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## INFLUENCE OF WELDING PARAMETERS ON JOINT PROPERTIES AND POSSIBILITY OF POST-WELD COLD-ROLLING OF FRICTION STIR WELDED ALUMINUM ALLOY 5083

### UTICAJ PARAMETARA ZAVARIVANJA NA KARAKTERISTIKE I MOGUĆNOST HLADNOG VALJANJA ZAVARENOG SPOJA LEGURE ALUMINIJUMA 5083 DOBIJENOG POSTUPKOM ZAVARIVANJA TRENJEM ALATOM

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#### Abstract

In this paper the structure and mechanical properties of similar AA5083- FSW joints were investigated, as well as the effects of post-weld cold-rolling of FSW joints. Two joints were formed using different welding parameters, in order to investigate the influence of parameters on joint properties. The welded joints were tested using non-destructive methods (visual and X-ray inspection, electrical conductivity variation) and destructive methods (tensile and hardness testing, metallographic analysis of macro- and microstructure). The joints were also cold-rolled. It was found that the joint welded using parameters  $V_{rot}/V_{tr} = 750/73$  rpm/mm can be successfully processed by cold rolling; it also has better mechanical properties than the joint welded using parameters  $V_{rot}/V_{tr} = 750/150$  rpm/mm, and had a more uniform hardness distribution. It was concluded that using parameters 750/73 results in a AA5083 weld of satisfactory quality was obtained.

#### 1. Introduction

Friction stir welding (FSW) is a technology developed in 1990s by *The Welding Institute-TWI* in Great Britain, mainly in order to overcome difficulties and problems that arise during

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#### Rezime

U ovom radu je ispitana mogućnost hladne deformacije valjanjem trake FSW spoja legure aluminijuma 5083 u stanju H111, kao i početna struktura i mehanička svojstva spoja. Primenom različitih parametara zavarivanja izrađena su dva zavarena spoja radi ispitivanja uticaja parametara zavarivanja na karakteristike spoja. Spojevi su ispitani metodama bez razaranja (vizuelna i radiografska kontrola i ispitivanje električne provodljivosti) i metodama sa razaranjem (raspodela tvrdoće, zatezna i metalografska ispitivanja). Zavareni spojevi su podvrgnuti hladnom valjanju. Nađeno je da se spoj parametara  $V_{rot}/V_{zav} = 750/73$  o/mm može oblikovati postupkom hladnog valjanja, kao i da se odlikuje boljim mehaničkim svojstvima i ravnomernijom raspodelom tvrdoće duž poprečnog preseka od spoja  $V_{rot}/V_{zav} = 750/150$  o/mm. Utvrđeno je da se parametrima 750/73 ostvaruje zavareni spoj legure aluminijuma 5083 zadovoljavajućeg kvaliteta.

conventional fusion welding of poorly weldable metals and alloys [1-6]. FSW is a solid state process, meaning that the base materials that are being joined are not melted during the process. The weld joint is formed by the action of a rotating pin tool, which generates heat as a result of friction,



and mechanically stirs the plasticized layer of soft metal that forms beneath the tool shoulder and around the pin [1-6].

As a result of intense plastic deformation at high temperatures, the stir zone undergoes a process of dynamic recrystallization [1]. This zone is also called the “nugget zone” and is formed right beneath the tool shoulder, with a width approximately equal to the diameter of the pin. Other characteristic zones present in the macrostructure of FSW joints are the thermo-mechanically affected zone (TMAZ) and the heat-affected zone (HAZ). The structural changes evident in the TMAZ and HAZ, as well as the present residual stresses, are of a higher or a lower intensity, depending on the temperature cycles that each zone is exposed to [2, 4]. Tool rotation rate,  $V_{rot}$  (rpm) and tool travel speed or welding speed,  $V_{tr}$  (mm/min) are very important welding parameters for FSW, as they dictate how much heat is generated and how intensely the material is mixed. The resulting quality of the weld is thus greatly influenced by these parameters. [1, 2, 4].

One of the limitations in FSW is the thickness reduction in the weld resulting from the forging effect of the tool shoulder, as well as the grain coarsening in the HAZ. These aspects result in a decrease in mechanical properties and formability of FSWed sheets. Post-weld cold rolling (PWCR)

has a potential to mitigate these negative effects and improve the mechanical properties of non-heat-treated Al alloy welds [7, 8]. The effect of the cold-rolling strain hardening process on the mechanical properties and deformability of the FSWed specimens must be investigated.

This study aims to investigate the influence of cold rolling on the mechanical properties of friction stir welded joints from aluminum alloy AA5083 H111, as well as the influence of tool rotation rate and welding speed on their structural properties.

## 2. Experimental part

Butt joints were obtained by performing FSW experiments on sheets made of AA5083 aluminum alloy in the H111 temper state. Table 1 shows the chemical composition of the AA5083 sheets. The sheets were 500 mm in length, 65 mm in width and 6 mm in thickness. Two joints were obtained using the same rotational speed,  $V_{rot} = 750$  rpm, but with different travel speeds:  $V_{tr} = 73$  mm/min (specimen 750/73) and  $V_{tr} = 150$  mm/min (specimen 750/150). The pin tool was characterised by a shoulder diameter of 25 mm and a threaded cone pin with a height of 6 mm. The pin tool material was quenched and tempered 56NiCrMoV7 hot work tool steel.

**Table 1.** Chemical composition of AA5083 sheets in [%]

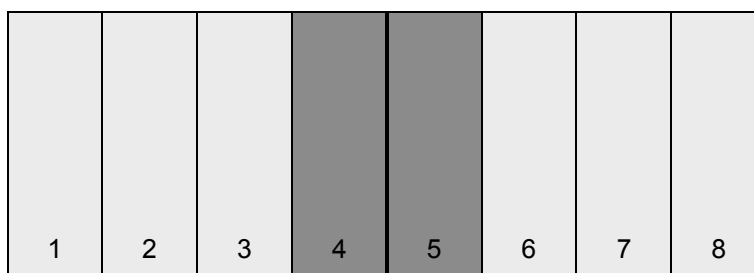
**Tabela 1.** Hemijski sastav AA5083 ploča u [%]

Mg	Mn	Si	Fe	Cu	Cr	Zn	Ti	Al
4.60	0.55	0.24	0.29	0.07	0.10	0.07	0.02	rest

### 2.1. Non-destructive testing

The specimens in as-welded condition were visually and X-ray checked in for the presence of defects and imperfections. Eddy current testing was

also performed on the FSWed specimens in different zones of the surface of the joints, as shown in Figure 1.



**Figure 1.** Zones of the welded specimen for Eddy current testing. Zones 4 and 5 represent the weld metal

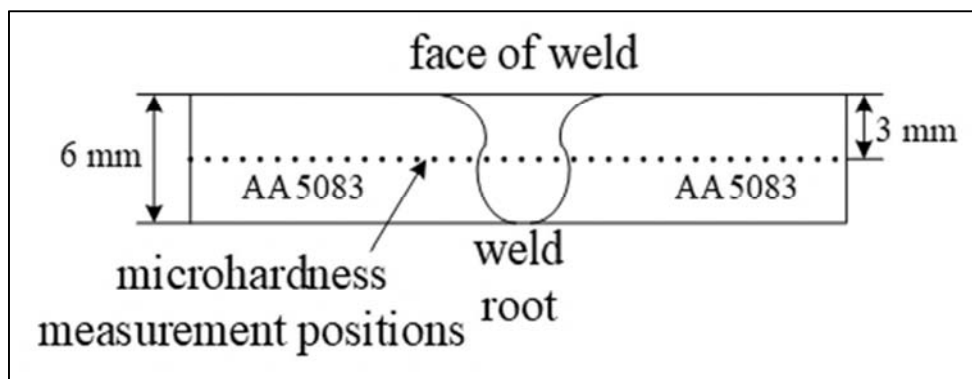
**Slika 1.** Zone zavarenog uzorka za ispitivanje vrtložnim strujama. Zone 4 i 5 predstavljaju metal šava



## 2.2. Hardness testing

Vicker's hardness (HV10) of the base metal (BM) was measured in accordance with standard EN ISO 6507-1: 2018. The distribution of the microhardness (HV1) at the cross-section of the joint (Figure 2) was carried out on specimens with the revealed macrostructure of the joint, in order to

precisely measure the hardness across all zones of the joint (BM, HAZ, TMAZ, nugget). The hardness diagrams were obtained by measuring the hardness along a horizontal line in the middle of the weld. The step between measurements was 0.5 mm.



**Figure 2.** Schematic diagram of the cross-section of the joint with the microhardness test positions

**Slika 2.** Šematski dijagram poprečnog preseka spoja sa položajima ispitivanja mikrotvrdoće

## 2.3. Uniaxial tensile tests

Flat tensile samples were machined from FSWed specimens, after which tensile tests were performed on the hydraulic universal testing machine "Shimadzu Servopulser", in accordance with standard EN ISO 6892-1:2012. The loading direction was perpendicular to the welding line and the tests were performed at room temperature on three tensile samples for each FSWed specimen.

## 2.4. Macro and microstructure analyses

Specimens were taken from the joint perpendicular to the welding direction in order to observe the macro- and microstructure at the cross-section of the joint. The specimens were then mechanically ground using sand papers with grit sizes P240 to P2500. The macrostructure was revealed by etching in Tucker's reagent (45 ml HCl, 15 ml HNO<sub>3</sub>, 15 ml HF, 25 ml H<sub>2</sub>O) for 10 seconds (specimen with the welding parameters  $V_{rot}/V_{tr} = 750/73$ ) and 17 seconds (specimen with the welding parameters  $V_{rot}/V_{tr} = 750/150$ ).

In order to observe the changes in the microstructure across all characteristic zones of the weld and to analyze the influence of different welding parameters on the structure, the same specimens were mechanically ground using sand papers with grit sizes P240 to P4000, mechanically polished with the use of a diamond polishing suspensions with particle sizes of 7/5 μm, 5/3 μm and 3/2 μm. Subsequently, the specimens were

electrochemically polished and etched. Electrochemical polishing of both specimens was carried out using a perchloric acid-based solution (200 ml ethanol, 35 ml H<sub>2</sub>O, 10 ml 60% solution of HClO<sub>4</sub>) at 12 V for 10 seconds. The specimens were electrochemically etched using Barker's reagent (5 ml HBF<sub>4</sub>, 200 ml H<sub>2</sub>O) at 12 V for 190 seconds (specimen 750/73), and 120 seconds (specimen 750/150).

## 2.5. Cold rolling of FSWed specimens and tensile tests

In order to investigate the effect of cold rolling (CR) on the mechanical properties of the welded sheets, part of the specimens was cold rolled, after which tensile tests were carried out. CR was performed in 7 different rolling passes, with a total thickness reduction of 50%. The rolling direction was perpendicular to the welding direction and the thickness of the rolled sheets was measured after each rolling pass. Table 2 shows the resulting specimen thickness and thickness reductions after each rolling pass.

Tensile samples were then machined from the cold rolled specimens and tensile tested on the hydraulic universal testing machine "Shimadzu Servopulser". The loading direction was perpendicular to the welding line and the tests were performed at room temperature on three tensile samples.

**Table 2.** Obtained thickness reductions of FSW joints during cold rolling**Tabela 2.** Dobijene redukcije debljine FSW spojeva tokom hladnog valjanja

welding parameters		CR pass						
		I	II	III	IV	V	VI	VII
750/73	thickness (mm)	5.63	5.23	4.95	4.72	4.50	4.13	3.09
	reduction (%)	6.2	12.8	17.5	21.3	25.0	31.2	48.5
750/150	thickness (mm)	5.65	5.26	4.96	4.71	4.50	4.15	3.15
	reduction (%)	5.8	12.3	17.3	21.5	25.0	30.8	47.5

### 3. Results and discussion

#### 3.1. Radiography

Radiographic control of the weld specimen 750/150 revealed a welding defect in the form of a short inner channel near the tool plunge location

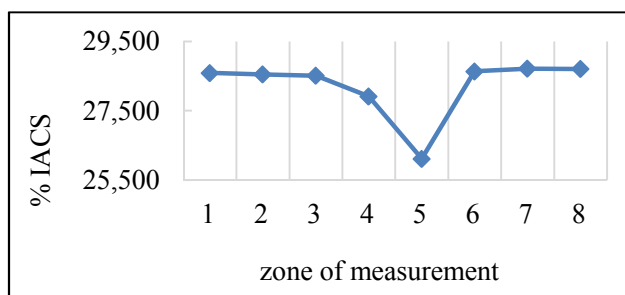
(Figure 3). As the largest part of the weld specimen was defect-free, this part of the specimen was discarded, and the rest of the specimen was used in the investigations.

**Figure 3.** Radiograph of specimen 750/150, showing the presence of an inner channel**Slika 3.** Radiografija uzorka 750/150, koja pokazuje prisustvo unutrašnjeg kanala

#### 3.2. Eddy current

Figure 4 shows the distribution of electrical conductivity for specimen 750/73. The decrease of conductivity in weld metal zones is attributed to the

refinement of grains in the stirring zone that typically occurs during FSW [1, 2, 9].

**Figure 4.** Distribution of electrical conductivity for specimen 750/73**Slika 4.** Raspodela električne provodljivosti za uzorak 750/73



### 3.3. Vicker's hardness

Base metal hardness was measured to be 84.5 HV10. Figure 5 shows the hardness distribution in the welded zones for both specimens. The diagrams have a similar shape, with a slight increase of the hardness in the nugget zone (NZ) comparing to the base metal, and a decrease in TMAZ. The heat input during welding causes grain

coarsening that leads to deterioration of mechanical properties characteristic for TMAZ and HAZ [3, 7]. In contrast, the increase of the hardness in NZ can be attributed to the grain refinement and a higher dislocation density compared to the base metal, enabled by intense stirring and very high temperatures in this zone [2].

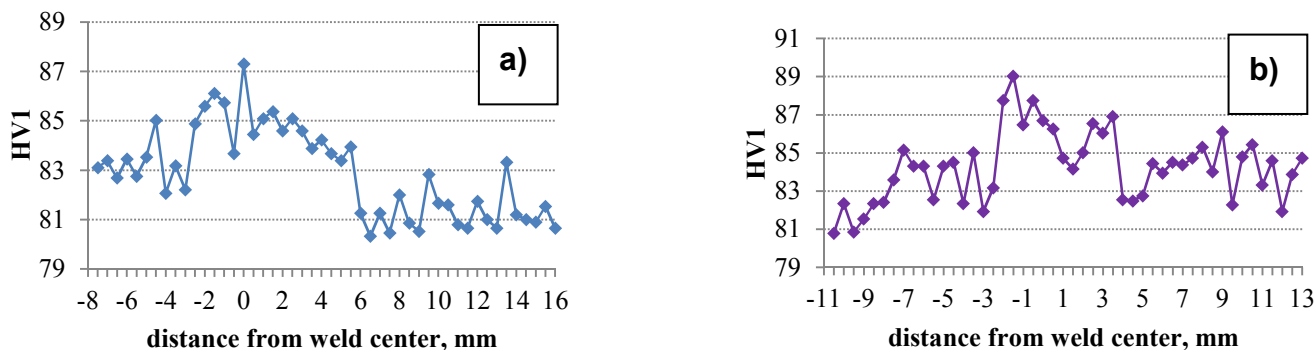


Figure 5. Hardness distribution across the specimen of weld joint (a) 750/73, (b) 750/150

Slika 5. Raspodela tvrdoće po uzorku zavarenog spoja (a) 750/73, (b) 750/150.

### 3.4. Tensile properties

Table 3 shows the mean values of the tensile test results. These results indicate that the welding parameters 750/73 rpm/mm give joints of better quality compared to the joints welded with parameters 750/150 rpm/mm. In almost all cases the fracture occurred in the TMAZ on the retreating

side, which indicates that the TMAZ is the weakest zone of FSW joints, as previous research has also shown [3]. The phenomenon of the fracture almost always occurring on the retreating side could be linked to the asymmetric nature of FSW joints [1, 2, 5]. The fracture was initiated at the weld root in all cases.

Table 3. Mean values of the tensile test results

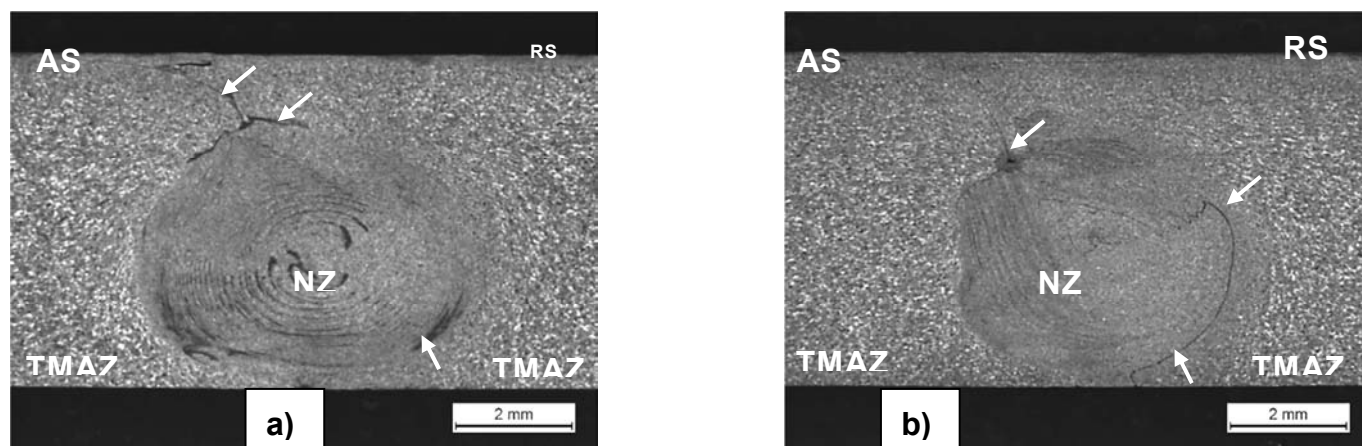
Tabela 3. Srednje vrednosti rezultata ispitivanja zatezanjem

Specimen	Yield strength (YS), MPa	Ultimate tensile strength (UTS), MPa	Elongation, %
750/73	182	279	5,05
750/150	188	216	1,76

### 3.5. Macro and microstructure

Figure 6 shows the macrostructure of both specimens. The characteristic zones of FSW joints are visible: the nugget and its onion ring structure formed as a result of material flow during FSW, and the thermo-mechanically affected zone (TMAZ) that

features deformed and oriented grains. Thin layers of dark colored areas in the NZ represent impurities that originate from the surface of the aluminum sheets and the pin tool. They were stirred into the material during FSW and follow the material flow patterns (Fig. 6).

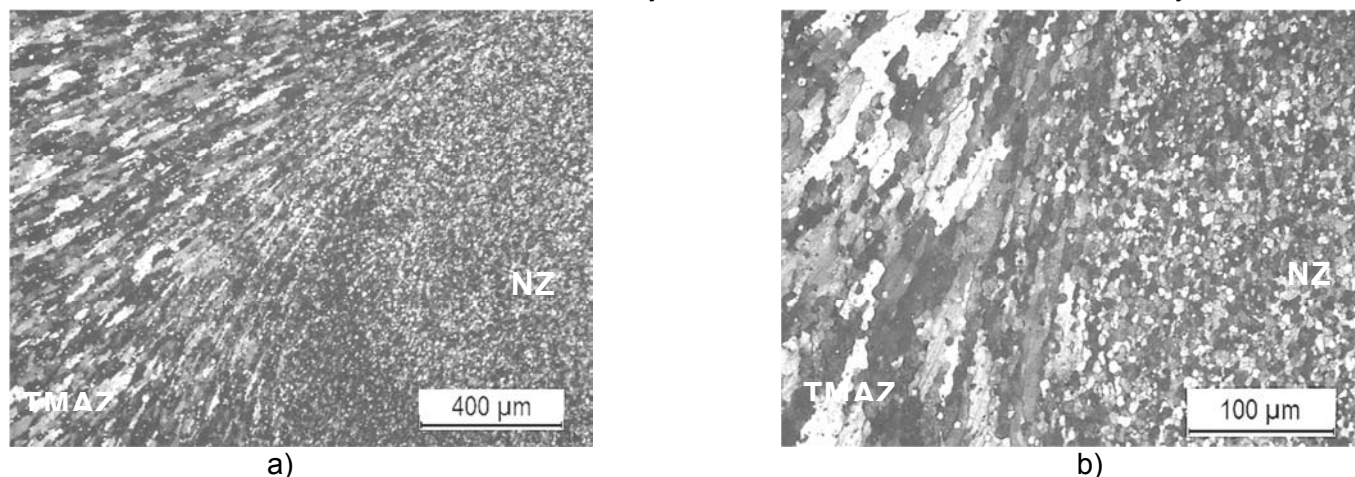


**Figure 6.** Macrostructure of (a) specimen 750/73, (b) specimen 750/150. Arrows indicate layers of impurities. (AS – advancing side, RS – retreating side, TMAZ – thermo-mechanically affected zone, NZ – nugget zone)

**Slika 6.** Makrostruktura (a) uzorka 750/73, (b) uzorka 750/150. Strelice označavaju slojeve nečistoća. (AS – napredujuća strana, RS – strana koja se povlači, TMAZ – zona uticaja termo-mehanike, NZ – zona sočiva (jezgra) šava

Optical microscopy revealed significant structural differences across the zones of the weld joints. Figure 7 shows typical microphotographs of the NZ/TMAZ interface. The NZ consists of very

fine equiaxial grains. The grain in the TMAZ are elongated and deformed in an upward direction. It was not possible to differentiate the HAZ from the TMAZ based on microstructure analyses.



**Figure 7.** Microstructure of (a) specimen 750/73, (b) specimen 750/150

**Slika 7.** Mikrostruktura (a) uzorka 750/73, (b) uzorka 750/150

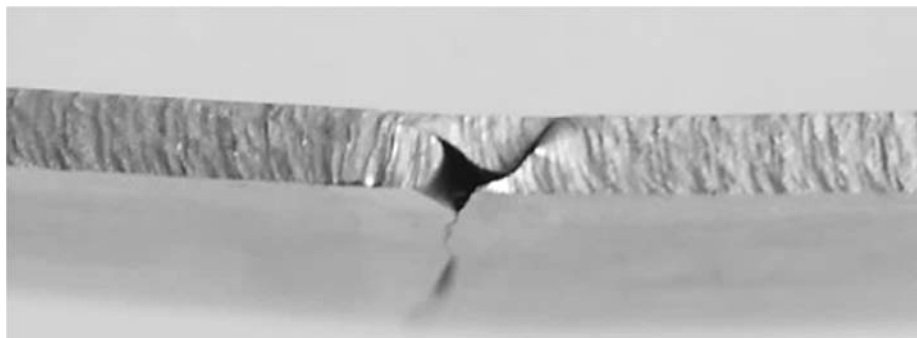
### 3.6. Effects of cold rolling

During post-weld cold-rolling of specimen 750/150, a crack along the NZ-TMAZ interface formed already in the second pass. The cold rolling was continued and after the final seventh pass, significant delamination along the root of the weld was also observed. The defects on the cold rolled specimen 750/150 are shown in Figure 8. Because of these defects, specimen 750/150 was excluded from further tensile testing. None of these defects were formed during cold rolling of specimen 750/73.

Table 4 shows the results of tensile testing of cold rolled FSW samples, welded with the

parameters 750/73. The ultimate tensile strength of the FSW joint increased by 26% after cold rolling, while the elongation was greatly reduced. This implies that the deformation capacity of the weld joint is close to exhaustion.

As in the tensile tests of non-cold-rolled FSW samples, the FSW samples after CR also fractured along the NZ-TMAZ interface on the retreating side, indicating that this is the weakest zone of FSW joints, regardless of post-weld cold rolling. The crack initiation was also at the weld root in all cases.



**Figure 8.** Defects formed on specimen 750/150 during cold rolling

**Slika 8.** Defekti nastali na uzorku 750/150 tokom hladnog valjanja

**Table 4.** Results of tensile testing of post-weld cold-rolled joints 750/73

**Tabela 4.** Rezultati ispitivanja zatezanjem hladno valjanih spojeva 750/73 nakon zavarivanja

specimen	1	2	3	mean value
UTS, MPa	401	343	314	353
Elongation, %	1.90	0.74	1.72	1.45

#### 4. Conclusions

Based on the performed examinations, following conclusions could be drawn:

The ultimate tensile strength and elongation of butt joints obtained by FSW are higher for welding parameters 750/73 rpm/mm compared joints made with parameters 750/150 rpm/mm.

The hardness distribution on the cross-section of the joint 750/73 is more uniform than at the joint 750/150.

Cold rolling of FSW joints showed that the joint obtained with the parameters 750/73 rpm/(mm/min) can be successfully processed further by cold rolling. It was shown that cold rolling of FSW butt joints can be used to increase the ultimate tensile strength of the joints, although the elongation is significantly decreased after cold rolling.

Cold rolling of FSW joint 750/150 with the achieved thickness reductions in this investigation was unsuccessful. It is possible that a lower reduction could be used to produce sound cold rolled FSW joint 750/150. This implies that the parameters for successful cold rolling of FSW joints depend on the welding parameters that were used.

Therefore, it was found that a higher quality FSW joint is obtained using welding parameters

#### 4. Zaključci

Na osnovu obavljenih ispitivanja, mogu se izvesti sledeći zaključci:

Maksimalne zatezne čvrstoće i izduženja sučeonih spojeva dobijenih FSW-om su veće za parametre zavarivanja 750/73 o/min/mm u poređenju sa spojevima napravljenim sa parametrima 750/150 o/min/mm.

Raspodela tvrdoća na poprečnom preseku spoja 750/73 je ravnomernija nego na spoju 750/150.

Hladno valjanje FSW spojeva je pokazalo da se spoj dobijen sa parametrima 750/73 o/min/(mm/min) može uspešno dalje obrađivati hladnim valjanjem. Pokazalo se da se hladno valjanje FSW sučeonih spojeva može koristiti za povećanje zatezne čvrstoće spojeva, iako se nakon hladnog valjanja izduženje značajno smanjuje.

Hladno valjanje FSW spoja 750/150 sa postignutim smanjenjem debljine u ovom istraživanju je bilo neuspešno. Moguće je da se niži stepen redukcije može koristiti za dobijanje pouzdanog hladno valjanog FSW spoja 750/150. Ovo ukazuje da parametri za uspešno hladno valjanje FSW spojeva zavise od primenjenih parametara zavarivanja.



$V_{rot}/V_{tr} = 750/73$  than with parameters  $V_{rot}/V_{tr} = 750/150$ .

Tako je utvrđeno da se kvalitetniji FSW spoj dobija korišćenjem parametara zavarivanja  $V_{rot}/V_{tr} = 750/73$ , nego sa parametrima  $V_{rot}/V_{tr} = 750/150$ .

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