International Journal of Advance Research and Innovation
Vol. 3(2), Apr-Jun 2015, pp. 151-164
Doi: 10.51976/ijari.321531
www.gla.ac.in/journals/ijari

Article Info

Received: 08 Apr 2015 | Revised Submission: 15 Apr 2015 | Accepted: 22 May 2015 | Available Online: 15 Jun 2015

Material Flow and Microstructural Studies in Friction Stir Welding / Processing of Aluminium: A Literature Review

V. Jeganathan Arulmoni, R.S. Mishra** and Ranganath M. S****

ABSTRACT

Material flow in friction stir welding / processing under different process parameters with aluminium has been studied by many scientists. All such studies have been considered and a detailed review is presented in this paper. Results indicated friction stir welding / processing with aluminium and alloys may successfully utilised, because of the significantly improved strength in the material and at the same time the ductility also retained, along with the substantiallyimproved hardness. FSP was found to be beneficial also in improving wear resistance.

Keywords: *Friction Stir Welding; Processing; Aluminium; Alloys; Wear; Properties*.

1.0 Introduction

Friction stir welding is a solid state joining process that provides many advantages compared with conventional fusion welding methods such as lower residual stresses, especially high joint strength and low distortion because of lower welding temperature and also elimination of porosities and solidification cracking because of no melting occurrence.

This welding method was invented in TWI in Cambridge, England in 1991 firstly for joining aluminium alloys. It also has made low cost welded joints because of much lower power consuming, no needs of joint edge preparations before welding application and also no gas shielding required compared with conventional welding methods.

Friction stir processing (FSP) was developed for micro structural modification of metallic materials. Welding/processing parameters, tool geometry, and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of material. In FSP, a rotating tool is inserted into a material and high plastic deformation is produced.

FSP is used to enhance ductility, induces super plasticity and improve corrosion resistance properties. FSP has been successfully applied to various cast aluminium and magnesium and copper alloys to eliminate casting defects and thereby improve their mechanical properties.

An FSW/FSP tool consists of a shoulder and a pin. The tool is plunged till the shoulder touches the work piece. The friction between the shoulder and work piece results in the biggest component of heating.

The main function of the tool is to 'stir' and 'move' the material. Tool rotational speed depends upon the hardness of the material. Processing speed is nothing but traverse speed.

An increase in traverse speed and decrease in rotation of the FSP tool may cause reduction in the grain size of the stir zone for the specimen friction stir processed without any metal particles.

The main objective of this paper is to discuss the study of friction stir welding / processing of aluminum and its alloys.

The investigations made by various scientists and authors regarding the effect of FSP parameters such as tool rotational speed, processing speed, groove width and depth on microstructure and micro hardness have been taken into consideration of this review study.

**Corresponding Author: Department of Mechanical and Production & Industrial Engineering, Delhi Technological University, Delhi, India (E-mail: ranganathdce@gmail.com)*
***Department of Mechanical and Production & Industrial Engineering, Delhi Technological University, Delhi, India*
****Department of Mechanical and Production & Industrial Engineering, Delhi Technological University, Delhi, India*

2.0 Literature Review

An exhaustive review of published data on the effect of process parameters on friction stir welding / processing works on aluminium and its alloys has been discussed. The review has been presented in a tabular form. Nearly 53 papers related to study of friction stir welding / processingof aluminium and aluminium alloys have been considered. The review table given below explains the details of parameters considered by earlier authors.

Serial No	Author and Year	Materials Used	Tool Utilised	Processing Parameters	Reteach Conducted
1.	A. Bastiera et al., [2008]	7050 aluminim alloy	Tool with Cylindrical pin radius is equal to 5 mm, shoulder radius is equal to 15 mm and pin height is equal to 9 mm.	The material behaviour for temperatures between 20 and 500 •C. Welding and rotational speeds are set respectively to 1.7 mms^{-1} and 260 rpm. The pin is tilted by 2• from the vertical axis and a cone angle of 7• under the shoulder is adopted.	A parametric study about the influence of welding and rotational speeds is carried out. Computational Fluid Dynamics package is used to establish the material flow and the temperature field during the process and to estimate the residual state induced by the process. The steady-state assumption and the original elastoviscoplastic constitutive law.
2.	A. Orozco-Caballero et al., [2013]	Al-Zn-Mg-Cu alloy commercial 3 mm Al 7075-T6 (nominal composition in wtpct 5.68Zn-2.51Mg-1.59Cu-0.19Cr-bal Al) rolled plates	Concentric threaded pin with flutes 3mm in diameter and 2 mm in length.	FSP using a rotation rate of 1000 rpm and a traverse speed of 500 mm min^{-1} along the rolling direction.	A finer grain size, 0.3 vs 0.5 mm, was obtained by processing at the highest cooling rate. Materials showed super plastic behaviour with a maximum elongation to fracture of about 510%. Grain boundary sliding was the operative deformation mechanism
3.	A. Yazdipoura et al., [2009]	Al 5083 non-heat treatable alloy (4.2mg, 0.60mn, 0.25S, 0.15Fe, 0.09zn, 0.09cr, 0.06cu, 0.02Ti bal AL) Mix of sic & mos2 50 mm x 100 mm	H-13 steel SD-15mm PD-4mm, PL-1mm, penetration depth was selected at 1mm, rapid cooling applied (mixture of methanol & dry ice)	560-900 rpm, traverse speed 16-57mm/min	Modeling, Microstructure, on cooling rate on the nano grains forming, grain refining mechanism
4.	A.G. Rao et al., [2009]	AL-30Si base alloy, permanent mould cast plates (Al, 30Si, 0.2mg, 0.1Fe)	A tool made of H13 steel having flat shoulder diameter of 25 mm and pin of 6 mm diameter.	1000 rpm, 16mm/min, single/two pass, 100% overlap, cooling for 2nd pass	This paper demonstrates the effect of two pass overlap friction stir processing on microstructural refinement of Al–30Si alloy, which delineates significant reduction in size and aspect ratio of silicon particles from average 200 to 2 µm and 4.93 to 1.75 µm respectively. The stir zone of two pass overlap FSP exhibits relatively homogeneous Si particle distribution.
5.	Adem Kurt et al., [2011]	1050 AL (0.4Fe, 0.12Si, 0.03cu, 0.02mg, 0.02mn, bal Al) , monolithic cold rolled plates Sic-10µm, SiC mixed with methanol applied to surface of the plates, 50 mm x 100 mm x 5 mm, no binder	AISI 1050 steel, cylindrical shoulder, no pin, SD-12mm	1050 AL (0.4Fe, 0.12Si, 0.03cu, 0.02mg, 0.02mn, bal Al) , monolithic cold rolled plates Sic-10µm, SiC mixed with methanol applied to surface of the plates, 50mmx100mmx5mm, no binder	Microstructural observations were carried out by employing optical microscopy of the modified surfaces. Mechanical properties like hardness and plate bending were also evaluated. The results showed that increasing rotating and traverse rate caused a more uniform distribution of SiC particles.
6.	B. Zahmatkesh et al., [2010]	AL2024 hot rolled T4 plates 76mm x 6.4mm x 305mm (0.058Si, 0.18Fe, 4.64cu,	The pin generally has cylindrical plain, frustum tapered, threaded and flat surfaces. In this study, threaded pin profile was used. The pin was 2.5 mm	tool rotating rate of 800 rpm, and travel speed of 25 mm/min with a tool tilt angle 3°	Microstructural evolution and tribologicalbehavior of friction stir processed (FSP) Al2024-T4 were investigated. Microstructural characteristics of the samples were investigated by optical microscopy

		0.69mn, 1.57mg, 0.02cr, 0.18zn, 0.04Ti)	in diameter and 2.5 mm in length.		(OM) and scanning electron microscopy (SEM).
7.	Chung-Wei Yang et al., [2012]	AA 4032 Al cast alloy homogenized at 413oC for 3h, furnace cooled and machined at 85mmx30mmx4 mm	PD-6mm, PL-2mm, SD-17mm	1400rpm, pressure 43.4mpa, 2 deg angle	FSP and artificial peak aging on erosion resistance test, micro hardness
8.	Devinder Yadav and RanjitBauri, [2012]	Pure aluminum 99.2% 12mm plate	M2 steel, SD-12mm, PD-3mm, PL-2.1mm, cylindrical tool	a tool rotation speed of 640rpm and traverse speed of 150mm/min with a downward force of 5 kN.	Friction stir processing refined the grain size to 3µm in a single pass from the starting coarse grain size of 84µm. Electron backscattered diffraction (EBSD) results showed occurrence of dynamic recrystallization and also revealed existence of different orientations within the stir zone and across the transition zone. Transmission electron microscopy (TEM) revealed fine grains with well defined boundaries.
9.	Douglas C. Hofmann and Kenneth S. Vecchio, [2005]	AA6061-T6 3.2 mm thick FSP, SFSP(submerged FSP) with water	Tool Steel SD-12,7mm, 19.1mm, PD-3.18mm, PL-2.79mm	2 HP mill, 1000 rpm, 0.42-1.69mm/s	This research demonstrates the use of submerged friction stir processing (SFSP) as an alternative and improved method for creating ultrafine-grained bulk materials through severe plastic deformation. SFSP is compared with friction stir processing (FSP) done in air, through the use of thermocouples and transmission electron microscopy.
10.	F.Y. Tsai and P.W. Kao, [2012]	Cast AL-Si base alloy,AC8A (11.8Si, 1.12Ni, 1.15cu, 1.06mg, 0.28Fe) solution heat treated at 883k for 4 hrs	Tool for FSP has a shoulder of 16 mm diameter and the tool pin has a 6 mm diameter and a 1.2 mm pitch height.	1400 rpm, 45mm/min	This study demonstrated that friction stir processing (FSP) could result in a significant improvement in tensile properties of AC8A, particularly in ductility. Both tool rotation rate and traversing speed could affect the strength of FSPed specimens, which was related to the characteristics of coarsening, dissolution and reprecipitation of the strengthening particles.
11.	G. Madhusudhan Reddy and K. Srinivasa Rao, [2010]	Cast A356 Al castings	A straight cylindrical friction stir tool (pin length 3 mm, pin diameter 6mm, shoulder diameter 15mm) made of high carbon steel was used in the present study.	A tool rotational speed of 2000 rpm, a transitional speed of 20 mm/minute, and plunging speed 30 mm/minute were employed.	The friction stir processed zone was characterized by metallography, electron micro probe analysis, hardness, dry sliding wear and potentio dynamic polarization testing. Hardness mapping showed that stir zones experienced increase of 40% compared to the as-cast metal. Further uniform micro-hardness was observed in the friction stir processed zone, which was not the case with as-cast A356 aluminum alloy.
12.	GhaderFaraji and ParvizAsadi, [2011]	Commercially available nano-sized (30 nm) Al2O3 particles with the purity of 99.9% were	The circular and square tools were used in this work. Tools were made of hardened H13 tool steel. Tools consisted of a pin with 5mm in diameter, 3mm in height, and a	The FSP tool was rotated in 900 and 1200rpm in the clock-wise direction. The traverse speed was changed from 40 to 80 mm/min. The tilted angle was 3•.	The microstructures, wear property and micro-hardness of AZ91 Mg alloy/alumina particle reinforced nano-composite produced by friction stir processing (FSP) were investigated.

		used in volume fraction of 8% to produce nano-composite layer on the surface of AZ91. AZ91 composition (in wt.%) was Al, 9.1; Zn, 0.68; Mn, 0.21; Si, 0.085; Cu, 0.0097; Ni, 0.001; Fe, 0.0029 and Mg, bal.	shoulder with 15mm in diameter.		
13.	H.J. Liu and X.L. Feng, [2012]	2219-T6 aluminum alloy plates	The tool was made of tool steel, and consisted of only a shoulder with a diameter of 22 mm.	The tool rotating speed (ω) was 1000 rpm, and the traverse speed (v) was 200–400 mm/min. The displacement control was used and the plunge depth was kept constant at 0.5 mm. The tilted angle was 2.5^0	The microstructure was characterized using optical microscopy, scanning electron microscopy, and transmission electron microscopy. Two types of heat treatments, aging treatment and solutionizing followed by water quenching and aging treatment, were applied to the processed samples.
14.	H.W. Zhang et al., [2007]	The material of the plate is Al 6061-T6 and is modeled as a rate-independent elastic–plastic material.	The radii of the pin and the shoulder are 3 and 7.5 mm, respectively.	To accelerate the convergence, the rotational and the translational speeds are both increased 1000 times in the analysis	Material flow in friction stir welding (FSW) under different process parameters is simulated by using the finite element technique based on the nonlinear continuum mechanics. Results indicate that the distribution of the equivalent plastic strain correlates well with the distribution of the microstructure zones in the weld.
15.	I. Charit and R.S. Mishra, [2003]	AL2024 hot rolled T4 plates solution heat treated, quench, natural aging, transverse direction and polished, 76mmx6.4mmx 305mm (0.07Si, 0.17Fe, 4.6cu, 0.64mn, 1.5mg, 0.01cr, 0.15zn, 0.03Ti)	High strength cobalt alloy	300 rpm, 25.4mm/min	The present study demonstrates that superplasticity at higher strain rates can be achieved in a commercial 2024 Al alloy via friction stir processing. Ductility values for the FSP alloy are substantially higher than that of the parent alloy (non-superplastic) at comparable temperature and strain rate ranges.
16.	K. Elangovan and V. Balasubramanian, [2008]	AA6061-T6 (1.1mg,0.12mn, 0.35Fe, 0.58Si, 0.22cu, bal Al) Heat treatable wrought, normal to rolling direction, 300mmx 150mmx6mm	High carbon steels. Different shapes , straight cylindrical, taper cylindrical, threaded cylindrical, square, triangular, different SD of each pin profile, SD-15mm, 18mm& 21mm,PD-6mm, PL-5.5mm, D/d ratio 2.5, 3.0 & 3.5	Axial loads 7kn, 1200 rpm, 1.25 mm/sec	In this investigation, an attempt has been made to understand the effect of welding speed and tool pin profile on FSP zone formation in AA2219 aluminium alloy.
17.	K. Elangovan and V. Balasubramanian, [2008]	AA6061-T6 (1.1mg,0.12mn, 0.35Fe, 0.58Si, 0.22cu, bal Al) Heat treatable wrought, normal to	High carbon steels. Different shapes refer fig, straight cylindrical, taper cylindrical, threaded cylindrical, square, triangular. SD-18mm,Pd-6mm, PL-5.5mm, D/d ratio	Axial loads 6kn, 7kn, 8kn, 1200 rpm, and 1.25 mm/sec.	Tool pin profile, axial force, mechanical properties

		rolling direction	3.0		
18.	K. Surekha and A. Els-Botes, [2011]	AA2219-T87 (6.1cu, 0.25mn,, 0.04Zn, 0.05Ti, 0.13Fe, 0.16Zr, 0.09V) 250mmx150mmx5mm	a non-consumable non-threaded tool made up of high-speed tool steel whose shoulder diameter is 12 mm and pin diameter and length are 5 and 2.8 mm respectively.	800, 1200,1600 rpm, speed 0.37mm/s, 0.76mm/s, three passes	Micro structure, corrosion behavior, multipass
19.	K. Surekha et al., [2008]	The material used in this work is AA2219-T87 alloy with the nominal composition in wt.% of Cu–6.1, Mn–0.25, Zr–0.16,V–0.09, Ti–0.05 and rest Al. The AA2219-T87 plates	a non-consumable threaded tool made up of high-speed tool steel.	Up to three passes were given at three rotation speeds of 800 (slow – S), 1200 (medium– M), 1600 (fast – F) rpmand two welding speeds (0.37 (slow – S) and 0.76 (fast – F) mm/s). The depth of the processed region was 2 mm in a 5 mm thick plate.	Anodic polarization and electrochemical impedance tests in 3.5% NaCl showed an improved corrosion resistance of the processed alloy, which increased with the number of passes. Salt spray and immersion tests also showed improved resistance to corrosion. The increased resistance to corrosion is attributed to the dissolution of CuAl2 particles, which was established by XRD and DSC studies.
20.	K.N. Ramesh et al., [2012]	Al-5086-O alloy 150x110mm2 6 mm plate	Hot die steel tool SD-24mm, PD-6 mm, PL-3mm, cylindrical pin, processing parallel to rolling direction	1025 rpm, fixed, traverse speed 30mm/min, 50mm/min, 110mm/min 150mm/min, mild steel backing plate 12 passes	Imp method material is cooling after each pass. CMP FSP performed for 12 passes without allowing any cooling, mech properties, one rotational speed, different combination feeds.
21.	L. Karthikeyan et al., [2010]	A 319 sand cast 200x50x10mm (Al, 5.2Si,2.51cu, 0.35Fe, 0.26mn, 0.15mg, 0.04Ni, 0.29Zn, 0.09Ti, 0.03Pb, 0.01Sn)	High carbon steel, cylindrical threaded, right handed 1 mm pitch, SD-18mm, PD-6mm, PL-5.7mm,	800, 1000,1200,1400,1600 rpm, 40.2, 75mm/min. single pass. For one feed-four speeds	Yield strength, tensile strength, ductility, microhardness
22.	L. Karthikeyan and V.S. Senthil Kumar, [2011]	AA6063-T6 (cu-0.01, mg0.5mg, 0.43Si, 0.02Fe, 0.06mn, 0.05Ni, 0.005Zn, 0.01Ti, 0.01Sn) 100x50x10mm	SD-18mm, PD-6mm, PL-5.7mm,pitch 1 mm threaded	Maximum power – 30 hp, maximum axial force – 25 kN and a maximum spindle speed – 3000 rpm.	In this investigation the surfaces of AA6063-T6 aluminum alloy were friction sir processed and the effects of process variables such as axial force, tool feed and rotational speed were studied.
23.	L. Karthikeyan et al., [2009]	2285 cast al alloy 4cu, 1.5mg, 0.6si, 0.6Fe, 0.6mn, 2Ni, 0.1Zn, 0.2Ti, 0.05Pb, 0.5Sn, bal Al, 200 mm x 50 mm x 10 mm	HSS SD-16mm, PD-5mm, PL-4.7mm, cylindrical	1400 rpm,1800rpm, 10,12,15mm/min, single pass	Micro, Mechanical properties, tensile, hardness, k type thermocouple
24.	L.B. Johannes et al., [2007]	Al 5083 non-heat treatable alloy (4.7mg, 0.51mn, 0.51Fe, 0.10cr, 0.11cu, bal AL) 8mm , countinous cast	MP159 high strength cobalt alloy PD&PL-6.4mm,SD-25mm, threaded right hand screw, counter clockwise	600 rpm, 25.4mm/min, single pass for optimum level, then 8 passes	Super plasticity, mechanical properties
25.	LivanFratini et al., [2009]	The FSW between 3.2 mmthick AA2139-T8 blanks were considered for the three joint	The utilized tools were made of H13 steel quenched at 1020 °C, characterized by a 52 HRc hardness. FSW process used three types:Butt joint, Lap joint, T-joint, Tool shoulder [mm] : 12 ,	The material was furnished in the T8 condition, namely after a solubilization at 530 °C for 4 h, a cooling in water and an artificial aging at 175 °C for 8 h, the blanks were cold stretched .	In the paper the microstructural phenomena in terms of average grain size occurring in friction stir welding (FSW) processes are focused. A neural network was linked to a finite element model (FEM) of the process to predict the average grain size values. The utilized net was trained

		configurations proposed	20, 20 Pin cone angle: 0^0 , 15^0 , 15^0 Pin major diameter [mm]: 4, 5.8, 6 Pin height [mm]: 2.7, 4.9, 5.5		starting from experimental data and numerical results of butt joints and then tested on further butt, lap and T-joints. The obtained results show the capability of the AI technique in conjunction with the FE tool to predict the final microstructure in the FSW joints.
26.	M. Chiumenti et al., [2013]	This rocess is primarily used on aluminum alloys, and most often on large pieces which cannot be easily heat treated to recover temper characteristics.	The movement of the pin is split into advancing speed (assigned to the work-piece in the opposite direction) and rotation (assigned to the pin).	During the welding process, the pin is rotating at a very high speed (e.g. 50–1500 rpm, depending on the work-piece material), a fully Lagrangian approach (which follows the material particles of the continuum in their motion) is unaffordable.	This work presents the strategy adopted for the numerical simulation of the FSW process. A coupled thermo-mechanical solution of both the momentum and energy balance equations is presented. A very general kinematic framework has been used to deal with the specific description of motion in the FSW problem.
27.	M.A. Garcı´a-Bernal et al., [2009]	Al 5083 cast alloy with mn contents as CC(continous strip casting) (4.72mg, 0.49mn, 0.19cr, 0.16Fe, 0.09Si) different mn contents 0.49, 0.74, 1.00	MP 159 alloy SD-16mm, conical threaded pin bottom 7mm, minor diameter 4.8 mm, PL-5mm, right hand screw .	400 rpm, 0.42 mm/s(1 ipm) , plunge depth 5.4mm, tilt angle 2.5o.	High strain rate , super plasticity
28.	M.A. García-Bernal et al., [2012]	Al 5083 cast alloy with mn contents as CC(continous strip casting) (4.72mg, 0.49mn, 0.19cr, 0.16Fe, 0.09Si) different mn contents 0.49, 0.74, 1.00	MP 159 alloy SD-16mm, conical threaded pin bottom 7mm, minor diameter 4.8 mm, PL-5mm, right hand screw, plunge depth 5.4mm, tilt angle 2.5o.	400 rpm, 0.42 mm/s(1 ipm)	Hot deformation behavior, strain rate, elongation
29.	M.L. Santella et al., [2005]	A 319, A356 200x50x16mm (A356-Al-7Si, 0.3mg, A319-Al, 6Si, 3.5Cu)	H-13 steel SD-13mm, pin cylindrical, hemispherical, PD-5.2mm, PL-3.4 mm	1000 rpm, 1.7mm/s fixed, 5-6 passes	Mechanical properties
30.	M.P. Miles et al., [2005]	6061 Al alloy 25mm thick and 7075 50 mm thick	SD-25mm, concave shoulder 8mm cylindrical pin, 2.8 degree, tool translation 3.3mm per pass	600 rpm, 100mm/min, processing depth 3mm for 25mm thick 6061, 350 rpm and 127mm/min processing depth 6mm for 50mm thick 7075 AL	FSP and mechanical properties
31.	Magdy M. El-Rayesa and Ehab A. El-Danaf, [2012]	AA6082-T651 (1.25i, 0.75mg,0.79mn bal AL) 129mmx100mmx6mm	Mo-W tool steel SD-15mm, concentric square pin, edge length 6mm, 5mm long	850 rpm, traverse speed 90, 140,224 mm/min. no of passes-overlapping	Microstructure, mechanical properties, multi pass
32.	Mehdi Zohoor et al., [2012]	The specimen used in this work was a 5 mm Al5083 sheet with 130 mmlength, 60 mmwidth.	The material of tool used in this work was H13 steel with shoulder diameter of 16 mm. The tool pin used in FSP is a standard M6 1 (pitch height of 1 mm, diameter of 6 mm and	The FSP parameters were 750 and 1900 rpm in tool rotational speed, 25 mm/min in traverse speed and tilted angle of 3^0. In order to fix the specimens, they were clamped onto	Results showed that the specimens with micro and nano-sized particles present fine grains and higher level of hardness. Tensile properties of specimens friction stir processed with and without Cu particles were also evaluated. According to the results,

		Then, the Cu particles were embedded and compressed into the groove	counterclockwise) with pin height of 3.2 mm.	the thick St37 steel by the bolts.	the composite with nano-sized particles exhibited enhanced tensile strength and ductility rather than AA5083 Aluminum alloy. X-ray diffraction (XRD) studies were carried out on the specimens FSPed with Cu particles in order to identify the phases present in the stir zone (SZ) of the specimens.
33.	Nhon Q. Vo et al., [2012]	A 3.75 mm thick sheet of twin-roll-cast (TRC) Al–Mg–Sc alloy with a nominal composition of Al–4.1Mg–0.47Sc–0.022Zr–0.041Ti–0.15Fe–0.043Si, wt.% (Al–4.5 Mg–0.28Sc–0.007Zr–.02Ti–0.07Fe–0.04Si, at.%) produced at CSIRO, Australia,	FSP tool is made of a step-spiral tool steel. The shoulder diameter and pin height are 12.0 and 2.20 mm, respectively. The pin diameter at the tip and the shoulder end (root) are 3.75 and 6.00 mm, respectively.	Two different tool rotational rates – 325 and 400 rpm – were utilized and the resulting samples are labeled F325 and F400. The tool traverse speed was 3.4 mm s^{-1} (8 inch min^{-1}) and the tilt angle of the tool, 2.5°, was constant during FSP processing.	In the stir zone of the sample processed at 400 rpm rotational rate, the microhardness increase is mainly due to grain refinement, rather than precipitate strengthening, because the Al3Sc precipitates, with spherical lobed cuboids and platelet-like morphology, grow and coarsen to a 10–20 nm radius. The Scsupersaturation across the stir-processed zone has a concentration gradient, which is higher on the retreating side and lower on the advancing side of the friction-stir tool.
34.	Olivier Lorrain et al., [2010]	The workpiece material was 4mm thick aluminium alloy 7020-T6 rolled plates.	Two tools, made of high carbon steel, were used to produce the joints.The tools differ from their pin profile: the first tool has a straight cylindrical pin (SC) whereas the second tool has a tapered cylindrical pin (TC3F) with three flats. The two tools have unthreaded pin. Their shoulder was concave and they were tilted by 2.5• to provide compressive force to the stirred weld zone.	Rotational and feed speeds ranged, respectively, from 300 to 1620rpm and 100 to 900mm/min	FSW experiments were performed using two different pin profiles. Both pins are unthreaded but have or do not have flat faces. The primary goal is to analyse the flow when unthreaded pins are used to weld thin plates. Cross-sections and longitudinal sections of welds were observed with and without the use of material marker (MM) to investigate the material flow. Material flow with unthreaded pin was found to have the same features as material flow using classical threaded pins: material is deposited in the advancing side (AS) in the upper part of the weld and in the retreating side (RS) in the lower part of the weld; a rotating layer appears around the tool.
35.	Peng Dong et al., [2014]	The base material used in this study was a 3 mm-thick 6005AT6 aluminium alloy plate, with the nominal chemical composition of Al–0.46 Mg–0.63Si–0.17Cu–0.2Mn–0.24Fe wt.%.	The shoulder diameter and the pin length of the tool were 10 mm and 2.8 mm, respectively.	The selected FSW parameters were 1200 rpm, 300 mm/min and 0.1 mmfor rotation speed, welding speed and plunge depth, respectively.	Microstructure, microhardness and corrosion susceptibility of friction stir welded joint in an AlMgSiCu alloy were investigated. It was found that the joint exhibits different corrosion susceptibility among the microstructural zones.
36.	Q. Zhang et al., [2012]	The starting materials used in this study were Al powder (99.9% purity, 13 µm), Ti powder (99% purity, 45 µm) and Cu powders	A steel tool with a concave shoulder 20 mm in diameter and a threaded conical pin 8 mm in root diameter, 5.5 mm in tip diameter and 4 mm in length was used for FSP both in air and water.	The forged plates were subjected to 4-pass FSP with 100% overlapping in air at a rotation rate of 1000 rpm and a traverse speed of 25 mm min^{-1} (defined as FSP-air). Some FSP-air samples were subjected to additional 2-	The forged sample exhibited lower strength and ductility due to the presence of coarse Al3Ti clusters with a size range of 50–100 m and coarse matrix grains. Four-pass FSP in air resulted in the refinement and redistribution of the Al3Ti clusters, and the generation of micron matrix grains, thereby increasing the strength

		(99% purity, 75 μm)		pass FSP, with 100% overlap in flowing water at a rotation rate of 1000 rpm and a traverse speed of 200 mm min^{-1} (defined as FSP-water).	and ductility of the composites. Furthermore, coarse Al2Cu particles dissolved and re-precipitated due to a relatively long duration of thermal exposure.
37.	R.S. Mishra et al., [2003]	Commercial available SiC powder (99.5% purity and 0.7 mm average particle size) and 5083Al alloy (Al/Mg/ Mn) rolled plate were used in this study.	A tacking tool with a pin height of 1.0 mm was used.	A constant tool rotating rate of 300 rpm was adopted and traverse rate and depth of shoulder was varied. The tool spindle angle (angle between spindle and workpiece normal) of 2.58 was used,	A novel surface modifying technique, friction stir processing (FSP), has been developed for fabrication of surface composite. Al/SiC surface composites with different volume fractions of particles were successfully fabricated.
38.	R.S. Mishra et al., [2000]	7075-T651 (5.6Zn, 2.5mg, 1.6cu,0.23cr) 6.5mm	FSP Tool	Single pass 0.3 mm length. Weld processing parameters are proprietary, but it can be noted that the traverse speed was 15 cm/min.	Tensile strength, strain rate
39.	S. Janaa et al., [2010]	Cast AL alloy (6.8Si, 0.063Fe, 0.016Cu, 0.571mg, 0.178Ti)	Concave shoulder and conical pin with stepped spiral feature, SD-12mm, PL-2mm, PD-4mm	2236 rpm, 0.42, 0.98, 2.33 & 3.67 mm/s, tool rotation counter clock wise, ref fig-no of passes, 1-6 passes and overlapping	Process parameters on grain growth(abnormal grain growth)
40.	S. Jerome et al., [2012]	Friction Stir Processing was used for the development of surface composite of aluminium 5083 alloy reinforced with TiC particles.	Pin Ø 6 mm, pin length: 2 mm, left handed thread	These tests were performed for base metal, single pass and double pass FSP with TiC particles. The size of the samples used was 20mm x20 mm and the sand particle size was 80μm. The slurry concentration of 25% and 50% was prepared and erosion rates were performed at 500 and 900 r.p.m.	The aim of the present study is to develop defect free surface composite of Al 5083 alloy reinforced with TiC particles and investigate the particle distribution in the matrix, mechanical properties and wear behavior of the composites. Microstructural observations were carried out by using optical and scanning electron microscopy (SEM). The microstructural studies revealed that distribution of particles were more uniform in samples subjected to double pass than the single pass FSP. The microhardness profiles along top surface and across the cross section of the processed samples were evaluated.
41.	S. Soleymani et al.,[2012]	Commercially Al5083 rolled plates of 3 mm thickness with a nominal composition of 4.3Mg–0.68Mn–0.15Si–bal. Al (in wtpct) were used as the base material. A mixture of SiC and MoS2 powders at weight ratio of 2 to 1 were used as the reinforcement.	A tool made of H-13 steel with a shoulder of 20 mm diameter and a pin of 6 mm diagonal length and 2.8 mm height	A single pass friction stir process with rotation speed of 1250 rpm and travel speed of 50 mm/min was subjected in room temperature to all samples with a tilt angle of 3• was used to perform the FSP.	Microstructure, hardness and dry sliding wear behavior of the hybrid composite have been investigated and compared with those of base metal and Al/SiC and Al/MoS2 composites. Microstructural analyses of the hybrid composite showed a uniform distribution of reinforcing particles inside the processed zone and a good bonding between surface processed layer and base material.
42.	Sima Ahmad Alidokht	A 356 Al alloy with backing plate (Al, 7.18Si,	H-13, SD-20mm, PD-6mm, PL-3.7mm, threaded pin, pitch distance 1mm, ref fig	500-1250 rpm, 50mm/min, tilt angle 3o	Wear behavior SEM, disc material AISI D3 material

	et al., [2012]	0.4mg,0.Fe)			
43.	T. Dieguez et al., [2012]	7075-T651 Al alloy 4mm thickness	H13 tool steel, Concave shoulder 12.5mm, square side pin of 2.5mm	514rpm, 51mm/min	Tensile properties
44.	T.S. Mahmoudn and S.S.Mohamed, [2012]	A413 cast Al alloy ingot machined into 400mmx100mmx10mm thickness	H-13 SD-26mm, PD-10mm,PI-9mm, R4 curved shape	900, 1120 and 1400 rpm, 20,40,63mm/min, 3 deg	Triboloigical, microstructure, mechanical , tensile specimen-fig in longitudinal and tranverse
45.	Telmo G. Santosa et al., [2014]	Butt joints were produced in cold rolled plates of AA6082-T6alloy with 4 mm thickness.	An FSW tool was developed in order to meet the following design criteria:- conduct the current without interfering with the machine electrical circuit;- confine the electric current to the layer below the probe, avoiding the current to flow through the tool main body and shoulder;- continuous adjustment of the probe length and facility of replacement;- guarantee the mechanical robustness of the tool body.	The overall system comprises the FSW machine, the electric current supply which consists of a 12 V battery with 720 A nominal current intensity and a data acquisition system.	This paper presents a variant of Friction Stir Welding (FSW) aiming to minimize or eliminate the rootdefects that still constitute a major constrain to a wider dissemination of FSW into industrial applications.The concept is based on the use of an external electrical energy source, delivering a high intensity current,passing through a thin layer of material between the back plate and the lower tip of the tool probe. Heatgenerated by Joule effect improves material viscoplasticity in this region, minimizing the root defects
46.	V. Balasubramanian , [2008]	Rolled plates of five different grades of aluminium alloys, namely, AA1050, AA6061, AA2024, AA7039 and AA7075 were used as the base materials in this investigation.	Threaded cylindrical pin profiled, non-consumable tool made of high carbon steel was used to fabricate the joints. Shoulder diameter 18mm, pin diameter 6mm, pin length 5.7mm, thread pitch 1mm,	An indigenously designed and developed machine (15 HP; 3000 rpm; 25 kN) was used to fabricate the joints.	an attempt has been made to establish relationship between the base material properties and FSW process parameters. FSW joints have been made using five different grades of aluminium alloys (AA1050, AA6061, AA2024, AA7039 and AA7075) using different combinations of process parameters. Macrostructural analysis has been done to check the weld quality (defective or defect free). Empirical relationships have been established between base metal properties and tool rotational speed and welding speed, respectively. The developed empirical relationships can be effectively used to predict the FSW process parameters to fabricate defect free welds.
47.	VahidFirouzdor and Sindo Kou, [2011]	6061 Al was welded to commercially pure Cu by FSW.	tools prepared from a H13 tool steel. The tool shoulder was 10 mm in diameter and concave. The pin was 4 mm in diameter and threaded, and the pin length was 1.6 mm. The tool was rotated counterclockwise when viewed from above and tilted 3 deg forward.	The travel speed varied from 38 mm/min (1.5 ipm) to 203 mm/min (8 ipm). The rotation speed was 1400 rpm.	Modified lap FSW significantly improved the weld quality in Al-to-Cu lap FSW.
48.	W. Woo et al.,[2012]	6061-T6 Al plate The nominal chemical composition was 1.0Mg, 0.6Si, 0.3Cu, and balanceAlwt%).	The hard steel tool has the diameter of the pin and the tool shoulder of 6.35 and 25.4 mm, respectively.	The Al plate sample continuously traverses at a constant traveling speed of 0.42 mm/s as the tool is rotating (156 revolutions/min). The measurement positions were predetermined at 5, 8 and 10 mm (underneath tool), and 15, 20, 30, 70	Significant neutron peak broadening was observed in situ underneath the tool of friction stir processing (FSP) in 6061-T6 aluminum alloy.

				and 100 mm (outside) from the tool center.	
49.	Wanchuck Woo et al., [2007]	AA6061-T6 solution heat treated and aged for 6 hrs at 185oc, 306x306x6.5mm, (1.0 mg, 0,6si, 0.3cu, bal al) ref fig for material size	H-13 Tool Steel SD-19.05mm, PD-6.35mm, PL-6.23mm. case 2. Without tool pin	1250 rpm, 4.7mm/s, 12.4 mpa compressed pr	Tool pin, shoulder, natural aging, micro
50.	Xiuli Feng, Huijie Liu and Sudarsanam Suresh Babu, [2011]	AA2219-T6 al-cu alloy plates fixed with tank filled with tank filled with water at 298k, 2.5mm thick	Pinless tool SD-22mm	1000 rpm, 200-400 mm/min plunge depth 0.5mm, angle 2.5o	Grain refinement, precipitation reactions
51.	Y. Tozaki et al., [2010]	The material used is aluminium alloy 6061-T4 plate with the thickness of 2mm whose chemical composition (wt.%) is Mg: 0.6, Si: 1, Cu: <0.01, Fe: <0.2, Mn: 0.05, Cr: <0.05, Zn: 0.3, Ti: <0.05, Al: bal.	It should be noted that the tool has no probe, but a scroll groove of 0.5mm depth on its shoulder surface, which is referred to as the scroll tool. For comparison with the scroll tool, two tools with different geometries were employed. One is a conventional probe tool with a standard metric M3 left-hand threaded probe whose length is 3.7mm, hereafter denoted as the probe tool. All tools have a concave shoulder of 10mm diameter with the angle of concavity of 11.5• and are made of high-speed steel	For the scroll tool and the plain tool, the tool rotational speeds of 2000 and 3000 rpm, the tool holding times of 1–7 s and the shoulder plunge depths of 0.5, 0.7 and 0.9mm were used. In all cases, the plunge rate was 10 mm/min. For the probe tool, the tool rotational speeds of 2000 and 3000rpm and the tool holding times of 0.2, 1, 2 and 3 s were employed, where the plunge rate and the shoulder plunge depth were 20mm/min and 0.2mm, respectively.	The experimental observations showed that the scroll tool had comparable or superior performance to a conventional probe tool. It was confirmed that sound welding could be achieved without a probe hole, in which the scroll groove played significant roles in the stirring of the material and the shoulder plunge depth was the important processing variable.
52.	Yong X. Gan et al., [2010]	The main focus of FSP was on aluminum based alloys and composites.	Review Paper		The objective of this article is to provide a review of friction stir processing (FSP) technology and its application for microstructure modification of particle reinforced composite materials.
53.	Z.Y. Ma et al., [2006]	A 356 T6 treatment, solution treated 540oC for 4 hr, 25oC water quenched and aged 155oC for 4h (Al, 7Si, 0.3mg,)	FSP Tool	Tool rotation rate (rpm) 300, 500, 700, 900 rpm	Friction stir processing (FSP)was applied to cast A356 Al to modify the as-cast microstructure. FSP homogenizes and refines the cast microstructure, completely eliminates porosity, and creates a microstructure with fine Si particles (0.25–0.42 _m) distributed in a fine grain aluminum matrix (3–4 _m).

3.0 Summary

The effect of friction stir processed aluminium along with parameters such as tool rotational speed, processing speed, groove width and depth on microstructure and micro hardness investigated and explained by many researchers have been discussed.

The strength of the friction stir processed material improved significantly and at the same time the ductility was also retained, the hardness also improved substantially. FSP was found to be beneficial in improving wear resistance.

The high wear behavior in the stir zone is attributed to a lower coefficient of friction and the improved micro-hardness in this region.

References

[1] A. Bastiera, M. H. Maitournama, F. Rogerb, K. Dang Vana, Modelling of the residual state of friction stir welded plates,Journal of materials processing technology, 200, 2008, 25–37

[2] A. Orozco-Caballero, C. M. Cepeda-Jiménez, P. Hidalgo-Manrique, P. Rey, D. Gesto, D. Verdera, O.A. Ruano, F. Carreno, Lowering the temperature for high strain rate superplasticity in an AleMgeZneCu alloy via cooled friction stir processing,Materials Chemistry and Physics, 142, 2013, 182-185

[3] A. Yazdipoura, A. Shafiei M, K. Dehghani, Modeling the microstructural evolution and effect of cooling rate on the nanograins formed during the friction stir processing of Al5083,Materials Science and Engineering A, 527, 2009, 192–197

[4] . G. Rao, B. R. K. Rao, V. P. Deshmukh, A. K. Shah, B. P. Kashyap, Microstructural refinement of a cast hypereutectic Al–30Si alloy by friction stir processing, Materials Letters, 63, 2009, 2628–2630

[5] Adem Kurt, Ilyas Uygur, ErenCete, Surface modification of aluminium by friction stir processing, Journal of Materials Processing Technology, 211, 2011, 313–317

[6] B. Zahmatkesh, M. H. Enayati, F. Karimzadeh, Tribological and microstructural evaluation of friction stir processed Al2024 alloy,Materials and Design , 31, 2010, 4891–4896

[7] Chung-Wei Yang, Yun-Han Chang, Truan-Sheng Lui, Li-Hui Chen, Effects of friction stir processing and artificial peak aging on erosion resistance of Al–11Si–4Cu–2Ni–0.7Mg cast alloy,Materials and Design, 40, 2012, 163–170

[8] D. Yadav, R. Bauri, Effect of friction stir processing on microstructure and mechanical properties of aluminium, Materials Science and Engineering A, 539, 2012, 85–92

[9] Douglas C. Hofmann, Kenneth S. Vecchio, Submerged friction stir processing (SFSP): An improved method for creating ultra-fine-grained bulk materials,Materials Science and Engineering A, 402, 2005, 234–241

[10] F. Y. Tsai, P. W. Kao, Improvement of mechanical properties of a cast Al–Si base alloy by friction stir processing, Materials Letters, 80, 2012, 40–42

[11] G. Madhusudhan Reddy, K. Srinivasa Rao, Enhancement of wear and corrosion resistance of cast A356 aluminium alloy using friction stir processing,Transactions of The Indian Institute of Metals, 63 (5), 2010, 793 - 798

[12] Ghader Faraji, Parviz Asadi, Characterization of AZ91/alumina nanocomposite produced by FSP,Materials Science and Engineering A, 528, 2011, 2431–2440

[13] H. J. Liu, X. L. Feng, Effect of post-processing heat treatment on microstructure and microhardness of water-submerged friction stir processed 2219-T6 aluminum alloy, Materials and Design, 2012

[14] H. W. Zhang, Z. Zhang, J. T. Chen, 3D modeling of material flow in friction stir welding under different process parameters, Journal of Materials Processing Technology, 183, 2007, 62–70

[15] I. Charit, R. S. Mishra, High strain rate super plasticity in a commercial 2024 Al alloy via friction stir processing,Materials and Engineering A, 359, 2003, 290-296

[16] K. Elangovan, V. Balasubramanian, Influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminiumalloy, journal of materials processing technology, 200, 2008, 163–175

[17] K. Elangovan, V. Balasubramanian, Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061

aluminiumalloy,Materials and Design, 29, 2008, 362–373

[18] K. Surekha, A. Els-Botes, Development of high strength, high conductivity copper by friction stir processing,Materials and Design, 32, 2011, 911–916

[19] K. Surekha, B. S. Murty, K. Prasad Rao, Microstructural characterization and corrosion behavior of multipass friction stir processed AA2219 aluminium alloy, Surface & Coatings Technology, 202, 2008, 4057–4068

[20] K. N. Ramesh, S. Pradeep, Vivek Pancholi, Multipass Friction-Stir Processing and its Effect on Mechanical Properties of Aluminum Alloy 5086, Metals & Materials Society and ASM International, 2012

[21] L. Karthikeyan, V. S. Senthilkumar, K. A. Padmanabhan, On the role of process variables in the friction stir processing of cast aluminum A319 alloy,Materials and Design, 31, 2010, 761–771

[22] L. Karthikeyan, V. S. Senthil Kumar, Relationship between process parameters and mechanical properties of friction stir processed AA6063-T6 aluminum alloy,Materials and Design, 32, 2011, 3085–3091

[23] L. Karthikeyan, V. S. Senthilkumar, V. Balasubramanian, S. Natarajan, Mechanical property and microstructural changes during friction stir processing of cast aluminum 2285 alloy, Materials and Design, 30, 2009, 2237–2242

[24] L. B. Johannes, R. S. Mishra, Multiple passes of friction stir processing for the creation of superplastic 7075 aluminum,Materials Science and Engineering A, 464, 2007, 255–260

[25] LivanFratini, Gianluca Buffa, Dina Palmeri, Using a neural network for predicting the average grain size in friction stir welding processes, Computers and Structures, 87, 2009, 1166–1174

[26] M. Chiumenti, M. Cervera, C. Agelet de Saracibar, N. Dialami, Numerical modeling of friction stir welding processes, Comput. Methods Appl. Mech. Engrg., 254, 2013, 353–369

[27] M. A. Garcı´a-Bernal, R.S. Mishra, R. Verma, D. Herna´ndez-Silva, High strain rate superplasticity in continuous cast Al–Mg alloys prepared via friction stir processing, Scripta Materialia, 60, 2009, 850–853

[28] M. A. García-Bernal, R. S. Mishra, R. Verma, D. Hernández-Silva, Hot deformation behavior of friction-stir processed strip-cast 5083 aluminum alloys with different Mncontents, Materials Science and Engineering A, 534, 2012, 186–192

[29] M. L. Santella, T. Engstrom, D. Storjohann, T.-Y. Pan, Effects of friction stir processing on mechanical properties of the cast aluminum alloys A319 and A356,Scripta Materialia, 53, 2005, 201–206

[30] M. P. Miles, M. W. Mahoney, C. B. Fuller, Prediction of Bending Limits in Friction-Stir-Processed Thick Plate Aluminum, Metallurgical and Materials Transactions A, 2005

[31] Magdy M. El-Rayesa, Ehab A. El-Danaf, The influence of multi-pass friction stir processing on the microstructural and mechanical properties of Aluminum Alloy 6082,Journal of Materials Processing Technology, 212, 2012, 1157–1168

[32] Mehdi Zohoor, M. K. Besharati Givi, P. Salami, Effect of processing parameters on fabrication of Al–Mg/Cu composites via friction stir processing, Materials and Design, 39, 2012, 358–365

[33] Nhon Q. Vo, David C. Dunand, David N. Seidman, Atom probe tomographic study of a friction-stir-processed Al–Mg–Scalloy, ActaMaterialia, 60, 2012, 7078–7089

[34] Olivier Lorrain, Véronique Favier, Hamid Zahrouni, Didier Lawrjaniec, Understanding the material flow path of friction stir welding process using unthreaded tools,Journal of Materials Processing Technology, 210, 2010, 603–609

[35] Peng Dong, Daqian Sun, Bing Wang, Yueying Zhang, Hongmei Li, Microstructure, microhardness and corrosion

susceptibility of friction stir welded AlMgSiCualloy, Materials and Design, 54, 2014, 760–765

[36] Q. Zhang, B.L. Xiao, P. Xue, Z.Y. Ma, Microstructural evolution and mechanical properties of ultrafine grained Al3Ti/Al–5.5Cu composites produced via hot pressing and subsequent friction stir processing, Materials Chemistry and Physics, 134, 2012, 294– 301

[37] R. S. Mishra , Z.Y. Ma, I. Charit, Friction stir processing: a novel technique for fabrication of surface composite, Materials Science and Engineering A, 341, 2003, 307-310

[38] R. S. Mishra, M. W. Mahoney, S.X. McFadden, N.A. Mara, A. K. Mukherjee, High Strain Rate Superplasticity in A Friction Stir Processed 7075 Al Alloy,Scripta mater, 42, 2000, 163–168

[39] S. Janaa, R.S. Mishra, J.A. Baumann, G. Grant, Effect of process parameters on abnormal grain growth during friction stir processing of a cast Al alloy, Materials Science and Engineering A, 528, 189–199

[40] S. Jerome, S. Govind Bhalchandra, S.P. Kumaresh Babu, B. Ravisankar, Influence of Microstructure and Experimental Parameters on Mechanical and Wear Properties of Al-TiC Surface Composite by FSP Route, Journal of Minerals & Materials Characterization & Engineering, 11(5), 2012, 493-507

[41] S. Soleymani, A. Abdollah-zadeh, S.A. Alidokht, Microstructural and tribological properties of Al5083 based surface hybrid composite produced by friction stir processing, Wear, 278– 279, 2012, 41– 47

[42] Sima Ahmad Alidokht, Amir Abdollah-zadeh, SoheilSoleymani, TohidSaeid, Hamid Assadi, Evaluation of microstructure and wear behavior of friction stir processed cast aluminum alloy,Materials Characterization, 63, 2012, 90–9 7

[43] T. Dieguez, A. Burgueno, H. Svobod, Superplasticity of a Friction Stir Processed 7075-T651 aluminum alloy, Procedia Materials Science, 1, 2012, 110 – 117

[44] T. S. Mahmoudn, S. S. Mohamed, Improvement of microstructural, mechanical and tribological characteristics of A413 cast Al alloys using friction stir processing, Materials Science & Engineering A, 558, 2012, 502–509

[45] Telmo G. Santosa, R. M. Miranda, Pedro Vilac¸ Friction Stir Welding assisted by electrical Joule effect, Journal of Materials Processing Technology, 2014

[46] V. Balasubramanian, Relationship between base metal properties and friction stir welding process parameters, Materials Science and Engineering A, 480, 2008, 397–403

[47] Vahid Firouzdor, Sindo Kou, Al-to-Cu Friction Stir Lap Welding,The Minerals, Metals & Materials Society and ASM International, 2011

[48] W. Woo, Z. Feng, X.-L.Wang, K.An, B.Clausen, T. A. Sisneros, J. S. Jeong, In situ neutron diffraction analysis of grain structure during friction stir processing of an aluminum alloy, Materials Letters, 85, 2012, 29–32

[49] Wanchuck Woo, Hahn Choo, Donald W. Brown, and Zhili Feng, Influence of the Tool Pin and Shoulder on Microstructure and Natural Aging Kinetics in a Friction-Stir-Processed 6061–T6 Aluminum Alloy, The Minerals, Metals & Materials Society and ASM International, 2007

[50] Xiuli Feng, Huijie Liu, Sudarsanam Suresh Babu, Effect of grain size refinement and precipitation reactions on strengthening in friction stir processed Al–Cu alloys, Scripta Materialia, 2011

[51] Y. Tozaki, Y. Uematsu, K. Tokaji, A newly developed tool without probe for friction stir spot welding and its performance, Journal of Materials Processing Technology, 210, 2010, 844–851

[52] Yong X. Gan, Daniel Solomon, Michael Reinbolt, [2010] Friction Stir Processing of Particle Reinforced Composite Materials, Materials, 3, 2010, 329-350

[53] Z. Y. Ma, S. R. Sharma, R. S. Mishra, Effect of friction stir processing on the microstructure of cast A356 aluminum, Materials Science and Engineering A, 433, 2006, 269–278