Chapter

Recent Advances in Joining of Aluminum Alloys by Using Friction Stir Welding

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Abstract

Aluminum and its alloys have gained much interest in advanced industrial applications due to its excellent mechanical properties. Welding is one of prominent fabrication technique which has to be performed to make assembling of different parts to create one complete product. Welding of aluminum alloys (al) using traditional welding methods is difficult task due to un-weldability of aluminum alloys, more defects in weldment, presence of aluminum oxide film, etc. Friction stir welding (FSW) is a novel welding technique which was developed specially to join the aluminum alloys without melting of materials to be joined. Achieving the good qualities of welded joint with enhanced efficiency of the FSW process needs, proper understanding of principles of FSW. In the present chapter, various aspects of FSW of aluminum alloys related to effects of process welding parameters and temperature distribution during welding on mechanical and metallurgical properties of weldment has been presented. Extending applications of FSW in joining of dissimilar aluminum alloys and welding of al alloys with other materials has also been discussed. Concluding remarks are drawn from the study. From the study, it is stated that FSW is suitable for mass production welding method for joining of similar/dissimilar aluminum alloy materials in large quantity of similar products.

Keywords: friction stir welding, aluminum alloys, mechanical properties, metallurgical properties, dissimilar welding

1. Introduction

Aluminum materials are being used for variety of purposes like industrial, household, construction, etc., because of its advantages compared with other materials. It is easily available third most abundant material in the earth crust. Pure aluminum materials cannot be used directly for industrial applications due to its poor mechanical and metallurgical properties. With addition of some additives like copper, manganese, magnesium, zinc, silicon, etc., to aluminum materials; aluminum alloys can be produced which possess extraordinary mechanical and metallurgical properties comparison with the pure form of aluminum. Different aluminum alloys which are developed and widely used for various industrial applications are given in **Table 1**. As per the statistics of consumption of materials in industries; steel is occupying first position due to their mechanical properties like hardness, strength, stiffness, etc., In the recent times, the usage of aluminum alloys is growing in many industrial applications instead of steel and steel-based alloys, due to

Alloy series	Major alloying element
1xxx	Pure aluminum
2xx	Copper (1.9–6.8%)
3xxx	Manganese (0.3–1.5%)
4xxx	Silicon (3.6–13.5%)
5xxx	Magnesium (0.5–5.5%)
6xxx	Magnesium and silicon (Mg 0.4–1.5%. Si 0.2–1.7%)
7xxx	Zinc (1–8.2%)
8xxx	Others

Table 1.
Various aluminum alloys and its major alloying elements [10].

its excellent properties such as corrosion resistance [1], light in weight as having one third density of steel, machinability, thermal and electrical conductivity, easy manufacturing methods, low cost of manufacturing, etc. The applications of aluminum alloys are found in variety of applications ranging from basic to complex such as in the making of aircraft bodies [2], construction [3], structural applications [4], transportation, packing, aerospace [5, 6], automobile [4], automotive, railway, personal computers, cutlery, aeronautical and shipbuilding industries [7], naval and marine [8]. All the mentioned applications need to join, two or more parts to create one complete structure or device. Welding is one of the most widely used fabrication technique for joining similar/dissimilar parts permanently. Tungsten inert gas (TIG) and metal inert gas (MIG) welding are generally used joining methods for different materials. But, in case of welding of aluminum alloys by TIG and MIG welding processes, produces welding defects on welded joint like porosity, lack of fusion, incomplete penetration and create many cracks such as hot crack, stress corrosion [9]. Defects in the welded joints weaken the quality characteristics. Welding of aluminum alloys by TIG and MIG welding techniques are not recommended and not economical as well.

Friction stir welding (FSW) is an innovative welding methodology developed to join especially aluminum alloys [4] and other light-weight materials, economically [11] without any severe distortions which expected to influence mechanical and metallurgical behavior of welded sample [6, 12]. The weldability of various aluminum alloys by fusion welding methods like TIG and MIG welding, and FSW are shown in **Figure 1**.

In FSW, the job that is being welded does not melt and recast [12]. Cavaliere et al. [13] had stated that FSW is novel fabrication approach which capable to replace other joining techniques like fastener, riveted and arc welding for production of large-scale applications. FSW has various advantages over other traditional welding techniques including the following:

i. The welding procedure is relatively easy, as, it does not require consumables or filler materials for welding

ii. It does not require shielding gas, no arc formation and no fumes generated, as it is environment friendly

iii. Joint edge preparation is not at all required and Oxide removal/pre-heating prior to welding is not needed, thus, welding time minimized little bit

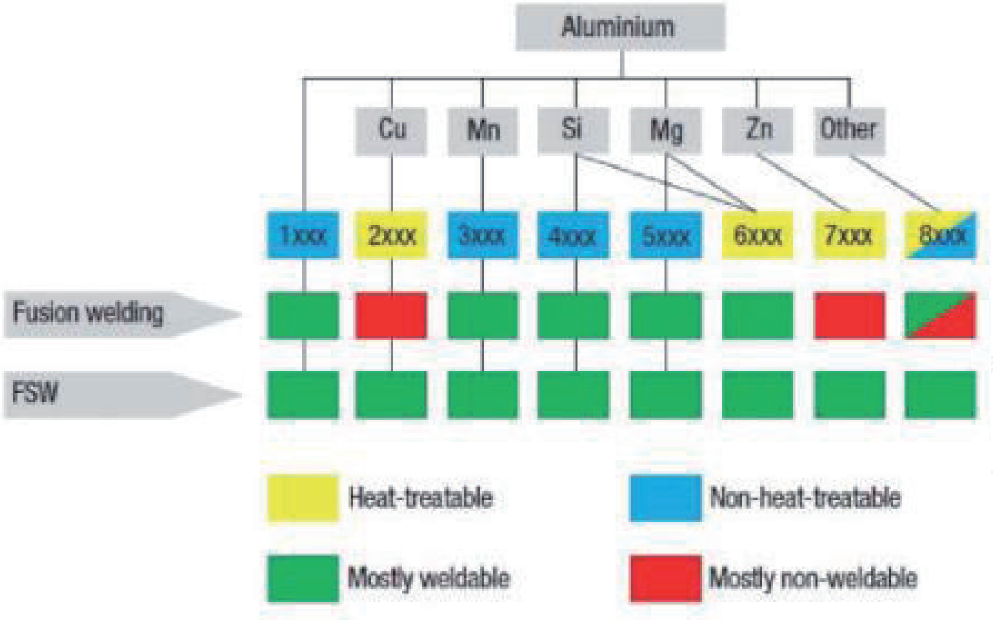

Figure 1.
Weldability of different aluminum alloys [10].

iv. FSW can be automated and performed in all directions, as it is conducted based on machine tool technology

v. Parent material chemistry is free from segregation of alloying elements.

vi. Process is solid phase with process temperature regimes much lower than in fusion techniques, thus avoiding welding defects like porosity, cracking, etc.

FSW is an efficient and effective process to produce high quality welds consistently, but its performance is depending on the optimum selection of process input parameters, welding machine parameters and work material properties. Improper selection of parametric combination(s) may deteriorate the output quality parameters like mechanical properties of welded joint. Systematic analysis is required to understand the FSW process to obtain best weld qualities of weldment. The important welding input parameters which may influence the joint quality in FSW are tool's rotational speed, welding speed, welding pressure, feed rate, pin temperature, temperature distribution, downwards forging force on the tool shoulder, rotating tool torque, forces generates from the weld in welding direction and perpendicular to weld seam, etc. FSW is a relatively newly developed method, much more studies need to conduct on different aspects to utilize it economically and effectively. FSW is attracting an increasing amount of research interest [14–16].

2. Working principle of FSW

Friction stir welding (FSW) is a solid-state welding process created and patented by The Welding Institute (TWI) in 1991 [17]. It is a relatively novel joining technology, which has caught the interest of many industrial sectors, including automotive, aeronautic and transportation due to its many advantages and clear industrial potential. The process adds new possibilities within component design and allows more economical and environmentally efficient use of materials [18, 19]. FSW can produce low-cost and high-quality joints of heat-treatable aluminum alloys without

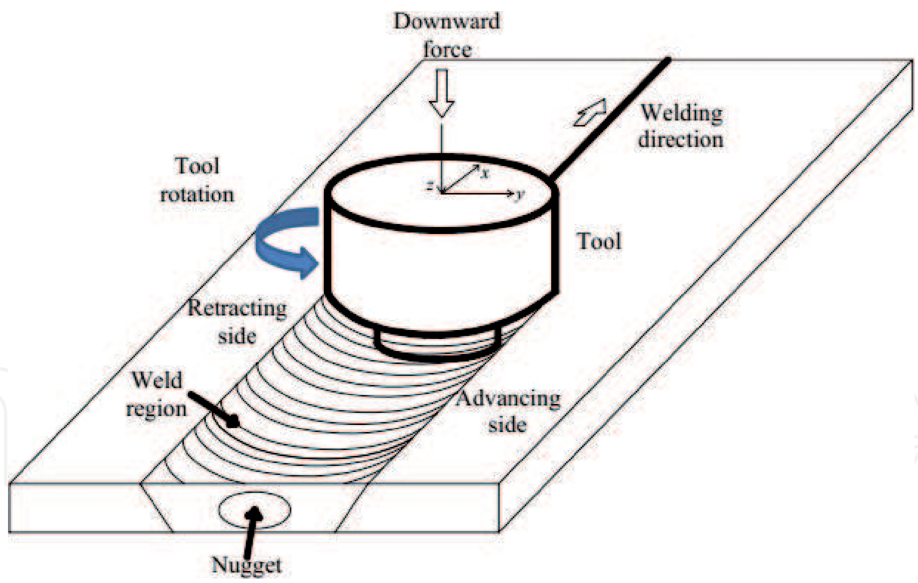

Figure 2.
Schematic diagram of the friction stir welding process [22].

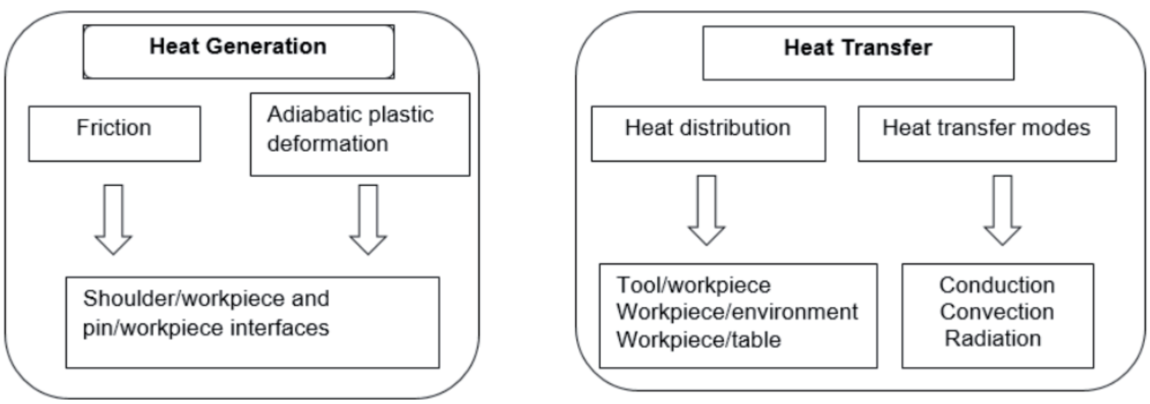

Figure 3.
The schematic diagram showing heat energy generation and distribution during FSW process [25].

use of consumable filler materials, no special preparation of the welding sample is required and can eliminate welding defects, little waste or pollution is generated during the welding process [20, 21]. Friction stir welding offers distinguish advantages like ease of handling by precise external process control and can create homogeneous welds with high levels of repeatability [21]. The working principle of FSW is shown in **Figure 2**.

In FSW, cylindrical rotating tool consisting of a concentric threaded pin and tool shoulder are used for welding the parts. A non-consumable rotating tool along with specially designed pin and shoulder is attached at the faying edges of the plates to be joined and traversed along the welded joint. The clamps are used to fix the two sheets on the bed and force is applied vertically to fix the tool on the collect of vertical milling machine. The friction between the welding tool i.e. rotating tool and workpiece is generated due to rotation of rotation tool on the plated to be welded which leads to plastic deformation of work piece. The plates get soften at the around the pin due to generation localized heat from the friction and the combination of tool rotation and translation leads the movement of the soften material from front of the pin to back of the pin. The welded joint is formed by deforming the material at temperatures below the melting point of parent material. If the direction of tool rotation and translation of the welding tool in same direction, then it is called advancing side whereas both the motions in opposite direction then it is called retreating side. In FSW process, geometry of the tool is very important which highly depends on deciding the quality levels of joint obtained.

During the FSW process, the temperature distribution is a function of the heat generated by the friction between the workpiece and tip and shoulder of the tool [4]. The heat generation is depending on the physical properties of the workpiece and the tool [23]. And the generated heat equal distribution is crucial for the quality of the weldment and heat distribution is depends on the thermal conductivities of the tools and workpieces, thermal capacities, the relative speed, and the intersection area [24]. The heat distribution is clearly shown in **Figure 3**.

3. Literature review

As mentioned earlier that fusion based welding of aluminum alloys is difficult because of limited weldability. Some aluminum alloys can be resistance welded but the surface preparation is problematic, and time consuming and surface oxide is being a major problem during welding [26] On the other hand, FSW can be used join most of the aluminum alloys without any surface oxide problems and no special cleaning is required prior to welding. Some of the research publications which reported to literature based on friction stir welding of aluminum alloys are discussed as follows:

Rhodes et al. [26] had been made an experimental analysis to study the significance of welding process on weld nugget (WN), heat affected zone (HAZ) and microstructural changes of FSWed 7075 aluminum alloy material. They stated from the study that friction stir welding process was useful to join unweldable aluminum alloys without introducing a cast microstructure and it was not influencing much on WN, HAZ and microstructure of welded joint compared to fusion welding techniques. Jata et al. [27] were investigated the effects of FSW method on microstructure and mechanical properties of friction stir welded aluminum alloy 7050- T7451. Researchers observed from analysis that FSW process transforms the initial millimeter sized pancake-shaped grains in the parent work-material to fine 1 to 5 micrometer dynamically recrystallized grains and it also redissolves the strengthening precipitates in the weld-nugget area. The fatigue strength of welded specimen depends on the bonding between the intergranular mechanism. Frigaard et al. [4] had been studied the microstructure evolution and its effects on hardness distribution of FSWed samples of AA6082-T6 and AA7108-T79 aluminum alloys with the use of numerical three-dimensional heat flow model. They observed that thermal effects were main reasons behind the strength losses of welded samples during FSW of age hardening aluminum alloys. This was because of high level welding speeds which introduces plastic deformation resulting initiation of the dissolution of hardening precipitates. The grain structure within the plastically deformed region was analyzed by electron backscattered diffraction (EBSD) technique in the scanning electron microscope (SEM) and stated that dynamic recovery is significant softening procedure for FSW of age hardening aluminum alloys. Lee et al. [28] had made an investigation-based on experiments study to enhance welding process performance of FSW of A356 Al alloy. Liu et al. [20] had made an experimental investigation to study, analyze the effects of process welding parameters on tensile properties of friction stir welded 2017-T351 aluminum alloy and optimum welding parameters to attain better quality response of weldment. They observed from analysis that tensile properties and fracture locations of the welded joints are significantly affected by the friction stir process parameters. Peel et al. [21] had made a research analysis on welded samples of aluminum AA5083 in friction stir welds process. They studied the influences of varied process conditions on microstructural, mechanical property and residual stress. They observed from the work that there is uncertainty of weld quality characteristics with varying welding speeds. Researchers mentioned in their research that thermal input is most significantly affecting welding responses than the mechanical deformation created by the tool.

Fersini and Pirondi [29] had been conducted a research work to study and analyze the fatigue behavior of friction stir welded aluminum alloy Al2024- T3 materials. Shen et al. [30] had been studied the mechanical properties and failure mechanisms of aluminum alloy AA 6061-T4 sheets in friction stir spot welding. Kah et al. [31] had been investigated the weld defects in aluminum alloys welded by friction stir welding and fusion welding. Researchers found that defects in aluminum alloy welds are less as compared to the fusion welds. Effertz et al. [32] had been analyzed and optimized the process welding parameters in friction spot welding of 7050-T76 aluminum alloy. They stated that process parameters in friction spot welding were highly influential for quality responses of weldment. Guo et al. [33] had been studied the fatigue performance of aluminum friction stir welded joints. Kaushik and Singhal [34] had made an experimental investigation to analyze the influences of FSW process on microstructure and mechanical properties of cast composite matrix AA6063 reinforced with 7 wt % SiC particles. They mentioned from the study that FSW had impacts on the growth, dissolution and reprecipitation of the hardening precipitates during welding. Mechanical properties like ultimate tensile strength, percentage elongation, hardness, of friction stir welded joint improved due to microstructural changes taken place during FSW process. Behrouz et al. [35] had investigated the effect of vibration on microstructure and thermal properties of Al5083 welded specimen made by friction stir spot welding (FSSW). They conducted experiments at rotation speed of 1500 rpm and different dwelling times. They observed from their study that vibration during FSSW leads to decrease of grain size weld region thereby improved mechanical properties. Kunitaka et al. [36] had been developed the corner adstir fillet stationary shoulder FSW (SSFSW) process for welding of the reinforced fillet joints. The welding of reinforced fillet welded is difficult with conventional FSW due to complexity and unpractical joint preparation. Researchers were observed better mechanical properties in reinforced fillet welded joints as like conventional FS welds. Silva et al. [37] had been studied the temperature distribution around a FSW tool on bead-on-plate welds in 20 mm thickness aluminum alloy, AA6082-T6. Shen [38] had been evaluated the weld performance in terms of microstructure, interfacial bonding, hardness, static and fatigue strength of 7075-T6 Al alloy welded joint in refill friction stir spot welding using a modified tool based on the experimental analysis.

Dissimilar welding is an important research area for many industrial applications. Joining two different materials to create cost effective product is difficult task due different materials properties and varying melting points [21]. Welding of aluminum alloys with other materials has huge industrial requirement. Friction stir welding (FSW) is extended to join various un-weldable aluminum alloys within other aluminum alloys and also with other materials like steel, manganese, etc. Some of the dissimilar welding of aluminum alloys with other materials are discussed as follows:

Cavaliere et al. [13] had been analyzed the mechanical and metallurgical properties of dissimilar friction stir welded aluminum alloys 2024 and 7075 respectively. After welding experiments, the microstructure of weldment had been investigated by optical microscopy and observed that grain structure and precipitates distribution differences initiated during welding process. Mechanical behavior of welded samples had been tested by performing tensile and fatigue tests. From the research analysis, they mentioned that proper understanding and correct selection of process variables are very crucial for optimal conduction of FSW process to obtain desired welding performance. Yutaka et al. [39] were discussed the influences of varied rotation speeds on microstructure and hardness of friction stir welded aluminum (Al) alloys 6063-T5 and T4. Researchers analyzed the relationships between the microstructure and mechanical properties of welded specimens. They observed that grain size of the stir zone increased exponentially with increasing of temperature. The hardness values in welded condition in weld center in weld of Aluminum alloy 6063-T5 and distributed homogeneously in the weld of Aluminum alloy 6063-T4. The effects of rotation speeds on hardness of weldment were insignificant except softened region of aluminum alloy 6063-T5. Song et al. [40] had been analyzed the mechanical properties of friction stir lap welded dissimilar AA2024–AA7075 aluminum alloy materials. They were also studied the defects in the welded joints and found good quality welds without major defects. Shen et al. [41] were made an experimental research to determine the influences of welding input parameters on interfacial bonding in dissimilar steel/aluminum friction stir welds. Investigators stated that control parameters were most significant for quality of the welded joint of dissimilar aluminum alloy and steel materials in friction stir welding. Ding et al. [42] had also been studied the quality levels of dissimilar aluminum alloy and AISI coated steel in friction stir welding process. They found better weld qualities and stated that FSW was better welding method for joining of aluminum alloys to steel materials. Tianhao et al. [43] had been applied friction stir scribe (FSS) technique to join the dissimilar aluminum alloy and mild steel materials. The difference between the FSW and FSS are reduced heat is supplied in FSS during dissimilar welding because of varying melting points of materials to be joined. They studied the fracture modes of welded joints under tensile shear loading. They observed from the study that fracture mode and quality of joint was highly depends on welding process parameters and tool scribe height.

Raju et al. [44] had been investigated the significances of friction stir parameters on responses: microstructure and corrosion of friction stir welded AA6061-T6 and AISI304 materials. They analyzed the effect of process variables on microstructures, intermetallic compounds and their phases, and thereby on corrosion of the aluminum-steel welded joint and stated that quality of welded joint depends on the correct selection of process parameters in FSW of dissimilar materials. Gopkalo [45] had analyzed the microstructure in heat affected zone (HAZ) of dissimilar friction stir welded age hardened Al-Mg-Zn and Al-Mg-Si alloys. Li et al. [46] had been studied the influences of friction parameters namely welding speed and rotational speed on microstructure and tensile strength in FSW of dissimilar AZ91 magnesium (Mg) alloy and A383 aluminum (AL) alloy materials. They stated from the study that optimum selection of process parameters was necessary to obtain defect free welded joint of AZ91 Mg alloy and A383 al alloy in friction stir welding. Jedrasiak and Shercliff [47] had been developed a finite element model to predict the spatial and temporal variation of heat generation and temperature in friction stir spot welding of aluminum and magnesium alloys. Guo et al. [33] had conducted research analysis to study the dependency of fatigue performance in friction stir welding of dissimilar 6061-T651 and 5083-H321 aluminum alloys. They observed from the investigation that kissing bond defect had significant effect on fatigue life and toe-flash defect had small or less effect on fatigue performance of dissimilar 6061-T651 and 5083-H321 aluminum alloys friction stir welds. Pratik et al. [48] studied the effects of cylindrical tool pin profile on macrostructure, microstructure, and tensile property of welded sample of dissimilar aluminum alloys AA6061 and AA7075 when other process parameters: tool traverse feed kept at 31.5 mm/s, tool rotational speed kept at 765 rpm, and tool tilt angle of 2° forward position. They stated that cylindrical tool pin profile was beneficial for obtaining defect free stir zone and better tensile properties on weldment.

From the extensive review of friction stir welding of aluminum alloys, it is stated that friction stir welding is best alternative to join almost all types of aluminum alloys. The uses of FSW can also be extended to weld dissimilar aluminum alloys and with other materials also. FSW can be used as mass production technology or fabrication process, as it does not have melting phase, no special preparation of welding joint, minimum problems related to welding metal re-solidification, uses non-consumable tool, etc. Performing FSW process to create aluminum sheets in economical manner is important area of work and it is highly depends on the proper understanding of principles of FSW, relations between the process parametric conditions and response characteristics, properties of work-piece material and welding tool, shape and geometry of welding tool, etc. More research investigations related to various aspects of FSW of similar aluminum (AL) alloys and dissimilar AL alloys and or with other materials will create a sound knowledge bank; from which industrial persons can be benefitted to conduct FSW process with enhanced efficiency. Present chapter is one step forward for making the FSW of similar and dissimilar aluminum alloys in an economical and predictive manner.

4. Conclusions

The followings are the conclusions drawn from the present study of advancements of FSW of aluminum alloys:

1. Aluminum alloys are useful alternative materials of steel, and those are used make products in many advanced industrial applications

2. Aluminum alloys are treated as un-weldable materials

3. Welding of aluminum alloys with fusion welding (tungsten inert gas, and metal inert gas) and resistance welding techniques are difficult and not economical methods

4. Friction stir welding (FSW) is solid state welding which used non-consumable rotating tool to weld aluminum alloys by using frictional energy

5. FSW does not need to weld joint preparation, melting of material to be joined and recast

6. Welding defects can be eliminated with FSW process

7. Fundamental understanding of FSW is required to conduct it efficiently and effectively

8. Selection correct process welding parameters, temperature distribution during welding, are important parameters which expected to influence the weld quality and welding performance.

9. FSW can be used weld similar and dissimilar aluminum alloys

10. FSW can also be used to join aluminum alloys with high strength steels and other light-weight materials

11. Advancements of various types of FSW process like friction stir scribe (FSS) technique, stationary shoulder FSW (SSFSW) process, friction stir spot welding (FSSW) to weld similar and dissimilar aluminum alloys are discussed

12. From the present study, it is mentioned that FSW is highly suitable for mass production process to produce large quantity parts with high production rate

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Conflict of interest

The author declaring no conflict of interest.

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References

[1] Schneider R, Heine B, Grant RJ. Mechanical behaviour of commercial aluminium wrought alloys at low temperatures. In: Light Metal Alloys Applications. Croatia. UK: InTech Open; 2014. pp. 61-76

[2] Rajkumar V, Venkatesh K, Arivazhagan N. Friction stir welding of aluminium alloys. In: Aluminium Alloys - Recent Trends in Processing, Characterization, Mechanical Behavior and Applications. UK: Intech open; 2017. pp. 81-97

[3] Mazzolani FM. Structural applications of aluminium in civil engineering. Structural Engineering International. 2006;**16**(4):280-285

[4] Frigaard Ø, Grong Ø, Midling OT. A process model for friction stir welding of age hardening aluminum alloys. Metallurgical and Materials Transactions A. 2001;**32A**:1189-1200

[5] Subodh KD, Kaufman JG. Aluminum alloys for bridges and bridge decks. In: Aluminium Alloys for Transportation, Packing, Aerospace and Other Applications. The Minerals, Metals & Materials Series. Switzerland AG: Springer; 2007. pp. 61-67

[6] John R, Jata KV, Sadananda K. Residual stress effects on near threshold fatigue crack growth in friction stir welded aerospace alloys. International Journal of Fatigue. 2003;**25**:939-948

[7] Sheikhi S, Bolfarini C. Preliminary study on the microstructure and mechanical properties of dissimilar friction stir welds in aircraft aluminium alloys 2024-T351 and 6061-T4. Journal of Materials Processing Technology. 2007;**6**:132-142

[8] Yuri H, John EC, Kester DC, Paul EK. Friction-stir welding and processing. Journal of Metals. 2015;**67**(5):996-997

[9] Debroy T, Bhadeshia HKDH. Friction stir welding of dissimilar alloys- a perspective. Science and Technology Welding Joining. 2010;**15**:266-270

[10] Pratik HS, Vishvesh JB. Friction stir welding of aluminium alloys: An overview of experimental findings – process, variables, development and applications. Proceedings of the Institution of Mechanical Engineers, Part L. 2019;**233**(6):1191-1226

[11] Rajakumar S, Muralidharan C, Balasubramanian V. Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints. Materials and Design. 2011;**32**(2):535-549

[12] Jata KV, Sankaran KK, Ruschau JJ. Friction-stir welding effects on microstructure and fatigue of aluminum alloy 7050-T7451. Metallurgical and Materials Transactions A. 2000;**31A**:2181-2192

[13] Cavaliere P, Nobile R, Panella FW, Squillace A. Mechanical and microstructural behaviour of 2024-7075 aluminium alloy sheets joined by friction stir welding. International Journal of Machine Tools and Manufacture. 2006;**46**:588-594

[14] Hakan A, Mumin T, Kurtulus Y, Ali B. Mechanical properties of friction stir welded 3003 aluminum alloy in different welding conditions. International Journal of Mechanical and Production Engineering. 2017;**5**(12):92-96

[15] Balasubramanian V. Relationship between base metal properties and friction stir welding process parameters. Materials Science and Engineering A. 2008;**480**:397-403

[16] Barcellona A, Buffa G, Fratini L, Palmeri D. On microstructural phenomena occurring in friction stir welding of aluminium alloys. Journal of Materials Processing Technology. 2006;**177**:340-343

[17] Thomas WM, Nicholas ED, Needham JC, Murch GM, Temple-SP, Dawes CJ. Friction stir butt welding. International Patent Application No. PCT/GB92/02203; 1991

[18] Dawes CJ, Thomas WM. Friction stir process welds aluminum alloys. Welding Journal. 1996;**75**(3):41-45

[19] Jata KV, Semiatin SL. Continuous dynamic recrystallization during friction stir welding of high strength aluminum alloys. Scripta Materialia. 2000;**43**:743-749

[20] Liu HJ, Fujii H, Maeda M, Nogi K. Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy. Journal of Materials Processing Technology. 2003;**142**:692-696

[21] Peel M, Steuwer A, Preuss M, Withers PJ. Microstructure, mechanical properties and residual stresses as a function of welding speed in aluminium AA5083 friction stir welds. Acta Materialia. 2003;**51**:4791-4801

[22] Ramona G, Jorge FS. Friction stir welding development of aluminium alloys for structural connections. Proceedings of the Romanian Academy Series A. 2013;**14**:64-71

[23] Verma S, Meenu, Misra JP. Study on temperature distribution during friction stir welding of 6082 aluminum alloy. Materials Today: Proceedings. 2017;**4**(2):1350-1356

[24] Ahmet Ç, Hatice A, Mustafa U. Analysis and joining of Al–Cu plates using friction-stir welding technique. European Mechanical Science. 2018;**2**(1):1-8

[25] Durdanovic MB, Mıjajlovic MM, Milcic DS, Stamenkovic DS. Heat generation during friction stir welding process. Tribology in Industry. 2009;**31**:8-14

[26] Rhodes CG, Mahoney MW, Bingel WH, Spurling RA, Bampton CC. Effects of friction stir welding on microstructure of 7075 aluminum. Scripta Materialia. 1997;**36**:69-15

[27] Jata KV, Sankaran KK, Ruschau J. Friction stir welding effects on microstructure and fatigue of aluminium alloy 7050- T7451. Metallurgical and Materials Transactions. 2000;**31A**:2181-2192

[28] Lee WB, Yeon YM, Jung SB. The improvement of mechanical properties of friction-stir-welded A356 Al alloy. Materials Science and Engineering A. 2003;**355**:154-159

[29] Fersini D, Pirondi A. Fatigue behaviour of Al2024- T3 friction stir welded lap joints. Engineering Fracture Mechanics. 2007;**74**(4):468-480

[30] Shen Z, Yang X, Zhang Z, Cui L, Yin Y. Mechanical properties and failure mechanisms of friction stir spot welds of AA 6061-T4 sheets. Materials and Design. 2013;**49**:181-191

[31] Kah P, Rajan R, Martikainen J, Suoranta R. Investigation of weld defects in friction stir welding and fusion welding of aluminium alloys. International Journal of Mechanical and Materials Engineering. 2015;**10**:26

[32] Effertz P, Quintino L, Infante V. The optimization of process parameters for friction spot welded 7050-T76 aluminium alloy using a Taguchi orthogonal array. International Journal of Advanced Manufacturing Technology. 2017;**91**(9-12):3683-3695

[33] Guo S, Shah L, Ranjan R, Walbridge S, Gerlich A. Effect of quality control parameter variations on the fatigue performance of aluminum friction stir welded joints. International Journal of Fatigue. 2019;**118**:150-161

[34] Kaushik N, Singhal S. Experimental investigations on microstructural and mechanical behavior of friction stir welded Aluminum matrix composite. International Journal of Engineering. 2019;**32**:162-170

[35] Behrouz B, Mahmoud A, Mohammad G. Effects of vibration on microstructure and thermal properties of friction stir spot welded (FSSW) aluminum alloy (Al5083). International Journal of Precision Engineering and Manufacturing. 2019;**20**:1219-1227

[36] Kunitaka M, Hiroshi S, Koji N, Shoko K, Yutaka SS, Hiroyuki K. Material flow and microstructure evolution in corner friction stir welding of 5083 Al alloy using adstir technique. In: Friction Stir Welding and Processing X. The Minerals, Metals & Materials Series. Switzerland AG: Springer; 2019. pp. 181-188

[37] Silva MA, Backer JD, Martin J, Bolmsjö G. In-situ temperature measurement in friction stir welding of thick section aluminium alloys. Journal of Manufacturing Processes. 2019;**39**:12-17

[38] Shen Z, Ding Y, Chen J, Fu L, Liu XC, Chen H, et al. Microstructure, static and fatigue properties of refill friction stir spot welded 7075-T6 aluminium alloy using a modified tool. Science and Technology Welding Joining. 2019;**24**(7):587-600

[39] Yutaka SS, Mitsunori U, Hiroyuki K. Parameters controlling microstructure and hardness during friction-stir welding of precipitation-hardenable aluminum alloy 6063. Metallurgical and Materials Transactions A. 2002;**33A**:625-634

[40] Song Y, Yang X, Cui L, Hou X, Yan X. Defect features and mechanical properties of friction stir lap welded dissimilar AA2024–AA7075 aluminum alloy sheets. Materials and Design. 2014;**55**:9-18

[41] Shen Z, Chen Y, Haghshenas M, Gerlich AP. Role of welding parameters on interfacial bonding in dissimilar steel/aluminum friction stir welds. Engineering Science and Technology, an International Journal. 2015;**18**(2):270-277

[42] Ding Y, Shen Z, Gerlich A. Refill friction stir spot welding of dissimilar aluminum alloy and AISI coated steel. Journal of Manufacturing Processes. 2017;**30**:353-360

[43] Tianhao W, Harpreet S, Rajiv SM, Yuri H, Piyush U, Blair C. Effect of hook characteristics on the fracture behaviour of dissimilar friction stir welded aluminium alloy and mild steel sheets. Science and Technology Welding Joining. 2019;**24**:178-184

[44] Raju PM, Sharath A, Arnab S, Omkar M, Surjya KP, Jyotsna DM. Interfacial microstructural and corrosion characterizations of friction stir welded AA6061-T6 and AISI304 materials. Metals and Materials International. 2019;**25**(3):752-767

[45] Gopkalo O, Liu X, Long F, Booth M, Gerlich AP, Diak BJ. Non-isothermal thermal cycle process model for predicting post-weld hardness in friction stir welding of dissimilar age hardenable aluminum alloys. Materials Science and Engineering A. 2019;**754**:205-215

[46] Li P, You G, Wen H, Guo W, Tong X, Li S. Friction stir welding between the high-pressure die casting of AZ91

magnesium alloy and A383 aluminum alloy. Journal of Materials Processing Technology. 2019;**264**:55-63

[47] Jedrasiak P, Shercliff HR. Small strain finite element modelling of friction stir spot welding of Al and Mg alloys. Journal of Materials Processing Technology. 2019;**263**:207-222

[48] Pratik SG, Vivek VP, Jay JV, Nishit DC, Rishab B. Effect friction stir welding of aluminum alloys AA6061/AA7075: Temperature measurement, microstructure, and mechanical properties innovations in infrastructure. Advance In Intelligent System and Computing. 2019;**757**:591-598