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Fracture toughness of base and weld metal of aluminum alloy EN AW 7049A T652 FSW joint

Udarna žilavost osnovnog materijala i metala šava spoja zavarenog FSW postupkom od aluminijumske legure EN AW 7049A T652

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Ključne reči: zavarivanje trenjem sa mešanjem, udarna žilavost, povlačenje strane WM, rekristalizacija

Key words: friction stir welding, fracture toughness, retreating side of the WM, recrystallization

Abstract

The paper analyses the impact of the tool geometry on the friction stir welding (FSW) method on fracture toughness values of the base metal (BM) and weld metal (WM) of a butt welded joints of a high strength aluminium alloy. Values of fracture toughness KJIc were obtained using single-edge notched bend (SENB) specimens with fatigue pre-crack sampled from the BM and TMAZ (thermo-mechanically affected zone). Single specimen method was used according to ASTM E 1820 and parameters of elastic-plastic fracture mechanics were determined (CTOD crack tip opening displacement and the J integral).

Although the welding tools had different values of cone angle (α = 2.5° - 10°) and the variable length of the pin (h = 5.1 mm - 5.4 mm) at a constant ratio of the number of tool revolutions and the speed of welding, the largest value of fracture toughness has the retreating side of the weld, then the advancing side of the WM, while the BM has the lowest value. This is the effect of recrystallization process in the retreating side of the WM due to combined rotating-straight forward motion of the tool during which the softened material is repeatedly transformed from one side to the other side around the centre of the tool.

Rezime

Papir analizira uticaj geometrije alata na metodu zavarivanja trenjem sa mešanjem (FSW) na vrednostima udarne žilavosti osnovnog materijala (BM) i metala šava sučeonog zavarenog spoja od legure aluminijuma visoke čvrstoće. Vrednosti žilavosti loma KJIc su dobijene korišćenjem epruveta sa zarezom sa jednom ivicom (SENB) na uzorcima koji su sadržali zamornu predprslinu iz BM i TMAZ (zona pod termo-mehaničkim uticajem). Metoda pojedinačnih uzoraka korišćena je u skladu sa ASTM E 1820 i određeni su parametri elasto-plastične mehanike loma (CTOD pomeranje otvora vrha prsline i J integral).

Iako su alati za zavarivanje imali različite vrednosti ugla konusa (a = 2,5° - 10°) i promenljive dužine klina (h = 5,1 mm - 5,4 mm) pri konstantnom odnosu broja obrtaja alata i brzine zavarivanja, najveću vrednost udarne žilavosti ima povučena strana šava, zatim uznapredovalu stranu WM, dok BM ima najmanju vrednost. Ovo je efekat procesa rekristalizacije na povučenoj strani WM zbog kombinovane rotaciono-ravnog kretanja alata tokom koje se omekšani materijal više puta transformiše sa jedne strane na drugu stranu, oko centra alata.

1. Introduction

The procedure of Friction stir welding (FSW) with a tool is dominant in connecting of metal sheet materials, in particular light metals. The high quality of the joint achieved in the absence of a liquid phase and without the use of a filler, enables the use of materials that before FSW were limited to weld, or even by conventional methods unweldable. Such material is a four component alumiunum alloy (Al-Zn-Mg-Cu) usually applied in military industry for production of artillery projectile carriers, warhead charge casings, housings for personal weapons and light housing for batteries based mainly on fuel cells. Of the alloy EN AW 7049 in T652 state which is an intermediate product for production of said components, specific for its high strength, low plasticity and explicit sensibility to fatigue and stress corrosion, it is required that such constructive structures, in exploitation conditions characterized by dynamic impacts and varying temperatures, maintain or improve technological-mechanical properties. This is particularly significant in welds that due to microstructural inhomogeneity represent macro inhomogeneous sites where stress concentration occurs as a potential cause of fracture. The problem is much more complex when it is an artificially aged, forged and homogenized relatively thick sheet made using local design. The aluminium alloy of high strength EN AW 7049 T652 used in the experiment was made from several batches of crude high purity Al 99.8% with the addition of alloying elements Zn, Mg and Cu, i.e. Zr, Ti, V, and B. This makes it unconventional compared to standard series 7 alloys [1]. After semi-continuous horizontal casting of cylindrical logs 200 x 6000 mm in size at a temperature of 700-705°C at a casting speed of 65-70 mm/min, level I of homogenization is performed at a temperature of 465 + 5°C for 6 h and maintaining for 3 h, while at the level II of homogenization the temperature is lower by 5°C and the retaining time 13 h longer. Cooling of the logs is in a chamber, naturally. After cutting with a circular saw across the diameter of 192 mm and length of 360 mm, the sample is three-point free forged on a press with nominal intensity pressure force of 300 MN. In the first stage to the height of 51 + 1 mm, with temperature of the tool between 150°C and 200°C and the temperature of the cartridge 420°C- 440°C at a forging rate of 5 mm/s. Reducing the height of the forging to 25 + 1 mm at a compacting speed of 3 mm/s, while at forging level III during the height reduction to 15 + 1 mm the speed was 2 mm/s, whereby the heat status of the tool and cartridge had not changed. [2]

1.Uvod

Postupak zavarivanja trenjem sa mešanjem (FSW) sa alatom je dominantan uspajanju pločastih metalnih materijala, posebno lakih metala. Visok kvalitet spojaa postignut u odsustvu tečne faze i bez upotrebe dodatnog materijala, omogućava korišćenje materijala koji su pre FSW-a bili ograničeni za zavarivanje, ili čak i konvencionalnim metodama nezavarljivi. Takav materijal je četvorna aluminijumska legura (Al-Zn-Mg-Cu) koja se obično primenjuje u vojnoj industriji za proizvodnju nosilaca artiljerijskih projektila, kućišta za bojevu glavu, kućišta za lično oružje i laganog kućišta za baterije bazirane uglavnom na gorivim ćelijama. Od legure EN AW 7049 u T652 stanju isporuke, koja je međuproizvod za izraduju pomenutih komponenti, specifične zbog svoje visoke čvrstoće, niske plastičnosti i eksplicitne osetljivosti na zamor i naponsku koroziju, zahteva se da takve konstrukcije, u uslovima eksploatacije koju karakterišu dinamički uticaji i različite temperature, održavaju ili poboljšavaju tehnološko-mehaničke osobine. Ovo je naročito značajno kod zavarenih spojeva koji zbog mikrostrukturne nehomogenosti predstavljaju makro nehomogene stranice gde se koncentracija napona javlja kao potencijalni uzrok loma. Problem je mnogo složeniji kada je veštački staren, kovan i homogenizovan relativno debeo sloj napravljen korišćenjem lokalnog oblika. Aluminijumska legura visoke čvrstoće EN AW 7049 T652 koja je korišćena u eksperimentu, napravljena je iz nekoliko serija neobrađenog Al 99,8% visoke čistoće uz dodavanje legirajućih elemenata Zn, Mg i Cu, tj. Zr, Ti, V i B. To je čini nekonvencionalnom u poređenju sa standardnim serijama legura 7 [1]. Posle polu-kontinuiranog horizontalnog livenja cilindričnih trupaca veličine 200 x 6000 mm na temperaturi od 700 do 705 ° C pri brzini livenja 65-70 mm/min, nivo I homogenizacije se izvodi na temperaturi od 465 + 5 ° C tokom 6 h i održavanje na 3 h, dok je na nivou II homogenizacije temperatura niža za 5 ° C i vreme zadržavanja 13 h duže. Hlađenje trupaca je prirodno u komori. Nakon sečenja kružnim testerom preko prečnika 192 mm i dužine 360 mm, uzorak je slobodno kovan na presi sa nominalnom silom pritiska 300 MN. U prvoj fazi do visine od 51 + 1 mm, temperatura alata je između 150 ° C i 200 ° C i temperatura uloška 420 ° C-440 ° C pri brzini kovanja od 5 mm/s. Smanjivanje visine kovanem na 25 + 1 mm pri brzini sabijanja od 3 mm/s, dok je kod kovanja na nivou III radi smanjenja visine do 15 + 1 mm brzina je bila 2 mm/s, pri čemu se status toplote alata i uloška nije promenio. [2]

Heat treatment in regime T652 includes quenching at 470°C for 1 h, rapid cooling in water for no longer than 15 s from opening the furnace, then cold additional deformation by compression in a press with a goal of eliminating residual stresses of the quenching process due to which the height of the cartridge is reduced by 1% -3%. Two-step artificial aging is in two iterations: 100°C-5 h and 160°C -5 h.
Appearance of microstructure in individual forging stages of alloy EN AW 7049 T652 is shown in Figure 1.

Toplotna obrada u režimu T652 uključuje kaljenje sa temperature od 470 ° C u trajanju od 1 h, brzo hlađenje u vodi najviše do 15s od otvaranja peći, a zatim hladna dodatna deformacija pritiskom u presi sa ciljem eliminisanja zaostalih napona usled procesa kaljenja zbog čega je visina uloška smanjena za 1% -3%. Dvostepeno veštačko starenje je u dve iteracije: 100 ° C-5 h i 160 ° C -5 h.
Izgled mikrostrukture u pojedinačnim fazama kovanja od legure EN AW 7049 T652 je prikazan na slici 1.

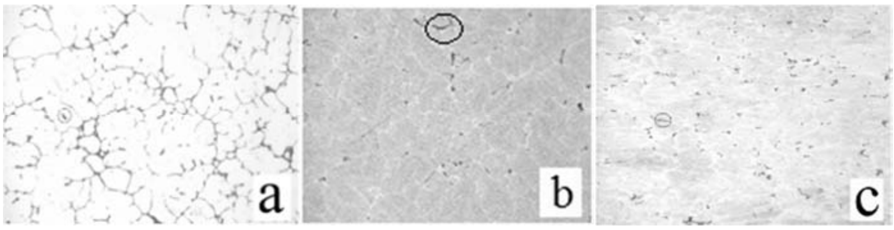

Figure 1. *The microstructure of BM a) cast state magnification x200 b) state after homogenization magnification x 200 c) the heat-treated state magnification x200*

Slika 1. *Mikrostruktura BM a) livenog stanja- uvećanje x200 b) stanje nakon homogenizacije- uvećanje x 200 c) termički obrađeno stanje- uvećanje x 200*

2. Experimental Procedure

For determining the chemical composition of the samples for friction stir welding on the optical emission quantometer type ARL 3580 with the "Peshiney" etalon samples, obtained was the chemical composition which compared to the chemical composition of the standard alloy EN AW 7049 is given in table 1.

2. Eksperiment

Za određivanje hemijskog sastava uzoraka za zavarivanje trenjem sa mešanjem na emisionom optičkom kvantometru tipa ARL 3580 sa "Peshiney" etalon uzorcima dobijen je hemijski sastav koji je u poređenju sa hemijskim sastavom standardne legure EN AW 7049 dat u tabeli 1.

Alloy marking Oznaka legure	Element content, mass% Saržaj elemenat, mas.%									
	Zn	Mg	Cu	Cr	Zr	Ti	V	B	Fe	Si
EN AW 7049A T652	7,45	2,45	1,53	0,17	0,15	0,015	0,003	0,003	0,12	0,11

Table 1. *Comparison of chemical composition of samples for friction welding with a tool and standard EN AW 7049A alloy*

Tabela 1. *Upoređivanje hemijskog sastava uzoraka za zavarivanje mešanjem pomoću alata i standardne legure EN AW 7049A*

For these investigations significant are manufacturing static properties and hardness of the BM of the specially designed alloy EN AW 7049. The FSW
(Friction Stir Welding) process is carried out so that a specially designed cylindrical tool on which is a conical pin considerably smaller and significantly of different geometry penetrates the welding work pieces. One type of tool (tool type B) for which the

Za ova istraživanja značajna su statička svojstva i tvrdoća BM specijalno dizajnirane legure EN AW 7049.
Proces FSW (zavarivanje trenjem sa mešanjem) se obavlja tako da specijalno dizajnirani cilindrični alat na kome je konični klin znatno manji i značajno različite geometrije prodire u radnekomade za zavarivanje. Jedan tip alata (alat tip B) za koji je efikasnost zatezanja spoja postignuta 76% u ET 05

tensile efficiency of the joint achieved is 76% in the ET 05 is shown in Figure 2, and the phases and cycles of the welding process are shown in Figure 3.

prikazan je na slici 2, a faze i ciklusi procesa zavarivanja su prikazani na slici 3.

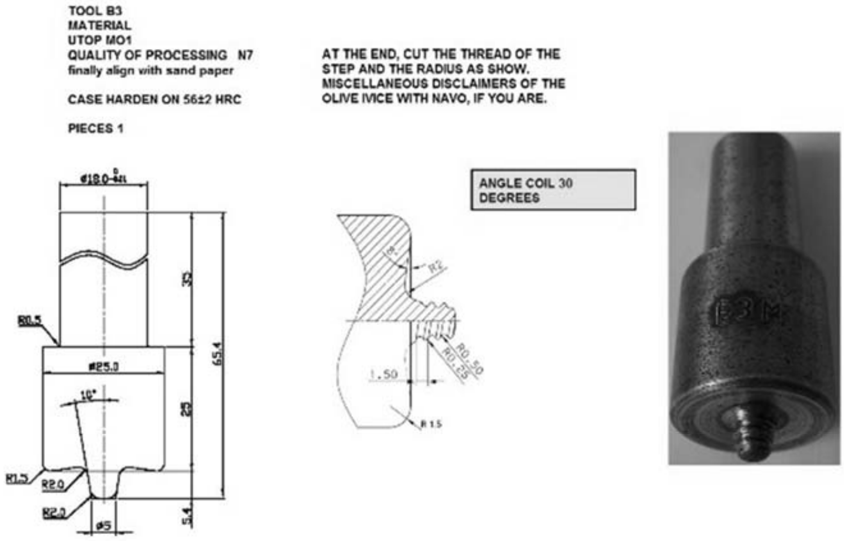

Figure 2. *The tool with a conical coil type B*
Slika 2. *Alat sa konusnim klinom tipa B*

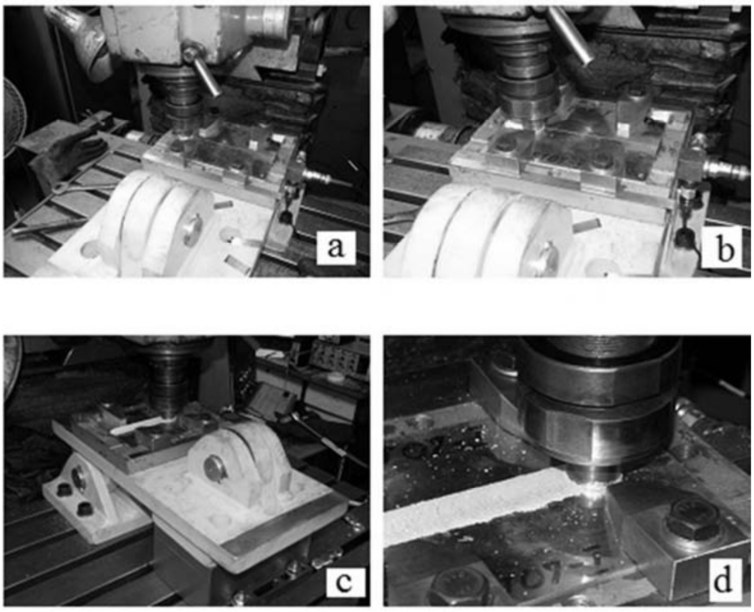

Figure 3. *Stages and cycles of the FSW process*
Slika 3. *Faze i ciklusi procesa ZTM*

Insight into the impact of welding parameters on fracture toughness is possible by applying a multi factor plan of the experiment by varying the values from minimum to maximum levels. Sheets 180 x 65 x 6 mm in size facing each other by thickness in the longitudinal direction are firmly clamped to the die-plate made of steel for improving 42CrMo4 with a work bench of the milling tool with CNC control.
The kinematic parameters: the number of tool revolutions n = 850 min^{-1} and the welding speed v = 80 mm/min are maintained constant. The depth of penetration of the tool into the BM was 0.2 mm,

Uvid u uticaj parametara zavarivanja na udarnu žilavost moguće je primenom multi- faktorskog plana eksperimenta promenom vrednosti od minimalnog do maksimalnog nivoa. Ploče dimenzija 180x65x6 mm postavljene jedna prema drugoj po debljini u uzdužnom pravcu, čvrsto su pričvršćene na lim matrice od čelika za poboljšanje 42CrMo4 sa radnim stolom alata za glodanje sa CNC kontrolom.
Kinematički parametri: broj obrtaja alata n = 850 min^{-1} i brzina zavarivanja v = 80 mm/min se održavaju konstantno. Dubina prodiranja alata u BM iznosila je 0,2 mm, dok je nagib alata u pravcu

while the tilt of the tool against the direction of welding was 1°. Speed of penetration of the tool pin was 0.25 mm/s and the tool head 0.01 mm/s did not change values during the welding of all four sheets [3]. After ET 05 welding, radiographic examination of the sheet was done to detect presence of volumetric defects, after which the samples are water jet cut for machining by milling and making SENB (single-edge notched bend) specimens per standard ASTM E 1820-15a. [4] The sampling locations of SENB specimens with notch orientation in different structural contents on the advancing side (AS) and the retreating side (RS) of the WM are shown in Figure 4 [5].

zavarivanja bio 1°. Brzina prodiranja klina alata iznosila je 0,25 mm/s, a glava alata 0,01 mm/s nije menjala vrednosti tokom zavarivanja sve četiri ploče [3]. Posle zavarivanja ET 05, obavljen je radiografski pregled pločata radi otkrivanja prisustva volumetrijskih defekata, nakon čega su uzorci rezani vodenim mlazom za mašinsku obradu na strugu i izradu SENB uzoraka po standardu ASTM E 1820-15a. [4] Lokacije uzorkovanja SENB epruveta sa orijentacijom zareza u različitim strukturnim sadržajima na napredovaloj strani (AS) i udaljenoj strani (RS) WM, prikazane su na slici 4 [5].

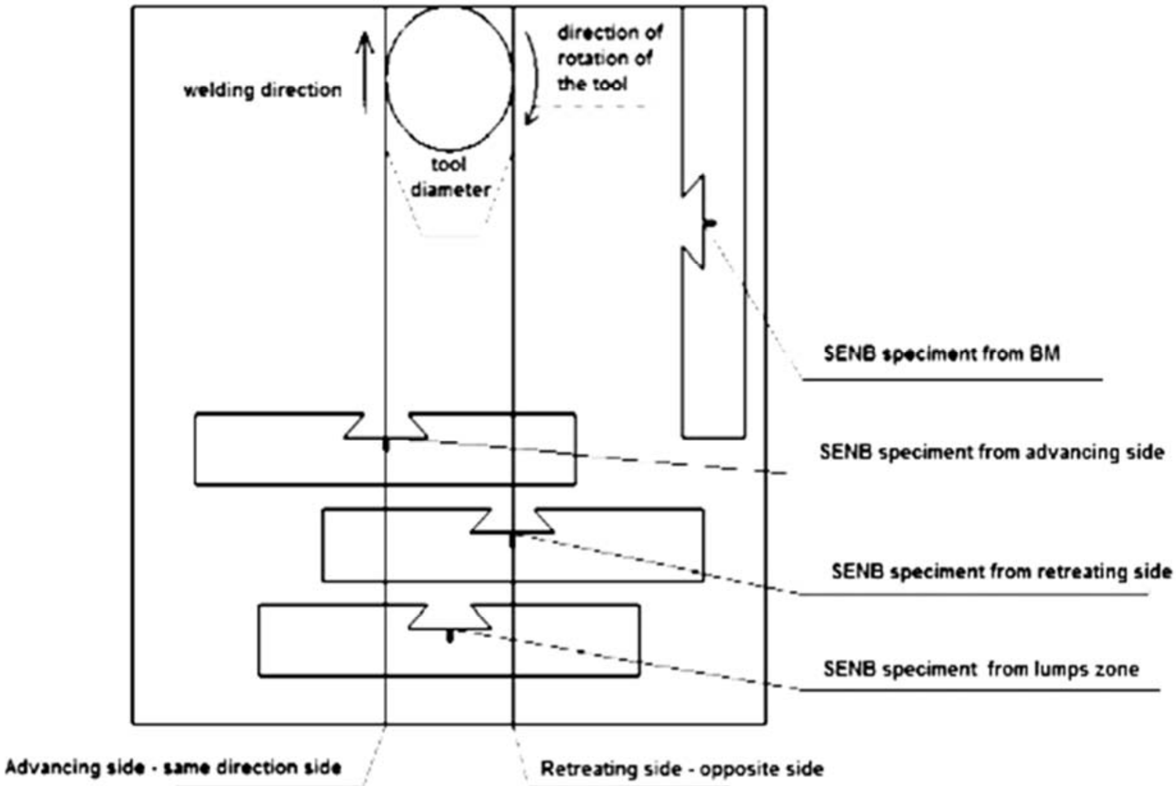

Figure 4. *Sampling locations on SENB specimens*
Slika 4. *Lokacije uzorkovanja na SENB uzorcima*

For determining parameter values of fracture toughness of the BM and WM the method of partial-successive compliance is used while recording the load-displacement line. Since the relief is elastic, compliance is obtained allowing to determine of the crack length. The test consists of: mechanical cutting of the specimen using a wire 0.02 mm in diameter on the device (see Figure 5a), then the initial fatigue on the Cractronik Rumulu with an integrated computer connection (Figure 5b), continued by single edge notch bending on the testing machine SMITWELD 1405 equipped with a computer unit for data acquisition and control (Figure 6) and the final fatigue on the Cractronik Rumulu prior to the final fracture of the specimen.

Za određivanje parametarskih vrednosti udarne žilavosti BM i WM koristi se postupak parcijalnog uzastopnog usaglašavanja pri snimanju linije promene opterećenja. Pošto je reljef elastičan, dobija se saglasnost koja omogućava utvrđivanje dužine prslina. Test se sastoji od: mehaničkog sečenja uzorka korišćenjem žice od 0,02 mm na uređaju (pogledajte sliku 5a), zatim početni zamor na Cractronik Rumulu sa integrisanim povezivanim računarom (slika 5b), nastavljen je savijanjem jedne ivice na mašini za testiranje SMITVELD 1405 opremljenom računarskom jedinicom za prikupljanje i kontrolu podataka (Slika 6) i konačni zamor na Cractronik Rumulu pre završnog loma uzorka.

Figure 5. *a) Device for creating an initial fatigue pre-crack b) Fatigue device Cractronic Rumuli*
Slika 5. *a) Uređaj za stvaranje inicijalne zamorne predprsline b) b) Uređaj za izazivanje zamora Craftronic Rumuli*

Figure 6. *The testing machine SMITWELD1405*
Slika 6. *Mašina za ispitivanje SMITVELD1405*

The above mentioned standard specifies that the minimum length of the crack must be greater than 45% and the maximum less than 55% of the height of the SENB specimen.

In addition to the data of the length of the notch for calculating used is the size of the specimen from the BM and from one experimental point ET 05 (chosen as the best, for which by previous single axliality tension determined was the highest value of tensile strength WM R_m = 485 MPa, the highest tensile joint efficiency 76% and the largest angle of 35° to crack initiation by bending around a roller). Based on the data determined is the maximum and minimum force applied at fatigue loading, and the value of the maximum and minimum stress intensity factor which is entered into the program of the computer unit of the fatigue device Lab View. Measuring the values of force, displacement and crack mouth opening for each of the specimens was performed respectively at room temperature. Based on the obtained data determined is the maximum and minimum force F that is applied in the fatigue test after which the value of the maximum and minimum stress intensity factor K_u is calculated. Both figures are inserted into the computer unit program of the fatigue device. At each of the points of failure it is necessary to record

Pomenuti standard navodi da minimalna dužina prsline mora biti veća od 45% a maksimalna, manja od 55% visine SENB epruvete.

Pored podataka o dužini zareza, za izračunavanje je korišćena veličina uzorka BM i iz jedne eksperimentalne tačke ET 05 (izabrana je kao najbolja, za koju je prema prethodnom jednoosnom zatezanju, utvrđena najviša vrednost zatezne čvrstoće WM Rm = 485MPa, najveća efikasnost zatezanja spoja 76% i najveći ugao od 35° za iniciranje prsline savijanjem oko valjka). Na osnovu podataka, utvrđena je maksimalna i minimalna sila koja se primjenjuje pri zamaranju, i vrednost maksimalnog i minimalnog faktora intenziteta napona koja se unosi u program računarske jedinice Lab Viev uređaja za zamor. Merenje vrednosti sile, pomeranja i otvaranja otvora prsline za svaki od uzoraka vršeno je na sobnoj temperaturi. Na osnovu dobijenih podataka, utvrđena je maksimalna i minimalna sila F koja se primenjuje u testu zamaranjema nakon čega se izračunava vrednost maksimalnog i minimalnog faktora intenziteta napona K_u. Obe slike se ubacuju u program računarske jedinice uređaja za zamor. Na svakoj od tačaka loma, neophodno je zabeležiti silu F, pomeranje otvora vrha prsline (CMOD) i odrediti usklađenost epruvete radi određivanja the force F, the crack mouth opening displacement (CMOD) and determine the compliance of the specimen to determine the crack growth using the difference in compliance values.

rasta prsline koristeći razliku u usklađenim vrednostima.

3. Results

Programming the database for evaluation of the results obtained with the "three point" fatigue test contains all the data which was obtained using previously calculated formulas and standard recommendations, which is shown in Table 2.

3.Rezultati

Programiranje baze podataka za procenu rezultata dobijenih testom zamora u tri tačke sadrži sve podatke koji su dobijeni korišćenjem ranije izračunatih formula i standardnih preporuka, što je prikazano u tabeli 4.

		W [mm]	B [mm]	a0 [mm]	Δa [mm]	bo [mm]	σ_{YS} [MPa]	σ_{TS} [MPa]	v [-]	E [MPa]
OM		11,94	5,64	6,024	1,193	5,916	582,03	642,93	0,3	73455
ET 05	ZG	11,90	5,79	6,116	0,604	5,784	342,4	484,84	0,3	71738
	SS	11,96	5,82	6.123	0,532	5,837	342,4	484,84	0,3	71738
	IS	11,96	5,81	5,603	0,610	6,357	342,4	484,84	0,3	71738

Table 2._Basic geometric measures and mechanical properties of specimens from the BM and WM for experimental point ET 05._

Tabela 2. _Osnovne geometrijske mere i mehaničke osobine uzoraka BM i WM za eksperimentalnu tačku ET 05._

For determining of the J-integral parameter, the most important is that the tests range so that the ratio of the maximum stress intensity factor K_{max} and the elastic modulus E is equal to 0,00015, being outside of this range can cause uncontrolled fracture as a consequence of the formation of a larger plastic zone.

The average value of the initial crack length through the cross-section of the specimen enables determining the value of crack growth DELTA, by microscopic measuring of crack length at nine points on the cross section.

Determining the J-integral is particularly important for the process of normalization after which obtained are resistance curves J-Δa (Figure 7) and CTOD (δ)-Δa (Figure 8). They were obtained after processing the results and represent the resistance curves of BM and TMAZ as part of the WM during stable crack growth.

Za određivanje parametra J-integrala, najvažnije je da se ispitivanja kreću tako da je odnos maksimalnog faktora intenziteta napona K_{max} i modula elastičnosti E jednak 0,00015, što je izvan ovog opsega, i može prouzrokovati nekontrolisani lom kao posledicu formiranja veće plastične zone.

Prosečna vrednost dužine inicijalne prsline kroz presek uzorka omogućava određivanje vrednosti rasta prsline DELTA, mikroskopskim merenjem dužine prslina u devet tačaka na poprečnom preseku.

Određivanje J-integrala je naročito važno za proces normalizacije, nakon čega se dobijaju krive otpornosti J-Δa (Slika 7) i CTOD (δ) -Δa (slika 8). Oni su dobijeni nakon obrade rezultata i predstavljaju krive otpornosti BM i TMAZ kao deo WM tokom stabilnog rasta prsline.

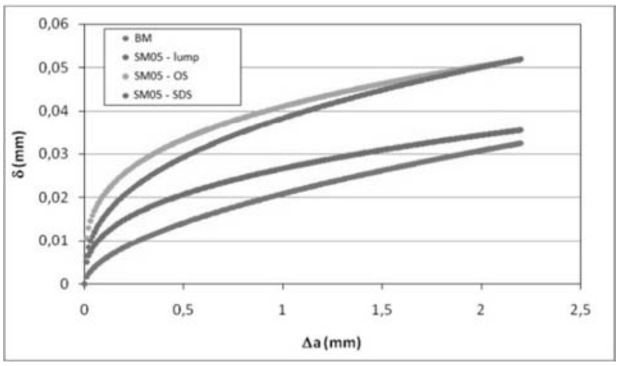

Figure 7. _Resistance curves J-Δa for experimental point ET 05 (nugget zone LZ, SDS same direction side, OS opposite side, BM-base material)_

Slika 7. _Krive otpornosti J-Δa za eksperimentalnu tačku ET 05 (zona grudve LZ, SDS ista strana, OS suprotna strana, BM-osnovni materijal)_

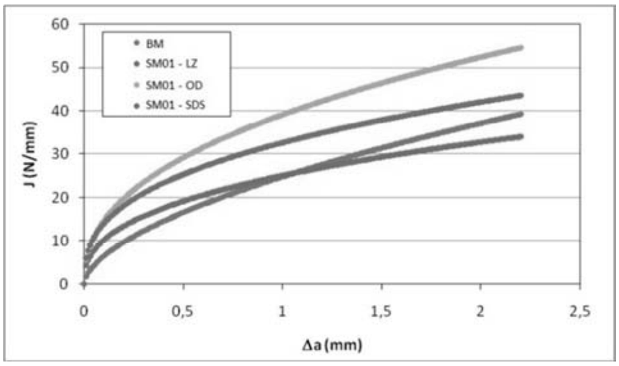

Figure 8. *Resistance curves δ - Δa for experimental point ET 05 (nugget zone (lump), SDS same direction side, BM - base material)*

Slika 8. *Krive otpornosti d - Δa za eksperimentalnu tačku ET 05 (zona grudve (komora), SDS ista strana BM-osnovni materijal)*

As an engineering critical value taken is the value at the intersection of the parallel at crack growth of 0.2 mm and resistance curves Jic - Δa and δ - Δa. That is actually fracture toughness of WM and BM for experimental point ET 05 of which a graph is given in Figure 9 where by comparative analysis of measured values of K_{JIC} in the TMAZ and BM relevant conclusions can be made.

Kao inženjerska kritična vrednost uzeta je vrednost na ukrštanju paralelno rastu prslinea od 0,2mm i krivama otpornosti J_{ic} - Δa i d - Δa. To je stvarna udarna žilavost WM i BM za eksperimentalnu tačku ET 05 za koju je grafikon prikazan na slici 9, gde se, komparativnom analizom izmerenih vrednosti $K_{JIC,}$ mogu izvesti relevantni zaključci za TMAZ i BM.

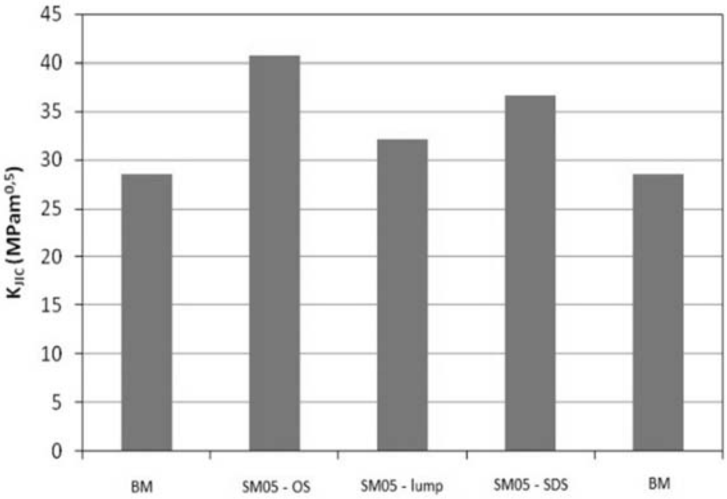

Figure 9. *Fracture toughness in the experimental point ET 05 (lump-lump zone, SDS - same direction side, OS-opposite side, BM-base material)*

Slika 9. *Udarna žilavost u eksperimentalnoj tački ET 05 (zona grumen-grumen , SDS - isti smer, OS-suprotna strana, BM-osnovni materijal*

4. Discussion of the results and conclusions

Examination of the parameters of elastic-plastic fracture mechanics of BM and WM of FSW welded forgings of alloy EN AW 7049A T652 determines the fracture toughness K_{JIc} as their level of sensitivity to the presence of a fatigue sharp pre-crack. It was proven that the highest fracture toughness is at the (RS) – retreating side of the WM, then the (AS) – advancing side and then at the WM core i.e. NZ. The lowest value of fracture toughness K_{JIc} has the BM in the ET 05, even 42% less than the K_{JIc} of the retrieving side of WM. These results correspond with the microstructural transformations on WM side where, due to the left

4. Diskusija rezultata I zaključci

Ispitivanje parametara elasto plastične mehanike loma BM i WM od FSW zavarenih odlivaka od legure EN AW 7049A T652 određuje žilavost loma K_{JIc} kao njihov nivo osetljivosti na prisustvo oštre predprsline. Dokazano je da je najveća žilavost loma na (RS) – uvučenoj strani WM, a zatim (AS) – napredovaloj strani, a zatim i na jezgru WM tj. NZ. Najmanju vrednost žilavosti loma K_{JIc} ima BM u ET 05, čak 42% manje od K_{JIc} uvučene strane WM-a. Ovi rezultati odgovaraju mikrostrukturnim transformacijama na strani WM, gdje se, zahvaljujući levom namotaju na klinu alata, omekšali materijal gurne sa vrha do oboda. Ovo je coil on the tool pin the softened material is pushed from the tip to the shoulder. This is due to the simultaneous influence of the primary and secondary phases of material flow. This particle torque allows the transfer of mass to take place at the back leveling edge with elements of retreating to the front side of the overlapping tool edge, which leads to dynamic recrystallization as a result of the simultaneous plastic deformation from the tool action and friction generated heat. This is actually the result of thermo-mechanical processing which is dominant in this welding process.

posledica istovremenog uticaja primarne i sekundarne faze protoka materijala. Ovaj obrtni moment čestice omogućava prenos mase na zadnju ivicu sa elementima povlačenja na prednju stranu preklapajuće ivice alata, što dovodi do dinamične rekristalizacije koja je rezultat istovremene plastične deformacije usled dejstva alata i stvaranja toplote usled trenja. Ovo je zapravo rezultat termo-mehaničke obrade koja je dominantna u ovom procesu zavarivanja

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