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REVIEW ARTICLE

Recent advances in friction stir welding and processing of light metal alloys

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Abstract

Due to its excellent energy efficiency and environmental friendliness, friction stir welding (FSW), a very effective solid-state joining process, has been referred to as green technology. It is a method that makes it possible to combine metallic materials, especially lightweight, high-strength aluminum and magnesium alloys that conventional fusion welding had deemed unweldable. As a result, it is regarded as the most critical advance in material joining over the last 20 years. Later, friction stir processing (FSP) was created based on the fundamental ideas of FSW. FSP has been shown to be a reliable and adaptable metalworking process for altering and manufacturing metallic materials. Since FSW/FSP of aluminum alloys has the potential to change the production process in the aerospace, defense, marine, automotive, and railway industries, it has attracted significant scientific and technological interest. It is crucial to optimize the process parameters and comprehensively assess the microstructural changes and mechanical characteristics of the welded/processed samples to promote the use of FSW/FSP technology and assure the structural integrity, safety, and durability of the FSW/FSP components. Thus, this review paper aims to summarize current developments in the mechanical characteristics and microstructural evolution of FSW/FSP aluminum alloys. The mechanism of recrystallization, grain boundary properties, phase transformation, texture evolution, characteristic microstructures, and the impact of these elements on the hardness, tensile and fatigue properties, and superplastic behaviour of FSW/FSP aluminium alloys are all given special consideration.

1. Introduction

Automotive, aerospace, electronics, transportation, and other industries extensively employ light metal alloys like aluminium and magnesium alloys [1–5]. This is caused by low density, excellent electromagnetic shielding, high specific strength, high damping, and good hot formability [2-4,6,7]. On the other hand, these alloys may be recycled and are inexpensive to cast [1,2,7,8]. Due to their strong resistance to carbon dioxide, appropriate thermal conductivity, and low inclination to absorb neutrons, magnesium alloys are also utilized in the nuclear industry [2]. Additionally, due to their excellent corrosive properties, aluminum alloys are used in marine, aerospace and automobile industries [9–14]. The ductility and formability of magnesium alloys are unsatisfactory at room temperature, leading to early failure under challenging stress conditions. The hexagonal close-packed (HCP) crystal lattice's poor symmetry, high basal roughness, and restriction on the number of active slip systems all contribute to this [2,15–17]. Due to these factors, there is insufficient strength, severe fatigue, and little creep resistance [2]. FSW's fundamental idea is incredibly straightforward. According to the schematic in Fig. 1a unique rotating tool made of a shoulder and pin is first placed into the margins of

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two sheets that need to be welded before moving along the joint line. The material flows intricately around the tool during FSW, from the advancing side (AS) to the retreating side (RS). The AS signifies the side when the rotating and welding directions are the same, and the RS marks the side where they are opposite. A revolving tool produces heat, transforming the material nearby from a hard solid state into a soft "plastic-like" state. Due to its lightweight nature, appealing look, fabricability, and corrosion resistance, aluminum became the choice for many applications [18]. In its purest form, aluminum is weak. Its mechanical qualities are enhanced by alloying it with iron, silicon, manganese, and magnesium to create non-heat-treatable alloys. Pure alloying of aluminum with copper, magnesium silicate, and zinc results in the development of heat-treatable high-strength aluminum alloys [19]. Depending on their mechanical and physical qualities, these alloys are employed in various disciplines, such as airframes, engines, missile bodies, fuel cells, and satellite components. Arc welding is one of the most frequently used modern industrial methods by heating metal components to their melting point and joining them together. Aluminum alloys that cannot be fused using the traditional arc welding process are created by factors such as the formation of aluminum oxide in the molten stage, hydrogen solubility, thermal expansion, and shrinkage during solidification [20].

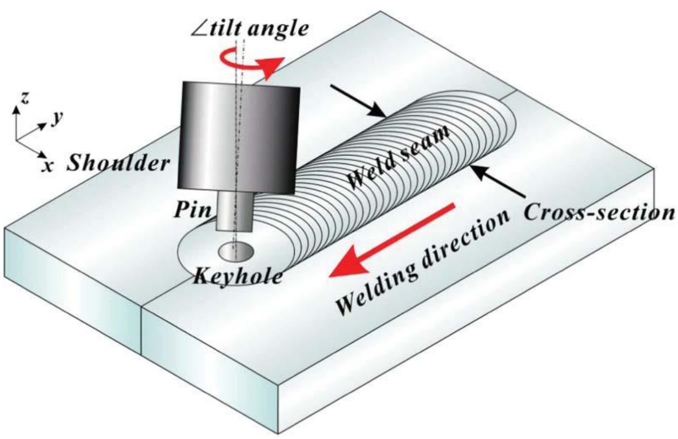

Figure 1: Schematic diagram of friction stir welding

1. Modification/enhancement of microstructure and mechanical properties of light metal alloys

A fine and equiaxed recrystallized grain structure distinguishes the center-located NZ. For instance, the 6061Al-T651 alloy's massive, elongated, pancake-shaped grains have been refined into tiny recrystallized grains (Fig. 2) [21]. The NZ material is thought to have undergone SPD at a high strain rate. Depending on the material, tool design, and operating conditions, cumulative strain and peak temperatures in this location might vary from 0.8 to 0.95 T_m [22, 23]. In the NZ, DRX developed refined and equiaxed grains after severe plastic deformation and high-temperature exposure.

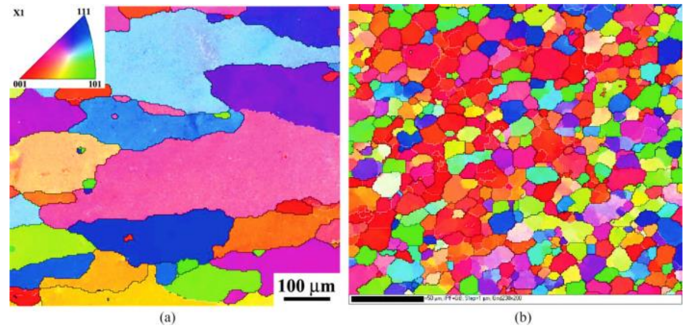

Figure 2: (a) EBSD diagram of base metal AA6061, (b) Nugget Zone

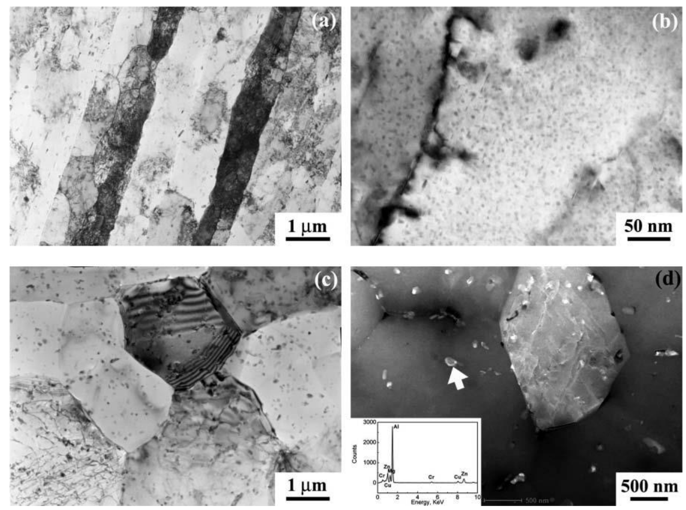

Figure 3: TEM image of friction stir welded joint of AA7075, (a) Subgrain boundaries, (b) Uniform and tiny disseminated precipitates, (c) Grain structure, (d) 2nd phase particles at NZ [24].

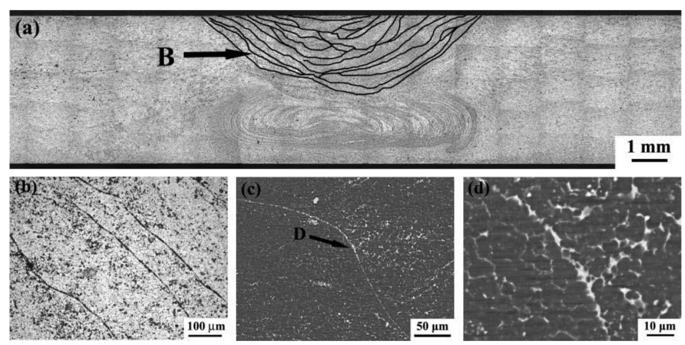

Figure 42. Separation bands on transverse cross sections of (a) FSW 2024Al-T351 alloy joint produced at a TRS of 800 rpm and a welding speed of 200 mm/min, magnified (b) OM and (c) SEM images of position B in (a), and (d) magnified image of arrow zone in (c) [28].

Characteristic microstructures in the NZ of the FSW joints, including onion-ring structures, segregation bands, zigzag lines, and kissing bonds, are generated and are related to the particular and intricate deformation mode in FSW/FSP. The mechanical characteristics and fracture behavior of the FSW joints of aluminum alloys are often significantly influenced by these distinctive microstructures, which draw a lot of attention from researchers. The NZ was distinguished by a fine and equiaxed recrystallized grain structure after FSW [24, 25]. Examinations using transmission electron microscopy (TEM) revealed no fine precipitates (Fig. 2) [24]. This suggests that FSW caused the fine ή phase to dissolve. Mahoney et al. reported similar outcomes as well [26]. Despite total dissolving occurring in the NZ, according to Dumont et al. [27], it did recover some hardness after cooling and subsequent natural age. GP zones formed and expanded in areas where supersaturation was sufficient during this time [27]. In the shoulder-driven zone (SDZ) of the NZ in FSW joints of precipitation-strengthened aluminum alloys, linear segregation bands made up of second-phase particles were occasionally seen in addition to the onion-ring structure. As indicated by the black lines in Fig. 4a [28], such linear segregation bands displayed distinct distribution characteristics from the onion-ring structure. Continuous linear segregation bands were readily discernible at higher magnifications in both optical microscopy (OM) and SEM images (Fig. 4 and 4c) [28]. Additionally, an SEM picture showed that practically all of the second-phase particles in the matrix had been dissolved (Fig. 4c). Secondary phase particles separated at the grain borders, as seen by the magnified picture of the arrow zone in Fig. 4c. The linear microstructure in Figure 42d was made up of a vast number of secondary phase particles at grain boundaries [29].

Table 1: Research summary of FSW/FSP of light metal alloys

S.No	Materials	Authors	Conclusions	References
1	ZE41A & AA6061	Champagne III et (2016)al.	Hybrid joint obtained using FSW and cold spray.	[30]
2	AZ31 & AA1100	Azizieh et al. (2016)	Maximum tensile strength of 122 MPa was achieved of base metal.	[31]
3	AZ31 & AA6013	Zhao et al. (2015)	Maximum tensile strength obtained 152.3 MPa through UFSW.	[32]
4	AZ31B-O & 6061-T6	Fu et al. (2015)	Maximum tensile strength achieved 70% of base metal (Mg).	[33]
5	AZ31 & AA6061	Regev et al. (2014)	Consideration of peak temperature plasticity over creep analysis.	[34]
6	AZ31-O & AA6061-T6	Masoudian et al. (2014)	Maximum tensile strength of 76% and 60% of Mg and respectively was achieved.Al	[35]
7	AA2024 & AA6061	Sadeesh (2014)	The tensile strength of 194 Mpa and 209 Mpa were attained.	[36]
8	AZ31&AA6061-T6	Lee et al. (2014)	Observation of plane orientation and fine grains in SZ.	[37]
9	Mg & AA6061	Liang et al. (2013)	Influence of tool rotatory speed and tool offset on weld properties.	[38]
10	Pure Mg & AA6063	Pourahmad et al. (2013)	Material flow analysis and IMCs development by steel shots.	[39]
11	AZ31B & 6063	Venkateswaran (2012)and	Showing relationship between weld interface and tensile strength.	[40]
12	AZ31C-O & 5083	Mofid et al. (2012)	Water cooling effect on maximum temperature and IMCs formation.	[41]
13	AZ31 & AA5754	Simoncini et al. (2012)	Influence of FSW constraints and tool shape.	[42]
14	AZ31B & AA6061	Malarvizhi (2012) and	Influence of tool shoulder diameter (heat generation) Mg–Al weldment quality.on	[43]
15	AZ31 & AA6061-T6	Chang et al. (2011)	Improved the tensile strength to 66% of base Mg by Hybrid laser-FSW.	[44]
16	AZ31B-H24 & 6061-T6	Firouzdor and (2010b)Kou	Base metals Positioning affects the IMCs formation.	[45]
17	AZ31B-H24 & 6061-T6	Firouzdor and (2010a)Kou	Formation constitutional liquation was perceived.	[46]
18	AZ31 & A5052	Yan et al. (2010)	Maximum hardness was obtained twice the base metals.	[47]
19	AZ31B & A5083	Yamamoto et al. (2009)	Tensile strength of 115 MPa and IMCs Al12 Mg17 & Al3 Mg2 was achieved.	[48]
20	AZ31 & AA6061	Firouzdor and (2009)Kou	Material positioning directly affects the heat input during FSW.	[49]
21	AZ31B-H24 & 2024-T3	Liu et al. (2009)	Showing galvanic corrosion due to the Al-Mg galvanic couples growth	[50]
22	AZ31 & AA6040	Kostka et al. (2009)	Observed 1 m thick IMC of fine-grained Al12 Mg17.	[51]
23	AZ31B-O & A5052P-O	Shigematsu et al. (2009)	Maximum tensile strength of 143 MPa was achieved at 1400 rpm.	[52]
24	AZ31B-O & A5052P-O	Kwon et al. (2008)	The tensile strength of 132 MPa was achieved at 1000 rpm.	[53]
25	AZ31B &A5052-H	Morishige et al. (2008)	The SZ hardness was lower than the laser welding fusion zone.	[54]

26	2024-T3 & AZ31	Khodir et al. (2007)	Variation in hardness value over SZ due to IMCs formation.	[55]
27	AZ31 & Al6040	Zettler et al. (2006)	Attained 80% weld efficiency of base material (AZ31).	[56]
28	AZ31 & 1060	Yan et al. (2005)	IMCs like Al12 Mg17 and Al3 Mg2 cause the cracking during FSW.	[57]
29	6061-T6- AZ91D & AZ31B-H24	Somasekharan et al. (2004)	Lamellar shear bands were seen in either side of Al or Mg.	[58]
30	AZ31 & A1050	Sato et al. (2004)	The IMC Al12 Mg17 was formed by constitutional liquation FSW. Formation of a very thin IMC layer, results in virtually no ductility.	[59]
31	AA6082 & AA8011	Husain Mehdi et al. (2022)	FSP was applied on single and double V groove TIG welded joint and observed excellent mechanical properties compared to TIG and FSW joints.	[60]
32	AZ31 & A1050	McLean et al. (2003)	Intermixing two phases at the intermediate layer. The formation of IMCs in SZ is restricted.	[61]
33	AZ31 & A1050	Hirano et al. (2003)	Preliminary study and defect-free joining by FSW of Al–Mg alloy.	[62]
34	Al–Zn–Mg–Cu alloy	Park et al. (2002)	In this study, the model accurately forecasts the maximum welding temperature distributions over the studied energy range.	[63]
35	AA6061-T6 Aluminum alloy	C. Hamilton et al [2009]	A novel slip factor based on the weld's energy per unit length was used to develop a thermal model for friction stir welding. Over a broad range of energy levels, the thermal model correctly predicts the maximum welding temperature.	[64]
36	A 3D FE model, with general validity for different joint was used to simulate	C. Hamilton et al [2008]	In friction stir welding operations, a new numerical method is studied to predict residual stress distributions.	[65]
37	Magnesium Alloy Mg-Y-Re	G. Buffa et al [2011]	A friction stir processed Mg-Y-RE alloy's corrosion behavior was investigated with grain refinement and heat treatment. With electrochemical testing and continual immersion testing, many patterns between microstructural conditions and corrosion behavior were found.	[66]
38	Al Alloy 1100	G.R. Argade at al [2012]	AA1100 which had been accumulatively roll-bonded (ARBed) underwent friction stir welding (FSW). FSW caused the fine granules of the SZ to reproduce and the ultrafine grains of the ARBed material nearby to somewhat increase.	[67]
39	AA7075 and AA6061	Mehdi et al. [2022]	Optimization technique was used to predict the mechanical properties of TIG+FSP welded joint.	[68]
40	Pure Titanium	L. Fratini et al [2010]	It investigated how the microstructure of commercial-quality titanium changed during FSW. The material flow was discovered to be caused mainly by prism slip and to be close to simple-shear deformation. The development of grain structure has been proven to be a multi-stage, complicated process.	[69]
41	AZ31 Magnesium Alloy	S.Mironov et al [2009]	On the side that is receding, there are more signs of stress. Grain expansion is shown with an increase in the processing variables that encourage heat generation. For this hot-rolled BM, FSW reduced the tensile mechanical characteristics.	[70]
42	AA7449 aluminium alloy.	L.Commin et al [2009]	To predict the precipitate dissemination in 7xxx alloys during FSP, a numerical, analytical model built on the Kampmann and Wagner numerical (KWN) model.	[71]
43	6061Al–T651	N.Kamp et al [2006]	The TS is crucial in affecting the welds' tensile characteristics and fracture mechanism under the welding conditions. FSW 6061Al-T651 joints welded at 400 mm/min had greater strength with a 45-shear fracture, whereas samples welded at 100 mm/min showed lower UTS with almost vertical fractures.	[72]

44	Aluminium matrix composites (AMCs)	Omar.S.Salih [2015]	The quantity of heat generated and the strength of FSW joints are significantly influenced by welding parameters such as tool rotation, speed, transverse speed, and axial force. A microstructural analysis revealed that the improper flow of plasticized metal caused the creation of the tunnel defect.	[73]
45	Al-4Mg-1Zr alloy with grain size of 0.7 µm	Z.Y. Ma [2010]	Low temperature and high strain rate super plasticity of greater than 1200% work was observed at 10^{-2} to $-1x10^{-1}$ s^{-1}.	[74]
46	Al-Si alloy A356	Z.Y.Ma et al [2003]	With higher tool rotation rates, FSP A356's strength improved. The tool's maximum strength for the conventional pin was seen at 900 rpm.	[75]
47	AA6082 and AA8011 AA5083 and AA8011	Mabuwa et al. [2022] Hashmi et al. [2022] Salah et al. [2022]	Si particle size, aspect ratio, and dispersion were unaffected by overlapping FSP. The FSP-broken Si particles were evenly distributed across the multi-pass FSP-processed zones.	[76-78]
48	Al-Mg-Sc alloy	Nilseh Kumar et al [2012]	Depending on the alloy's processing and initial thermos-mechanical state, the grain size ranged from 0.89 to 0.39 m. With an increase in the Zener-Holloman parameter, the grain size was reported to be reduced.	[79]
49	A356 Alloy	S.R Sharma [2004]	Significant refining, microstructure homogeneity, and porosity reduction were linked to an improvement in fatigue life. The aluminum matrix underwent a considerable breakage and homogeneous dispersion of Si particles as a result of FSP, and porosity was also eliminated.	[80]
50	AA6082 AA5083 and AA6061	H. Mehdi [2022] P. Rani et al [2022]	Nanoparticles ZrB2 was used the reinforcement particles to enhance the mechanical and microstructure of AA6082. The processed region revealed the maximum tensile strength compared to the base metal.	[81-83]
51	Cast Al-Alloy of F357	S. Jana et al [2007]	Si particles were not polished further than a particular point by the numerous passes. The multi-pass run of the second setup shows that FSPed material can limit the amount of AGG.	[84]
52	Al-SiC Composite	R.S Mishra et al [2003]	When the desired depth (2.28mm) is too great, the tool's shoulder pushes all of the pre-placed SiC particles away, and little to no composite surface forms. SiC particles could not be mixed with Al-alloy because the target depth (1.78mm) was too tiny. Particles of SiC were successfully incorporated into the aluminum matrix at the target depth of 2.03 mm.	[85]
53	AA2024 and AA7050	A.N. Salah et al. [2021]	The maximum tensile strength was achieved at high TRS of dissimilar aluminum alloys AA2024 and AA7050. The brittle intermetallic compound was generated at low TRS and low TS, disseminated at high TRS and observed excellent mechanical properties of the welded joints.	[86]
54	cast A356 aluminum	Z.Y.Ma et al [2006]	Higher tool rotation rates produce a more homogenous microstructure. Si particles are distributed differently throughout the FSP zone, with varying sizes and volume fractions, indicating uneven material flow.	[87]
55	Al–7Si–0.6 Mg alloy	S.Jana, et al [2007]	When specimens were tested at the same stress level and with a stress ratio of R=0, FSP increased the fatigue life of a cast Al-7Si-0.6 Mg alloy by 15.	[88]
56	Aluminum alloy 7050-T65	J-Q-Su et al [2002]	During friction stir welding, the base metal's original grain structure is removed and replaced with a fragile equiaxed grain structure in the dynamic re-crystallized zone. The strengthening precipitates have coarsened substantially compared to the parent material microstructure (DXZ).	[89]
57	Commercial superplastic 7475 Al alloy sheets	Indrajit Charit et al [2002]	Weld HAZ has a stable microstructure that nonetheless exhibits superplastic characteristics. Due to the increased flow stress at 783 K compared to source metal (16-18 MPa versus 2-9 MPa), the high-strength weld nugget is unlikely to deform during superplastic forming.	[90]

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