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PROMENA TEMPERATURE I VERTIKALNE SILE TOKOM PROCESA ZAVARIVANJA TRENJEM MEŠANJEM

CHANGE OF TEMPERATURE AND VERTICAL FORCE DURING FRICTION STIR WELDING

Originalni naučni rad / Original scientific paper

UDK / UDC: 621.791.1:669.71.018

Rad primljen / Paper received:

Maj 2013.

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Ključne reči: zavarivanje trenjem mešanjem, aluminijumske legure visoke čvrstoće, alat, promena temperature, promena sile.

Keywords: friction stir welding, high strength aluminium alloys, welding tool, temperature range, force range.

Izvod

Cilj rada je analiza promene vertikalne sile i temperature tokom procesa zavarivanja trenjem mešanjem (FSW) legura aluminijuma visoke čvrstoće (2024 T3).

FSW postupak je složen nelinearan proces praćen velikim plastičnim deformacijama, visokim temperaturama i plastičnim tečenjem materijala u zoni zavarivanja. To je postupak spajanja materijala u tzv. čvrstoj fazi, kombinovanim delovanjem toplote i mehaničkog rada. Analiza promene sile i temperature tokom procesa zavarivanja omogućava bolje razumevanje i kontrolu samog procesa.

U radu je analizirana i praćena promena sile u vertikalnom pravcu pomoću dinamometra i promena temperature na gornjoj površini radne ploče u blizini čela valjka alata pomoću termovizijske kamere.

Abstract

The aim of this paper is to analyze changes of vertical force and temperature during friction stir welding process of high strength aluminum alloys (2024 T3).

FSW process is a complex nonlinear process accompanied by large plastic deformation, high temperatures and plastic material flow in the welding zone. It is the procedure of material connecting in the so-called solid phase, through the combined action of heat and mechanical work. Analysis of force and temperature changes during the process of welding allows better understanding and control of the process.

This paper analyzes the change of force in the vertical direction using a dynamometer and temperature changes on the upper surface of the working panel near the tops of the roller tool using thermal imaging cameras.

UVOD

Pojava grešaka tipa prsline u zavarenim spojevima ostvarenim procesima topljenjem legura aluminijuma visoke čvrstoće predstavlja ozbiljan tehnološki problem. To je posebno izraženo kod legura serije 2000 i 7000. Ovo ograničenje značajno je umanjilo njihovo područje primjene sve do uvođenja u masovnu proizvodnju FSW postupka krajem prošlog veka. Od tada pa do danas neprestano raste primena ovog postupka u proizvodnji različitih elemenata u građevinarstvu, trasnportnoj industriji, brodogradnji, avioindustriji, kosmičkoj industriji itd [1-5].

Pored mogućnosti spajanja svih vrsta aluminijumskih legura, moguće je uspešno zavarivati: bakar i njihove legure, olovo, titanijum i njegove legure, legure

INTRODUCTION

Hot cracking in high strength aluminium alloys welded joints obtained using melting is very serious technological problem, especially pronounced for 2xxx and 7xxx series. This limitation significantly decreases and reduces application of these alloys. By the end of last century introduction of friction stir welding (FSW) have overcome some of the problems. Since, the application of FSW is increasing industrial use for different components in transportation and automotive industry, shipbuilding and airspace industry [1-5].

FSW is used also for welding of copper and copper alloys, lead, titanium and titanium alloys, Mg and Mg alloys, zinc, nickel and even some steels. It can be used for similar and dissimilar materials and parts with magnezijuma, cink, meki čelik, nerđajući čelik, legure nikla. Mogu se zavarivati istorodni i raznorodni materijali. Ovim postupkom mogu se zavariti ploče, limovi, cilindrični delovi, delovi mašinskih sklopova i to u svim međusobnim položajima [1-5]. U poređenju sa konvencionalnim postupcima zavarivanja, koji podrazumevaju topljenje materijala u zoni zavarivanja, FSW postupak ima veliki broj prednosti i omogućava dobijanje zavarenih spojeva odličnih mehaničkih karakteristika [6].

OSNOVI PROCESA

Radni deo uređaja za FSW postupak (alat) se sastoji od dva dela koji rotiraju velikom brzinom, valjka i trna, slika 1. Valjak rotira po površini radnih ploča, usled čega se trenjem i plastičnom deformacijom materijala u zoni zavarivanja oslobađa energija koja zagreva limove (delove) koji se spajaju na temperature koje odgovaraju temperaturama tople plastične prerade.

Istovremeno, trn koji se nalazi sa donje strane valjka, profilisanog oblika sa navojem ili žljebovima, rotira unutar zagrejane obe ploče i mehanički meša materijal obe ploče krećući se linijom spajanja. Korišćenjem FSW postupka dobijaju se zavareni spojevi visokog kvaliteta bez pora, prslina i deformacija [7].

EKSPERIMENTALNI DEO

Eksperimentalni deo se odnosi na praćenje promene vertikalne sile i temperature na gornjoj površini radne ploče u blizini periferije alata u toku procesa zavarivanja aluminijumskih ploča primenom FSW postupka.

Radne ploče su dimenzija 180x65x3 mm i izrađene su od legure aluminijuma visoke čvrstoće 2024 T3. U tabeli 1. je prikazan hemijski sastav osnovnog materijala 2024 T3.

different geometries (plates, sheets, cylinders, components) and thicknesses [1-5].

In comparison to conventional welding processes that include melting, FSW has high number of advantages when primary crystals during solidification lead to cracking.

FUNDAMENTALS OF PROCESS

Two mayor parts of working tool for FSW are pin and shoulder. Tool rotates with high rotation rate. Shoulder rotates on the surface of both welding pieces causing intensive friction. This friction generates heat that increases the temperature of both pieces, usually to temperatures similar to temperatures of plastic deformation.

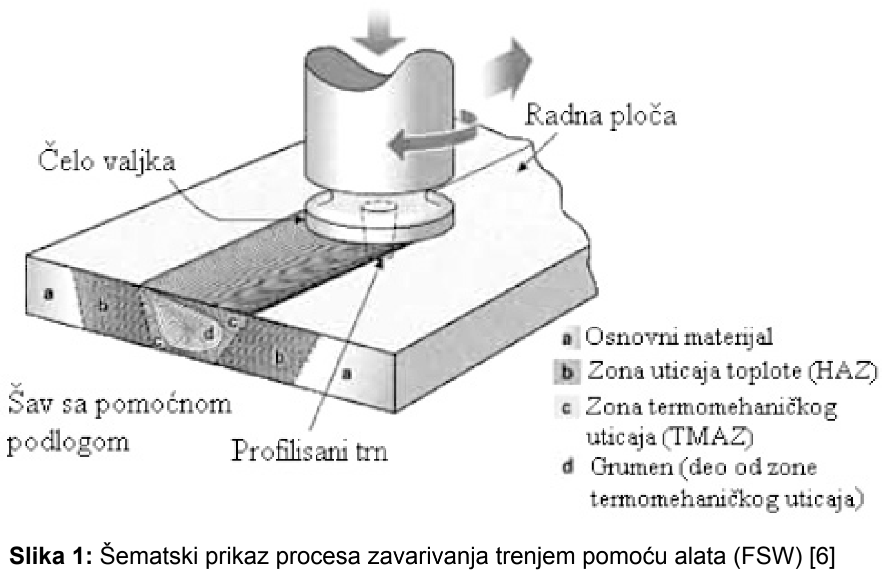
Simultaneously, the pin that is below shoulder and during rotation it mixes heated zones in both pieces. Using FSW enables formation of weld joint without porosity, cracks and residual deformation [7], mainly due to absence of melting.

EXSPERIMENTAL PART

Main goal of the experimental part was focused on monitoring vertical force and temperature on upper part of plate close to rotating tool during FSW of aluminum alloy plates.

Dimensions of welding plates were 180x65x3 mm. Plates were fabricated from commercial high strength 2024 T3 Al alloy. Chemical composition of 2024 T3 base metal is given in table 1.

Changes of vertical force was measured using trocomponent dynamometer with piezo DAVAC KISTLER, type 9443, figure 2. Maximal load for vertical z axe is 30kN. In order to protect dynamometer from overload, lever mechanism presented in figure 3 is introduced.



Slika 1: Šematski prikaz procesa zavarivanja trenjem pomoću alata (FSW) [6]

Figure 1: Friction Stirr Welding – sketch of the process (a) Base material; (b) Heat Affected Zone – HAZ; (c) Thermomechanicallz Affected Zone (TMAZ); (d) Nugget – part of TMAZ [6]

Promena vertikalne sile je merena trokomponentnim dinamometrom sa piezo davačima – KISTLER, tip 9443, slika 2. Maksimalna sila kojom se sme opteretiti dinamometar u pravcu *z* ose je 30KN. Da bi se obezbedio dinamometar od preopterećenja napravljen je polužni mehanizam čime je sila, koju beleži dinamometar, četiri puta umanjena u odnosu na radnu silu, slika 3.

Temperature changes during FSW are monitored using thermovision camera FLIR system, therma CAM P640, figure 4. Measurement range is -40 do 2000 °C, with accuracy ±2 °C. Using new generation detector, high quality 640x480 pixel resolution figures were generated.

Therma CAM Quick Report 1.1 software was used to evaluate recorded results and produce diagrams temperature vs. distance (time) on upper side of plate close to working tool.

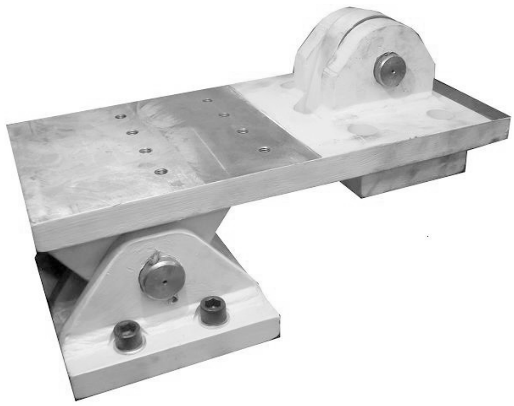
Tabela 1: Hemijski sastav osnovnog materijala [8]

Table 1: The chemical composition of the base material [8]

Legura aluminijuma	Sadržaj elemenata, mas %							
	Cu	Mg	Mn	Fe	Si	Zn	Ti	Al
2024-T3	4,80	1,41	0,72	0,28	0,13	0,07	0,15	Ostatak

Slika 2: Dinamometar – KISTLER, tip 9443

Figure 2: Dinamometar – KISTLER, type 9443



Slika 3: Polužni mehanizam

Figure 3: Lever mechanism

Promena temperature u toku procesa zavarivanja je praćena termovizijskom kamerom FLIR system, tip therma CAM P640, slika 4. Merni opseg kamere je od -40 do 2000 °C, sa tačnošću ±2 °C. Uz pomoć detektora nove generacije napravljene su slike visokog kvaliteta, rezolucije 640x480 piksela.

Pomoću Therma CAM Quick Report 1.1 softvera, obrađeni su rezultati zabeleženi kamerom i napravljeni dijagrami promene temperature na gornjoj površini radne ploče u blizini periferije alata u toku FSW procesa.

Za zavarivanje trenjem mešanjem je korišćen alat napravljen od Cr-V-Mo alatnog čelika (56NiCrMoV7) sa koncentričnim krugovima na čelu valjka i levom zavojnicom na trnu. Tvrdoća alata nakon termičke obrade kaljenja i otpuštanja iznosila je 54 HRC. Leva zavojnica obezbeđuje bolje tečenje materijala oko trna i njegovo kretanje na dole, a koncentrični krugovi obezbeđuju intenzivnije trenje između kontaktnih površina alata i radne ploče.

Na slici 5 je dat izgled alata pre i posle procesa zavarivanja. Alat je imao dobru postojanost na habanje, nije došlo do defrmacije trna i do lepljenja materijala radnih ploča na žlebovima.

Rotating tool was made of Cr-V-Mo tool steel, with concentric circles at the top of CELA valjka and left screw on the pin. Hardness of tool was 54HRC after heat treatment. It is assumed that left screw provides better flow of material both around pin and down. Also, concentric circles should improve friction between plates and tool.

Figure 5 shows used tools before and after welding. Tool had good wear resistance and no material was glued on it.

Experiment was performed on CNC tool machine. This machine provided excellent control of welding parameters and accurate reproducibility. Figure 6 shows full setup of equipment before testing, while figure 7 shows detail related to temperature recording during welding.

Welding parameters used in this work are given in table 2.

RESULTS AND DISCUSSION

Photo taken by thermovision camera 12 seconds after start of welding of sample 1 is shown in figure 8. The

Slika 4: Termovizijska kamera – FLIR system, tip - thermaCAM P640

Figure 4: Thermal Imager - FLIR system, type - thermaCAM P640

Slika 5: Alat, pre i posle upotrebe

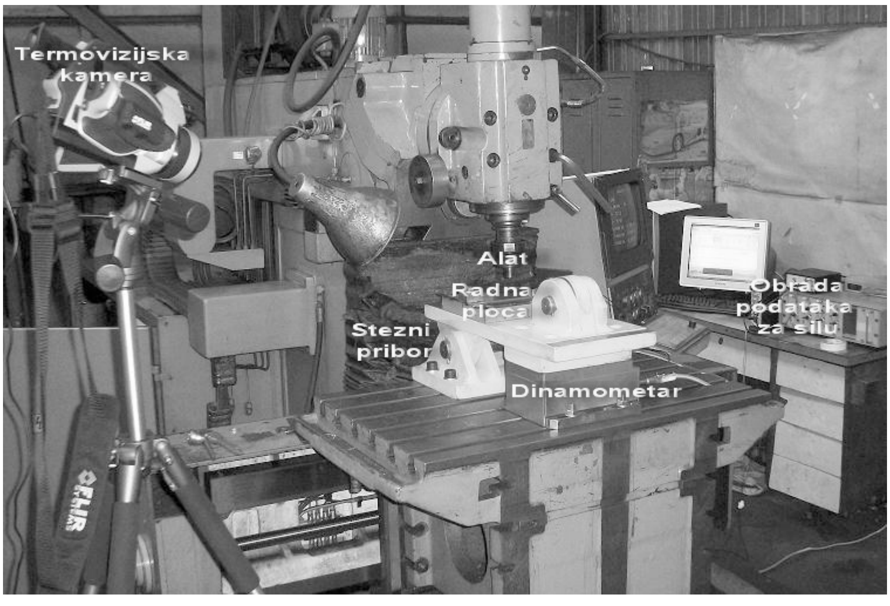
Figure 5: The tool before and after use

Eksperiment je izveden na CNC alatnoj glodalici, tip AG400 priključne snage 12 KW. Time je omogućeno odvijanje procesa zavarivanja po tačno zadatim parametrima zavarivanja i pononovljivost postupka. Na slici 6 je dat izgled CNC glodalice sa opremom za merenje temperature i sile tokom procesa zavarivanja. Na slici 7 je prikazano beleženje temperature termovizijskom kamerom u toku procesa zavarivanja.

cross indicates the place for which the temperature change was monitored. The spot is close to the tool.

Temperature vs. time diagrams recorded during welding of samples 1 and 2 are shown in figures 9a and 9b, respectively.

The initial temperature of sample 1 was 45°C, while 55°C was recorded for sample 2. This difference is



Slika 6: CNC glodalica sa mernom opremom

Figure 6: CNC milling machine with measuring equipment

Slika 7: Beleženje temperature termovizijskom kamerom

Figure 7: Recording temperature with thermal imaging camera

Tabela 2: Parametri zavarivanja

Table 2: Welding parameters

Uzorak Specimen	Brzina prod. alata Tool Penetration rate	Brzina rotac. alata Tool rotation rate	Dub. prod. čela alata Penetration depth	Brzina zavarivanja Welding speed
	v (mm/s)	*n (obr/min)*	*h (mm)*	*v (mm/min)*
1	0,05	400	0,2	40
2	0,05	447	0,2	44,7

U tabeli 2 su prikazani parametri zavarivanja za koje su prikazani rezultati merenja promene sile i temperature tokom procesa zavarivanja.

REZULTATI I DISKUSIJA

Na slici 8 je data fotografija zabeležena termovizijskom kamerom u 12. sekundi od početka procesa zavarivanja uzorka 1. Krstićem je obeležena tačka na radnoj ploči za koju je praćena promena temperature tokom procesa zavarivanja. To je tačka u blizini periferije čela valjka alata.

Na slici 9 su prikazani dijagrami promene temperature u toku procesa zavarivanja uzoraka 1 i 2.

U toku eksperimenta je došlo do zagrevanja steznog pribora, tako da se početna temperatura uzoraka razlikovala. Početna temperatura uzorka jedan je bila 45°C, a uzorka dva 55°C. Ovo nije imalo uticaja na proces zavarivanja. U toku faze prodiranja trna alata u radnu ploču (40 sekundi), temperatura sporije raste. Od trenutka kontakta čela valjka alata sa radnom prločom kontakna površina je znatno veća, intenzivnije je trenje i plastična deformacija, pa je i intenzivnije generisanje toplote, usled čega dolazi do naglog skoka temperature. Kada se dostigla radna temperatura u zoni zavarivanja, proces se attributed to heating of clamps during first experiment, and seems that had no influence on welding process itself.

During pin penetration stage (first 40s), temperature rises slowly. After the first contact between tool shoulder and welding material, contact surface is much larger leading to more intensive friction and plastic deformation. Both processes generates large amount of heat, giving steep rise of temperature. This rise is up to 370-400°C, temperature region in which the welding process is stabilized and progresses in stable manner, i.e. temperature level can be treated as constant. This temperature region is used for routine plastic deformation. Also, this behaviour is in good agreement with previously published data [9].

Force vs. time diagrams recorded during welding of samples 1 and 2 are shown in figures 10a and 10b, respectively. Two characteristic increases are recorded during penetration stage. First one can be related to penetration of pin into plates to be welded. Second jump is related to contact of tool shoulder to welding plates, due to lower temperature in comparison to penetrated area.

In welding phase – phase of translation movement, another smaller increase was recorded. It is assumed stabilizovao i beležena temperatura se kretala u intervalu 370 - 400°C. Zavarivanje trenjem mešanjem je ponovljiv proces, radna temperatura u zoni zavarivanja ne može preći likvidus temperaturu i održava se približno konstantnom u granicama tople plastične prerade [9].

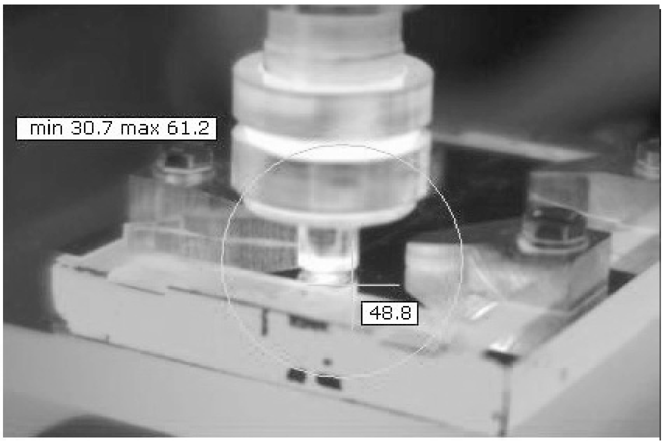
Na slici 10, prikazani su dijagrami promene vertikalne sile u toku procesa zavarivanja uzoraka 1 i 2. U fazi prodiranja alata su zabeležena dva karakteristična skoka sile. Prvi skok se javlja u toku prodiranja trna u radnu ploču dok materijal nije dovoljno zagrejan, a drugi skok se javlja u trenutku kontakta čela valjka alata sa radnom pločom, kada je materijal radne ploče zagrejan ali ne dovoljno za novu kontaktnu površinu. U fazi pravolinijskog kretanja alata – fazi zavarivanja, došlo je do manjeg skoka sile na mestu prolaza alata blizu steznih papučica.

Ovo je u radu [10] objašnjeno time da materijal radne ploče pod dejstvom steznih papučica pruža nešto veći otpor kretanju alata. To bi bilo moguće objašnjenje i za pad sile kada alat naiđe na slobodne krajeve radne [10] that it is due to passing of tool in the vicinity of clamps, i.e. lolcal stronger stiffening. This is in good agreement with decrease of force when tool reaches end of plates. Knowing this, it can be assumed that force is close to constant in welding phase.

CONCLUSIONS

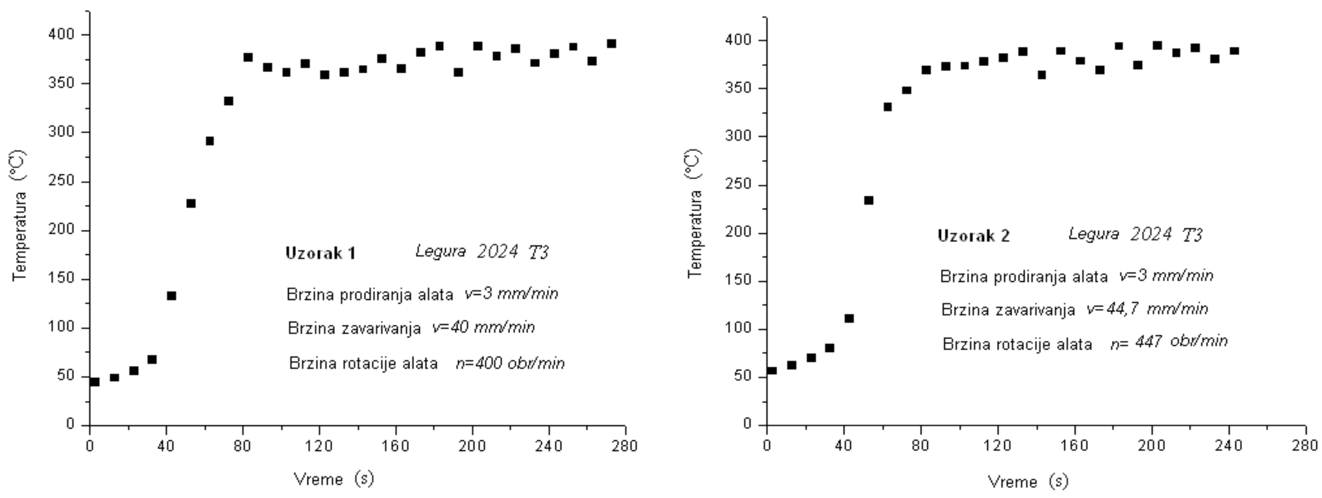
This research have provided following conclusions:

- Welding tool has good wear resistance (no deformation of pin) and no gluing of welding material to tool,
- Temperature of working pieces close to tool shoulder is recorded to be in range 370 - 400°C,
- During penetration phase, two characteristic increases are recorded and connected to moments od pin and tool shoulder penetration,
- It can be assumed that after establishing stabilized welding regime, temperature and vertical force are constant.



Slika 8: Termovizijska slika zabeležena u 12. sekundi, uzorak 1

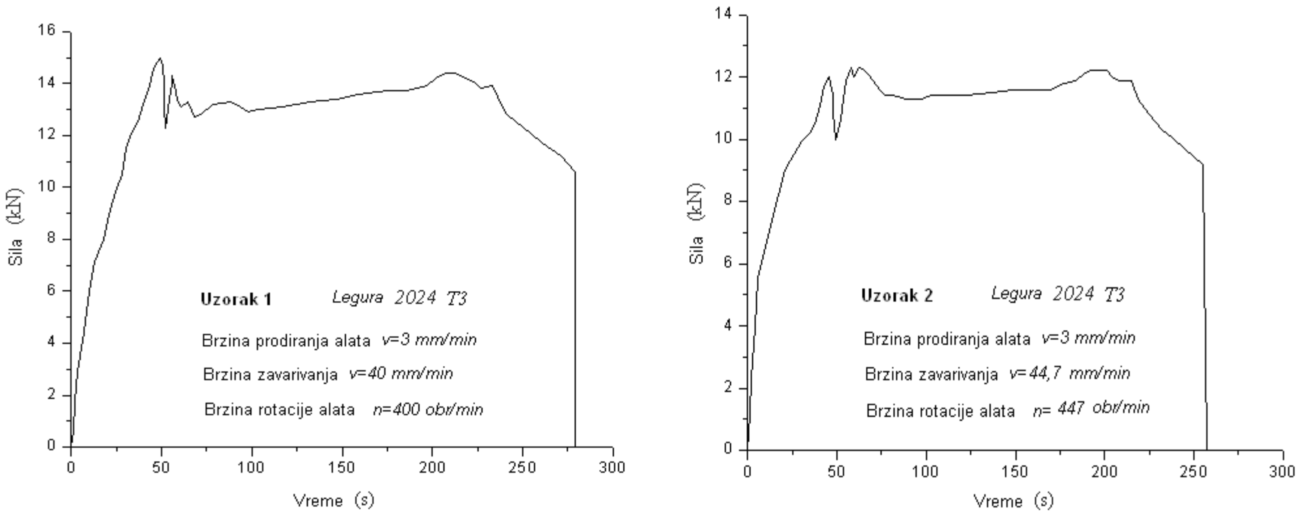
Figure 8: Thermal image recorded in 12 seconds, a specimen 1



a) b)

Slika 9: Promena temperature u toku procesa zavarivanja: (a) uzorak 1; (b) uzorak 2

Figure 9: The temperature change during the welding process, (a) specimen 1, (b) specimen 2



a) b)

Slika 10: Promena sile u toku procesa zavarivanja: (a) uzorak 1; (b) uzorak 2

Figure 10: Change of force during the welding process: (a) specimen 1, (b) specimen 2

ploče, pri kraju procesa zavarivanja. Ako se zanemari skok sile na mestima steznih papučica, može se zaključiti da je sila približno konstantna od trenutka postizanja stabilnog režima zavarivanja.

ZAKLJUČCI

Na osnovu istraživanja i prikazanih rezultata u ovom radu može se zaključiti sledeće:

- Alat ima dobru postojanost na habanje, nije došlo do deformacije trna i do lepljenja materijala radnih ploča na žlebovima,
- Temperatura radne ploče u blizini periferije čela valjka alata se kreće u intervalu 370 - 400°C,
- U toku faze prodiranja alata javljaju se dva karakteristična skoka sile: u trenutku prodiranja trna i u trenutku prodiranja čela valjka alata,
- Nakon uspostavljanja stabilnog režima zavarivanja temperatura u zoni zavarivanja i vertikalna sila su približno konstantne.

Zahvalnost

Autori se zahvaljuju Ministarstvu prosvete i nauke Srbije za podršku preko projekata TR 34018 i TR 34016.

Acknowledgement

Authors acknowledge the financial support of Ministry of Education, science and technological development through projects TR 34018 i TR 34016.

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