P*	*0,049Nb*
0,08Sn	*0,18Ni*	*0,012As*	*0,047Al*	*Pcm = 0,149*	*CE = 0,270*
Weld metal properties					
SAW Weld.Mat.	*R_e /MPa/*	*R_m /MPa/*	*δ_5 /%/*	*Toughness −60°C /J/*	*CTOD /mm/*
OP121TT Fluxocord 35.22	*480*	*520—620*	*24*	*> 50, as welded > 35, stress rel.*	*— — —*
Chemical composition					
0,05C	*0,20Si*	*1,2Mn*	*0,04Cr*	*0,20Mo*	*0,005B*
Ti add.	*Pcm = 0,175*	*CE = 0,370*			
Chemical composition of real weld metal					
0,05C	*0,36Si*	*1,67Mn*	*0,70Cr*	*0,41Mo*	*0,025V*
0,031Ti	*0,023Al*	*0,04Sn*	*0,04Sb*	*0,006B*	*0,007As*
0,009S	*0,020P*	*0,022Nb*			
Pcm = 0,246	*CE = 0,557*	*O_2 = 227ppm*	*HD < 2,6 ml /100 g*		

3.2. Welding of test plates and specimen preparation

A welding technique with more passes was used on double-V grooved steel plate. For the root weld accomplishment a ceramic insert was used. There were two

Po varjenju je bila polovica vsake plošče napetostno odžarjena pri 580°C v času 3 ur, nekaj izrezanih preizkušancev pa še pri 650°C ter s kombinirano termično obdelavo. Preizkušanci so bili izrezani iz zvarnega spoja v izhodnem in napetostno odžarjenem stanju. Pripravljeni so bili metalografski preizkušanci, žilavostni preizkušanci zarezani v krovni in korenski legi ter CTOD preizkušanci iz celotne debeline; vsi zarezani pravokotno na površino plošče v sredini staljenega zvara.

3.3. Udarna in lomna žilavost staljenega zvara

Udarni Charpijevi preizkušanci so bili pretežno odvzeti iz krovne lege zvara in preizkušani v izhodnem in različno termično obdelanih stanjih. Namen je bil ugotoviti vpliv M/A strukturnih faz na udarno žilavost. Nekaj preizkušancev je bilo odvzetih iz korenskega dela zvara z namenom ugotoviti vpliv Nb, ki se je izcejal iz osnovnega materiala v zvar ter ugotoviti, ali je prisotna termična reverzibilna krhkost. Rezultati za udarno in lomno žilavost staljenega zvara v izhodnem stanju, zvarjenega z in brez predgrevanja, so dani v **tabeli 2.**

Tabela 2: Udarna žilavost in vrednosti za CTOD

Stanje	Lokacija zareze	Temperatura /°C/	Žilavost /J/	CTOD /mm/	Trdota /HV5/
1.	2.	3.	4.	5.	6.
Brez predgrevanja, varjeno	krovni sloj, korenski sloj	+20 −20 +20	92 50 88	—	274
	celotna debelina	+20 0 −20		$0{,}148-\sigma_u$ $0{,}094-\sigma_c$ $0{,}064-\sigma_c$	
Brez predgrevanja, žarjeno 580°C	krovni sloj, korenski sloj	+20 −20 +20 −20	72 24 20 8		
	celotna debelina	+20		$0{,}034\sigma_c$	
Brez predgrevanja, žarjeno 650°C	krovni sloj	−20	23		260
Predg. in varjeno	krovni sloj	−20	65		257
Predg. in žar. 580°C	krovni sloj	+20 −20	103 29		
Predg. in žar 650°C	krovni sloj	+20 −20	114 42		236
Brez predgrevanja, varjeno Ref /8/, 1% Ni	krovni sloj	−20	78		
	celotna debelina	+20 0 −20		$0{,}420-\sigma_u$ $0{,}062-\sigma_c$ $0{,}091-\sigma_c$	
Brez predgrevanja, žarjeno, 580°C, Ref. /8/, 1% Ni	krovni sloj	−20	65		
	celotna debelina	+20 0 −20		$0{,}323-\sigma_u$ $0{,}103-\sigma_c$ $0{,}062-\sigma_c$	

test plates prepared, welded with two different technologies; A-without preheating and B-with preheating.

Welding data:

plate thickness	*— 30 mm*
preheating	*— without (A), 150°C (B)*
heat input	*— 15 KJ/cm*
$\Delta t_{8/5}$	*— 5,4 s (A), 10,5 s (B)*
interpass temp.	*— 50oC (A), 200°C (B)*
heating after welding	*— 200°C*

After welding each half of the plate was stress relieved at 580°C in a period of 3 hours but some specimens were heated to 650°C with combinated heat treatment. Test samples were cut from the weld in as welded and stress relieved condition . Test specimens were cut out for metallographic examination, toughness, notched in face and root area of the weld, and CTOD specimens form the whole weld thickness, all notched perpendiculary on the plate surface with the notch location in the middle of the molten weld.

3.3. Notch and fracture toughness of the molten weld metal

Table 2: *Notch toughness and CTOD values*

Condition	*Notch location*	*Temperature /°C/*	*Toughness /J/*	*CTOD /mm/*	*Hardness /HV5/*
1.	*2.*	*3.*	*4.*	*5.*	*6.*
Without preheat., as welded	*face weld* *root weld*	*+20* *−20* *+20* *−20*	*92* *50* *88* *16*	—	*274*
	whole thickness	*+20* *0* *−20*		$0{,}148-\delta_u$ $0{,}094-\delta_c$ $0{,}064-\delta_c$	
Without preheat., heated, 580°C	*face weld* *root weld*	*+20* *−20* *+20* *−20*	*72* *24* *20* *8*		
	whole thickness	*+20*		$0{,}034-\delta_c$	
Without preheat., heated, 650°C	*face weld*	*−20*	*23*		*260*
Preheated as welded	*face weld*	*−20*	*65*		*257*
Preheated heated 580°C	*face weld*	*+20* *−20*	*103* *29*		
Preheated heated 650°C	*face weld*	*+20* *−20*	*114* *42*		*236*
Without preheat., as welded, Ref. /8/, 1% Ni	*face weld*	*−20*	*78*		
	whole thickness	*+20* *0* *−20*		$0{,}420-\delta_u$ $0{,}062-\delta_c$ $0{,}091-\delta_c$	
Without preheat., heated, 580°C, Ref. /8/, 1% Ni	*face weld*	*−20*	*65*		
	whole thickness	*+20* *2* *−20*		$0{,}323-\delta_u$ $0{,}103-\delta_c$ $0{,}062-\delta_c$	

Za primerjavo so dani rezultati iz reference /8/, kjer je bil uporabljen komercialni dodajni material (1% Ni). Varjeno je bilo z isto nizko vnešeno toploto in brez predgrevanja kakor pri tej preiskavi. Tudi v tem primeru so se pojavila vidna LKP na preloma vrednosti, dobljene pri CTOD preizkusu ob pojavu "pop-in" efekta, so uporabljene različne oznake. Za nastop "pop-in" efekta po počasni rasti razpoke je oznaka (σu), za nastop "pop-in" efekta takoj za otopitvijo razpoke pa (σ_c). Občutljivost na popuščno reverzibilno krhkost /13/ se je določala z Watanabe faktorjem J /14/ in z udarno žilavostjo; rezultati so dani v **tabeli 3.**

Tabela 3: Popuščna krhkost, določana z udarno žilavostjo

Tehnologija varjenja	Brez predgrevanja			Predgrevanje na 150° C		
	Vmesna temp. 50° C			Vmesna temp. 200° C		
Termična obdelava*	Lokacija zareze	T /°C/	Žilavost /J/	Lokacija zareze	T /°C/	Žilavost /J/
550° C	krovna lega, krovna lega, korenska lega	+20 −20 −20	72 23 10	krovna lega, krovna lega, —	+20 −20 —	103 30 —
550° C + 750° C	krovna lega	−20	55	krovna lega	+20	108
550° C + 710° C + 550° C	krovna lega	−20	30	krovna lega	+20	86

*Pri vsaki temperaturi po 4 ure;
Watanabe faktor $J = (Si + Mn) + (P + S) \times 10^4$; v našem primeru je $J = 512$

Za $J = < 200$ je nizka občutljivost na reverzibilno popuščno krhkost

Za $J = > 400$ je visoka občutljivost na reverzibilno popuščno krhkost

3.4. Metalografske preiskave z optičnim in vrstičnim mikroskopom

Preiskave so bile opravljene na metalografskih obrusih, odvzetih iz plošč, varjenih brez in s predgrevanjem. **Sliki 1 in 2** prikazujeta stebričaste dendrite z drobno intragranularno strukturo in nizko vsebnostjo ferita po kristalnih mejah v staljenem zvaru, zavarjenem brez predgrevanja. Drobna struktura, posneta z vrstičnim mikro-

Slika 1
Brez predgrevanja.

Fig. 1
Without preheating.

Notch toughness specimens were mostly cut out from face area and tested in as welded and different heat treated conditions. The aim was to find out the influence of M/A structural phases on notch toughness. Some specimens were cut out from root area with the aim to find out the influence of Nb, segregated from the base material to the weld and also if the reversible temper embrittlement is present. The result of notch and fracture toughness of the molten weld metal in as welded condition and welded with and without preheating are shown in ***Table 2.***

For comparison, the results from the reference /8/ are given, where the commercial welding material (1% Ni) was used. Welding was carried out with the same low heat input energy and without preheating as in this examination. In this case visible LBZ on the fractured surfaces of the specimen also appeared at +20 degrees Celsius Different designations are used for the CTOD values at "pop-in" effect appearance. At "pop-in" effect appearance, after the slow crack growth, the designation (δ_u) is used and designation (δ_c) at "pop-in" effect appearance immediately after the crack tip is blunted. The sensitivity on reversible temper embrittlement /13/ was determined with Watanabe factor J /14/ and with notch toughness; the results are shown in ***Table 3.***

Table 3: *Temper embrittlement determined with notch-toughness*

Welding technology	*Without preheating*			*Preheating 150° C*		
	Interpass temp. 50° C			*Interpass temp. 200° C*		
*Heat treatment**	*Notch location*	*T /°C/*	*Toughness /J/*	*Notch location*	*T /°C/*	*Toughness /J/*
500° C	*face weld* *root weld*	*+20* *−20* *−20*	*72* *23* *10*	*face weld* *—*	*+20* *−20* *—*	*103* *30* *—*
550° C 750° C	*face weld*	*−20*	*55*	*face weld*	*+20*	*108*
550° C+ 750° C+ 550° C	*face weld*	*−20*	*55*	*face weld*	*+20*	*108*

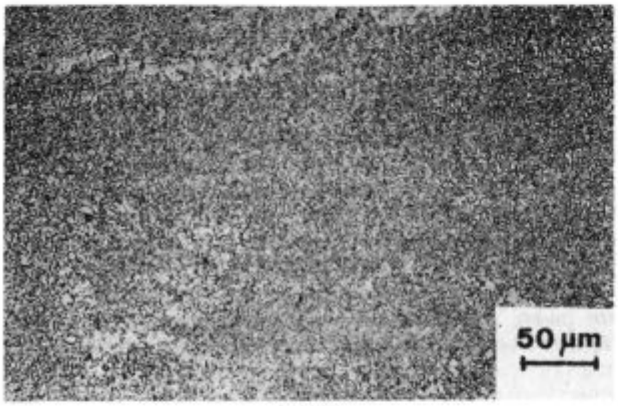
**at each temperature 4 hours;*
Watanabe factor $J = (Si + Mn) + (P + S) \times 10^4$; *in our case is* $J = 512$

For $J = < 200$ *is sensibility on reversible temper embrittlement low*

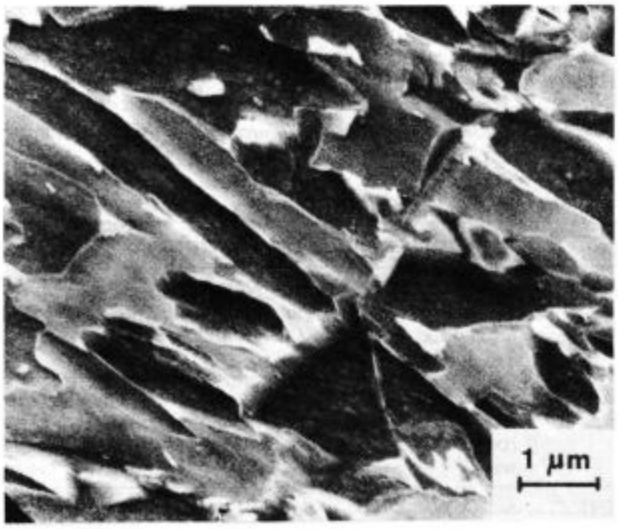
For $J = > 400$ *is sensibility on reversible temper embrittlement high*

3.4. Metallographic examinations with optic and line microscope

Metalographic specimens were cut out and examined from steel plates, welded without and with preheating. ***Fig. 1*** *and* ***Fig. 2*** *show columnal dendrites with fine intragranular structure and low ferrite content on crystal boundaries in the molten weld, welded without preheating. Fine structure taken off with a line microscope in the face weld area is shown in* ***Fig. 3****; oblong M/A phases along intragranular precipitated ferrite are visible.* ***Fig. 4*** *shows the microstructure after stress relieved heating; several cementite precipitations on the boundary between M/A phase and ferrite are perceived. Microstructure of the molten weld, welded with preheating is shown in* ***Fig. 5****; there are less M/A phases and or-*

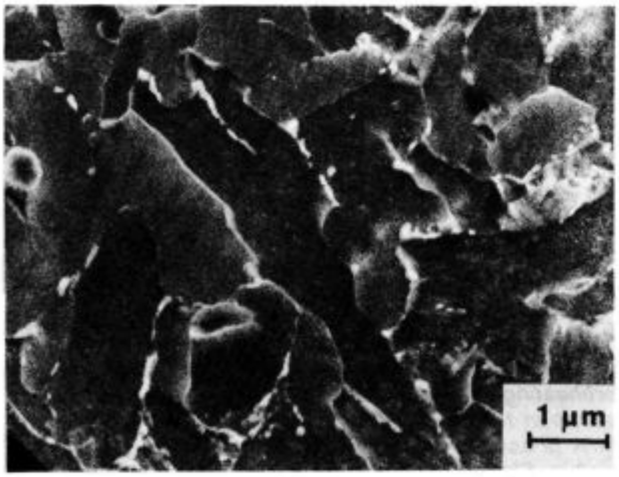


Slika 2
Ista struktura kot slika 1.
Fig. 2
The same structure as in Fig. 1.



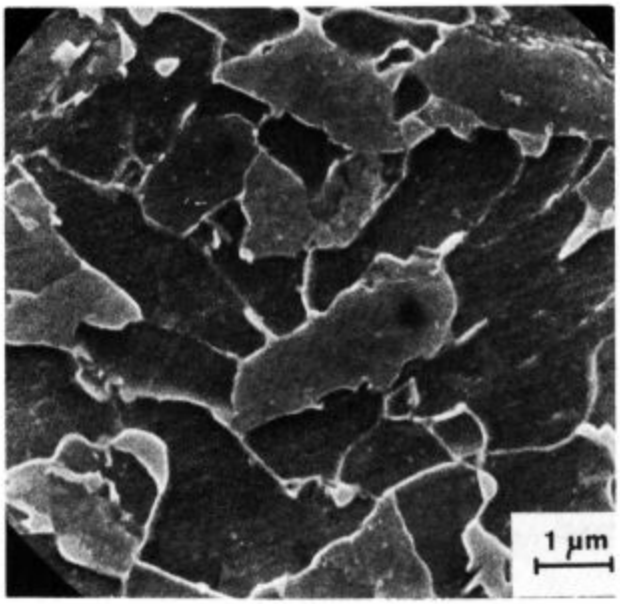
Slika 3
SEM mikrostruktura zvara, brez predgrevanj.

Fig. 3
SEM microstructure of the weld, without preheating.



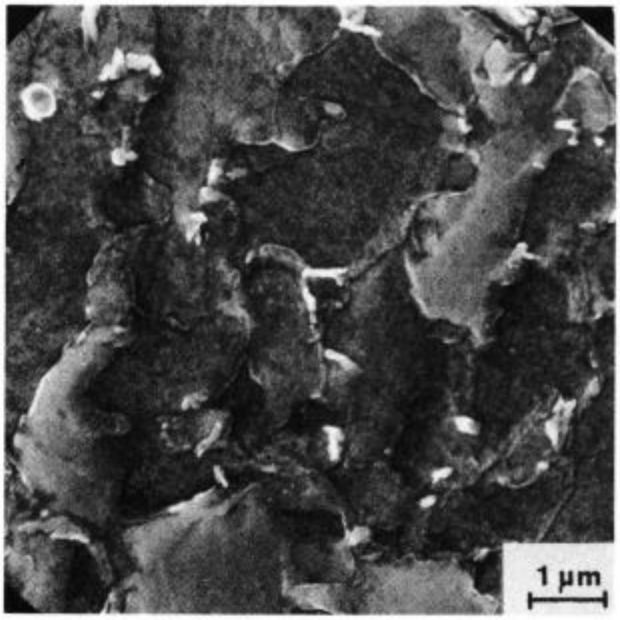
Slika 4
Ista struktura - nap. žarjeno pri 580 °C.

Fig. 4
The same structure - stress - relieved heated at 580 °C.



Slika 5
SEM mikrostruktura zvara, s predgrevanjem.

Fig. 5
SEM microstructure of the weld, with preheating.

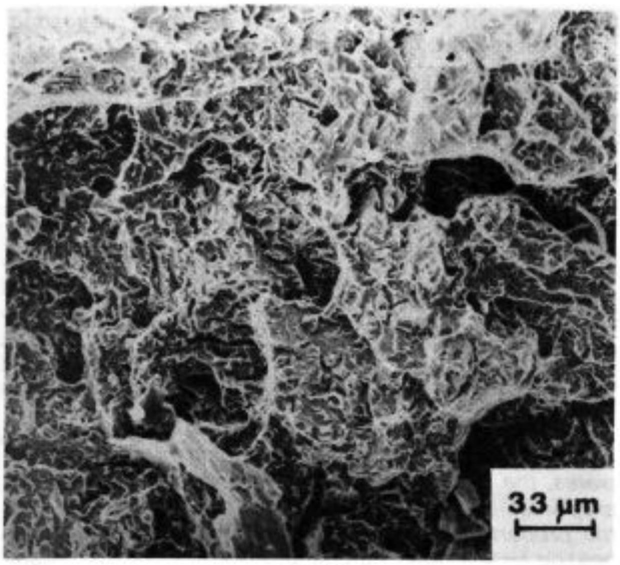


Slika 6
Ista struktura - nap. žarjena pri 580 °C.

Fig. 6
The same structure - stress - relieved heated at 580 °C.

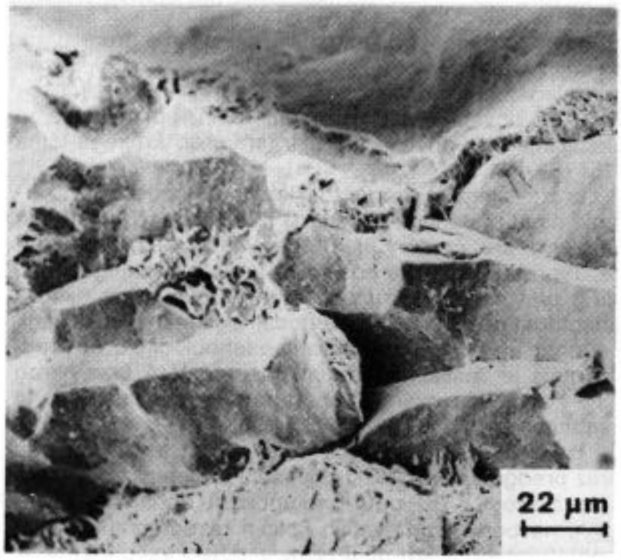
ientation is less distinctive. The same microstructure after stress-relieved heating is shown in ***Fig. 6****; a strong tendency of cementite coagulation is visible.*

The examination of LBZ areas has detected a quasi brittle fracture in the fractured area of the specimen in as-welded condition - ***Fig. 7.*** *The fracture area of stress relieved specimen shows besides the quasi brittle fractures also the presence of intergranular brittleness along the columnar dendrites as it is shown in* ***Fig. 8.***



Slika 7
LKP - kvazi krhki transkristalni prelom.

Fig. 7
LBZ - quasi brittle transcrystal fracture.



Slika 8
LKP - intergranularni krhki prelom.

Fig. 8
LBZ - intergranular brittle fracture.

skopom v krovni legi, je razvidna iz **slike 3**; vidne so podolgovate M/A faze vzdolž intragranularno izločenega ferita. Mikrostruktura po napetostnem žarjenju je razvidna iz **slike 4**; zaznavni so številni cementitni izločki na meji med M/A fazo in feritom. Mikrostruktura staljenega zvara, zavarjenega s predgrevanjem, je razvidna iz **slike 5**; M/A faz je manj in usmerjenost je manj izrazita. Ista mikrostruktura po napetostnem žarjenju je razvidna iz **slike 6**; vidna je tendenca močnega skepljanja cementita.

Pregled površin LKP je odkril kvazi krhki lom v prelomu preizkušanca v izhodnem stanju — **slika 7.** Površina preloma v napetostno žarjenem preizkušancu je poleg kvazi krhkega preloma pokazala še nastop intergranularne krhkosti vzdolž stebričastih dendritov, kot je razvidno iz **slike 8.**

4. DISKUSIJA REZULTATOV

Preiskave so pokazale bistveno razliko v udarni Charpijevi žilavosti med osnovnim materialom in staljenim zvarom. Kljub dodatkom Ti-B in ugodni vrednosti O_2 (ca. 227 ppm) v zvaru, ki pospešuje tvorbo acikularnega ferita in preprečuje tvorbo primarnega ferita, je bila dosežena udarna žilavost nižja od pričakovane. Lomna žilavost v prisotnosti ostre utrujenostne razpoke pa je pokazala popolno krhkost že pri temperaturah pod 0°C. Vzrok za to je varjenje brez predgrevanja in z nizko dovedeno toploto. Posledica tega je tvorba drobne mikrostrukture, ki vsebuje ferit s sekundarno fazo v obliki M/A strukturne faze namesto acikularnega ferita. Dodatki Cr, Mo in Nb težijo k pospeševanju tvorbe M/A faze, v kateri vsebnost C naraste tudi nad 1% /10/. Razpotegnjene M/A faze vzdolž intrgranularno izločenega ferita so lahko potencialni izvori zgodnjega začetka loma in zato nizke žilavosti. Dodatek Nb in njegovo izcejanje (0,04% v korenu in 0,01% v temenu) imata bistveni vpliv na udarno žilavost.

Kemična sestava staljenega zvara je povišala Watanabe faktor $J > 400$, tako da je posledica pojava popuščne reverzibilne krhkosti (Sl. 8). Zaradi navedenega ni iz-

4. RESULTS DISCUSSION

The examinations have shown the essential differences in Charpy toughness values of the base material and the molten weld. In spite of Ti-B additions and favourable oxygen content (ca. 227 ppm) in the weld, accelerating the acicular ferrite formation and prevention of primary ferrite formation, the notch-toughness values achieved were lower as it was expected. But the fracture toughness in the presence of sharp fatigue crack has shown the absolute brittleness also at temperatures under 0 degree Celsius. The reason is welding without preheating and with low heat input energy. The result is formation of the fine microstructure containing ferrite with secondary phase in the shape of M/A structural phase in state of acicular ferrite. The addition of Cr, Mo and Nb has a tendency of M/A phase formation in which the carbon content can rich the values greater than 1 % /10/. Oblong M/A phases along the intragranular precipitated ferrite can be the potential sources of early fractures beginning and the reason for low toughness values.

Chemical composition of the molten weld has increased the Watanabe factor $J= > 400$*, so that it results in the reversible temper embrittlement appearance /8/. That is the reason why there is no toughness improvement at heating above 650 degrees Celsius where the causes for temper embrittlement are dissolving, on the other side an intensive precipitating of* Fe_3C *appears on the boundary between oblong ferrite and M/A phase. The size of* Fe_3C *precipitates are increasing with elevated temperature under the coagulation mechanism what is the reason for brittle fracture at elevated temperature /15/ (Fig. 4).*

From the above we can conclude, that stress-relieved heating does not have a favourable effect on molten weld toughness if M/A structural phases are present into it. M/A phases formation is a consequence of too high alloyment or/and too high cooling speed, so that their presence depends on the weld material selection and welding technology. Using the welding technology without preheating the content of M/A structural phase boljšanja žilavosti po segrevanju nad 650°C, kjer se povzročitelji za popuščno krhkost raztapljajo, na drugi strani pa se hkrati pojavi intenzivno izločanje Fe_3C na meji med razpotegnjenim feritom in M/A fazo. Velikost izločkov Fe_3C se povečuje s povišanjem temp. po mehanizmu skepljanja, kar privede pri višji temp. do krhkega loma /15/ (Sl. 4).

Iz zgornjega je mogoče sklepati, da napetostno žarjenje nima ugodnega učinka na izboljšanje žilavosti staljenega zvara, če so v njem prisotne M/A strukturne faze. Tvorba M/A faz je posledica previsoke nalegiranosti ali/in previsoke hitrosti ohlajevanja, tako da je njihova prisotnost odvisna od izbire dodajnega materiala in varilne tehnologije. Pri uporabi varilne tehnologije brez predgrevanja je znašala vsebnost prisotne M/A faze okrog 38% v staljenem zvaru. Z uporabo predgrevanja se je ta vsebnost znižala na okrog 33%.

Iz raziskave je mogoče sklepati, da je pri varjenju brez predgrevanja in nizki dovedeni toploti za dosego visoke žilavosti v TVP potrebno uporabiti dodajne materiale, ki ne bodo tvorili večjih količin razpotegnjenih M/A faz. Navedeno lahko dosežemo z nižjimi vsebnostmi Si, Al, Cr in Mo in z dodatki Ti-B, ki pospešujejo tvorbo aciularnega ferita. Na drugi strani je podoben efekt mogoče doseči z uporabo predgrevanja in višjo dovedeno toploto ne glede na prisotnost omenjenih legirnih elementov. Vendar je takšna varilna tehnologija uporabna le, če izberemo jeklo, ki ni občutljivo na rast zrna, ker bomo v nasprotnem primeru dobili nizke vrednosti za žilavost v TVP. Omenjena moderna jekla so izdelana na osnovi TiN in BN izločevalnih efektov s vsebnostjo raztopljenega N pod 10 ppm.

Pri varjenju preizkusnih plošč se vmesna temperatura visoko dvigne in lastnosti staljenega zvara niso primerljive z lastnostmi na dejanskem zvarnem spoju, ki je narejen brez predgrevanja ali z nizkimi $\Delta t^{8/5}$ časi. Namesto da bi se varilo brez predgrevanja, dejansko varimo plošče z visokim predgrevanjem (često >200°C).

Takšni rezultati niso uporabni za varjenje brez predgrevanja na dejanskih zvarnih spojih, kjer se zaradi dolgih zvarov in velikih površin vmesna temperatura zniža oz. pade celo na sobno. Takšen varilni postopek lahko znatno vpliva na žilavost izhodnih zvarnih spojev in tako na varnost celotne zavarjene konstrukcije. Torej je navedeno vzrok za pazljivo in temeljito izbiro verifikacije varilne tehnologije, ki mora odgovarjati dejanskim pogojem pri izvedbi varjenja v delavnici in na montaži.

5. ZAKLJUČEK

Preiskava EPP zavarjenih raztaljenih zvarov, ki so zavarjeni brez predgrevanja in z nizko dovedeno toploto z uporabo več varkov na nizko ogljičnem finozrnatem jeklu, je odkrila naslednje:

— Udarna in lomna žilavost raztaljenega zvara je odvisna od izbire dodajnega materiala in varilne tehnologije.

— Pri varjenju in preizkušanju zavarjenih plošč morajo biti izpolnjeni pogoji, ki bodo reprezentirali dejanske pogoje v delavnici in na montaži.

— Varilna tehnologija brez predgrevanja in z nizko dovedeno toploto, da bi dosegli dobre žilavostne lastnosti v TVP, lahko povzroči v raztaljenem zvaru v zrnih s primarnim feritom po kristalnih mejah in intragranularnim feritom s sekundarno fazo tvorbo krhkih M/A faz, ki lahko znatno znižajo žilavost. Odločitev, ali uporabiti predgrevanje ali ne, je odvisna od ekvivalenta Pcm osnovnega in staljenega zvara in pričakovanih lastnosti.

in molten weld was 38 %, while with using the preheating this content was decreased to ca. 33 %.

From this examination we can conclude that for welding without preheating and low input energy to achieve high toughness in HAZ it is necessary to use welding materials which will not form higher quantities of oblongated M/A phases. We can achieve that with lower contents of Si, Al, Cr and Mo and with additions of Ti-B, which accelerate the acicular ferrite formation. On the other side we can achieve a similar effect with the use of preheating and higher heat input energy regardless to above mentioned alloying elements. But such welding technology is useful only if we choose steel which is not sensible to grain growth because in the opposite case we will get low toughness values in the HAZ. The above mentioned modern steels are produced on the base of TiN and BN precipitation effects with the nitrogen content under 10 ppm. During the welding of experimental plates, the interpass temperature raise high up and the properties of the molten weld are not comparable with the properties of the actual weld welded without preheating or with low $\Delta t8/5$ *time. Instead of welding without preheating we actually weld them with high preheating (often > 200 degrees Celsius).*

Such results are not useful for welding without preheating on actual welded joints because of their longness and greatness the interpass temperature decreases or even falls down to room temperature. Such welding process can have a considerable effect on as welded weldments and in this way it effects on security of the whole welded construction. All that has been stated is the reason for a careful and profound choose of verification of welding technology which has to respond to actual welding conditions in the workshop and assembling.

5. CONCLUSION

The examination of SA welded molten welds, welded without preheating and with low heat input energy, with more run technique on low carbon fine grained steel has discovered the following:

— Notch and facture toughness of the molten weld depends on welding material choose and welding technology.

— During welding and testing of welded plates such conditions has to be fulfilled that can represent the actual condition in the workshop and assembling.

— Welding technology without preheating and with low heat input energy can in the molten weld in the grains with primary ferrite with secondary phase, cause the formation of brittle M/A phases, which can considerably decrease the toughness. Decission to use or not to use the preheating depends on Pcm equivalent of base metal and molten weld and on properties expected.

— By CTOD method determinated fracture toughness is otherwise conservative but gives a good insight into the quality estimation of the welded joint.

— The LBZ appearance in the molten weld on the fractured area of CTOD specimens has to be already estimated at room temperature with large test (Wide Plate Tests) with fatigue crack inserted on the surface area. Test has to be carried out at the lowest operating temperature of the future construction /16/.

— Stress releaving with heating has negative consequences because of the M/A structural phases presence. Cementite precipitation on the boundary between ferrite and M/A phase additionally decrease toughness. In the case of stress-releaved heating it is recom-

— Lomna žilavost, določana po metodi CTOD, je sicer konservativna, vendar daje dober vpogled v oceno kvalitete zvarnega spoja.

— Pojav vidnih LKP v staljenem zvaru na lomni površini CTOD preizkušancev že pri sobni temp. je potrebno oceniti z velikimi preizkusi (Wide Plate Tests) s površinsko vgrajeno utrujenostno razpoko. Preizkus je potrebno opraviti pri najnižji temp. obratovanja bodoče konstrukcije /16/.

— Termično sproščanje zaostalih napetosti ima negativne posledice zaradi prisotnosti M/A strukturnih faz. Izločanje cementita na meji med feritom in M/A fazo še dodatno zniža žilavost. V primeru uporabe napetostnega žarjenja je priporočljivo preveriti možnost pojava reverzibilne popuščne krhkosti, ki je odvisna od količine in izcej legirnih elementov ter nečistoč v raztaljenem zvaru.

mended to control the possibility of reversible temper embrittlement appearance, which depends on the quantity and segregations of alloying elements and impurements in the molten weld.

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