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ELIMINACIJA TUNELA PRI ZAVARIVANJU TRENJEM ALATOM LEGURE AL 5052-H32

AVOIDANCE OF TUNNEL TYPE DEFECT IN FSW WELDED AL 5052-H32 PLATES

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Keywords: friction stir welding, Al alloys, heat input.

Izvod

U radu su predstavljena iskustva na eliminaciji greške tunela u zavarenim spojevima dobijenih zavarivanjem ploča postupkom zavarivanja trenjem alatom na leguri Al 5052-H32. U cilju određivanja uticaja parametara zavarivanja (odnos brzine rotacije alata i brzine zavarivanja-translacije) na pojavu greške tunela i kvalitet zavarenog spoja, parametri su varirani u širokom opsegu. Zavareni spojevi su ispitivani metodama bez razaranja (vizuelno, penetrantima i rentgenski) i sa razaranjem (metalografski, zatezanje, tvrdoća i savijanje). Zavareni spojevi sa najboljim osobinama postignuti su kod spojeva zavarenih korišćenjem odnosa u opsegu od 6.45 do 8.22. Rezultati ukazuju da su to odnosi koji obezbeđuju optimalni način tečenja materijala oko trna alata, tj. da je kontinuirani dotok materijala na povratnu stranu dovoljan da homogeno popunjava prazninu i spreči pojavu kanala.

Abstract

Some experiences in elimination of tunnel type defect Friction Stir Welding of Al alloy 5052-H32 are presented in this paper. In order to evaluate the influence of the processing parameter (ratio between rotation and translation speed during welding) on the occurrence of tunnel type defects and quality of welded joint, different welding parameters were varied.

Welded joints were tested by means of both non-destructive (visual inspection, X-ray inspection) and destructive (metallographic, bending, tension and hardness) testing. Best results were obtained for the ratio between 6.45 and 8.22. Results suggest that with this ratio, the material flows around the pin with optimal speed, i.e. sufficient amount of material is available to fulfill the gap and prevent tunnel formation.

UVOD

Postupak zavarivanja trenjem alatom (FSW) obezbedjuje spajanje metala bez topljenja i korišćenja dodatnog materijala, kao što je prikazano na slici 1.

Pokazano je da se primenom ovog postupka dobijaju zavareni spojevi sa zahtevanim nivoima čvrstoće i plastičnosti, uključujući i sisteme za koje je dokazano da su teško zavarljivi uobičajenim postupcima zavarivanja topljenjem. Postupak je posebno pogodan za spajanje ploča i limova, mada je modifikovan i za zavarivanje cevi i komplikovanijih geometrija. Zavareni spoj se dobija dejstvom alata na ploče; trenje dovodi do zagrevanja ploča a alat vrši mešanje i spajanje dve ploče. Toplota se generiše na kontaktnoj površini alata i ploča usled trenja zbog rotacije i translacije alata, a spajanje vrši usled dejstva trna alata. Takođe, temperatura se dodatno povećava zbog adijabatskog zagrevanja u okolini trna. Optimalna dostignuta temperatura je oko 0,8 od temperature topljenja. Kako je ovim postupkom

INTRODUCTION

Friction stir welding (FSW) involves the joining of metals without both fusion and filler materials, as shown in figure 1.

It has been demonstrated that the process results in strong and ductile joints, sometimes in systems which have proved difficult using conventional welding techniques. The process is most suitable for components which are flat and long (plates and sheets) but can be adapted for pipes, hollow sections and positional welding. The welds are created by the combined action of frictional heating and mechanical deformation due to a rotating tool.

The heat is generated primarily by friction between a rotating--translating tool, the shoulder of which rubs against the work piece. Also, there is a volumetric contribution to heat generation from the adiabatic heating due to deformation near the pin. The maximum temperature reached is of the order of 0.8

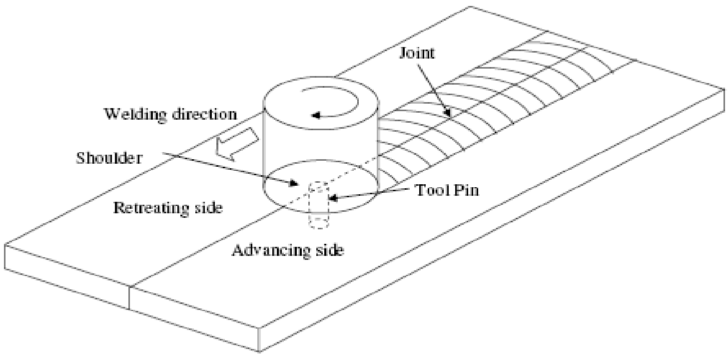
eliminisano topljenje, uobičajeni pristup ocene zavarljivosti na osnovu pojave prslina se principijelno ne koristi [1-10].

Mikrostruktura spoja dobijenog FSW postupkom značajno zavisi od konstrukcionog rešenja alata, brzine rotacije, brzine zavarivanja (translacije), pritiska alata na ploče duž vertikalne ose i karakteristika materijala koji se zavaruje. U strukturi zavarenog spoja može se identifikovati veći broj zona (slika 2): zona uticaja toplote u klasičnom smislu, (ZUT), zona termomehaničkog uticaja (TMAZ), zona grumena i osnovni metal. Centralna zona – grumen, u kojoj se mogu identifikokvati linije tečenja materijala, je zona u kojoj je najveća plastična deformacija.

of the melting temperature. Due to absence of melting, problems with conventional "cracking" approach to weldability are principally avoided [1-10].

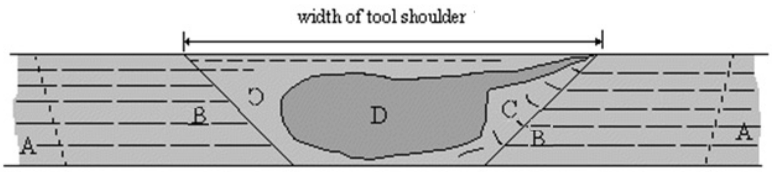
The microstructure of a friction-stir weld depends in detail on the tool design, the rotation and translation speeds, the applied pressure and the characteristics of the material being joined. There are a number of zones: the heat-affected zone (HAZ) is as in conventional welds, thermomechanically affected zone (TMAZ), nugget and base metal.

The central nugget region containing the onion-ring flow-pattern is the most severely deformed region, although it frequently seems to dynamically



Slika 1: Šematski prikaz postupka zavarivanja trenjem alatom [1]

Figure 1: Schematic view of FSW process [1]



Slika 2: Poprečni presek FSW zavarenog spoja [2] (A) osnovni metal, (B) zona uticaja toplote; (C) zona-termomehaničkog uticaja; (d) grumen

Figure 2: Cross-section of weld: zones in FSW weld joint [2] (A) Base metal; (B) HAZ; (C) TMAZ; (D) Nugget

Unutar ove zone često dolazi do dinamičke rekristalizacije [11] koja rezultuje strukturom koju karakterišu ravnoosna i sitna zrna. Slojevitost se javlja kao posledica načina na koji alat prenosi materijal sa prednje na zadnju stranu. Cilindrični slojevi se, prema tome, vezuju za ekstruziju i rotaciju kojima alat podvrgava materijal. U nekim slučajevima se, usled neusklađenosti brzine rotacije i brzine zavarivanja, može javiti greška koja se naziva tunel i koja je karakterustična za FSW. Zato je cilj ovog rada da utvrdi optimalni odnos brzine rotacije i brzine zavarivanja kako bi se dobio zavareni spoj dobrih osobina.

EKSPERIMENTALNI DEO

Mehaničke osobine legure aluminijuma Al 5052-H32 koja sadrži 2.25%Mg, 0.12%Si, 0.02%Cu, 0.27%Fe, 0,12%Mn, 0,03%Zn i 0.2Cr, ispitane u ovom radu,

recrystallize [11], so that the detailed microstructure may consist of equiaxed grains. The layered structure is a consequence of the manner in which a threaded tool deposits material from the front to the back of the weld. It seems that cylindrical sheets of material are extruded during each rotation of the tool, which on a weld cross-section gives the characteristic rings [1-10].

In some cases, due to disagreement between rotation and welding speed, typical tunnel defects can occur. Therefore, the aim of this work was to establish the optimal ratio between rotation and welding speed of the tool in order to avoid tunnel type defect and obtain the welded joint with good properties.

EXPERIMENTAL

Mechanical properties of Al alloy 5052-H32 containing 2.25%Mg, 0.12%Si, 0.02%Cu, 0.27%Fe, 0,12%Mn, date su u tabeli 1. Zavarene su ploče dimenzija 200x130x6,5mm. Alat je napravljen od alatnog čelika sa profilisanom glavom i koničnim trnom.

Dužina zavarivanja je oko 150mm. Brzina zavarivanja (translacije - v_{wel}) je bila u opsegu 46 - 380 mm/min, a brzina rotacije (v_{rot}) između 450 i 1500 obrtaja u minutu. Rad u ovim opsezima je omogućio dobijanje odnosa dve brzine v_{rot} / v_{wel} između 3,16 i 32,6.

U cilju otkrivanja površinskih i/ili unutrašnjih grešaka, zavareni spojevi su ispitani vizuelno, penetrantima i rentgenskim zracima. Dalja ispitivanja su rađena isključivo na uzorcima kod kojih nisu registrovane greške.

Ona su obuhvatala određivanje makrostrukture i mikrostrukture optičkom mikroskopijom, merenje tvrdoće po Vikersu HV3, ispitivanja zatezanjem (prema ASTM E-8M) i ispitivanje savijanjem. Kompletna procedura ispitivaanja je data u tabeli 2.

0,03%Zn and 0.2Cr, tested in this work are given in Table 1. Welded plates were dimensions of 200x130x6.5mm. Tool used for the welding was made of tool steel, with profiled head and conical pin. The slope of the tool was 1° and was kept constant.

Welding distance was close to 150 mm on each pair of plates. Welding speed (v_{wel}) was varied between 46 and 380 mm/min, while rotation speed (v_{rot}) was between 450 and 1500 rpm. This range of values have enabled obtaining the ratio v_{rot} / v_{wel} between 3,16 and 32,6.

In order to reveal presence of surface and/or volume defects, welded joints were subjected to visual, penetrant and X-ray examination. Further examination was performed only on specimens that had no defects, and have consisted of revealing macro and microstructure on optical microscopes and tensile testing (in agreement with ASTM E-8M standard), Vickers hardness HV3 (in agreement with SRPS C.T3.051) and bending testing. Complete testing methodology of welded joints is given in Table 2.

Tabela 1: Mehaničke osobine Al legure 5052-H32

Table 1: Mechanical properties of Al alloy 5052-H32

R_{p02}, MPa	Rm, MPa	A, %	HV
175	232	21,8	69

Tabela 2: Metodologija ispitivanja zavarenog spoja

Table 2: Testing methodology of welded joints

Ispitivanje bez razaranja Non destructive testing	Korak 1 Step 1	Vizuelno ispitivanje Visual examination
	Korak 2 Step 2	Ispitivanje penetrantima Penetrant examination
	Korak 3 Step 3	Ispitivanje rentgenom X-ray examination
Ispitivanje sa razaranjem Destructive testing	Korak 4 Step 4	Ispitivanje makrostrukture Evaluation of macrostructure
	Korak 5 Step 5	Ispitivanje mikrostrukture Evaluation of microstructure
	Korak 6 Step 6	Ispitivanje zatezanjem Tension testing
	Korak 7 Step 7	Ispitivanje tvrdoće Hardness testing

REZULTATI I DISKUSIJA

Tipični izgled zavarenog spoja i poprečni presek dobijen pri različitim odnosima urot / uzav prikazani su na slikama 3 i 4. U nekim slučajevima tunel je vidljiv i golim okom (slika 3a), dok je u drugim otkriven ili penetrantskim (slika 3b) ili rentgenskim ispitivanjem (slika 3c). Na slici 3d je prikazan uzorak bez grešaka.

Greška tunel se pojavljuje u slučajevima neadekvatnog tečenja materijala sa vodeće na

RESULTS AND DISCUSSION

Typical macroscopic view of welded joints and cross sections obtained in tests with different $\upsilon_{rot} / \upsilon_{zav}$ ratios are shown in figure 3 and 4. In some cases these defects were visible by naked eye (figure 3a), while in prateću stranu oko trna. Ovo ponašanje se najčešće dovodi u vezu sa velikom brzinom zavarivanja (translacije) [1,12]. Pojava tunela načelno se može eliminisati ili smanjenjem brzine zavarivanja ili modifikacijom alata [8,9].

Rezultati ukazuju da se zavareni spoj sa zahtevanim osobinama dobija kada odnos brzine rotacije i brzine zavarivanja leži u opsegu izmedju 6.45 i 8.22, što je u saglasnosti sa ranije publikovanim rezultatima [1,12,13].

Dalja ispitivanja su bila ograničena samo na ove spojeve. Na slici 5 prikazana je karakteristična mikrostruktura pojedinih zona zavarenog spoja dobijenog zavarivanjem sa odnosom 6.45. Zatezna čvrstoća , izduženje i efikasnost zavarenog spoja (odnos zateznih čvrstoća zavarenog spoja i osnovnog metala) dati su u tabeli 3.

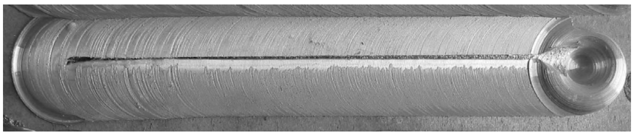
Vrednosti zatezne čvrstoće zavarenih spojeva ukazuju da je efikasnost zavarenih spojeva između

some cases they were revealed after penetrant (figure 3b) or radiographic examination (figure 3c). Defect free sample is presented on figure 3d.

Tunnel defects occur in the case when the material flow from following to leading side around the pin is not adequate, i.e. when welding (translation) speed is very high [1,12]. This behaviour can be eliminated either by decrease of the welding speed or by modification of tools geometry [8,9].

Results indicates that optimal results are obtained when the ratio $\upsilon_{rot} / \upsilon_{wel}$ lies between 6,45 and 8,22. In that respect, results obtained in this work are in good agreement with previously published data [1,12,13].

These results have directed further testing only to these ratios. Set of figures related to microstructural examination of weldments obtained for ratio v_{rot} / v_{wel} = 6,45 is given in figure 5. Ultimate Tensile Strength, Elongation and joint efficiency ($Rm_{weldment}$ / $Rm_{base\ metal}$) of welded joints are given in Table 3.



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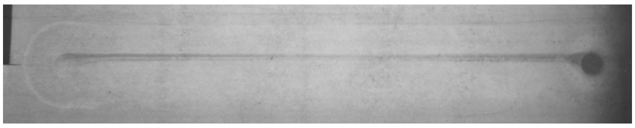

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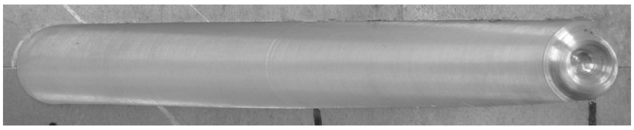
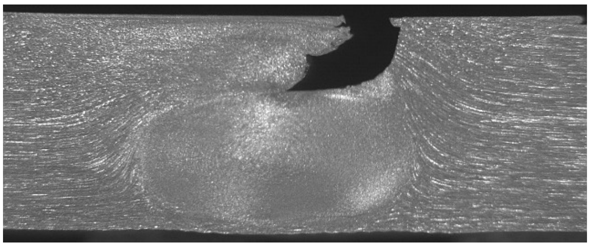


d)

Slika 3: FSW na leguri Al 5052-H32- Greška tunel: (a) vidljiva golim okom; (b) otkrivena pentrantima;(c) otkrivena radiografijom;(d) bez greške)

Figure 3: FSW of 5052-H32 Alloy - Tunnel defect: (a) visible by naked eye; (b) revealed by penetrant; (c) revealed by radiographic examination; (d) joint without defect



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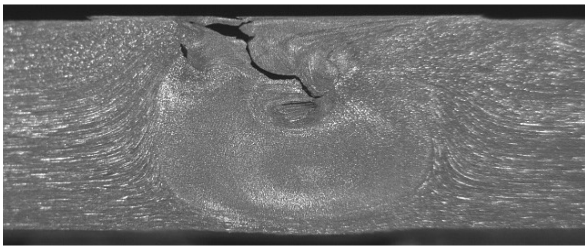

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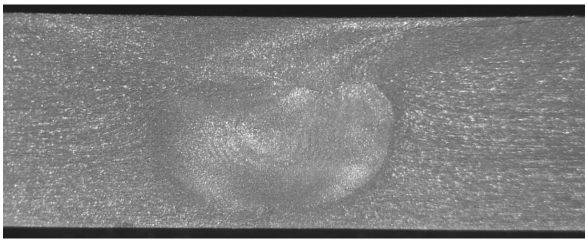


c)

Slika 4: Makrostruktura FSW zavarenog spoja: (a) prisustvo tunela nastalog na kontaktu grumena i zone termomehaničkog uticaja; (b) tunel nastao u grumenu i (c) spoj bez prisustva tunela

Figure 4: Macrostructure of FSW weld joint; (a) tunnel in contact nugget-TMAZ; (b) tunnel in nugget and (c) no present defects

70% i 80%. Ova efikasnost je zadovoljavajuća i u saglasnosti sa mišljenjima da se kod zavarivanja FSW postupkom ostvaruje efikasnost spoja koja je veća u odnosu na konvencionalne postupke topljenjem [1,3,5,12,14].

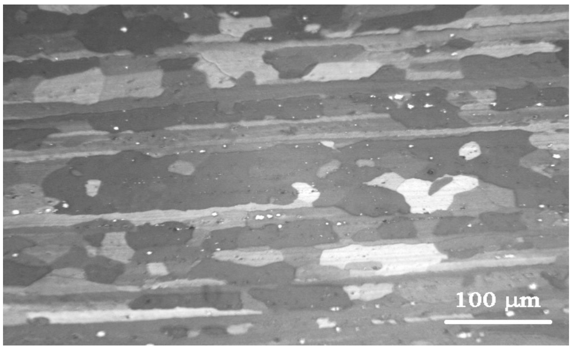
Do nastanka prsline koja je dovela do loma dolazilo je unutar zone termomehaničkog uticaja na vodećoj strani, veoma blizu samog grumena.

U svim slučajevima površina preloma ima izgled tipičan za duktilni lom, slika 6. Prslina je rasla duž linije kontakta između grumena i zone termomehaničkog uticaja. Pretpostavljeno je da je ovo ponašanje ponovo uslovljeno načinom tečenja materijala oko trna, tj. da je u pitanju isti fenomen koji dovodi do stvaranja tunela, samo da u ovom slučaju nije naglašen.

Obtained values for UTS show that mostly in all cases is the ratio obtained for weld joint and base metal are between 70% and 80%. This is in very good agreement with the expectation that FSW joints should have greater ratio in comparison to joints welded using traditional techniques [1,3,5,12,14].

Crack initiation in all cases was in the thermo-mechanically affected zone on the leading side, very close to the nugget.

In all cases, the fractured surface had typical appearance of ductile fracture, fig.6. Crack propagated along the line contact between nugget and thermo-mechanically affected zone. It is assumed that this behavior can be again related to the materials flow close to pin, i.e. probably the same feature that can introduce tunnel type defects.



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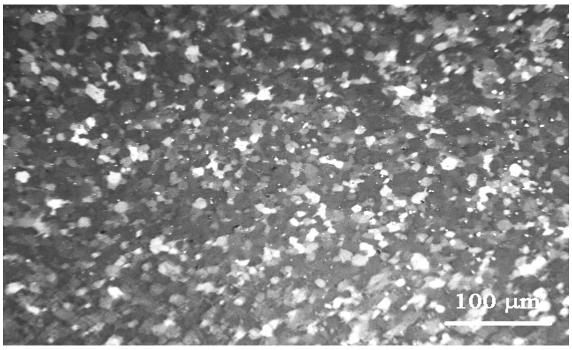

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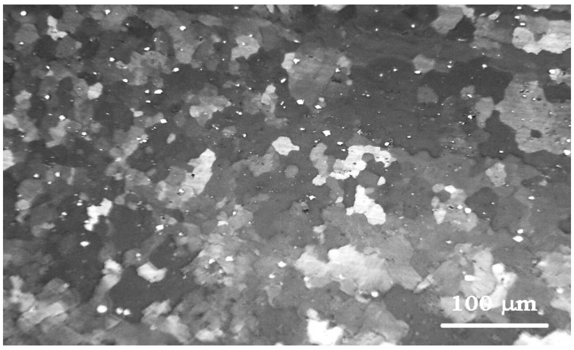

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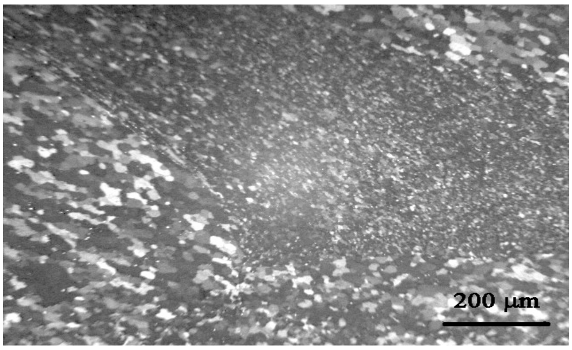

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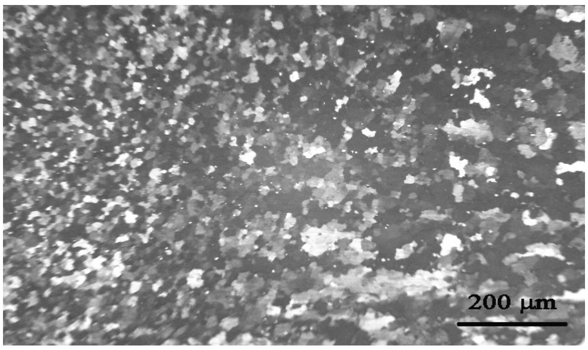


e)

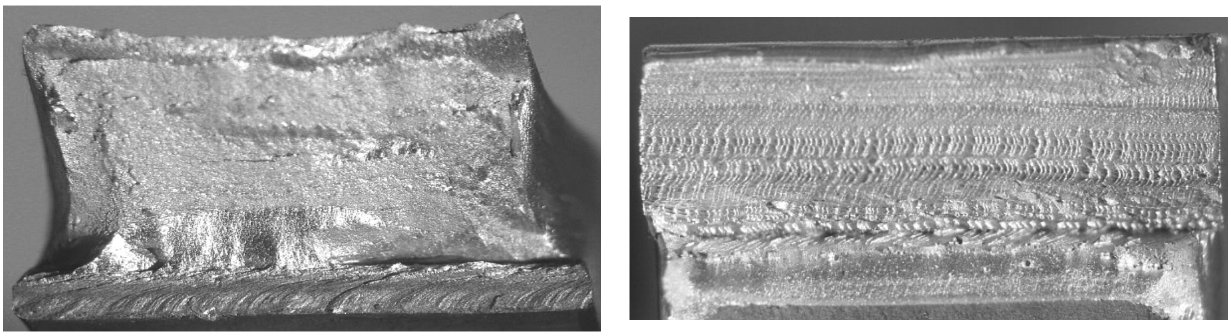
Slika 5: Karakteristične mikrostrukture zavarenog spoja dobijenog pri odnosu v_{rot} / v_{wel} = 6,45: (a) osnovni metal; (b) grumen; (c) zona termomehaničkog uticaja; (d) linija kontakta grumen - zona termomehaničkog uticaja na povratnoj strani i (e) linija kontakta grumen - zona termomehaničkog uticaja na vodećoj strani

Figure 5: Typical microstructures in welded joint obtained at ratio v_{rot} / v_{wel} = 6,45: (a) Base metal; (b) Nugget; (c) TMAZ; (d) Contact line nugget-TMAZ retreating side and (e) Contact line nugget-TMAZ leading side

Tabela 3: Results of tensile testing

Table 3: Testing methodology of welded joints

Ratio v_{rot} / v_{wel}	Rm (MPa)	A (%)	Joint efficiency (%)	Place of fracture
6,45	181	13,20	78,0	TMAZ leading side
	152	9,00	65,5	
	166	7,20	71,5	
	180	12,50	77,6	
Average	170	10,47	73,1	
8,06	183	7,00	78,9	TMAZ leading side
	183	7,80	78,9	
	156	4,00	67,2	
	113	2,90	48,7	
Average	159	5,43	68,4	
8,22	183	9,80	78,9	TMAZ leading side
	180	7,00	77,6	
	186	11,50	80,1	
	179	7,10	77,1	
	181	7,40	78,0	
Average	182	8,56	78,4	



a) b)

Slika 6: Izgled prelomljene površine uzoraka zavarenih pri odnosu v_{rot} / v_{wel} = 8,22, ispitanih zatezanjem (a) duktilni prelom i (b) linije tečenja

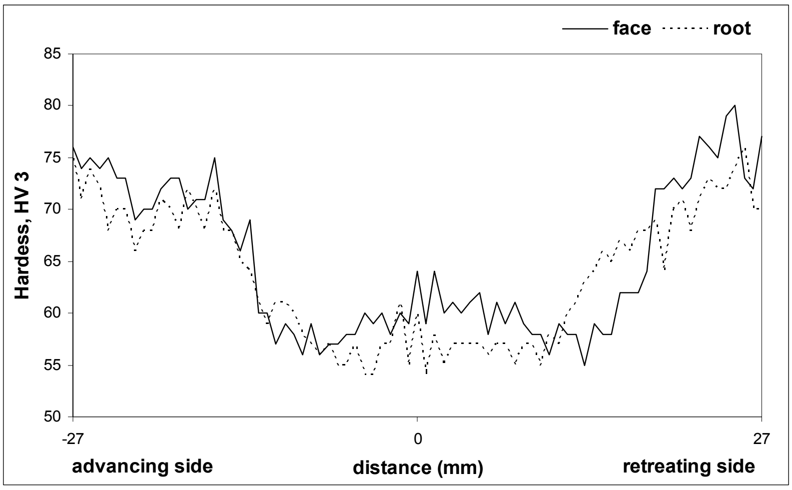
Figure 6: Fractured surface of tension specimen in welded joint obtained at ratio v_{rot} / v_{wel} = 8,22: (a) surface typical for ductile fracture; (b) influence of pin at materials flow

Raspodela tvrdoće u zavarenom spoju u dobroj je korelaciji sa prisutnim mikrostrukturama, slika 7. Najviše vrednosti tvrdoće zabeležene su u ZUT-u i zoni termomehaničkog uticaja. Pretpostavljeno je da je ovo ponašanje posledica termomehaničke prerade i zagrevanja usled trenja koja mogu dovesti do rekristalizacije.

Tako je efekat najveći u zoni termomehaničkog uticaja, dok je porast tvrdoće relativno mali u zoni grumena. Takođe, odnos najmanje vrednosti tvrdoće i tvrdoće osnovnog metala je veoma blizak vrednosti efikasnosti spoja.

Hardness distribution show very strong dependence of the microstructure. It decreases in the HAZ and TMAZ, as shown in figure 7. It assumed to be because of the heat generated during welding and subsequent recrystallization. Therefore, this effect is greatest in TMAZ, while in the nugget the is sluggish. Also, the ratio between lowest value in TMAZ and hardness of the base metal is close to value of joint efficiency obtained from tensile properties.

At the cross section, macroscopic observations have revealed all typical zones in the welded joint. The influence of the two speed ratio in the range 6,45 –



Slika 7: Tvrdoća zavarenog spoja zavarenih pri odnosu v_{rot} / v_{wel} = 8,22

Figure 7: Hardness distribution obtained in joint obtained at ratio v_{rot} / v_{wel} = 8,22

Na presecima svih zavarenih spojeva zapažaju se sve karakteristične zone FSW zavarenog spoja. Uticaj odnosa dve brzine u opsegu 6,45 – 8,22 nije sasvim jasan, te je pretpostavljeno da u ovim slučajevima razlika unetih toplota nema veliki uticaj.

U grumenu i zoni termomehaničkog uticaja zrno je veoma fino. Pretpostavljeno je da je rafinacija zrna posledica deformacije i rekristalizacije na povišenoj temperaturi. U nekim slučajevima se pretpostavlja i pojava dinamičke rekristalizacije. Sa druge strane, usled nehomogenog zagrevanja unutar zone pod uticajem toplote, neka zrna su započela rast, te je struktura nehomogena [11,15].

REZIME

U cilju određivanja uticaja parametara zavarivanja (odnos brzine rotacije alata i brzine zavarivanja-translacije) na pojavu greške tunela i kvaliteta zavarenih spojeva, dobijenih zavarivanjem ploča postupkom zavarivanja trenjem alatom na leguri Al 5052-H32, parametri su varirani u širokom opsegu. Zavareni spojevi su ispitivani metodama bez razaranja (vizuelno, penetrantima i rentgenski) i sa razaranjem (metalografski, zatezanje, tvrdoća i savijanje). Zavareni spojevi sa najboljim osobinama su dobijeni za spojeve zavarene korišćenjem odnosa u opsegu od 6.45 do 8.22. Efikasnost spoja se kreće u opsegu 70-80%. U ovim spojevima se jasno zapažaju sve karakteristične zone spoja, uz očekivanu veličinu zrna u njima. Raspodela tvrdoće je u saglasnosti sa određenim mikrostrukturama. Rezultati ukazuju da navedeni odnosi koji obezbeđuju optimalni način tečenja materijala oko trna alata, tj. da je kontinuirani dotok materijala na povratnu stranu dovoljan da homogeno popunjava prazninu i spreči pojavu kanala.

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8,22 is not clear, implying that the difference in heat input is not significant.

On the other hand, grain size revealed in the nugget and part of TMAZ is very fine. It is expected that, during very intensive deformation on high temperature, grain refinement is introduced both by deformation and recrystallization. There are also some opinions that even dynamic recrystallization can occur. On the other hand, due to partial heating, in parts of the HAZ, the microstructure seems to be non homogenous, leading to increase in grain size [11,15].

SUMMARY

In order to evaluate the influence of the ratio between rotation and translation (welding) speed during FSW on the integrity and quality of welded joint fabricated of Al alloy 5052-H32, different welding parameters were employed. Welded joints were tested by means of both non-destructive (visual inspection, X-ray inspection) and destructive (metallographic, bending, tension and hardness) testing. Results indicate that the best results were obtained for the ratio between 6 and 8.3.

It is assumed that with this ratio, the material flows around the pin with optimal speed, i.e. there will be no defects of tunnel type.

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