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High-frequency linear friction welding between aluminum alloys and stainless steal

Zavarivanje linijskim visokofrekventnim trenjem legura aluminijuma i nerđajućeg čelika

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Abstract

Intermetallic compound is one of the dominant factor for the dissimilar joints, e.g., Al-Fe joints. Since the joint strength generally decreases with the increasing intermetallic compound layer thickness, the development of joining process that can inhibit the intermetallic compound growth is required. In the present study, we show the dissimilar joining between 5083/6063 aluminum alloys and 304 stainless steel by high-frequency linear friction welding working at 245 Hz. In order to investigate the relationship between the mechanical properties and high-frequency linear friction process, the frictional heat at the interface was controlled by varying friction pressure. We found that sound joints with joint efficiency (95% and 90% for 5083 and 6063 aluminum alloys/304 stainless steel, respectively) were produced by short-time high-frequency linear friction welding process below 2 s. Microstructural observation showed that thin intermetallic compound layer was formed at the interface for both joints, and that the intermetallic compound layer thickness was influenced by the dependence of the plastic flow behavior during linear frictional motion on pressure. We believe the high-frequency linear friction welding was demonstrated to enable the sound joining of various materials by controlling the friction

Rezime

Intermetalno jedinjenje je jedan od dominantnih faktora za raznorodne spojeve, na primer, Al-Fe spojeve. S obzirom da se čvrstoća spoja obično smanjuje sa povećanjem debljine sloja intermetalnog jedinjenja, potrebno je razviti proces spajanja koji može inhibirati rast intermetalnih jedinjenja. U ovoj studiji prikazujemo spajanje raznorodnih materijala, legura aluminijuma 5083/6063 i nerđajućeg čelika 304 zavarivanjem visokofrekventnim linearnim trenjem pri 245 Hz. Da bi se istražila veza između mehaničkih svojstava i postupka visokofrekventnog linearnog trenja, toplota trenja na međupovršini (interfejsu) je kontrolisana promenljivim pritiskom trenja. Otkrili smo da su ispravni spojevi sa efikasnošću spojeva (95% i 90% za legure aluminijuma 5083 i 6063 / nerđajući čelik 304) proizvedeni kratkoročnim postupkom zavarivanja visokofrekventnim linearnim trenjem ispod 2 s. Mikrostrukturno posmatranje pokazalo je da se na interfejsu oba spoja formira tanak sloj intermetalnog jedinjenja i da je debljina sloja intermetalnog jedinjenja bila pod uticajem zavisnosti ponašanja plastičnog protoka tokom linearnog trenja od pritiska. Verujemo da je zavarivanje visokofrekventnim linearnim trenjem pokazalo da omogućava ispravno spajanje različitih materijala kontrolom pritiska trenja. Detaljni rezultati

pressure. The detailed results and discussion will be addressed in my presentation.

1. Introduction

Many studies have investigated the dissimilar joining between aluminum and steel, which involves the formation of intermetallic compound (IMC) layer at the interface. Growth of IMC layer generally results in the decrease of joint strength [1,2]. Therefore, the solid-state process has been applied to the dissimilar joining. Linear friction welding (LFW) is one of the solid-state joining method using frictional heat generated by the linear motion of weld materials. Although the LFW process has been used for high- melting-point or high-strength materials [3], it was difficult to be applied to aluminum alloys [4]. On the other hand, we developed the high-frequency LFW process for the joining of aluminum alloys [5]. The increase of friction frequency leads to the high heat flux, enabling the effective joining of aluminum alloys at short time [6].

In this study, we report the high-frequency LFW for aluminum alloy/stainless steel dissimilar joining. Aluminum alloys are basically classified into heat-treatable and non-heat treatable alloys, whose softening behaviors are different during heating, dependent on their strengthening mechanism. Herein, the bondability between 5083 or 6063 aluminum alloy and 304 stainless steel, which is a representative austenitic stainless steel, was investigated. Further, the change of joint strength and interfacial structure during the process was investigated by varying the friction pressure that is a factor for heat generation.

2. Experimental procedure

5083-O and 6063-T5 aluminum alloys (A5083 and A6063) and 304 stainless steel (SUS304) plates, which were 35 mm in square with 10 mm thickness, were used as specimens. These plates were fabricated to have projection part of 11 mm in square with 2 mm thickness at the center for linear friction. High-frequency LFW is composed of a friction process of butt materials and a forge process. Friction frequency and amplitude were 245 Hz and 1.8 mm, respectively. To investigate the influence of friction pressure for each aluminum alloy, the percentage of friction pressure against proof stress at room temperature, α, was introduced as 20–60% for A5083/SUS304 joint and 5–40% for A6063/SUS304 joint; proof stress of each alloy was 145 MPa. Friction time was varied from 0.5–6 s for A5083/SUS304 joint and 0.2–6.0 s for A6063/SUS304 joint. Joints after friction process were forged at 150 MPa for 5 s.

The joint strength was measured by tensile test at a

i rasprava biće razmatrani u mojoj prezentaciji.

1. Uvod

Mnoge studije su istraživale raznorodne spojeve aluminija i čelika, što uključuje formiranje sloja intermetalnog jedinjenja (IMC) na interfejsu. Rast IMC sloja uglavnom rezultuje smanjenjem čvrstoće spoja [1,2]. Stoga se postupak u čvrstom stanju primenio na spajanje raznorodnih materijala. Zavarivanje linearnim trenjem (LFW) je jedan od metoda spajanja u čvrstom stanju, koristeći toplotu trenja, koja se generiše linearnim kretanjem materijala za zavarivanje. Iako se postupak LFW koristio za materijale sa visokom tačkom topljenja ili visokom čvrstoćom [3], bilo je teško primeniti na legure aluminijuma [4]. S druge strane, razvili smo visokofrekventni LFW postupak spajanja aluminijumskih legura [5]. Povećanje frekvencije trenja dovodi do visokog toplotnog toka, što omogućava efikasno spajanje aluminijumskih legura u kratkom vremenu [6].

U ovoj studiji izveštavamo o visokofrekventnom LFW za aluminijumske legure / nerđajući čelik koji se međusobno razlikuju. Aluminijske legure su u osnovi klasifikovane u legure koje se obrađuju toplotom i koje se ne mogu toplotno tretirati, a čija se omekšavanja razlikuju tokom zagrevanja, u zavisnosti od mehanizma ojačavanja. Ovde je ispitivana spojivost između 5083 ili 6063 legure aluminija i 304 nerđajućeg čelika, koji je reprezentativan austenitni nerđajući čelik. Dalje, promena čvrstoće spoja i međufazne strukture tokom procesa, istražena je promenom pritiska trenja koji je faktor za stvaranje toplote.

2. Eksperimentalni postupak

Aluminijumske legure 5083-O i 6063-T5 (A5083 i A6063) i ploče od nerđajućeg čelika 304 (SUS304), koje su bile 35mm kvadrat debljine 10 mm korišćeni su kao uzorci. Ove ploče su izrađene tako da imaju izbočeni deo od 11 mm u kvadratu sa debljinom od 2 mm u sredini za linearno trenje. Visokofrekventni LFW sastoji se od procesa trenja sučeljenih materijala i procesa kovanja. Frekvencija trenja i amplituda bili su 245 Hz i 1,8 mm, respektivno. Da bismo istražili uticaj pritiska trenja za svaku leguru aluminijuma, uveden je procenat pritiska trenja nasuprot dokazanom naponu na sobnoj temperaturi, α, 20–60% za spoj A5083 / SUS304 i 5–40% za spoj A6063 / SUS304; dokazani napon svake legure bio je 145 MPa. Vreme trenja variralo je od 0,5–6 s za spoj A5083 / SUS304 i 0,2–6,0 s za spoj A6063 / SUS304. Spojevi nakon trenja kovani su pri 150 MPa tokom 5 s.

Čvrstoća spoja je ispitivanjem zatezanjem brzinom od 10 mm / min.

rate of 10 mm/min. The joint cross-section parallel to the friction direction was observed by optical microscopy (OM) and scanning electron microscopy (SEM) to evaluate the shape change and joint microstructure during the process.

Presek spoja paralelnog smeru trenja posmatran je optičkom mikroskopijom (OM) i skenirajućom elektronskom mikroskopijom (SEM) da bi se procenila promena oblika i mikrostruktura spoja tokom procesa.

3. Results and discussions

Fig. 1 shows the tensile strength of A5083/SUS304 and A6063/SUS304 joints after high-frequency LFW. Dashed lines represent the strength of the base alloys, which were 317.6 MPa for A5083 and 184.3 MPa for A6063. We confirmed that friction pressure influenced on the relationship between friction time and joint strength. As for A5083/SUS304 joint (Fig. 1(a)), high pressure showed the high joint strength at the early friction process and the gradual decrease with further friction. In contrast, low friction pressure led to the delay of joining behavior compared with high pressure. The middle pressure showed the intermediate distribution. As for A6063/SUS304 joint (Fig. 1(b)), the relation was basically similar to that in A5083/SUS304 joint although the joining behavior occurred much early. It is emphasized that joint efficiency of each joint reached 94.9% and 89.7%. Thus, high-frequency LFW is found to form the sound joint by appropriate friction pressure for base alloys.

The decrease of strength with the friction time in A6063/SUS304 joint can be explained by softening behavior during the process. The effect of precipitation hardening in A6063 becomes lost after excessive friction owing to heating in high-frequency LFW. In contrast, no particular softening behavior would generally appear in A5083 that is a non-heat- treatable alloy, which indicates that the change in strength was attributed to the interfacial microstructure.

3. Rezultati i diskusija

Slika 1 prikazuje zateznu čvrstoću spojeva A5083/SUS304 i A6063/SUS304 nakon visokofrekventnog LFW. Isečene linije predstavljaju čvrstoću baznih legura koje su bile 317,6 MPa za A5083 i 184,3 MPa za A6063. Potvrdili smo da pritisak trenja utiče na odnos vremena trenja i čvrstoće spoja. Što se tiče spoja A5083/SUS304 (Sl. 1 (a)), visoki pritisak je pokazao visoku čvrstoću spoja tokom procesa ranog trenja i postepeno smanjenje sa dodatnim trenjem. Suprotno tome, nizak pritisak trenja doveo je do odlaganja spajanja u poređenju s visokim pritiskom. Srednji pritisak pokazao je međuraspodelu. Što se tiče spoja A6063/SUS304 (slika 1 (b)), odnos je u osnovi bio sličan onom u spoju A5083/SUS304, iako se spajanje dogodilo mnogo ranije. Naglašava se da je zajednička efikasnost svakog spoja dostigla 94,9% i 89,7%. Tako je pronađeno da visokofrekventni LFW formira ispravni spoj odgovarajućim pritiskom trenja za bazne legure.

Smanjenje čvrstoće tokom vremena trenja u spoju A6063/SUS304 može se objasniti omekšavanjem tokom procesa. Efekat taložnog itvrdnjavanja u A6063 gubi se nakon prekomernog trenja usled zagrevanja u visokofrekventnim LFW. Suprotno tome, u A5083 se generalno ne pojavljuje neko posebno stanje omekšavanja, a to je legura koja se ne može toplotno tertirati, što ukazuje da se promena čvrstoće pripisuje mikrostrukturi na međupovršini.

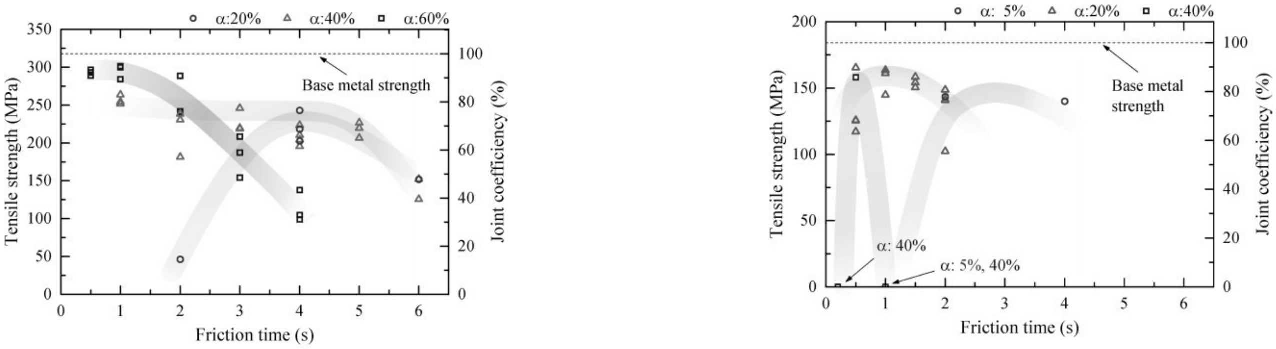

***Fig. 1** The influence of loading ratio α and friction time on the tensile trength of (a) A5083/SUS304 and (b) A6063/SUS304 joints.*
***Sl. 1** Uticaj opterećenja na odnos α i vremena trenja na zatezanu čvrstoću na (a) A5083 / SUS304 i (b) A6063 / SUS304.*

Fig. 2(a) represents interfacial structure of A5083/SUS304 joint for α=40% and 60%. While thin interfacial (IMC) layer was present for both friction pressures, the thickness significantly changed in accordance with the pressure; a layer

Slika 2 (a) predstavlja strukturu međupovršine spoja A5083/SUS304 za α= 40% i 60%. Dok je za oba pritiska trenja bio prisutan tanki intermetalni (IMC) sloj, debljina se značajno promenila u skladu sa pritiskom; sloj ispod 500 nm formiran je pod below 500 nm was formed in high pressure whereas a layer about 1–2 μm in low pressure. On the other hand, we confirmed similar evolutions of interfacial structure for both pressure. Firstly, thin IMC layer formed at early process. Subsequently, the layer mainly remained thin during friction process whereas some layers locally grew. Finally, additional fiction led to the crack formation and local fracture in the grown IMC layer. Since torn IMC was observed in aluminum side at the middle of process, it is supposed that stable layer thickness would be due to the tearing of IMC layer caused by plastic flow during linear friction. The shear load attributed to plastic flow initiates the crack in the grown IMC layer and leads to the fracture; the separation of IMC layer would be the evidence of torn grown IMC. Such crack formation in IMC layer lowers the interfacial strength of the joint. Fig. 2(b) represents the interfacial structure of A6063/SUS304 joint for α=20%. No reaction layer was observed at the interface for every friction time. Thick interfacial reaction layer generally tends to form in Al-Mg alloy compared with Al-Mg-Si alloy because of the alloying element of Si. This fact supports the difference of thickness between two aluminum alloys. Moreover, we found change in interfacial structure in A5083/SUS304 joint was consistent with joint strength depending on friction pressure and friction time. Here, we focused on the plastic flow of joined materials in order to correlate the formation of interfacial structure to friction process. Fig. 3 shows the cross-sectional OM images of joint shape. It was confirmed that aluminum alloy was squeezed out in association with the friction against little shape change in steel. In A5083/SUS304 joint (Fig. 3(a)), high friction pressure led to more squeezing than low one. Squeezing in A6063/SUS304 remarkably occurred at the early process (Fig. 3(b)). Moreover, projection part of aluminum was fully removed by squeezing after 1.5 s. This means the friction works like as steel is buried in aluminum alloy.

visokim pritiskom dok je sloj oko 1-2 μm pri niskom pritisku. S druge strane, potvrdili smo slične evolucije međufazne strukture za oba pritiska. Prvo, tanki sloj IMC-a formiran je u ranom postupku. Nakon toga, sloj je uglavnom ostao tanak tokom trenja, dok su neki slojevi lokalno rasli. Konačno, dodatno trenje je do stvaranja pukotina i lokalnog loma u naraslom sloju IMC-a. Pošto je na sredini procesa u aluminijumu uočeno cepanje IMC, pretpostavlja se da bi stabilna debljina sloja nastala kidanjem sloja IMC bila uzrokovana plastičnim protokom pri linearnom trenju. Sporno opterećenje pripisano plastičnom toku inicira pukotinu u naraslom sloju IMC-a i dovodi do loma; odvajanje sloja IMC-a bio bi dokaz oštećenja IMC-a. Takvo stvaranje pukotina u IMC sloju smanjuje međufaznu čvrstoću sloja. Sl. 2 (b) predstavlja strukturu međupovršine spoja A6063/SUS304 za α = 20%. Nije primećen reakcioni sloj na međupovršini za svako vreme trenja. Debeli međupovršinski sloj uglavnom nastaje u Al-Mg leguri u poređenju sa Al-Mg-Si legurom zbog legirajućeg elementa Si. Ova činjenica potvrđuje razliku debljine između dve legure aluminijuma. Štaviše, otkrili smo da je promena međufazne strukture u spoju A5083/SUS304 bila u skladu sa čvrstoćom spoja u zavisnosti od pritiska trenja i vremena trenja. Ovde smo se fokusirali na plastični tok spojenih materijala kako bismo povezali formiranje međufazne strukture i procesa trenja.

Slika 3 prikazuje slike OM poprečnog preseka oblika spoja. Potvrđeno je da se aluminijska legura stisla (skupila) zajedno sa trenjem nasuprot maloj promeni oblika kod čelika. U spoju A5083/SUS304 (Sl. 3 (a)), visok pritisak trenja doveo je do većeg stiskanja nego kod niskog. Stiskanje u A6063/SUS304 se u značajnom stepenu dogodilo u ranom procesu (Sl. 3 (b)). Štaviše, istureni deo aluminijuma je u potpunosti uklonjen pritiskom nakon 1,5 s. To znači da trenje deluje kao što je čelik sahranjen u leguri aluminijuma.

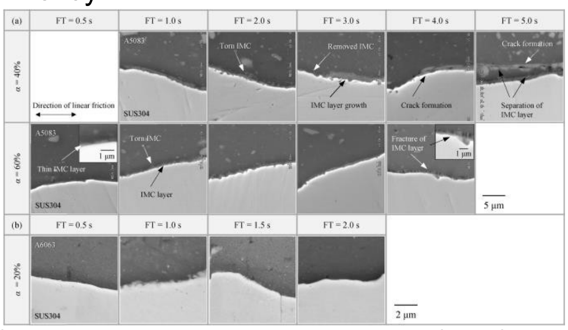

Fig. 2 *Cross-sectional SEM images of the joints showing temporal evolutions of interfacial structure for (a) A5083/SUS304 and (b) A6063/SUS 304 joints.*

Sl. 2 *SEM slike poprečnog preseka spojeva koji prikazuju vremenske evolucije structure međupovršine za (a) A5083 / SUS304 i (b) A6063 / SUS 304 spojeve.*

Each aluminum alloy shows the softening behavior during heating, which lead to the plastic flow. In particular, Al-Mg- Si alloy shows a typical decrease in hardness above 200 °C, resulting from growth or dissolution of precipitates, while Al-Mg alloy shows gradual decrease [7]. Hence, the softening behavior markedly facilitates the plastic flow of Al-Mg-Si alloy and squeezing. It is presumed that the softening behavior should be attributed to the change in friction pressure on the basis of heat flux at the interface; higher friction pressure induces more heat flux and plastic flow. The presumption also implies sufficient plastic flow and subsequent joining behavior would start late in low friction pressure. Further, plastic flow should influence on the IMC layer thickness in A5083/SUS304 joint. Large plastic flow induces large shear load on the interface, which induces tearing of IMC layer. Thus, friction pressure plays a significant role in determining IMC layer thickness and the following strength in A5083/SUS304 joint. On the contrary, excessive pressure could lead to inefficient welding for A6063/SUS304 joint owing to the excessive squeezing and softening of base alloy. These influence of friction pressure on the squeezing behavior is consistent with the weldability in Fig. 1. Thus, it is conducted that joint performance of A5083/SUS304 joint is due to the morphology of IMC attributed to plastic flow. Regarding A6063/SUS304 joint, the squeezing behavior also relates to the change in joint strength. However, it is noted that the joint efficiency was comparable to the other friction process instead of typical decrease of the strength. This indicates that characteristic interfacial structure contributing to strong bond is formed by high-frequency LFW.

Svaka legura aluminijuma pokazuje ponašanje omekšavanja tokom zagrevanja, što dovodi do plastičnog protoka. Konkretno, legura Al-Mg-Si pokazuje tipično smanjenje tvrdoće iznad 200 ° C, što je posledica rasta ili rastvaranja taloga, dok legura Al-Mg pokazuje postepeno smanjenje [7]. Stoga ponašanje omekšavanja značajno olakšava plastični protok legure Al-Mg-Si i stiskanja. Pretpostavlja se da omekšavanje treba pripisati promeni pritiska trenja na osnovu toplotnog protoka na međupovršini; veći pritisak trenja indukuje veći toplotni protok i plastičnost. Pretpostavka takođe podrazumeva dovoljnu plastičnost i naknadno spajanje počelo bi kasno pri niskom pritisku trenja. Dalje, plastičnost treba da utiče na debljinu sloja IMC u spoju A5083/SUS304. Velika plastičnost indukuje veliko opterećenje na smicanje na međupovršini, što indukuje kidanje sloja IMC. Prema tome, pritisak trenja igra značajnu ulogu u određivanju debljine sloja IMC i sledeće čvrstoće u spoju A5083/SUS304. Suprotno tome, prekomerni pritisak može dovesti do neefikasnog zavarivanja spoja A6063/SUS304 usled prekomernog stiskanja i omekšavanja bazne legure. Ovakav uticaj pritiska trenja na stiskanje je u skladu sa zavarivljivošću na slici 1. Stoga se izvodi da je izgled spoja A5083/SUS304 posledica morfologije IMC koja se pripisuje plastičnom tečenju. Što se tiče spoja A6063/SUS304, stiskanje se takođe odnosi na promenu čvrstoće spoja. Međutim, treba primetiti da je efikasnost spoja uporediva sa drugim procesom trenja umesto tipičnog smanjenja čvrstoće. To ukazuje da je karakteristična struktura međupovršine koja doprinosi jakoj vezi formirana visokofrekventnim LFW.

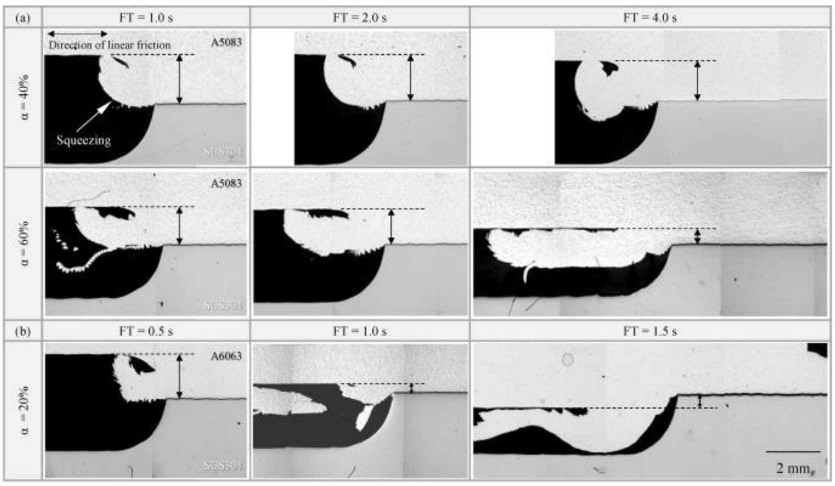

Fig. 3 *Cross-sectional OM images showing time dependence of squeezing behavior for (a) A5083/SUS 304 and (b) A6063/SUS304 joints. Arrows in figures represent the distance between the surface of aluminum and projection part of steel.*
Sl. 3 *OM slike poprečnog preseka koje pokazuju vremensku zavisnost ponašanja stiskanja za (a) A5083 / SUS 304 i (b) A6063 / SUS304. Strelice na slikama predstavljaju udaljenost između površine aluminijuma i isturenog dela čelika.*

Consequently, the HFLFW process allowed dissimilar joining between Al-Mg or Al-Mg-Si alloys and stainless steel, which was difficult to achieve by low-frequency friction welding owing to certain process characteristics. The control of friction pressure according to the type of welded material played a significant role in suppressing interfacial structure formation to effectively afford strong joints.

Shodno tome, postupak HFLFV omogućio je spajanje legura Al-Mg ili Al-Mg-Si i nerđajućeg čelika, što je bilo teško postići niskofrekventnim zavarivanjem trenjem zbog određenih karakteristika procesa. Kontrola pritiska trenja prema vrsti zavarenog materijala igrala je značajnu ulogu u suzbijanju formiranja međufazne strukture da bi se efektno dobili čvrsti spojevi.

4. Conclusions

High-frequency LFW was successfully used to join aluminum alloys with stainless steel at short friction times, with friction pressure control affording the required heat flux at the interface. The efficiency of the thus obtained joints was comparable to that of joints obtained by conventional friction-based methods. The thickness of the IMC layer was significantly suppressed by high-frequency linear friction joining, which facilitated the plastic flow of aluminum. Based on these results, high-frequency can be applied to the joining of other materials, not being limited to aluminum alloys and steels.

4. Zaključci

Visokofrekventni LFW uspešno se koristi za spajanje legura aluminijuma sa nerđajućim čelikom uz kratko vreme trenja, a kontrola pritiska trenja omogućava potreban toplotni protok na međupovršini. Efikasnost tako dobijenih spojeva bila je uporediva sa efikasnošću spojeva dobijenih konvencionalnim metodama zasnovanim na trenju. Debljina sloja IMC je značajno potisnuta postupkom visokofrekventnog linearnog trenja, što je olakšalo plastično tečenje aluminijuma. Na osnovu ovih rezultata, visoka frekvenca se može primeniti za spajanje drugih materijala, a ne ograničavajući se na legure aluminijuma i čelike.

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