FRICTION STIR WELDING: A REVEIW

[1]Mohd Atif Wahid, [2]Rohit Shandley, [3] Ashish Jacob
[1]Research Scholars, [2]M.Tech Student,
[1]Department of Mechanical Engineering,
[1,] Jamia Millia Islamia (A Central University),New Delhi-25, India
[#]Corresponding author details: Mohd Atif Wahid,wahidatif89@gmail.com

Abstract: Friction stir welding (FSW) is a newly developed solid-state welding method which came into existence in 1991 and has gained a lot of prominence for joining different materials like aluminum, copper, magnesium etc. This process is highly efficient, environmental friendly and has wide applications in the aerospace, shipbuilding and transportation industries. Unlike fusion welding process, FSW does not involve melting of the material, therefore various fusion welding defects are not present in FSW leading to improved mechanical properties of the joint. This paper provides an overview of the FSW process and its variants. The basic principle of FSW is described along with the important process parameter affecting the microstructure and joints properties. Microstructure evolution and some important mechanical properties are also discussed.

Index Terms- Friction Stir Welding, Microstructure, Mechanical Properties, Process parameter

I. INTRODUCTION

Friction stir welding was developed during 1991 at TWI where the heat for welding is converted from mechanical to thermal energy (Thomas et al., 1991). Friction stir welding does not lead to any melting of the material which prevents undesirable welding defects like solidification defects etc, most of them occur due to the micro-structural changes that creep into the weld zone at high temperatures involved during fusion welding (Atabaki et al.,2014). This method of joining is extremely safe for the operator from a health and safety viewpoint as hazardous, fumes, gases, vapours, radiation, and electromagnetic noise is eliminated (Atabaki, 2012). Furthermore, a superior weld with enhanced mechanical properties is obtained compared to fusion welding (Rana et al., 2012 and Mishra et al.,2005). FSW could be used in any orientation without any particular regard to any gravitational forces. This is one of the reasons why FSW is regarded as a valuable than other unconventional welding processes.

FSW process involves a non-consumable rotating tool that intrudes deep into the work surfaces. The frictional heat produced due to workpiece and tool interaction results in the softening of the material and then the material is plastically deformed and moved from advancing side to the retreating side due to traverse movement of the tool resulting in a solid joint (Wahid et al., 2016). The working principle of FSW is schematically shown in **Figure 1** (Siddiquee et al., 2014). FSW process involves a lot of friction wherein most of the friction is generated by the shoulder and the frictional force generated by the pin is less as compared to that of the shoulder. The continuous working of the soften material by the tool prevents defects, helps in grain refinement and helps to achieve better mechanical properties (Cam et al., 2017).

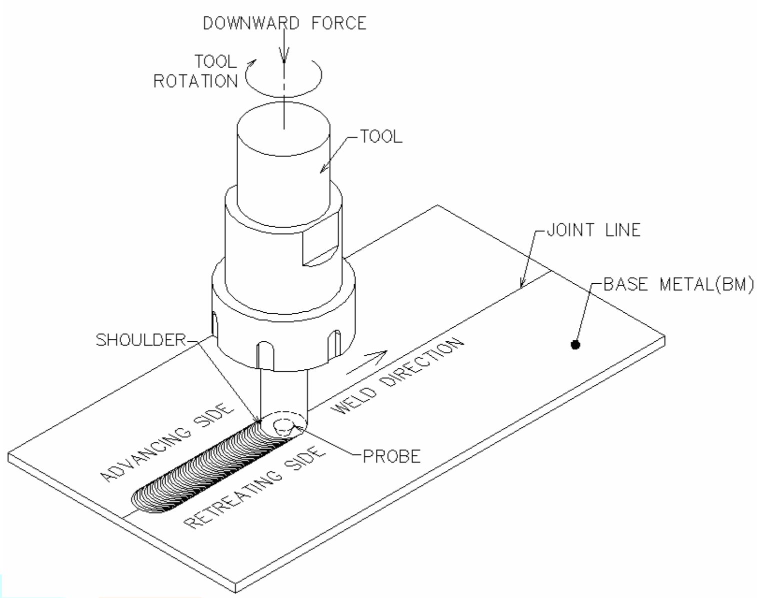

Fig.1 The working principle of FSW

In this paper literature review on the current status and development of FSW employed mostly for aluminum alloys and its important process parameters affecting the microstructure and mechanical properties are discussed.

II. PROCESS PARAMETERS

FSW requires good knowledge of the various parameters of the welding process. The main parameters include tool tilt angle, tool material, the rotational speed, tool traverse speed etc. Each of the parameters has a direct impact on the weld (Cavaliere, 2014). These parameters are discussed in the subsequent section.

2.1 Tool geometry

Geometry of the tool includes shoulder and a probe that helps in localized heating, material mixing and material flow. Maximum heat is produced by the shoulder in comparison to pin which also assists in compressing the plasticized material beneath it hence preventing the overflow of material from the work-piece. Flow of material is affected both by tool shoulder and pin. Various important factors in tool geometry are diameter of shoulder and pin including the shape, size and its surface features (Raguraman et al., 2014). Nowadays flat, concave and convex shoulder profiles are used for welding. Each of them has a different effect while welding. Probe is either flat or domed in shape but in general flat shape is used due to simplicity in design. Certain pin profiles like straight cylindrical, concave type generally the ones that are used. The concave type shoulder is more preferred because it has a lesser peak temperature and also it helps in directing the material to centre of the pin (Biswas et al., 2011).

2.2 Welding Parameters

After careful selection of the tool geometry according to working material and thickness there are some variables that are varied during the course of process for achieving good quality of welds. These variables are axial force, tool tilting angle, plunging of tool, tool traverse speed and rotational speed.

The traverse and rotational speeds are significant parameters affecting the weld quality. Rotational speed of the tool result in frictional heating, material mixing and stirring of the material whereas welding speed help in material movement and heat generation (Hwang et al., 2010).

Tilting angle of the tool is another important factor which helps in holding of the stirred material beneath the tool surface and also assists in movement of material around the pin. Large tilt angle provide snugger weld and improved flow of material. Tool tilt angle should be increased with increase in plate thickness (Payganeh et al., 2011). Plunge depth of tool shoulder affects the generation of frictional heat and down force for plasticizing and compacting the work material (Zhang et al., 2013).

III. MATERIAL FLOW

In FSW, the flow of material is predominantly affected by FSW tool dimension and its profile in company with the various welding parameter as discussed above. If these process parameters are not selected properly various defects can take place.

3.1Material flow modeling

Various techniques such as marker tracing technique (Seidel et al., 2001), analyzing the characteristics of welding defects (Chowdhury et al., 2010) etc. are commonly used for investigation of material flow. Furthermore, several modeling techniques like mathematical modeling (Nunes et al., 2001), metal working model (Arbegast et al, 2003) etc. are also prominent techniques for prediction of material flow. The **Figure 2** indicates the material flow zones and material deformation zones using metal working model given by (Arbegast et al, 2003). The different zones include preheat zone, extrusion zone, initial deformation zone, forged zone and post heat/cool down zone. In pre heat zone rise in temperature generally takes place due to tool shoulder which causes frictional heating. In initial deformation zone temperature of the material rises above the critical temperature due to heating. Due to pin stirring extrusion zone is developed which governs the material movement around the pin from advancing to retreating side. Due to plastic deformation by the tool mixing of the material takes place in the forging zone. Solidification and material particle settlement takes place in the cooling zone. The cooling rate has a considerable effect on the tensile properties of the joints.

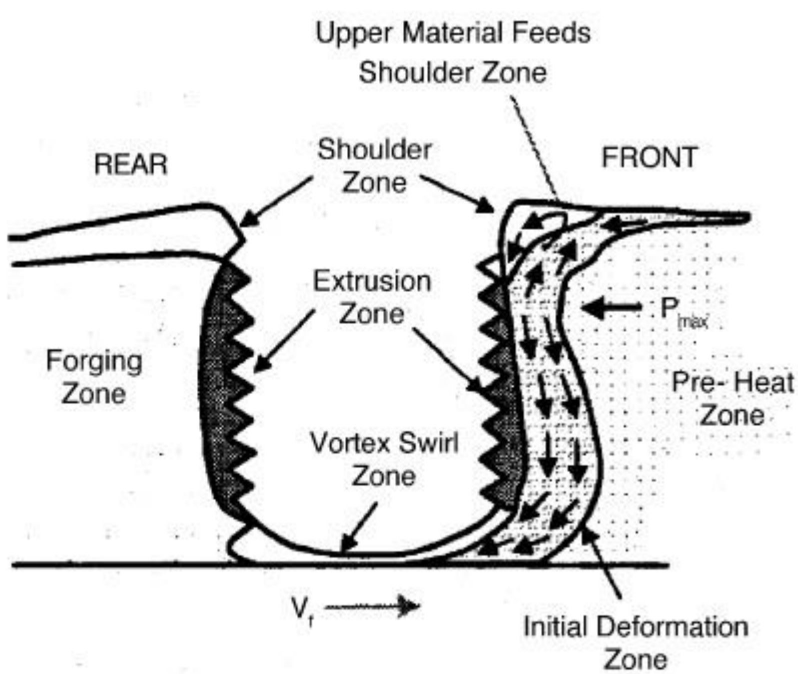

Fig. 2 Material flow diagram in FSW

IV. MICROSTRUCTURE AND MECHANICAL PROPERTIES

The properties and the performance of various welding processes are governed by the microstructure of the particular weld. This element is what defines how well the weld is and how well the mixing took place and how well will be the properties. Various process parameters, material flow and temperature evolved during FSW cause significant changes in microstructure and properties of the welds. These properties are discussed below.

4.1 Macro/ Micro features

FSW microstructure was first categorized by Threadgill,1997 as shown in Figure 3 .The HAZ (heat affected zone) is indicated by A while B represents the TMAZ (Thermo-mechanically affected zone) and C shows the weld nugget or Stir zone (SZ). FSW produces an asymmetric microstructure which is shown by the retreating and the advancing side.

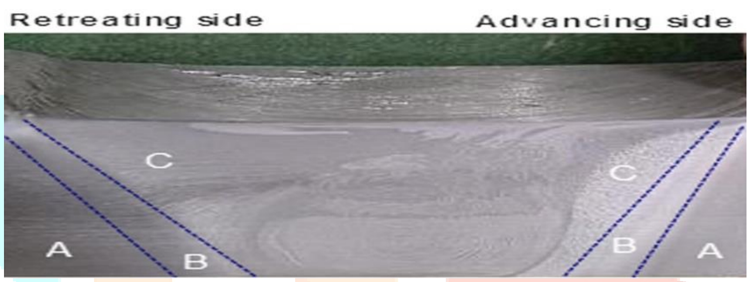

Fig.3 Micro structural zone classification

Due to very extreme thermal profiles and high plastic deformation in the SZ dynamic recrystallization takes place leading to fine equiaxed grains (Li et al., 2011). Different strengthening phases may also be also present in the SZ based on heat generation and material composition (Wang et al., 2012). Patterns called onion ring are also sometimes visible in the SZ directly reflecting the flow of material during FSW (Mishra et al., 2005). These onion rings could be related to the extrusion of single layer of semi cylinder with a set of another semi cylinder resulting in the formation of onion ring structure. TMAZ is distinguished by highly deformed structure and it is the transition zone between SZ and base material (Savolainen et al., 2007). TMAZ consists of highly extruded, elongated and upward oriented grains. Precipitate evolution and coarsening of grains is also witnessed sometimes in TMAZ (Sabri et al., 2016).Non-deformed coarse grains are present in HAZ as no deformation takes place in this region. Many researchers have shown that FSW grain coarsening and existence of precipitate free zones in the HAZ (De et al., 2011).The microstructure development in different zones are shown in **Figure 4** below (Liu et al., 2011 and Sabri et al., 2016).

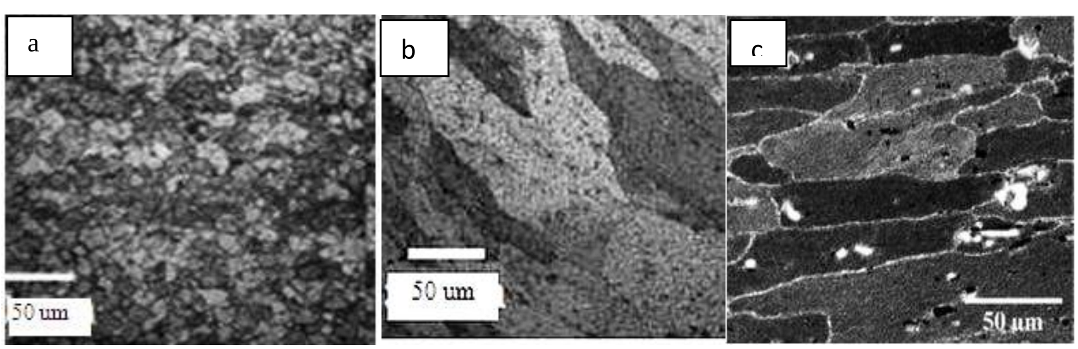

Fig.4 Microstructure (a) SZ (b) TMAZ (c) HAZ.

4.2 Mechanical Properties:

In FSW, microstructural changes in and around the proximity weld zone due to which it has an influence on the weld mechanical properties. The various mechanical properties are tensile strength, hardness, fracture toughness, impact fatigue etc.

In general, tensile strength and hardness is less than the base material but with proper selection of process parameter tensile value and hardness improvement could be achieved near to that of the base material. FSW has better tensile properties as compared to most solid state joining processes and fusion welding processes. Each of the zones in FSW has different strengths and ductility. Each zone has a different resistance to the deformation owing to the grain size, precipitate sizes and distribution leading to different tensile strength and hardness (Mahoney et al., 1998).Sato et al., 2001 experimented to observe the effect of post weld treatment on the weld properties. They observed that the aged FSW test specimen had a slightly higher tensile strength than that the base material. They also found improvement in the ductility of the welded sample.

In FSW various investigations have shown different in hardness for heat and non- heat treatable aluminum alloys (Gallais et al., 2008 and Klobc et al., 2012).This hardness/strength improvement in heat treatable AAs in general depends upon precipitate distribution, dislocation density and solid solution strengthening and hardness depend commonly on grain size in FSW of non- heat treatable alloys.

Good fatigue resistance is also very important property as various structure in aerospace, marine etc. are subjected to cyclic loading and strains resulting in deformation of the structure due to fatigue and cyclic loading. Numerous researches have reported in literature based on fatigue life (Ni et al., 2009), crack growth (Takao et al., 2010), low cycle fatigue (Feng et al., 2010).

There is also a suitable need for assessing fracture behavior of the joints produced using FSW. Parameters like crack opening displacement for elastic–plastic loading and crack tip intensity factors for linear elastic loading are common in assessing fracture toughness.

V. DEVELOPMENTS IN FSW

The basic concept of FSW may be used to develop new process for modification in microstructure and consequently improvement in mechanical strength and other properties of the joints. These modifications of FSW are discussed in the following section.

5.1 Friction Stir Processing (FSP)

Friction stir processing is a variant of FSW, where frictional heat and intense plastic deformation are utilized to achieve microstructural enhancement, homogenous distribution of secondary phases and elimination of porosity. FSPed regions are characterized by fine grain structures and it is possible to impart superplasticity to selective regions in a component, unlike conventional methods. With the use of FSP, superplasticity of thick sections combined with high strain rate can be achieved.

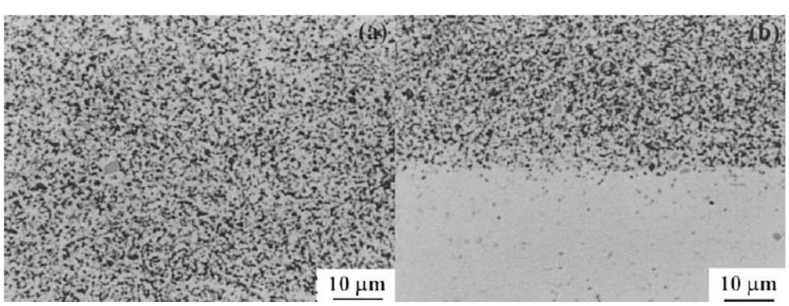

Fig.5 Optical Micrographs showing (a) distribution of SiC particles (27 vol.%) in the aluminum alloy matrix, and (b) bonding of the surface composite and aluminum alloy substrate. (Misra et al., 2003)

Surface and bulk composites can be conveniently fabricated using FSP as shown in **Figure 5**. Misra et al., 2003 had successfully fabricated a SiC surface composite on an aluminum substrate. Here SiC particles were added on the surface and stirred into the ductile aluminum matrix. Other methods of reinforcement of powders include incorporation of powder filled in slots, in holes on the surface as well as perpendicular to the surface, or by the use of pre-compacted extruded strips. Other ceramic particles such as Al_2O_3, WC, B_4C have also been added to fabricate surface composites. Johannes et al. (Johannes et al., 2006) were the first to demonstrate the use of carbon nanotubes in aluminum using FSP route. Multi-functional properties can be imparted to the matrix by addition of shape memory alloy particles (Dixit et al., 2007). Recntly, cellular materials were also processed using FSP. It has been shown (Hangai et al., 2012) that FSP can be used to finely disperse a foaming agent in a precursor. The FSPed precursor can be foamed by heating. Formation of in-situ phases in the metal matrix is achievable with FSP (Gangil et al., 2017).
The use of a threaded tool can be used to direct the stirred material upwards, separating from the plasticized material to form a channel. This process known as friction stir channeling has applications in the heat exchangers (Balasubramanian et al., 2009).

5.2 Underwater Friction Stir Welding (UFSW)

Although the heat produced in FSW is less when compared to fusion welding still it is high enough to cause softening of materials generally in heat treatable aluminum alloys leading to reduction in mechanical performance of the weld due to dissolution and coarsening of the strengthening precipitates. So to overcome the thermal effects of FSW different cooling medium such as water can be used to enhance the mechanical and micro structural properties by absorbing the excessive heat during the welding. In UFSW, water as the cooling media is used to regularize the temperature prevailing in the welded joint (Zhang et al., 2014).The welding is performed in two ways either the water continuously flows above the work the surface or water is stored in a container where the material to be welded is placed. Due to high absorbing capability of water excess heat is absorbed and thus the low heat exists in different zones of FSW which is not suitable for coarsening of the precipitates. Moreover various welding defects such as porosity, solidification cracking, shrinkage etc. gets minimize and hence the mechanical properties further enhances (Wang et al.,2015).UFSW can be used in shipbuilding, submarines, oil and fuel tanks and various offshore structures involving fabrication and repair.

VI. CONCLUSION

This review paper outlines the basic principle and various important process parameters affecting the microstructure and mechanical properties of the joints produced using FSW. From this review it can be concluded that for obtaining a defect free weld, an optimum combination of tool design and welding parameters are required. Mechanical properties of the joints can be improved significantly if optimum welding conditions are achieved. Based on the concept of FSW newly modified techniques have also come into existence. FSP is one such technique which is gaining prominence in field of microstructural modification, metal matrix composites fabricating etc. UFSW is also gaining importance as a very valuable welding process due to its ability to provide superior mechanical properties over FSW and fusion welding.
In spite of various advantages further improvements in FSW are still required. Substantial possibility is there to analyze heat input, heat balance, flow stress on advancing/retreating and top/bottom sides. Material flow pattern is poorly understood properly and need further understanding in UFSW. Computational techniques must be adopted for optimizing tool geometry as tool wear is an important feature and requires deep understanding.

REFERENCES

[1]Thomas W M, Nicholas E D, Needham J C, Murch M G, Smith P T, Dawes C J.1991. Friction stir butt welding: UK, 9125978 [P].
[2]Atabaki, M., Nikodinovski, M., Chenier, P., Ma, J., Harooni, M., Kovacevic, R. M. 2014.Welding of aluminum alloys to steels: an overview. Journal for Manufacturing Science and Production 14(2):59-76.

[3]Akinlabi, Esther T.2012. Friction Stir Welding Process: A Green Technology .World Academy of Science, Engineering and Technology 6(11) : 2514-2516.
[4]Rana, R.S., Purohit, R., Das, S.2012. Microstructure and Mechanical Properties of Aluminum Alloys and Aluminum Alloy Composites. International Journal of Scientific and Research Publications 2(6): 22503153.
[5] Mishra, R.S., Ma, Z. Y.2005. Friction stir welding and processing. Materials Science and Engineering: R: Reports 50(1) :1-78
[6]Wahid, M.A., Siddiquee, A.N., Khan Z.A., Asjad M. 2016. Friction Stir welds of Al alloy-Cu: An investigation on effect of plunge depth. Archive of Mechanical Engineering 63(4): 619-634.
[7]Siddiquee, A. N., Pandey, S. 2014. Experimental investigation on deformation and wear of WC tool during friction stir welding (FSW) of stainless steel [J]. International Journal of Advanced Manufacturing Technology 73: 479–486.
[8]Çam,G., İpekoğlu, G. 2017. Recent developments in joining of aluminum alloys. The International Journal of Advanced Manufacturing Technology 91(5-8) :151-66.
[9]Cavaliere, P. 2014. Friction stir welding of Al alloys: Analysis of processing parameters affecting mechanical behavior, Procedia CIRP (11), pp. 139–144.
[10] D.Raguraman, D. Muruganandam, L.A.Kumaraswamidhas. 2014. Study of tool geomtery on Friction stir welding of AA 6061 and AZ61, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE).
[11]P. Biswas and N.R.Mandal. 2011.Effect of Tool Geometries on Thermal History of FSW of AA1100. Supplement To The Welding Journal, Volume 90, 129S-135S.
[12] Y.M.Hwang,P.L.FanC.H.Lin, 1 September 2010. Experimental study on Friction Stir Welding of copper metals, Journal of Materials Processing Technology , 210(12): 1667-1672.
[13]Payganeh G H, Mostafa N B A, Dadgar Asl Y, Ghasemi F A , Boroujeni M S. 2011. Effects of friction stir welding process parameters on appearance and strength of polypropylene composite welds . International Journal of the Physical Sciences, 6(19): 4595-4601.
[14] Zhang H, Liu H. 2013. Mathematical model and optimization for underwater friction stir welding of a heat-treatable aluminum alloy. Materials and Design, 45: 206–211.
[15]Seidel T U, Reynolds A P. 2001. Visualization of the material flow in AA2195 friction-stir welds using a marker insert technique. Metallallurgical and Materials Transaction, 32: 2879. -2884.
[16]Chowdhury S M, Chen D L, Bhole S D, Cao X. 2010. Tensile properties of a friction stir welded magnesium alloy: effect of pin tool thread orientation and weld pitch [J]. Materials Science and Engineering A, 6064–6075.
[17] Nunes A C Jr., In: Das S K, Kaufman J G, Lienert T J (Eds.).Aluminum 2001, [C]// Proc. Aluminum automotive and Joining symposia, Warrendale: PA, 2001, TMS, 235
[18] W.J. Arbegast, in: Z. Jin, A. Beaudoin, T.A. Bieler, B. Radhakrishnan (Eds.). 2003. Hot Deformation of Aluminum AlloysIII, TMS, Warrendale, PA, USA, p. 313.
[19] Threadgill P L. 1997. Friction stir welds in aluminium alloys – preliminary microstructural assessment. TWI Bulletin, 28:30-33
[20] Li B, Shen Y. 2011. The investigation of abnormal particle-coarsening phenomena in friction stir repair weld of 2219-T6 aluminum alloy. Materials and Design, 32: 3796–3802.
[21] Wang Kuai-She, Wu Jia-Lei, Wang W, Zhou Long-Hai, Lin Zhao-Xia, Kong Liang. 2012 .Underwater friction stir welding of ultrafine grained 2017 aluminum alloy.Journal of Central South University of Technology, 19: 2081−2085.
[22] Savolainen K, Mononen J, Saukkonen T, Hannien H. 2007. Similar and dissimilar Friction Stir Welding of Aa7075. Proc 6th ISFSW.
[23] Sabari S S, Malarvizhi S, Balasubramanian V, Reddy G. 2016.The effect of pin profiles on the microstructure and mechanical properties of underwater friction stir welded AA2519-T87 aluminium alloy. International Journal of Mechanical and Materials Engineering, 11:5.
[24] De P S, Mishra R S. 2011. Friction stir welding of precipitation strengthened aluminium alloys: scope and challenges. Science and Technology of Welding and joining, 16:343-347.
[25] Liu Hui-Jie, Zhang Hui-Jie, Yu L. 2011. Effect of welding speed on microstructures and mechanical properties of underwater friction stir welded 2219 aluminum alloy . Materials and Design, 32(3): 1548–1553.
[26] Sabari S S, Malarvizhi S, Balasubramanian V. 2016. Influences of tool traverse speed on Tensile properties of air cooled and water cooled friction stir welded AA2519-T87 Aluminium alloy joints . Journal of Materials Processing Technology, 237:286-300
[27] Sato Y, Park S H C, Kokawa H. 2001. Microstructural factors governing hardness in friction-stir welds of solid-solution-hardened Al alloys [J]. Metallurgical Materials Transaction A 32(12): 3033–3042.
[28] Gallais C, Denquin A, Bréchet Y, Lapasset G. 2008.Precipitation microstructures in an AA6056 aluminium alloy after friction stir welding: Characterisation and modelling . Material Science and Engineering A, 496(1/2): 77−89.
[29] Klobc Ar D, Kosec L, Pietras A, Smolej A. 2012.Friction-stir welding of aluminium alloy 5083 . Mater Technol, 46: 483–488.
[30]Ni D R, Wang D, Feng A H, Yao G, Ma Z Y. 2009. Enhancing the high-cycle fatigue strength of Mg–9Al–1Zn casting by friction stir processing . Scripta Mater, 61:568–571.
[31] Takao O, Masako S, Haruka M, Toshiya N, Shigeru M, Motoo A. 2010. Evaluation of crack nucleation site and mechanical properties for friction stir welded butt joint in 2024-T3 aluminum alloy [J]. International Journal of Advanced Manufacturing and Technology, 50:127–135.

[32] Feng Ah, Chen Dl, Ma Zy. 2010. Microstructure and low-cycle fatigue of a friction-stir-welded 6061 aluminum alloy . Metallallurgical and Materials Transaction A, 41:2626–2641.
[33] Mishra, R.S., Ma, Z.Y. and Charit, I. 2003. Friction stir processing: a novel technique for fabrication of surface composite. Materials Science and Engineering*: A*, *341*(1): 307-310.
[34] Johannes, L.B., Yowell, L.L., Sosa, E., Arepalli, S. and Mishra, R.S. 2006. Survivability of single-walled carbon nanotubes during friction stir processing. Nanotechnology, 17(12): 3081.
[35] Dixit, M., Newkirk, J.W. and Mishra, R.S. 2007. Properties of friction stir-processed Al 1100–NiTi composite. Scripta Materialia, 56(6) : 541-544.
[36] Hangai, Y., Takahashi, K., Utsunomiya, T., Kitahara, S., Kuwazuru, O. and Yoshikawa, N. 2012. Fabrication of functionally graded aluminum foam using aluminum alloy die castings by friction stir processing. Materials Science and Engineering: A, 534 :716-719.
[37] Gangil, N., Siddiquee, A.N. and Maheshwari, S. 2017. Aluminium based in-situ composite fabrication through friction stir processing: A review. Journal of Alloys and Compounds.
[38] Balasubramanian, N., Mishra, R.S. and Krishnamurthy, K. 2009. Friction stir channeling: Characterization of the channels. Journal of Materials Processing Technology, 209(8):3696-3704.
[39] Zhang J, Shen Y, Yao X, Xu H, Li B. 2014. Investigation on dissimilar underwater friction stir lap welding of 6061-T6 aluminum alloy to pure copper. Materials and Design, 64: 74–80.
[40] Wang Q, Zhao Z, Zhao Y, Yan K, S. Lu. 2014. Corrosion behavior of spray formed 7055 aluminum alloy joint welded by underwater friction stir welding. Materials and Design, 68: 97–103.