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Review

# A review of the application of friction stir welding on hard-to-weld materials

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**ABSTRACT**

Engineering materials require the joining of various members to form usable structures. Among the commonly used joining methods are riveting and fusion welding. Riveting has a challenge of low joint tensile strength while some important materials cannot be welded by the fusion method. To solve the fusion welding challenge, the welding institute invented a solid-state metal joining technique called friction stir welding for joining aluminium alloys. Friction stir welding has however gained remarkable attention for application to metals hard to weld by fusion. This review paper analyses applications of friction stir welding on hard-to-weld metals by fusion. The selected metals include steels, magnesium, copper, titanium and aluminium alloys.

**Keywords:** FSW, Hard-to-Weld Materials.

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## INTRODUCTION

Engineering materials require the joining of various members to form usable structures. Three general methods of joining exist namely; Mechanical by interlocking of components, direct by solid state bonding or fusion, and indirect by use of intermediate material like adhesives, cement or braze [1]. Materials such as aluminium alloys, magnesium alloys, copper alloys and titanium alloys have had joining challenges using the fusion method [2][3]. Fusion welding methods include; oxyacetylene gas welding, shielded metal arc welding, gas tungsten arc welding, submerged arc welding, laser beam welding, hybrid welding and electron beam welding [4][5][6]. The commonly used tungsten inert gas (TIG) welding to join materials like aluminium alloys in the past caused coarse dendritic structures, micro-cracks, porosity and loss of strength and hardness [7][8][9]. Similar problems may be encountered in other fusion joining techniques such as gas metal arc (MIG) welding and laser beam welding even in arc-based additive manufacturing of aluminium alloys [10][11].

Friction stir welding (FSW), is a solid-state metal joining process invented by Wayne Thomas and E. Thomas at The Welding Institute (TWI) in 1991 for welding aluminium and its alloys has yielded promising results. It is an alternative method with better results compared to fusion welding on a wide range of metals as well as in joining dissimilar metals [12][13][14][15][16][17][18][19][20]. An FSW tool moves in a cyclic manner approaching the joint of workpieces firmly mounted on back plates, plastics moving along the interface causing a solid-state joint between them [21][22].

Advantages of FSW over fusion welding include; maintenance of original metallurgical characteristics of the base metal, no required filler material, no welding gas emission, edge preparation not needed, minimum distortion and consumes less power [23][24][25][26][27][28]. Research on ways of improving the FSW joint integrity is ongoing which includes Ultrasonic pre-heating that has yielded a reduction in welding load, reduced tool wear and enhanced material flow on the joint [29][30][31].

However, friction stir welded joint integrity depends on a number of factors including; process parameters, welding tools and joint preparation [32][33][34][35]. This present

work evaluates current achievements in FSW of hard-to-weld metals namely some steels, magnesium, copper, titanium and aluminium alloys for purposes of enhancing its results.

## LITERATURE REVIEW

### Friction stir welding process

Friction stir welding is conducted at temperatures below the melting temperature of the base metals being joined. Major constraints in FSW are; rotational speed, traverse speed, tilt angle, tool offset and downward force [5][36]. FSW is commonly employed in butt and lap joints where a non-consumable rotating tool plunges into two rigidly clamped plates on backing plates [37]. The advancing side is one where a rotating tool moves in the same direction as the traversing speed while the retreating side tool rotation opposes the traversing direction. The advancing side is normally on the right-hand side of the micrograph since machine tools rotate clockwise by default [38][21]. A typical micrograph of the FSW region shows distinct regions of the nugget zone (stirred zone), thermo mechanically affected zone (TMAZ) and heat affected zones (HAZ) [39]. The basic setup and process of friction stir welding are illustrated in Figure 1.

Friction stir welding tools are of various materials and designs. A typical cylindrical, threaded tool made of steel is illustrated in Figure 2.

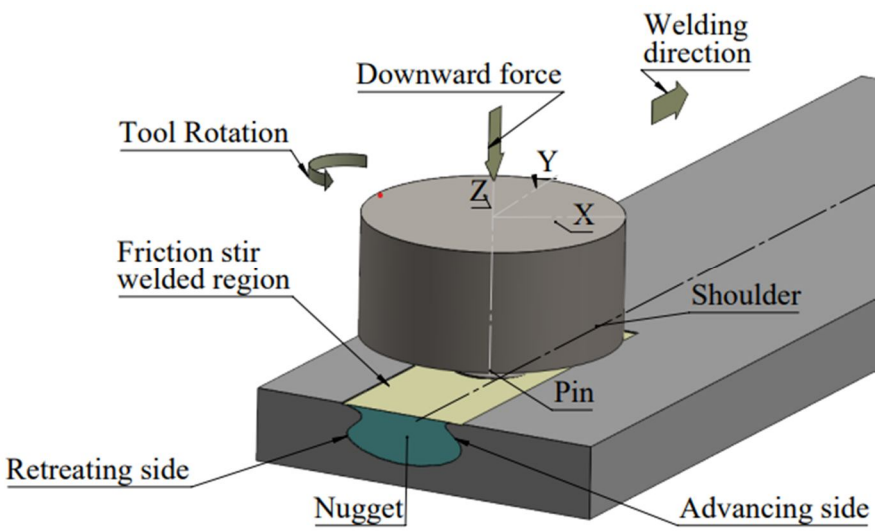


**Figure 1.** Sample of friction stir welding setup and process.

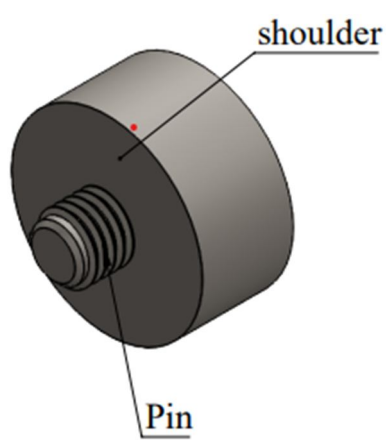


**Figure 2.** Basic friction stir welding tool parts.

## Friction stir welding of steels

Friction stir welding of steel is possible and thus numerous studies have recently been conducted on friction stir weldability of steels [40][41][42][43][44]. However, it has several limitations such as; the requirement of a very durable tool, high temperatures (500 to 1000°C) to plasticize the metals, high hardness of steels, very high tool damage rate and high flow stress which causes severe tool degradation. Tools used for FSW of steels must be able to withstand all kinds of wear, have high strength and hardness and have high fracture toughness. Recommended tool materials are; commercial pure tungsten (Cp-W) and polycrystalline cubic boron nitride (PCBN). With pre-heating or in-situ heating applied to material joints before FSW, ordinary tools like high-speed steels and carbide tools can be used. Laser heating is used for magnetic and non-magnetic materials whereas induction is used for ferromagnetic steels. Ultrasonic vibration is also used in heating joints prior to FSW operation [45]. Advanced high-strength steels (AHSS) have become modern industrial favorites in weight reduction and high crash-worthiness in vehicles. However, further weight reduction of up to 30% is possible with the use of inter-metallic, where aluminium alloys are the most preferred combination materials [46].

Steel grades sensitive to thermal cycles offer better joint results with FSW compared to fusion [47]. The most frequently used steels are carbon steels with small amounts of manganese (1.65% max), silicon (0.60% max), and copper (0.60% max). An increase in carbon content in steel makes it harder and stronger through heat treatment with a corresponding decrease in ductility [48]. Phase transformations increase with an increase in carbon content hence the higher the carbon content in steel the lower the fusion weldability. Fusion welding is only acceptable in low-carbon steels (0.30%) and medium-carbon steels (0.30 to 0.60%). This makes FSWed joint properties majorly rely on the welding speed and rotational speeds[48]. Kanwal Jit et al established that high-carbon steel (EN-31) and low-carbon steels (SAE-1020) are extensively used in automotive and manufacturing industries. The large variation in the percentage of carbon makes it difficult to weld them traditionally. Using grey relational analysis, the researcher determined optimum FSW parameters as 40 kg/cm$^2$, forging pressure of 100 kg/cm$^2$ and spindle speed of 1120 rpm [49]

FSW experimental research conducted on 6.35 mm hot rolled AISI 1018 steel plates parallel to the rolling direction at 0.43 to 1.68 mm/s welding speed and 450 to 650 rpm rotational speed attained a peak temperature of 1000°C. This resulted in a higher tensile strength of 476 MPa compared to the base metal of 463 MPa [50]. Hedetoshi et al investigated the impact of FSW parameters on mechanical and microstructural properties of joints of different carbon steels namely; IF Steel, S12C and S35C. It was found that apart from IF steel, the strength of S12C steel increased with an increase in welding speed (decrease in heat input) while the strength of S35C steel gave peak strength at 200 mm/min [51][52][53].

Bhatia et al. conducted FSW on AISI 1018 using a tungsten carbide tool at a spindle speed of 450 rpm, welding speed of 60 mm/min and a tool shoulder diameter of 20 mm. The resulting joint was defect-free and attained 414.1 MPa which is 99.5% joint efficiency [54]. Ling Cui et al. successfully conducted FSW on high carbon steel material, S70C (0.72 wt.%C) below $A_1$ point as an optimal condition without any transformation. It was noted that both the material composition and temperature cycle affect the mechanical and microstructural properties of the joint. FSW welding parameters are easily controlled without pre-heating or post-heating [55].

## Friction stir welding of magnesium alloys

Magnesium is less dense compared to aluminium. It is the 6$^{th}$ most abundant on the earth's surface and 3$^{rd}$ most plentiful in seawater. It has a low tendency to absorb neutrons, and sufficient resistance to carbon dioxide. Lightweight, outstanding specific strength, sound damping capabilities, hot formability, good cast ability and recyclability but limited strength. Major areas of engineering applications include nuclear power plants, marine, railway, aerospace, shipbuilding and land transportation [56][57].

In the automotive industry, magnesium alloys have gained popularity due to their attractive properties such as; high die-casting rates, electromagnetic interference shielding properties, parts consolidation, dimensional accuracy, excellent machinability, stiffness to weight ratio, low density of 1.738 g/cm$^3$, and good thermal conductivity [58]. Unnikrishnan et al obtained the maximum tensile strength of AZ61A (in wt.% Al 5.96, Zn 1.28, Mn 0.17, Bal. Al) using FSW welding parameters of 1194 rpm, 92.19 mm/min, and 5.05 KN axial load [59].

Gontarz reported that out of 1,832 parts, 1,200 of them were made from magnesium alloys in a passenger aircraft Boeing 727 between 1962 and 1984. These include doors and brackets made of AZ61A-grade magnesium alloy [60]. Magnesium alloys are not easily weldable by fusion due to high solidification shrinkage, low surface tension, low viscosity and solubility in liquid hydrogen. Friction stir welding is a suitable alternative for welding magnesium alloys [61]. Kulkarni et al. reported a reduction of engine weight by 7% after replacing the aluminium alloy engine cylinder block, front cover and oil pan with magnesium alloys. It was further reported that the replacement of AA 6061-t651 with Magnesium alloy EN-MB10020 resulted in improved fuel economy by 10% [62].

Strength, formability and heat resistance in magnesium are improved using alloying elements such as; aluminium,

zinc, zirconium, cerium, yttrium, silver, and thorium [63]. Some of the best-known magnesium alloys are tabulated in Table 1.

Further uses of Magnesium alloys include; steering columns, engine and transmission cases/covers, and seat frames in automobiles. In aircraft structures, it is used to make gearbox housing due to its excellent damping characteristics. Electronically, used for making mobile telephones and computers, due to its lightweight, conductive and heat radiators [63].

**Table 1.** Prominent magnesium alloys [63].

| Mg alloy | Alloying elements | Prominent properties |
|---|---|---|
| AZ91 | 9%Al- 0.7%Zn- 0.13%Mg | General-purpose alloy with room temperature strength and castability |
| AZ31 | 3%Al- 1%Zn- 0.2%Mn | Good formability and weldability |
| AM60 | 6%Al-0.15%Mn | Good in toughness and ductility |
| ZK60 | (5-6)%Zn- (0.3-0.9)%Zr | Good strength at room temperature and high hot workability |
| ZE41 | 4.2%Zn- 0.7%Zr- 1.2% rare earth elements | Good creep strength and heat-resistant |
| AS41 | 4.2%Al – 1%Si | Good creep strength up to 150°C |

## Friction stir welding of copper and copper alloys

Copper and its alloys are used in a variety of engineering applications including; magnetic resonators, heat exchangers, air conditioners, metallurgical oven coolers, bus bars for electrolysis and superconductors. Numerous studies have also been conducted on friction stir welding of copper alloys [64][65]. For example, Kati Savolainen et al conducted FSW on one Cu -OF, three Cu-DHP, and two CuAl5ZnSn where satisfactory results were obtained. No specimen failed at the weld joint in a tensile transverse test [66]. Copper grains have an elongated shape of approximately 30 microns. Research has generally established that the FSW quality is mostly determined by welding parameters of axial force, rotational speed and welding speed all of which depend on thermo physical properties and plate thickness. 86% of the energy generated comes from the tool shoulder, 3% from the tip while the rest is generated by the pin [67]. Copper alloys are identified by use of a unified numbering system comprising of a C plus five numbers. The main categories of copper alloys are tabulated in Table 2.

**Table 2.** Copper and its alloys [68].

| Cu alloy designation | Elements and description |
|---|---|
| C100xx – C150xx | Commercially pure copper |
| C151xx-C199xx | Age hardened Cu (W/Cd, Cr, Fe) |
| C2xxxx | Cu-Zn alloys (brasses) |
| C3xxxx | Cu-Zn-Pb alloys (leaded brasses) |
| C4xxxx | Cu-Zn-Sn alloys (Tin brasses) |
| C5xxxx | Cu-Sn and Cu-Sn-Pb (phosphor bronze alloys) |
| C6xxxx | Cu-Al and Cu-Si bronzes |
| C7xxxx | Cu-Ni copper nickel and Cu-Ni-Sn copper nickel silver |

Kaushal et al. notes that copper chromium zirconium (CuCrZn) is a unique and excellent alloy with high thermal and electrical conductivity, good corrosion resistance, moderate strength and excellent resistance to softening at elevated temperatures. Applications of this alloy include nuclear reactor components such as; heat sink material for fusion reactors, first wall and diverter components. The challenge of this Cu-0.8Cr-0.1Zr alloy is welding using the conventional fusion method [69]. Shankar et al. conducted FSW of pure copper alloy to AA 1050 at 1400 rpm, 63 mm/min as the optimum parameters obtained through the weld pitch ratio method. The joint achieved 91% of aluminium base material strength. This combination is commonly used for bus bars yet not so much research conducted on it so far [70].

## Friction stir welding of titanium alloys

Titanium is the fourth most abundant metallic element in Earth's crust. Its alloys have a wide range of applications that include the automotive industry, machine tools, pulp

and paper industry, food processing, superconductors, jewelry industry, optics, sports equipment, musical equipment, personal security and safety, transportation, cutting implements, shape memory alloys, airframes, engines, satellite rockets, chemical processing, power generation plants, shipbuilding, deep drilling and biomedical engineering equipment among others [71]. It has good mechanical properties at a wide range of temperatures, low density, excellent corrosion resistance, low thermal conductivity, non- magnetism and good workability. Pure titanium (Gr 1, 2, 3 and 4) and alloy Ti-6Al-4V are the most applicable titanium materials in medicine [72].

Titanium has a high melting point. This necessitates the use of tools made of materials of high melting points and abrasion resistance such as; nickel alloys, tungsten-based alloys, polycrystalline cubic boron nitride and polycrystalline diamond for FSW. Lauro investigated three plate lap joint FSW of Ti-6Al-4V, 2.5 mm titanium alloy using a tool made of Tungsten 25 Rhenium alloy. Superplasticity properties were attained at a slightly above 920°C but there was a lot of material sticking to the tool hindering continuous welding. The material is highly used in aeronautics and aerospace [73][74]. Main titanium alloys and their applications are tabulated in Table 3.

**Table 3.** Titanium alloys and their applications [72].

| Titanium alloy | Application in aircraft and automotive industry |
|---|---|
| Ti-3Al-2.5V(Gr-9) | Production of cell structures and high pressure lines |
| Ti-5Al-2.5Sn(Gr-6) | Used in turbo pumps, high pressure space shuttles |
| Ti-8Al-1Mo-1V | Used for blades of military engines |
| Ti-6Al-2Sn-4Zr-2Mo(+Si) | Parts of gas turbine engines including discs and rotors at temperatures up to 540°C in high pressure compressors |
| Ti-6Al-4V(Gr-4) | Static and rotating components of gas turbine engines, fuselage, nacelles, landing gear, wing and tail surfaces. Also suspension springs, bumper, exhaust valves, connecting rods, body and fuselage in vehicles. |
| Ti-6Al-2Sn-2Zr-2Mo-2Cr +Si | Used for F22 program for Lockheed/Boeing |
| Ti-6Al-2Sn-4Zr-6Mo | Used at temperatures up to 315°C for military engines with yield strength of 1035 MPa especially F100 and F-119. |
| Ti-5Al-2Sn-2Zr-4Mo-4Cr | Fans and compressor discs at below 400°C |
| Ti-13V-11Cr-3Al | Aircraft SR-71 wings, body, frames, partitions and ribs |
| Ti-10V-2Fe-3Al | Whole main landing gear leading to weight saving of 270 kg per aircraft in Boeing 77. |
| Ti-6Al-2Sn-4Zr-2Mo-0.1Si(Gr-2) | Exhaust valves and system |

Chumaevskii et al attained a tensile strength of 90%of base metal on FSW Ti-6Al-4V, 2.5mm butt joint using nickel-based heat resistant 2hs6u alloy. Downward load of 4500 kg and spindle speed ranging from 340 to 380 rpm [75]. Titanium alloys are classified into α-alloys commonly used in chemical and medicine industries, (α+β) – alloys with the tensile strength of 700 to 1000 MPa commonly used in aerospace and β-alloy also used in aviation. Alihan et al conducted FSW on Ti-4Al-3Mo-1V using nickel-based heat-resistant alloy, ZhS6U and obtained a joint tensile strength equal to base metal [76]

Gangwar et al. produced a defect-free FSW joint, 5 mm thick between TI-6242SG and Ti-54M at 225 and 325 rpm and 100 to 150 mm/min. The research concluded also that the migration of materials from the retreating side to the advancing side is primarily dependent on traverse speed [77].

## Friction stir welding of aluminium and its alloys

Aluminium is the most abundant metallic element in the earth's crust [78]. Attractive properties like high strength, a lower density of 2.7 g/cm$^3$ compared to steel 7.83 g/cm$^3$ and recyclable ability make aluminium alloys be referred to as green metal and more attractive compared to steels [79][80]. Alloys of aluminium are classified into cast and wrought categories. They are further classified as heat-treatable and non-heat-treatable alloys. Non-heat treatable AA (3xxx, 4xxx and 5xxx) have magnesium and

manganese as principal alloying elements. These alloys are work-hardened and weldable by fusion though softened at the joint due to loss of work hardening [81]. The heat-treatable aluminium alloys include; 2xxx (principal alloying element Cu), 6xxx (principal alloying element Mg and Si) and 7xxx (principal alloying element Zn). In aluminium alloys, the heat-treatable wrought 2xxx and 7xxx series are the strongest and unweldable by fusion due to the low melting points of principal alloying elements [38][82][83][84][85].

The use of dissimilar aluminium alloys has also attracted a wide range of applications in industries including; aerospace, power generation, defense, transportation and shipbuilding [7][86][85]. Most of the FSW studies reported in the open literature are on the FSW of Al-alloys [87][88][89][90]. For example, Salamat et al. performed FSW on both similar (AA5083-AA5083) and dissimilar (AA5083-AA6061), 5 mm thick butt joints at 1000 rpm and 100 mm/min using a simple threaded pin tool. Tensile strength achieved for similar (AA5083-AA5083) was 77% of base metal while (AA5083-AA6061) achieved 93 and 34% of base metal respectively. Whereas both have good ductility and outstanding corrosion resistance, AA5083 and AA6061 have an ultimate tensile strength of 328 and 116 MPa, respectively. The research recommended the use of different types of tools for the same welding parameters for future researchers [91]. Table 4 gives the main categories of aluminium and its alloys, main alloying elements, prominent properties and applications [79][92].

**Table 4.** Aluminium and its alloys [79].

| AALO series | Alloying elements | Prominent properties | Application |
|---|---|---|---|
| 1xxx | Super purity and commercial purity aluminium. | Non-Heat treatable | • Electrical conductors<br>• Chemical process equipment<br>• Foils<br>• Decorative finishes<br>• Capacitors |
| 2xxx | Al-Cu and Al-Cu-Mg | Heat treatable | • Welding wires<br>• Fuel tanks<br>• Aircraft body |
| 3xxx | Al-Mn and Al-Mn-Mg | Non-Heat treatable | • Foils<br>• Aluminium sheets |
| 4xxx | Al-Si | Non-Heat treatable | • Filler material<br>• Welding and brazing wire<br>• Forged engine pistons |
| 5xxx | Al-Mg alloys | Non-Heat treatable | • Transportation structural plates<br>• Large tanks for petrol, milk, grain<br>• Pressure vessels<br>• Architectural components |
| 6xxx | Al-Mg-Si | Heat treatable | • Transportation structural plates<br>• Large tanks for petrol, milk, grain<br>• Pressure vessels<br>• Architectural components |
| 7xxx | Al-Zn-Mg and Al-Zn-Mg-Cu | Heat treatable | • Light weight military bridge<br>• Aircraft construction |
| 8xxx | Miscellaneous | | • Nuclear energy installation<br>• Bottle caps<br>• Soft bearings<br>• Aerospace applications |

Mamgain et al. investigated the impact of rotational speed in AA6063, 3 mm butt FSWed joint mechanical and microstructural properties. Tensile strength of 191 and 131 MPa were achieved at 1000rpm and 1400rpm respectively. The higher results were achieved due to the refinement of grains and recrystallization in the stirred zone [93]. Research to determine the influence of rotational speed and welding speed on dissimilar aluminium alloys (AA6063-AA8011), 6mm FSW butt joint was conducted by Kailainathan et al. It employed the use of high carbon high chromium oil hardened steel as a tool. Maximum tensile strength obtained of 134 MPa at 1200 rpm and 60 mm/min [94]. Ananthapadmanaban et al conducted FSW on dissimilar aluminium alloy (AA5052-AA6082), 4mm to find out the impact of tool profile and welding speed on joint hardness. A threaded, cylindrical end chamfered tool produced maximum hardness at a rotational speed of 727 rpm and a welding speed of 0.0875 mm/sec [95].

Kumar et al. analyzed the impact of tool profile, rotational speed and the welding speed on the strength properties of the AA7075 FSWed joint. Extensive research was reported on FSW between AA2024 and AA7075 [96]. Threadgill et al in a review established that FSW joint static mechanical properties are determined by heat input and generally equal or exceed the performance of MIG welds. It is also noted that the FSW of aluminium alloys occurs below 500°C and recommends investigation of the occurrence and significance of flaws in friction stir welding [38]. Muruganandan et al investigated the impact of rotational speed on the tensile strength and ductility of AA 7075. The rotational speed of 600 to 1200 rpm produced defect-free FSW joints. Specimens tested also passed both root and face tests allowing for very high bend angles without cracks [97].

Dhancholia et al. conducted FSW on a 5 mm thick AA6061 and AA7039 at 800 to 1000 rpm and 30 to 50 mm/min to establish optimum welding parameters using response surface methodology. The results established a joint confidence level of 95% in ultimate tensile strength, yield strength, hardness value and impact strength. It was noted that better weld efficiency is obtained when a high-strength material is placed on the retrieving side [98]. Prashnanth et al. established superior tensile strength using a square tool profile at 500 rpm tool rotational speed, 25 mm/min welding speed and 5 MPa force after FSW on AA6061 and AA5083, 5mm thick plates. AA6061 is used for heavy-duty structures like truck frames, shipbuilding, rail coaches and helicopter rotor skins. AA5083, the strongest in non-heat-treatable alloys used in shipbuilding and rail cars with exceptional performance in extreme environments like seawater and industrial chemical environments [99].

Singh et al. studied the impact of Zn interlayer and tool rotational speed on microstructure and mechanical properties of heat-treated AA6082, 6 mm thick plates. It was found that zinc interlayer particles do not form any intermetallic compound with aluminium alloy and no significant improvement in tensile strength of the joints with an interlayer using a cylindrical threaded tool [100]. Patel et al., using a response surface methodology, established that an increase in pin length increases tensile strength using response surface methodology. However, large shoulder-diameter tool at high welding speeds leads to a decrease in the tensile strength of FSWed joints. The research notes that the mechanical properties of welded materials are measured in terms of tensile strength[101] Starink et al established that strength and strength variations of AA2024 are principally determined by precipitation hardening in heat-treatable alloys. Suppressing the precipitation phase can be achieved through modification of alloy chemistry and accelerated weld cooling leading to an increase in FSW joint strength [102].

Research to investigate the impact of the position of aluminium alloy on either the advancing or retreating side on metallurgical and mechanical properties of dissimilar alloys concluded that maximum strength is achieved when the higher-strength alloy is placed on the advancing side. This was attributed to the presence of key alloying elements of higher strength material at the nugget zone of higher weight percentage [103][104]. Mehri et al. conducted FSW perpendicular to the plate rolling direction while investigating the impact on the microstructure of AA7075-T6. A one-and-one relationship between substructure density, grain size and tensile properties with rotational speed was noted [105]. Sun et al. also performed FSW on AA2219-T6, 6mm thick while investigating joint fatigue. The FSW was conducted perpendicular to the plate rolling direction[106]. Chao He et al investigated fatigue crack initiation on the stir zone of AA7075 FSW joint. FSW was performed perpendicular to the plate rolling direction [107]. Zhang et al conducted high-speed FSW on AA7075-T6, 2 mm thick butt joints while investigating the microstructural and mechanical properties of the joint. The welding was conducted parallel to the plate rolling direction. Stronger heat-affected zones and harder nugget zones were obtained at higher welding speeds [108].

## Future research needs

Research on the applicability of friction stir welding is far from over. There are intricacies which are involved in the process of achieving maximum joint tensile strength to be as close to the base metal as possible. It is recommended that a relationship between the welding parameters, material, tool profile and weld temperature control be investigated in detail to ease the application of FSW on all metals.

## CONCLUSION

Remarkable research has been conducted on friction stir welding on aluminium alloys and other unweldable materials by the fusion method. However, no specific conclusion has been reached on the optimum conditions required for a quality weld across the materials. A challenge has been noted due to varying base metal characteristics which require unique parameter combinations to over particular outcomes in the weld. Friction stir welding of steels and titanium alloys has not reached commercial application levels due to the numerous challenges experienced in the process. However, magnesium alloys, copper alloys and aluminium alloys have reached a commercial level in the application of friction stir welding even as more research is needed to relate welding parameters to material composition, thickness, orientation and preparation in terms of FSW joint microstructural and mechanical properties.

### REFERENCES


[1] J. Alonso-Santos, M. G. Téllez-Arias, E. Bedolla, and J. Lemus-Ruiz, "Microstructural behavior during bonding of alumina to niobium by liquid state diffusion," Mater. Sci. Forum, vol. 755, no. 2013, pp. 171–177, 2013, doi: 10.4028/www.scientific.net/MSF.755.171.

[2] S. Patnaik, S. Chattopadhyaya, and S. Shankar, "Friction Stir Welding and its Applications: An Overview," AIP Conf. Proc., vol. 2681, no. April 2018, 2022, doi: 10.1063/5.0116234.

[3] F. Zhi-hong, H. Di-qiu, and W. Hong, "Friction Stir Welding of Aluminum Alloys 1 Introduction Microstructure of FSW Influential Factors of Weld Quality," J. Wuhan Univ. Technol. Sci. Ed., vol. 19, no. 1, pp. 61–64, 2004.

[4] E. A. Metzbower, "Laser Beam Welding of Aluminum Alloy 5456," Am. Weld. Soc. J., vol. 51–9245, 1982.

[5] N. Kashaev, V. Ventzke, and G. Çam, "Prospects of laser beam welding and friction stir welding processes for aluminum airframe structural applications," J. Manuf. Process., vol. 36, no. October, pp. 571–600, 2018, doi: 10.1016/j.jmapro.2018.10.005.

[6] X. R. B. N. and M. E. Ivan Bunaziv, Odd M. Akselsen, "Laser Beam and Laser Arc Hybrid Welding of Aluminium alloys," MDPI, vol. 11, no. 1150, p. NA-NA, 2021, doi: 10.1002/9783527610433.chb206006.

[7] M. M. Abd Elnabi, A. El Mokadem, and T. Osman, "Optimization of process parameters for friction stir welding of dissimilar aluminum alloys using different Taguchi arrays," Int. J. Adv. Manuf. Technol., vol. 121, no. 5–6, pp. 3935–3964, 2022, doi: 10.1007/s00170-022-09531-3.

[8] R. Rai, A. De, H. K. D. H. Bhadeshia, and T. DebRoy, "Review: Friction stir welding tools," Sci. Technol. Weld. Join., vol. 16, no. 4, pp. 325–342, 2011, doi: 10.1179/1362171811Y.0000000023.

[9] A. Heidarzadeh et al., "Friction stir welding/processing of metals and alloys: A comprehensive review on microstructural evolution," Prog. Mater. Sci., vol. 117, no. September 2020, p. 100752, 2020, doi: 10.1016/j.pmatsci.2020.100752.

[10] G. Ipekoğlu and G. Çam, "Formation of weld defects in cold metal transfer arc welded 7075-T6 plates and its effect on joint performance," IOP Conf. Ser. Mater. Sci. Eng., vol. 629, no. 1, 2019, doi: 10.1088/1757-899X/629/1/012007.

[11] G. Çam, "Prospects of producing aluminum parts by wire arc additive manufacturing (WAAM)," Mater. Today Proc., vol. 62, no. February, pp. 77–85, 2022, doi: 10.1016/j.matpr.2022.02.137.

[12] P. Jayaseelan, T. V Christy, and S. Gowtham, "2 P. Jayaseelan , T. V. Christy and S. Gowtham," in Friction Stir Welding; Principles and Applications, 1st ed., Tamil Nadu: Nova Science Publishers, 2023, pp. 2–9.

[13] L. Qu, N. Ma, X. Xiao, K. Zhang, and H. Li, "Microstructure and Properties of Nonlinear Lap Joint of 6061 Aluminum Alloy by Friction Stir Welding," Metals (Basel)., vol. 13, no. 8, 2023, doi: 10.3390/met13081494.

[14] L. Ceschini, I. Boromei, C. Gambaro, G. Minak, A. Morri, and F. Tarterini, "Friction stir welding of aluminium based composites reinforced with Al 2O3 particles," Mater. Sci. Forum, vol. 638–642, pp. 87–92, 2010, doi: 10.4028/www.scientific.net/MSF.638-642.87.

[15] M. M. Z. Ahmed, M. M. El-Sayed Seleman, D. Fydrych, and G. ÇAM, "Review on friction stir welding of dissimilar magnesium and aluminum alloys: Scientometric analysis and strategies for achieving high-quality joints," J. Magnes. Alloy., no. xxxx, 2023, doi: 10.1016/j.jma.2023.09.039.

[16] U. Abdul Khaliq et al., "A review on friction stir butt welding of aluminum with magnesium: A new insight on joining mechanisms by interfacial enhancement," J. Mater. Res. Technol., vol. 27, no. October, pp. 3757–3786, 2023, doi: 10.1016/j.jmrt.2023.10.158.

[17] M. M. Z. Ahmed, M. M. El-Sayed Seleman, D. Fydrych, and G. Çam, "Friction Stir Welding of Aluminum in the Aerospace Industry: The Current Progress and State-of-the-Art Review," Materials (Basel)., vol. 16, no. 8, 2023, doi: 10.3390/ma16082971.

[18] G. Çam, V. Javaheri, and A. Heidarzadeh, "Advances in FSW and FSSW of dissimilar Al-alloy plates," J. Adhes. Sci. Technol., vol. 37, no. 2, pp. 162–194, 2023, doi: 10.1080/01694243.2022.2028073.

[19] G. Çam and G. İpekoğlu, "Recent developments in joining of aluminum alloys," Int. J. Adv. Manuf. Technol., vol. 91, no. 5–8, pp. 1851–1866, 2017, doi: 10.1007/s00170-016-9861-0.

[20] G. Çam, "Friction stir welded structural materials: Beyond Al-alloys," Int. Mater. Rev., vol. 56, no. 1, pp. 1–48, 2011, doi: 10.1179/095066010X12777205875750.

[21] P. L. Threadgill, "Terminology in friction stir welding," Sci. Technol. Weld. Join., vol. 12, no. 4, pp. 357–360, 2007, doi: 10.1179/174329307X197629.

[22] D. Klobčar, L. Kosec, A. Pietras, and A. Smolej, "Friction-stir welding of aluminium alloy 5083," Mater. Tehnol., vol. 46, no. 5, pp. 483–488, 2012.

[23] M. Chiumenti, M. Cervera, C. Agelet de Saracibar, and N. Dialami, "Numerical modeling of friction stir welding processes," Comput. Methods Appl. Mech. Eng., vol. 254, pp. 353–369, 2013, doi: 10.1016/j.cma.2012.09.013.

[24] X. Meng, Y. Huang, J. Cao, J. Shen, and J. F. dos Santos, "Recent progress on control strategies for inherent issues in friction stir welding," Prog. Mater. Sci., vol. 115, no. April 2020, p. 100706, 2021, doi: 10.1016/j.pmatsci.2020.100706.

[25] H. Li, J. Gao, Q. Li, and F. S. W. Weld, "Fatigue of Friction Stir Welded Aluminum Alloy Joints : A Review," Appl. Sci., vol. 8, no. 2626, pp. 1–9, 2018, doi: 10.3390/app8122626.

[26] A. Mehri, A. Abdollah-zadeh, N. Habibi, M. Hajian, and J. T. Wang, "The Effects of Rotational Speed on Microstructure and Mechanical Properties of Friction Stir-Welded 7075-T6 Thin Sheet," J. Mater. Eng. Perform., vol. 29, no. 4, pp. 2316–2323, 2020, doi: 10.1007/s11665-020-04733-w.

[27] M. Guerra, C. Schmidt, J. C. Mcclure, L. E. Murr, and A. C. Nunes, "Flow patterns during friction stir welding," Elsevier Sci. Ltd, vol. 49, pp. 95–101, 2003, doi: 10.1016/S1044-5803(02)00362-5.

[28] W. M. U. Thomas, E. D. Nicholas, A. Hall, and C. Cb, "Friction stir welding for the transportation industries," Elsevier Sci. Ltd, vol. 18, no. 4/6, pp. 269–273, 1998.

[29] S. Kumar, C. S. Wu, G. K. Padhy, and W. Ding, "Application of ultrasonic vibrations in welding and metal processing : A status review," Elsevier Sci. Ltd, vol. 26, pp. 295–322, 2017, doi: 10.1016/j.jmapro.2017.02.027.

[30] J. L. Z. Ju, Y. Shuyuan1, L. Yongzhi1, and Z. Heng1, "Design of a Novel Integrated Ultrasonic Tool Holder for Friction Stir Welding,"

Res. gate, vol. 8, no. 6, pp. 56–63, 2022, doi: https://doi.org/10.21203/rs.3.rs-1250127/v1.
[31] S. K. Saxena, C. S. Wu, and G. K. Padhy, "WSE & CAWE 2017," in Ultrasonic Vibrations in Friction Stir Welding: State of the art, 2017, no. October.
[32] D. B. Darmadi, F. N. Abdillah, and R. Raharjo, "Controlling the pressure force to obtain a better quality of aluminum 6061 friction stir welded joint," Eastern-European J. Enterp. Technol., vol. 3, no. 1–99, pp. 6–10, 2019, doi: 10.15587/1729-4061.2019.159286.
[33] Z. Ge, S. Gao, S. Ji, and D. Yan, "Effect of pin length and welding speed on lap joint quality of friction stir welded dissimilar aluminum alloys," Int. J. Adv. Manuf. Technol., vol. 98, no. 5–8, pp. 1461–1469, 2018, doi: 10.1007/s00170-018-2329-7.
[34] K. J. Quintana and J. L. Silveira, "Mechanistic models for the forces in FSW of aluminum alloy 5052-H34," Int. J. Adv. Manuf. Technol., vol. 96, no. 9–12, pp. 3993–4008, 2018, doi: 10.1007/s00170-018-1859-3.
[35] I. Kalemba-Rec, M. Kopyściański, D. Miara, and K. Krasnowski, "Effect of process parameters on mechanical properties of friction stir welded dissimilar 7075-T651 and 5083-H111 aluminum alloys," Int. J. Adv. Manuf. Technol., vol. 97, no. 5–8, pp. 2767–2779, 2018, doi: 10.1007/s00170-018-2147-y.
[36] V. Pratap, S. Kumar, A. Ranjan, and B. Kuriachen, "Recent research progress in solid state friction-stir welding of aluminium – magnesium alloys : a critical review," J. Mater. Res. Technol., vol. 9, no. 3, pp. 6217–6256, 2020, doi: 10.1016/j.jmrt.2020.01.008.
[37] R. Nandan, T. DebRoy, and H. K. D. H. Bhadeshia, "Recent advances in friction-stir welding - Process, weldment structure and properties," Prog. Mater. Sci., vol. 53, no. 6, pp. 980–1023, 2008, doi: 10.1016/j.pmatsci.2008.05.001.
[38] P. L. Threadgilll, A. J. Leonard, H. R. Shercliff, and P. J. Withers, "Friction stir welding of aluminium alloys," Int. Mater. Rev., vol. 54, no. 2, pp. 49–93, 2009, doi: 10.1179/174328009X411136.
[39] R. S. Mishra and Z. Y. Ma, "Friction stir welding and processing," Mater. Sci. Eng. R Reports, vol. 50, no. 1–2, pp. 1–78, 2005, doi: 10.1016/j.mser.2005.07.001.
[40] G. Çam, G. Ipekoglu, T. Küçükömeroglu, and S. M. Aktarer, "Applicability of friction stir welding to steels," J. Achiev. Mater. Manuf. Eng., vol. 80, no. 2, pp. 65–85, 2017, doi: 10.5604/01.3001.0010.2027.
[41] T. Küçükömeroğlu, S. M. Aktarer, and G. Çam, "Investigation of mechanical and microstructural properties of friction stir welded dual phase (DP) steel," IOP Conf. Ser. Mater. Sci. Eng., vol. 629, no. 1, 2019, doi: 10.1088/1757-899X/629/1/012010.
[42] G. İpekoğlu, Tevfik Küçükömeroğl, Semih M Aktarer, D Murat Sekban, and GürelÇam, "Investigation of microstructure and mechanical properties of friction stir Investigation of microstructure and mechanical properties of friction stir welded dissimilar St37 / St52 joints," Mater. Res. Express, vol. 6, no. January, pp. 1–8, 2019.
[43] T. Küçükömeroğlu, S. M. Aktarer, G. İpekoğlu, and G. Cam, "Mechanical properties of friction stir welded St 37 and St 44 steel joints," Mater. Test., vol. 60, no. 12, pp. 1163–1170, 2018, doi: 10.3139/120.111266.
[44] T. Küçükömeroğlu, S. M. Aktarer, G. İpekoğlu, and G. Çam, "Microstructure and mechanical properties of friction-stir welded St52 steel joints," Int. J. Miner. Metall. Mater., vol. 25, no. 12, pp. 1457–1464, 2018, doi: 10.1007/s12613-018-1700-x.
[45] D. G. Mohan and C. Wu, "A Review on Friction Stir Welding of Steels," Chinese J. Mech. Eng., vol. 24, no. 137, pp. 1–17, 2021, doi: 10.1186/s10033-021-00655-3.
[46] P. Kah, R. Rajan, J. Martikainen, and R. Suoranta, "Investigation of weld defects in friction-stir welding and fusion welding of aluminium alloys," Int. J. Mech. Mater. Eng., vol. 10, no. 1, 2015, doi: 10.1186/s40712-015-0053-8.
[47] M. Khedr, A. Hamada, A. Järvenpää, S. Elkatatny, and W. Abd-Elaziem, "Review on the Solid-State Welding of Steels: Diffusion Bonding and Friction Stir Welding Processes," Metals (Basel)., vol. 13, no. 1, pp. 1–30, 2023, doi: 10.3390/met13010054.
[48] F. C. Liu, Y. Hovanski, M. P. Miles, C. D. Sorensen, and T. W. Nelson, "A review of friction stir welding of steels: Tool, material flow, microstructure, and properties," J. Mater. Sci. Technol., vol. 34, no. 1, pp. 39–57, 2018, doi: 10.1016/j.jmst.2017.10.024.
[49] K. J. Singh, "Multi-objective optimization of high carbon steel ( EN-31 ) and low carbon steel ( SAE-1020 ) using Grey Taguchi method in rotary friction stir welding," Emerald Insight, vol. 9, no. 4, pp. 385–400, 2019, doi: 10.1108/GS-10-2018-0047.
[50] K. Chiteka, "Friction Stir Welding of steels: AReview Paper," IOSR J. Mech. Civ. Eng., vol. 9, no. 3, pp. 16–20, 2013, doi: 10.9790/1684-0931620.
[51] H. Fujii, L. Cui, N. Tsuji, M. Maeda, K. Nakata, and K. Nogi, "Friction stir welding of carbon steels," Elsevier, vol. 429, no. A, pp. 50–57, 2006, doi: 10.1016/j.msea.2006.04.118.
[52] K. Chiteka, "Friction Stir Welding of steels : AReview Paper," IOSR J. Mech. Civ. Eng., vol. 9, no. 3, pp. 16–20, 2013, [Online]. Available: www.iosrjournals.org.
[53] K. M. Venkatesh, M. Arivarsu, M. Manikandan, and N. Arivazhagan, "Review on friction stir welding of steels," Mater. Today Proc., vol. 5, no. 5, pp. 13227–13235, 2018, doi: 10.1016/j.matpr.2018.02.313.
[54] A. Bhatia and R. Wattal, "Friction stir welding of carbon steel: Effect on microstructure and tensile strength," Mater. Today Proc., vol. 26, no. xxxx, pp. 1803–1808, 2019, doi: 10.1016/j.matpr.2020.02.378.
[55] L. Cui, H. Fujii, and K. Nogi, "Friction stir welding of a high carbon steel," ELSEVIER, vol. 56, pp. 637–640, 2007, doi: 10.1016/j.scriptamat.2006.12.004.
[56] Rajesh, T. Rajasekaran, and T. Rajasekaran, "Literature review on friction stir welding of magnesium alloys," IOP Conf. Ser. Mater. Sci. Eng., vol. 912, no. 3, 2020, doi: 10.1088/1757-899X/912/3/032053.
[57] K. Singh, G. Singh, and H. Singh, "Review on friction stir welding of magnesium alloys," J. Magnes. Alloy., vol. 6, no. 4, pp. 399–416, 2018, doi: 10.1016/j.jma.2018.06.001.
[58] M. L. S. Naiyi Li, Tsung-YU, Ronald P. Cooper, Dan Q. Houston, Zhili Feng, "Friction Stir Welding of Magnesium AM60 Alloys," Essent. Readings Magnes. Technol., vol. 9781118858, pp. 487–492, 2014, doi: 10.1002/9781118859803.ch79.
[59] U. M A and E. R. D. J, "Friction Stir Welding of Magnesium Alloys - A Review," Adv. Mater. Sci. Eng. An Int. J., vol. 2, no. 4, pp. 07–18, 2015, doi: 10.5121/msej.2015.2402.
[60] A. Gontarz, K. Drozdowski, A. Dziubinska, and G. Winiarski, "A study of a new screw press forging process for producing aircraft drop forgings made of magnesium alloy AZ61A," Aircr. Eng. Aerosp. Technol., vol. 90, no. 3, pp. 559–565, 2018, doi: 10.1108/AEAT-11-2016-0238.
[61] N. K. Kadigithala and C. Vanitha, "Effects of welding speeds on the microstructural and mechanical properties of AZ91D Mg alloy by friction stir welding," Int. J. Struct. Integr., vol. 11, no. 6, pp. 769–782, 2020, doi: 10.1108/IJSI-12-2019-0131.
[62] S. Kulkarni, D. J. Edwards, E. A. Parn, C. Chapman, C. O. Aigbavboa, and R. Cornish, "Evaluation of vehicle lightweighting to reduce greenhouse gas emissions with focus on magnesium substitution," J. Eng. Des. Technol., vol. 16, no. 6, pp. 869–888, 2018, doi: 10.1108/JEDT-03-2018-0042.
[63] A. Singh and S. P. Harimkar, "Laser surface engineering of magnesium alloys: A review," Jom, vol. 64, no. 6, pp. 716–733, 2012, doi: 10.1007/s11837-012-0340-2.
[64] T. Küçükömeroğlu, E. Şentürk, L. Kara, G. İpekoğlu, and G. Çam, "Microstructural and Mechanical Properties of Friction Stir Welded Nickel-Aluminum Bronze (NAB) Alloy," J. Mater. Eng. Perform., vol. 25, no. 1, pp. 320–326, 2016, doi: 10.1007/s11665-015-1838-x.
[65] G. Çam, H. T. Serindağ, A. Çakan, S. Mistikoglu, and H. Yavuz, "The effect of weld parameters on friction stir welding of brass plates," Materwiss. Werksttech, vol. 39, no. 6, pp. 394–399, 2008, doi: 10.1002/mawe.200800314.
[66] K. Savolainen, J. Mononen, T. Saukkonen, H. Hänninen, and J. Koivula, "Friction stir weldability of copper alloys," Tribologia, vol. 24, no. 2, pp. 15–33, 2005.

[67] M. Miličić, P. Gladović, R. Bojanić, T. Savković, and N. Stojić, “Friction stir welding (FSW) process of copper alloys,” Metalurgija, vol. 55, no. 1, pp. 107–110, 2016.

[68] J. Michel, “Introduction to Copper and Copper Alloys CDA Mission,” no. May, 2013.

[69] K. Jha et al., “Heat Transfer and Materials Flow Modeling of FSW for CuCrZr Alloy Using Experimentally Determined Thermo-Physical Properties,” Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 52, no. 2, pp. 680–690, 2021, doi: 10.1007/s11661-020-06107-2.

[70] S. Shankar and S. Chattopadhyaya, “Friction stir welding of commercially pure copper and 1050 aluminum alloys,” Mater. Today Proc., vol. 25, no. xxxx, pp. 664–667, 2019, doi: 10.1016/j.matpr.2019.07.719.

[71] L. A. I. H. Z. Hang, F , c i a. New York: NOVA, 2023.

[72] G. Danail, F. Nikolay, and D. Stoyan, “Classification, properties and application of titanium and its alloys,” Proc. Univ. Ruse, vol. 55, no. 2, pp. 27–32, 2016, [Online]. Available: http://conf.uni-ruse.bg/bg/docs/cp16/2/2-5.pdf.

[73] A. Lauro, “Friction stir welding of titanium alloys,” Weld. Int., vol. 26, no. 1, pp. 8–21, 2012, doi: 10.1080/09507116.2011.581351.

[74] H. Liu, L. Zhou, Y. Huang, and Q. Liu, “Study of the key issues of friction stir welding of titanium alloy,” Mater. Sci. Forum, vol. 638–642, no. May 2015, pp. 1185–1190, 2010, doi: 10.4028/www.scientific.net/MSF.638-642.1185.

[75] A. V. Chumaevskii, A. I. Amirov, E. N. Moskvichev, A. N. Ivanov, and E. A. Kolubaev, “Structure and Properties of a Permanent Joint of Ti-6Al-4V Titanium Alloy Formed by Friction Stir Welding,” Russ. Phys. J., vol. 65, no. 5, pp. 765–770, 2022, doi: 10.1007/s11182-022-02695-1.

[76] A. Amirov et al., “Features of Permanent Joints of Titanium (α+β)-Alloys Obtained by Friction Stir Welding Using a Nickel Superalloy Tool,” Metals (Basel), vol. 13, no. 2, 2023, doi: 10.3390/met13020222.

[77] K. Gangwar, R. Mamidala, and D. G. Sanders, “Friction stir welding of near α and α+β titanium alloys: Metallurgical and mechanical characterization,” Metals (Basel), vol. 7, no. 12, pp. 1–24, 2017, doi: 10.3390/met7120565.

[78] K S. Smith, and H. L. O. Huyck, “An Overview of the Abundance, Relative Mobility, Bioavailability, and Human Toxicity of Metals,” Soc. Econ. Geol., vol. 6A, pp. 29–70, 1999, doi: 10.5382/rev.06.02.

[79] Davis J. R., “Aluminium and Aluminium alloys,” ASM Int., vol. 42, no. 11, pp. 351–416, 2001, doi: 10.1361/autb2001p351.

[80] E. Georgantzia, M. Gkantou, and G. S. Kamaris, “Aluminium alloys as structural material: A review of research,” Eng. Struct., vol. 227, no. October, 2021, doi: 10.1016/j.engstruct.2020.111372.

[81] P. H. Shah and V. J. Badheka, Friction stir welding of aluminium alloys: An overview of experimental findings – process, variables, development and applications, vol. 233, no. 6. 2019.

[82] A. P. Singh, Y. R. Gautam, M. K. Verma, and R. Niranjan, “Laser welding challenges of Aluminum alloys : A review,” Int. J. Res. Anal. Rev., vol. 8, no. 2, 2021.

[83] Y. Dai, L. Yan, and J. Hao, “Review on Micro-Alloying and Preparation Method of 7xxx Series Aluminum Alloys : Progresses and Prospects,” MDPI, vol. 15, no. 1216, pp. 1–26, 2022, doi: . https://doi.org/10.3390/ma15031216.

[84] M. S. Dahiya, V. Kumar, and S. Verma, “A critical review on friction stir welding of dissimilar aluminium alloys,” Lect. Notes Mech. Eng., pp. 707–719, 2019, doi: 10.1007/978-981-13-6412-9_66.

[85] Y. Ni, L. Fu, Z. Shen, and X. C. Liu, “Role of tool design on thermal cycling and mechanical properties of a high-speed micro friction stir welded 7075-T6 aluminum alloy,” J. Manuf. Process., vol. 48, no. May, pp. 145–153, 2019, doi: 10.1016/j.jmapro.2019.10.025.

[86] A. Global, “Alcoa Global Cold Finished Products ALLOY 6061 Understanding Cold Finished Aluminum Alloys,” Chem. Anal., vol. 6, pp. 1–2.

[87] G. İpekoğlu and G. Çam, “Effects of initial temper condition and postweld heat treatment on the properties of dissimilar friction-stir-welded joints between AA7075 and AA6061 aluminum alloys,” Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 45, no. 7, pp. 3074–3087, 2014, doi: 10.1007/s11661-014-2248-7.

[88] G. Çam, G. Ipekoğlu, and H. Tarık Serindağ, “Effects of use of higher strength interlayer and external cooling on properties of friction stir welded AA6061-T6 joints,” Sci. Technol. Weld. Join., vol. 19, no. 8, pp. 715–720, 2014, doi: 10.1179/1362171814Y.0000000247.

[89] G. Ipekoglu, S. Erim, B. G. Kiral, and G. Çam, “Investigation into the effect of temper condition on friction stir weldability of AA6061 Al-alloy plates,” Kov. Mater., vol. 51, no. 3, pp. 155–163, 2013, doi: 10.4149/km_2013_3_155.

[90] G. Çam, S. Güçlüer, A. Çakan, and H. T. Serindag, “Mechanical properties of friction stir butt-welded Al-5086 H32 plate,” Materwiss. Werksttech., vol. 40, no. 8, pp. 638–642, 2009, doi: 10.1002/mawe.200800455.

[91] N. F. M. Selamat, A. H. Baghdadi, Z. Sajuri, and A. H. Kokabi, “Friction stir welding of similar and dissimilar aluminium alloys for automotive applications,” Int. J. Automot. Mech. Eng., vol. 13, no. 2, pp. 3401–3412, 2016, doi: 10.15282/ijame.13.2.2016.9.0281.

[92] E. W. i g Manfred Liebrucks, Manfred Rumberger, “Aluminium and its alloys Alumina raw materials,” BERLIN, 1978. [Online]. Available: https://aei.pitt.edu/51551/1/B0447.pdf.

[93] A. Mamgain, A. Pratap Singh, and V. Singh, “Welding Investigation on AA6063-T6 Aluminium alloy during Friction Stir Welding process,” J. Kejuruter., vol. 35, no. 2, pp. 411–419, 2023, doi: 10.17576/jkukm-2023-35(2)-12.

[94] S. Kailainathan, S. K. Sundaram, and K. Nijanthan, “Influence of Friction Stir Welding Parameter on Mechanical Properties in Dissimilar (AA6063-AA8011) Aluminium Alloys,” Int. J. Innov. Res. Sci. Eng. Technol., vol. 03, no. 08, pp. 15691–15695, 2014, doi: 10.15680/ijirset.2014.0308083.

[95] M. R.Ananthapadmanaban, S. Sathishkumar, R. Sarathhariharan, T. Ruban, and P. Nikilan, “Friction stir welding of aluminium alloys aa5052 and aa6082 using vertical milling machine 1,” Int. J. Eng. Sci. Math., vol. 7, no. April, pp. 40–51, 2018.

[96] M. Shailesh Kumar Pandey, Pardeep Gahlot, Vikas Rohilla, “A Review on Friction Stir Welding of Aluminium alloy 7075,” Int. J. Recent Technol. Eng., vol. 6, no. 2277–3878, pp. 1–4, 2017, doi: 10.1186/s10033-021-00655-3.

[97] D. Muruganandam, K. S. Sreenivasan, and S. R. Kumar, “Study of Process Parameters in Friction Stir,” in Industrial Engineering and Operations Management, 2011, pp. 22–27.

[98] D. D. Dhancholia, A. Sharma, and C. Vyas, “Optimisation of Friction Stir Welding Parameters for AA 6061 and AA 7039 Aluminium Alloys by Response Surface Methodology ( RSM ),” Int. J. Adv. Mech. Eng., vol. 4, no. 5, pp. 565–571, 2014.

[99] B. Prashanth, K. Shravan Kumar, and D. Prakash, “Tensile Strength and Hardness Test on Friction Stir Welded Aluminium 6061-T6 and 5083-H111-O Alloys,” vol. 2, no. 1, pp. 88–93, 2017, [Online]. Available: www.ijsdr.org88.

[100] A. Singh, V. Kumar, and N. K. Grover, “A study of microstructure and mechanical properties of friction stir welding aluminium alloy AA6082 with Zn interlayer,” Mater. Res. Express, vol. 6, no. 11, pp. 0–10, 2019, doi: 10.1088/2053-1591/ab4b1f.

[101] S. P. M. Krishna, “Experimental Investigation of Friction Stir Welding of Aluminium Alloys Using Response Surface Methodology,” Sch. J. Eng. Technol., vol. 4, no. 1, pp. 6–14, 2016, [Online]. Available: www.saspublisher.com.

[102] M. J. Starink, A. Deschamps, and S. C. Wang, “The strength of friction stir welded and friction stir processed aluminium alloys,” Scr. Mater., vol. 58, no. 5, pp. 377–382, 2008, doi: 10.1016/j.scriptamat.2007.09.061.

[103] S. Verma and J. P. Misra, “Experimental investigation on friction stir welding of dissimilar aluminium alloys,” Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng., vol. 235, no. 5, pp. 1545–1554, 2021, doi: 10.1177/09544089211008694.

[104] R. Cook, T. Handboy, S. L. Fox, and W. Arbegast, “Friction stir welding of dissimilar aluminum alloys,” Frict. Stir Weld. Process. III - Proc. a Symp. Spons. by Shap. Form. Comm. Miner. Met. Mater. Soc. TMS, pp. 35–42, 2005, doi: 10.4236/wjet.2018.62025.

[105] A. Mehri, A. Abdollah-zadeh, N. Habibi, M. Hajian, and J. T. Wang, "The Effects of Rotational Speed on Microstructure and Mechanical Properties of Friction Stir-Welded 7075-T6 Thin Sheet," J. Mater. Eng. Perform., vol. 29, no. 4, pp. 2316–2323, 2020, doi: 10.1007/s11665-020-04733-w.

[106] G. Sun, Y. Chen, S. Chen, and D. Shang, "Fatigue modeling and life prediction for friction stir welded joint based on microstructure and mechanical characterization," Int. J. Fatigue, vol. 98, pp. 131–141, 2017, doi: 10.1016/j.ijfatigue.2017.01.025.

[107] C. He, K. Kitamura, K. Yang, Y. J. Liu, Q. Y. Wang, and Q. Chen, "Very High Cycle Fatigue Crack Initiation Mechanism in Nugget Zone of AA 7075 Friction Stir Welded Joint," Adv. Mater. Sci. Eng., vol. 2017, 2017, doi: 10.1155/2017/7189369.

[108] J. Zhang, P. Upadhyay, Y. Hovanski, and D. P. Field, "High-Speed Friction Stir Welding of AA7075-T6 Sheet: Microstructure, Mechanical Properties, Micro-texture, and Thermal History," Metall. Mater. Trans. A Phys. Metall. Mater. Sci., vol. 49, no. 1, pp. 210–222, 2018, doi: 10.1007/s11661-017-4411-4.