Darko Veljić[1], Aleksandar Sedmak[2], Marko Rakin[3], Nenad Radović[3], Negica Popović[1], Horia Daşcău[4], Nikola Bajić[1]

PREDNOSTI ZAVARIVANJA TRENJEM SA MEŠANJEM U ODNOSU NA ELEKTROLUČNO ZAVARIVANJE - ZAŠTITA ZDRAVLJA I ŽIVOTNE SREDINE I BEZBEDNOST NA RADU

ADVANTAGES OF FRICTION STIR WELDING OVER ARC WELDING WITH RESPECT TO HEALTH AND ENVIRONMENTAL PROTECTION AND WORK SAFETY

Originalni naučni rad / Original scientific paper
UDK /UDC: 331.45/.46:621.791
Rad primljen / Paper received: 25.07.2015

Adresa autora / Author's address:
1) IHIS Science & Technology Park, IHIS Techno Experts Research & Development Centre, Belgrade, Serbia
2) University of Belgrade, Faculty of Mech. Engng., Serbia
3) University of Belgrade, Faculty of Techn. and Metallurgy, Serbia, email: marko@tmf.bg.ac.rs
4) National R&D Institute for Welding and Material ISIM, Timişoara, Romania

Ključne reči
- zavarivanje
- zavarivanje trenjem mešanjem
- sigurnost na radu
- zaštita zavarivača

Izvod

U savremenoj industrijskoj proizvodnji, svaki proizvodni proces treba da bude ispitan u pogledu uticaja na životnu sredinu. Za svaku kompaniju koja investira u novi proces je od značaja pažljivo razmatranje HSE (Health, Safety and Environment) problema na radnom mestu. Zavarivanje trenjem sa mešanjem nudi brojne prednosti u pogledu zaštite zdravlja, životne sredine i bezbednosti na radu u odnosu na druge procese zavarivanja zasnovane na primeni električnog luka. Elektrolučno zavarivanje proizvodi čitav spektar ultraljubičastog zračenja koje je štetno po čovekovo zdravlje, pre svega oči i kožu. Izlaganje ovom zračenju bez adekvatne zaštite može dovesti do ozbiljnih povreda. Ukoliko se ne koriste odgovarajuće mere zaštite, zavarivač vrlo lako može dobiti opekotine. Ovo je naročito izraženo kod elektrolučnog zavarivanja aluminijuma, gde je zbog velike provodljivosti materijala potrebno koristiti električni luk veće energije i čija površina ima veću refleksiju od čelika. Ovaj rad govori o FSW procesu zavarivanja i njegovim prednostima u odnosu na elektrolučne postupke zavarivanja, sa posebnim osvrtom na zaštitu zdravlja, životne sredine i bezbednosti na radu.

Keywords
- welding
- friction stir welding
- work safety
- welder protection

Abstract

In modern industrial production, every manufacturing and assembly process should be assessed with respect to its influence on the environment. For a company that invests in a new process, a careful analysis of HSE problems (Health, Safety and Environment) is very important. Friction stir welding (FSW) process offers numerous advantages regarding health protection, environmental effects and work safety in comparison with other welding procedures, such as arc welding. Arc welding produces a broad spectrum of UV radiation, harmful for human health (skin, eyes). Exposure to this radiation without an adequate protection can lead to severe injuries. If appropriate protective measures are undertaken, the welder can easily be exposed to heat injuries. This is especially pronounced for arc welding of aluminium alloys, because high material conductivity of Al requires a high-energy arc, and also because its surface has more pronounced reflection than steel. This work deals with the FSW welding process and its advantages in comparison with arc welding processes with respect to health protection, environmental problems and work safety.

UVOD

Zavarivanje trenjem mešanjem (*Friction stir welding* - FSW) je razvijeno i patentirano na Institutu za Zavarivanje TWI, Kembridž, Velika Britanija, 1991. godine /1, 2/, čiji je glavni cilj bio prevazilaženje problema koji su se javljali tokom zavarivanja (pre svega aluminijumskih legura) procesom topljenja. Od svog uvođenja, ovaj proces je stalno unapređivan i obim njegove primene je proširen. Zavarivanje trenjem mešanjem predstavlja proces spajanja u čvrstom stanju primenom kombinacije toplote i mehaničkog rada čime se dobijaju visokokvalitetni spojevi, bez uobičajenih defekata karakterističnih za proces topljenja.

INTRODUCTION

Friction stir welding (FSW) was developed and patented at the Welding Institute (TWI, Cambridge, UK) in 1991, /1, 2/, with the main aim to overcome the problems occurring during the welding of (primarily aluminium alloys) by melting processes. From its introduction, this process kept improving and the spectrum of applications has increased. FSW is a solid state joining process which uses a combination of heat and mechanical work for obtaining high-quality joints without the usual defects characteristic for the melting processes.

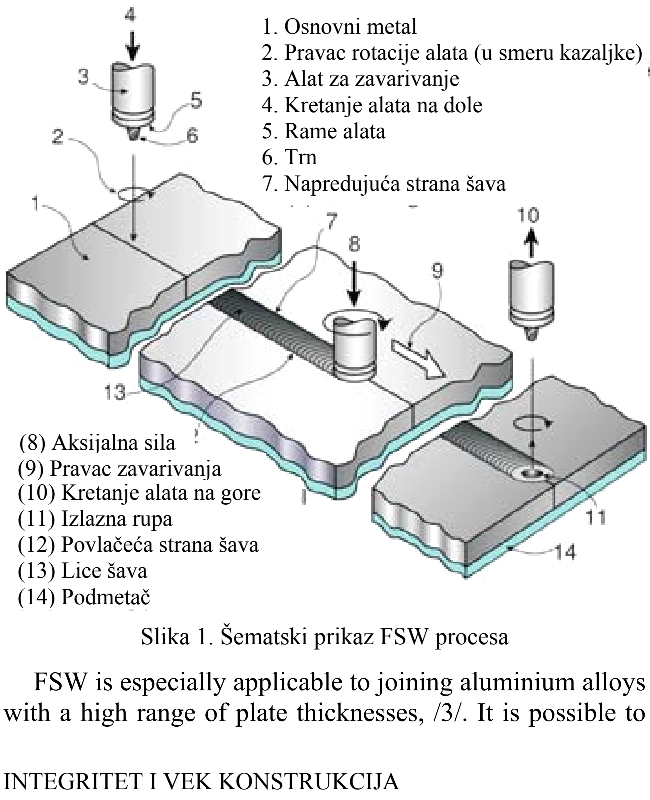
FSW postupak je naročito primenljiv za spajanje legura aluminijuma, sa širokim rasponom debljine ploče, /3/.

Moguće je zavarivati ploče debljine do 50 mm u jednom prolazu, i do 75 mm korišćenjem dvostranog zavarivanja. Pored mogućnosti zavarivanja svih tipova aluminijumskih legura, danas je ovim postupkom moguće obrađivati i mnoge druge materijale, poput bakra, titana, magnezijuma i drugih legura, čelika niže čvrstoće, legura nikla, itd. /4/. U literature se mogu naći brojne studije izrade i ispitivanja zavarivanja trenjem mešanjem, /5-10/. Za određivanje polja napona i temperature tokom ovog procesa se često primenjuje numerička analiza, koja se pokazala veoma korisnom u tu svrhu, /5-9/, kao i u slučaju mnogih drugih procesa, /11-13/.

Sam proces je našao industrijsku primenu u brodogradnji, vazduhoplovnoj industriji, automoto industriji, itd. Dodatni (filer) materijal ili zaštitni gas se ne koriste. Proces se može lako automatizovati tako da nema potrebe za visokokvalifikovanom radnom snagom. Radno okruženje u slučaju FSW je čistije nego kod lučnog zavarivanja, i takođe nema štetnih gasova, dima, UV i drugog štetnog zračenja. Nije potrebna nikakva specijalna priprema površina ili ivica ploče pre zavarivanja, što u velikoj meri umanjuje troškove.

OSNOVA PROCESA

Zavarivanje trenjem mešanjem predstavlja proces koji se sastoji iz dve faze: zavarivanja (tj. zarivanjem alata u materijal) i faze linearnog zavarivanja, prikazane na sl. 1. U fazi zarivanja, tvrd, nepotrošni rotirajući alat prodire u ploče koje treba zavariti. U fazi linearnog zavarivanja, alat se kreće duž linije šava, /5, 6/. Tokom ovog procesa, rotacija alata stvara uslove za generisanje energije trenja između alata i obrađivanog komada, kao i za plastičnu deformaciju materijala. Obe ove energije dovode do zagrevanja ploča, čime se omogućava njihovo spajanje pri temperaturama nižim od njihove tačke topljenja.



Slika 1. Šematski prikaz FSW procesa

FSW is especially applicable to joining aluminium alloys with a high range of plate thicknesses, /3/. It is possible to weld plates of up to 50 mm in a single pass, and up to 75 mm using double-sided joining. In addition to joining almost all types of aluminium alloys, many other materials can nowadays be processed using FSW; examples are copper, titanium, magnesium, and their alloys, lower-strength steels, nickel alloys, etc. /4/. Numerous studies of fabrication and testing of friction stir welded joints can be found in literature, /5-10/. As a very useful tool, numerical analysis is often used for determining the stress and temperature fields during this process, /5-9/, as well as during other welding processes /11-13/.

The process itself has found industrial application in shipbuilding, aerospace industry, automotive industry, and so on. Additional (filler) material or shielding gas are not used. It can easily be automated, so highly qualified labour is not required. The work environment for FSW is cleaner than for arc welding, and also without harmful gases, smoke, UV and other harmful radiation. No special preparation of surfaces or edges of the plates to be welded are necessary, which significantly decreases costs.

BASIS OF THE PROCESS

FSW is primarily a two-stage process: plunge welding stage (i.e. plunging of the welding tool into the material) and linear welding stage, as shown in Fig. 1. In the plunge stage, the hard, non-consumable rotating tool penetrates the plates to be welded. In the linear welding phase, the tool moves along the joint line, /5, 6/. During this process, the tool rotation creates conditions for generation of energy by friction between the tool and the workpiece, as well as by plastic deformation of the material. Both energies heat the plates, enabling their joining at temperatures lower than the melting point of the material.

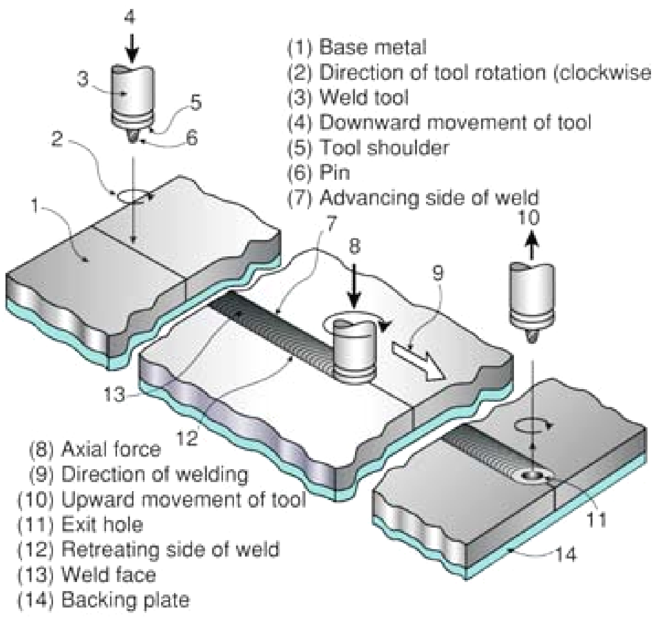
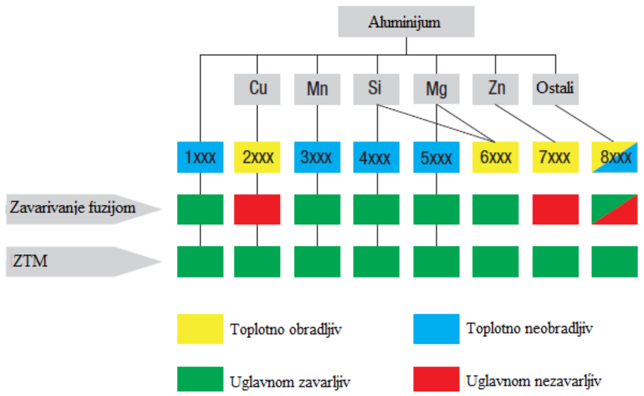


Figure 1. Schematic illustration of the FSW process.

Generisana termička energija zagreva susedne ploče (delove) do temperature vrele plastične obrade - tzv. stanja paste (npr. 80% temperature topljenja; za većinu aluminijumskih legura maksimalna temperature zavarivanja ne prelazi 450°C). Istovremeno, igla rotirajućeg alata mehanički meša materijal obe ploče.

Nakon ovakvog spajanja (zagrevanjem i mehaničkim mešanjem), zona spoja se kuje preko kontakta sa ramenom alata. Koren šava se oblikuje podmetačem, dok je lice šava glatko i ravno, usled kontakta sa ramenom alata. Ova procedura omogućava izbegavanje topljenja materijala tokom zavarivanja, što dovodi do efikasnog zavarivanja legura sa livenom strukturom, bez prisustva specifičnih grešaka (poroznost, segregacije). Tokom mehaničkog mešanja, struktura postaje više sitnozrna i njene mehaničke osobine se poboljšavaju, /2/. Veličina zrna u zoni mešanja može biti manja nego u osnovnom materijalu, pa su mehaničke osobine zavarenog spoja ponekad bolje u poređenju sa OM.

Zavarivanje trenjem sa mešanjem se može koristiti za spajanje ploča napravljenih od istog ili različitih materijala (nehomogeni spojevi). Zavarljivost Al legura za topljenje i FSW proces je prikazano u šemi na sl. 2. Može se zaključiti da se FSW može primeniti na praktično bilo koju leguru.



Slika 2. Zavarljivost različitih aluminijumskih legura, /15/

PREDNOSTI ZAVARIVANJA MEŠANJEM TRENJEM

Zavarivanje trenjem mešanjem ima veoma bitne prednosti u odnosu na elektrolučno zavarivanje, vezane za zaštitu zdravlja, okoline i bezbednost na radu. Na sl. 3 je prikazan radnik na FSW mašini, dok sl. 4 prikazuje radnika koji zavaruje elektrolučno. Količina zaštitne opreme se značajno razlikuje, što ukazuje na to da je FSW proces bezbedniji.

Slika 3. Rad na mašini / Figure 3. Machine operation.

Generated thermal energy heats the joining plates (parts) up to the hot plastic processing temperature - paste-like state (e.g. up to 80% of melting temperature; for most Al alloys the maximal welding temperature does not exceed 450°C). At the same time, the rotating tool pin mechanically stirs the material of both plates.

After this joining (heating and mechanical stirring), the joint zone is forged through the contact with the tool shoulder. The root of the weld is shaped by the backing plate, while the face of the weld is smooth and flat, due to the contact with the tool shoulder. This procedure enables avoidance of material melting during the welding process, which leads to efficient welding of alloys with cast structure, without specific defects (porosity, segregations). During the mechanical stirring, the structure is becoming more fine-grained and its mechanical properties are improved, /2/. Grain size in the stirring zone can be smaller than in the base material; hence mechanical properties of the welded joint can be better than in the base material.

Friction stir welding can be used for joining plates produced from the same - or from different materials (dissimilar joints). Weldability of Al alloys by melting processes and by FSW, is shown in Fig. 2. It can be seen that FSW can be used for virtually any alloy.

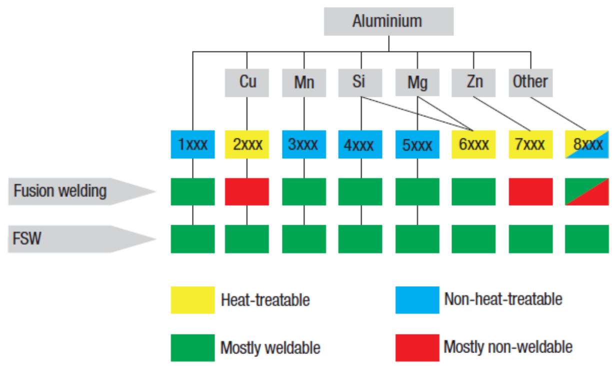


Figure 2. Weldability of various aluminium alloys, /15/.

ADVANTAGES OF FSW

FSW has some very important advantages compared to arc welding, regarding health- and environmental protection and achieving work safety. Figure 3 shows a worker operating the FSW machine, while Fig. 4 shows a welder performing arc welding. The amount of safety equipment is very different, indicating a better work safety with FSW.

Slika 4. Elektrolučno zavarivanje / Figure 4. Arc welding.

Prednosti FSW postupka u poređenju sa procesima topljenja su brojne:

- FSW je lako automatizovati.

- Proces zagrevanja trenjem, mehaničkim mešanjem i kovanjem u oblasti spoja obezbeđuje zavareni spoj bez pora.
- Manje količine unosa toplote (proizvedene trenjem) u zoni zavarivanja omogućavaju minimalan ugib i deformaciju. Na primer, aluminijumska ploča debljine 2.8 mm će biti izložena bočnom savijanju od 0.25 mm na dužini od 12 m.
- Zavareni spoj ne sadrži nemetalne uključke i nečistoće.
- Izražena ravnomernost spoja po dužini.
- Izuzetne mehaničke osobine u pogledu zatezanja, savijanja, kao i otpornosti na zamor.
- Bez prisustva dima tokom zavarivanja, što znači da nema potrebe za lokalnim sistemom ventilacije i da nema opasnosti po zavarivača od gasova i isparenja.
- Nema prslina u zavarenom spoju.
- Zavarivanje se može izvesti u gotovo svi mogućim položajima, zbog toga što se proces odvija u čvrstom stanju.
- Ušteda energije.
- Nema potrebe za dodatnim materijalom, tj. nema troškova proizvodnje, skladištenja i transporta istog.
- Zaštitni gas nije potreban tokom zavarivanja, što znači da nema potrebe za investicijama u posude pod pritiskom i gasne instalacije, što takođe poboljšava bezbednost na radu.
- Nivo buke tokom zavarivanja mešanjem trenjem je zanemarljiv. Najčešće korišćeni procesi za zavarivanje aluminijuma su tehnike MIG-puls ili TIG sa kvadratnim talasima. Kada se koriste za komade srednje debljine, oba postupka zahtevaju veliku količinu energije. Štaviše, frekvencije pulsa i kvadratnih talasa zahtevaju od radnika da koriste opremu za zaštitu od buke (nažalost, ovo se često ignoriše).
- Nema potrebe za sertifikovanim zavarivačima.
- U serijskoj proizvodnji, površine za spajanje zahtevaju minimalnu pripremu.
- Za Al, Cu i druge legure, ploče debljine do 50 mm se mogu zavariti u jednom prolazu.
- Zavareni spojevi ne zahtevaju završnu obradu, poput brušenja, koje ima negativan uticaj na radno okruženje. Nema povećane potrošnje energije i potrebe za investicijom u dodatnu opremu.
- Nema UV i IR zračenja, što znači da nema potrebe za zaštitnom opremom kao kod elektrolučnog zavarivanja (sl. 5).

Tabela 1. Faktori koji doprinose visokim nivoima emisije UV zračenja pri zavarivanju aluminijumskih legura

Faktor	Uticaj na emisije UV zračenja
Velika provodljivost	Aluminijum ima 4-5 puta veću provodljivost od čelika, što zahteva više energije luka da bi se struja u dovoljnoj meri koncentrisala na spoj
Sjajna površina	Aluminijum reflektuje bolje od čelika
Potrebna tehnika	Zavarivači koriste tehnike sa izraženim zračenjem poput elektrolučnog zavarivanja u zaštiti gasa

Advantages of FSW in comparison with melting processes are numerous:

- FSW is easy for automation.
- Processes of friction heating, mechanical stirring and forging in the joint region produce a welded joint without pores.
- Low amount of heat input (produced by friction) in the welding zone enables minimal deflection and deformation. For example, aluminium plate of 2.8 mm thickness can be exposed to 0.25 mm of the lateral bending at the length of 12 m.
- The welded joint does not contain non-metallic inclusions and impurities.
- High uniformity of the joint along its length.
- Excellent mechanical properties regarding tension, bending, and a resistance to fatigue.
- No smoke is generated during the welding, which means that local ventilation systems are not required and there is no health risk for the welder from gases and fumes.
- There are no cracks in the welded joint.
- Welding is possible in virtually all positions, because it is a solid-state process.
- Energy saving.
- No filler material, i.e. no costs of its production, storage and internal transport.
- No shielding gas during welding – no investments in pressure vessels and gas installations which also improves the work safety.
- Noise level during FSW is negligible. The most common welding processes for aluminium are the MIG-pulse or TIG square-wave techniques. When used for workpieces of medium thickness, both processes require a high amount of energy. Furthermore, with pulse or square-wave frequencies, noise protection for the worker is a must (unfortunately, this is often ignored).
- No certified welders are required.
- In serial production, minimum preparation of the joining surfaces is required.
- For Al, Cu and their alloys, plates with thicknesses of up to 50 mm can be welded in a single pass.
- The welded joint does not require some finishing treatment, such as grinding which has a negative impact on the work environment. There is no increased energy consumption and additional equipment investment.
- No UV and IR radiation which means that the protective equipment used for arc welding technique (Fig. 5) is not necessary.

Table 1. Factors contributing to the high levels of UV emission for welding of aluminium alloys.

Factor	Effect on UV emissions
High conductivity	Aluminium is 4–5 times as conductive as steel, requiring higher arc energy to concentrate sufficient power to effect a weld
Shiny surface	Aluminium is more reflective than steel
Technique required	Welders using high radiation techniques such as gas metal and gas tungsten arc welding

Slika. 5. Zaštitna oprema za elektrolučno zavarivanje, /14/

Figure 5. Protective equipment for arc welding, /14/.

Elektrolučno zavarivanje proizvodi ceo spektar UV zračenja, štetnog po zdravlje ljudi, pre svega za kožu i oči. Izloženost UV zračenju može dovesti do ozbiljnog oštećenja kože, što dovodi to potrebe za korišćenjem odgovarajućih mera zaštite. Ovo je naročito izraženo kod aluminijumskih legura, usled visoke provodljivosti (samim tim potrebnom većom energijom luka) i veće reflektivnosti aluminijuma u poređenju sa npr. čelikom. U tabeli 1 su dati faktori koji doprinose visokom nivou emisije UV zračenja pri zavarivanju Al legura. Tabela 2 sadrži nivoe UV zračenja u zavisnosti od procesa zavarivanja. Kao što je pomenuto, zavarivanje trenjem sa mešanjem ne dovodi do emisije UV zraka.

Tabela 2. Procesi zavarivanja i emisija UV zračenja

Nivo emisije UV zračenja	Postupak zavarivanja
Visok	Elektrolučno u zaštiti gasa MIG/MAG Elektrolučno u zaštiti gasa TIG
Srednji	Većina post. elektrol. zavarivanja
Nizak	Elektrolučno pod troskom
Minimalan ili jednak nuli	Oksiacetilensko Elektrootporno Zavarivanje trenjem Lasersko, elektronskim snopom Zavarivanje trenjem sa mešanjem

PRIMENA ZAVARIVANJA MEŠANJEM SA TRENJEM

U današnje vreme, proizvodnja prevoznih sredstava za putni, železnički, vodeni i vazdušni transport je zasnovana na upotrebi aluminijuma i njegovih legura, iz kako ekonomskih tako i ekoloških razloga. U početku, za zavarivanje aluminijumskih legura su korišćene samo uobičajeni procesi zavarivanja, poput MIG i TIG, u kombinaciji sa zakivcima. Ove procese karakterišu visok unos toplote i pojava problema termičke deformacije materijala i formiranja aluminijum oksida. Ovi problemi se mogu rešiti uvođenjem zavarivanja mešanjem trenjem u proces proizvodnje.

Arc welding produces an entire spectrum of UV rays, harmful to human health, primarily skin and eyes. Exposure to UV radiation can lead to severe skin damage which leads to necessity of appropriate protective measures. This is especially pronounced for aluminium alloys, due to the high conductivity (and therefore higher required arc energy) and reflectiveness of aluminium in comparison with e.g. steel. Table 1 gives factors which contribute to high levels of UV emission for welding aluminium alloys. Table 2 contains levels of UV radiation depending on the welding process. As mentioned previously, friction stir welding does not produce UV emission.

Table 2. Welding processes and UV emission.

Level of UVR emission	Welding processes
High	Gas metal arc welding Gas tungsten arc welding
Medium	Most arc welding processes
Low	Submerged arc welding
Minimal or nil	Oxy-acetylene welding Resistance welding Friction welding Laser and electron beam welding Friction stir welding

INDUSTRIAL APPLICATION OF FSW

Nowadays, production of transportation machines for road, railway, water and air transport is based on the use of aluminium and its alloys, due to both economic and ecological reasons. Initially, only conventional welding processes were used for joining aluminium alloys, such as MIG and TIG, combined with joining by rivets. These processes are characterized by high heat input and occurrence of problems of thermal deformation of the material and formation of aluminium oxide. These problems are solved by the introduction of friction stir welding into the manufacturing procedure.

Od svih industrijskih sektora, brodogradnja je među prvima usvojila tehnologiju zavarivanja mešanjem trenjem. Primena ove tehnologije je u stalnom porastu, naročito kod montažnih ploča.

Primena FSW u vazduhoplovnoj industriji ima značajnih prednosti u poređenju sa starijim tehnologijama proizvodnje (kako u vojnim, tako i u civilnim letelicama) koji koriste zakivke. Ovo je dovelo do značajnih ušteda u pogledu vremena potrebnog za proizvodnju, pripreme delova, ukupne mase aviona, kao i povećane nosivosti i smanjenih troškova proizvodnje.

Još jedna bitna primena zavarivanja mešanjem trenjem je u proizvodnji železničkih vozila, poput brzih vozova, tramvaja, rezervoara za železnički transport, kontejnera, itd.

Zavarivanje mešanjem trenjem se takođe koristi u automoto industriji. Cilj je proizvodnja lakih vozila, čime se može doprineti većoj nosivosti, boljoj potrošnji goriva i unapređenim ekološkim performansama.

ZAKLJUČAK

Zavarivanje mešanjem trenjem (FSW) nudi brojne prednosti u odnosu na lučno zavarivanje, naročito u pogledu zaštite zdravlja, okoline i obezbeđivanja bezbednog rada.

Sam proces ne zahteva upotrebu dodatnih materijala ili zaštitnog gasa, i može se lako automatizovati, što znači da nema potrebe za visokokvalifikovanom radnom snagom. Radno okruženje je čisto, bez isparenja i gasova, mirisa, UV i drugih vrsta štetnog zračenja. Takođe, nema potrebe za posebnom obradom površina ili ivica, što pojednostavljuje proces i smanjuje troškove.

Prednosti zavarivanje mešanjem trenjem su prepoznate od strane brojnih kompanija širom sveta, u raznim inženjerskim granama, i primena ovog procesa je u stalnom porastu.

ZAHVALNICA

Autori se zahvaljuju podršci Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije u okviru projekata TR 34016 i TR 35006.

Shipbuilding is among the first industrial sectors that have adopted technology for friction stir welding. The application of FSW keeps increasing, especially for prefabricated panels.

Application of FSW in the aerospace industry has significant advantages in comparison with older production technologies (for both military and civil aircrafts) using riveted joints. This leads to significant savings in terms of fabrication time, preparation of parts, overall mass of an airplane, as well as improved load-carrying capacity and decreased manufacturing costs.

Another important application of FSW is in the production of railway vehicles, such as high-speed trains, trams, tanks for railway transport, containers, and so on.

Friction stir welding is also used in automotive industry. The aim is to produce light-weight vehicles which can contribute to better load carrying capacity, fuel consumption and improved ecological performances.

CONCLUSIONS

The friction stir welding (FSW) process offers numerous advantages when compared to arc welding, especially regarding health protection, environmental protection and work safety assurance.

The process itself does not require the use of filler material or shielding gas, and it can easily be automated, so highly qualified labour is not necessary. The work environment is cleaner; there are no fumes and gases, odours, UV and other types of harmful radiation. Also, special treatment of surfaces or edges is not required, which simplifies the process and decreases the costs.

Advantages of FSW have been recognised by many companies worldwide, in various engineering branches, and its application keeps increasing constantly.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from the Serbian Ministry of Education, Science and Technological Development under the projects TR 34016 and TR 35006.

LITERATURA – REFERENCES

1. Thomas, W.M., Nicholas, E.D., Needham, J.C., Murch, M.G., Temple-Smith, P., Dawes, C.J., Improvements relating to friction welding, European Patent Specification EP 0 615 480 B1. l2.espacenet.com/dips/viewer?PN=EP0615480
2. Veljić, D., Doctoral thesis (in Serbian), University of Belgrade, Faculty of Mech. Engng., Belgrade, Serbia (2012).
3. Reynolds, A.P., Lockwood, W.D., Seidel, T.U., *Processing property correlation in friction stir welds*, Materials Science Forum, 331-3: 1719-1724 (2000).
4. http://www.twi.co.uk/j32k/getFile/fswmat.html, Friction Stir Welding - Materials and thicknesses
5. Veljić, D., et al., *Numerical simulation of the plunge stage in friction stir welding*, Structural Integrity and Life (*Integritet i vek konstrukcija*), 11(2): 131-134 (2011).
6. Veljić, D., Rakin, M. Perović, M., Medjo, B., Radaković, Z., Todorović, P., Pavišić, M., *Heat generation during plunge stage in friction stir welding*, Thermal Science, 17: 489-496 (2013).
7. Veljić, D., Perović, Sedmak, A., M., Rakin, M. Trifunović, M., Bajić, N., Bajić, D., *A coupled thermo-mechanical model of friction stir welding*, Thermal Science, 16: 527-534 (2012).
8. Veljić, D., Sedmak, A., Rakin, M. Bajić, N., Medjo, B., Bajić, D., Grabulov, V., *Experimental and numerical thermo-mechanical analysis of friction stir welding of high-strength aluminium alloy*, Thermal Science, 17/s1: 28-37 (2013).
9. Živojinović, D., Sedmak, A., Grbović, A., *Crack growth analysis in friction stir welded joint zones using extended finite element method*, Struc. Int. and Life, 13(3): 179-188 (2013).
10. Eramah, A., Tadić, S., Sedmak, A., *Impact fracture response of friction stir welded Al-Mg alloy*, Struc. Int. and Life, 13(3): 171-177 (2013).
11. Berković, M., Maksimović, S., Sedmak, A., *Analysis of welded joints by applying the finite element method*, Struc. Int. and Life, 4(2): 75-83 (2004).
12. Aburuga, T., Sedmak, A., Radaković, Z., *Numerical aspects for efficient welding computational mechanics*, Thermal Science, 18/s1: 139-148 (2014).
13. Ivanović, I., Sedmak, A., Miloš, M., Živković, A., Lazić, M., *Numerical study of transient three-dimensional heat conduction problem with a moving heat source*, Thermal Science, 15(1): 257-266 (2011).
14. http://www.millerwelds.com/resources/articles/basics-welding-safety