REVIEW OF JOINING VARIOUS MATERIALS BY FSW PROCESS AND APPLICATIONS

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ABSTRACT

Welding is necessary in industries like light and heavy-duty manufacturing, construction, automotive, aerospace, maintenance, repair works, etc. Friction stir welding (FSW) is a recently created welding technique that is employed with a non-consumable pin in all of the above-mentioned production areas. The cross-sectional size and shapes of the pin are also showing a great impact on the properties of the joints. This review article begins with the history of welding methods and it covers the topics of welding evolution, principle, joining of similar and dissimilar materials using FSW, applications and defects, as well as the various process factors in managing the qualities of the welded joint. The necessity of FSW is inevitable as it shows a good response of the mechanical properties with solid state temperature. It is a versatile welding process that has the capacity to join numerous materials, beginning with aluminium alloys and moving on to magnesium alloys, steel, composites, polymers, and dissimilar metals combinations.

KEYWORDS: FSW of composites, capabilities of FSW, FSW defects, dissimilar FSW, welding.

1. INTRODUCTION

Around 3000 years ago, Egyptians learned to weld iron pieces together and various things of iron were made and linked by hammering action. In the mid-nineteenth century, an Englishman named Sir Humphrey Davies discovered acetylene and used a battery system to create an arc between two carbon electrodes [1]. Arc welding with a metal and carbon arc was created in the late 1800s and early 1900s, replacing gas cutting and welding. C. L. Coffin submitted the first US patent for an arc welding technology in 1892. Other types of welding procedures developed in the meantime included seam welding, flash butt welding, resistance welding, seam welding, and resistance welding. Goldschmidt devised a welding procedure called thermit welding in 1903, which is mostly used to link railway lines [2]. At the onset of World War I, the demand for metallic material manufacturing had skyrocketed, and welding was the finest service available. When World War I came to a close in 1919, 20 members formed the American Welding Society (AWS), a non-profit organisation with the goal of advancing welding and related techniques [3]. In 1920, General Electric Company created automated welding that employed bare electrodes and direct current to construct the back axle housing of a car. Several researchers worked on arc and fusion zone protection, leading to the creation of gas-shielded welding technology. The atomic hydrogen joining procedure, named so by Alexander and Langmuir, employed hydrogen as shielding gas and it was less common [4]. Stud welding was invented in the New York Navy Yard in 1930, and it drew the attention of the shipbuilding and construction industry. National Tube Company in McKeesport, Pennsylvania, created submerged arc welding (SMAW) at the same time. The approach is regarded as one of the most common and successful ways to join pipes. The welding technology was developed by Coffin in the 1890s, and it is known as gas tungsten arc welding (GTAW) or tungsten inert gas welding (TIG).

In the 1920s, Hobart investigated the use of helium as shielding gas. Meredith refined, patented, and renamed the technology Heliarc welding in 1941. The electron beam welding technique was developed in the late 1940s by the French Atomic Energy

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Commission and the Zeiss Company, which employed a focused beam in a vacuum atmosphere to join materials. R. Gage created plasma arc welding in the late 1950s, which is quite similar to Gas Tungsten Arc Welding (GTAW), and it quickly became a common method for cutting nonferrous metals [2]. In 1956, the Soviet Union invented friction welding, or inertia welding, in which frictional heat was supplied using high pressure and rotating speed. Friction welding has become a more prevalent welding process in the United Kingdom and the United States. The laser was created in the 1960s, and after many decades, its welding application became practical, proving to be a good welding technology for high-strength automated welding [5]. Table 1 lists the various welding procedures as well as their invention data.

Today, there are over 90 welding methods available, with new materials being developed on a regular basis for use in nuclear, marine, and aerospace applications [6]. All welding procedures may be divided into two categories: fusion welding and solid-state welding. Chemical bonding of the base materials occurs in the liquefied form in the fusion welding process, and filler materials such as filler wire roll or consumable electrodes can be utilised to assure the union. Fusion welding techniques such as Metal Inert Gas (MIG), Tungsten Inert Gas (TIG), Laser Beam Welding (LBW), and Electron Beam Welding (EBW) have several drawbacks due to the change from solid to liquid and then back to solid during joining. After welding, the material's structure resembles that of casting and results in a reduction in the weld metal's mechanical qualities such as ultimate tensile strength, fatigue strength, and ductility. Heat input is higher during fusion welding, resulting in a wider heat affected zone (HAZ) and a decrease in the mechanical characteristics of the welded joint [7]. Solid-state welding technologies were developed to address the aforementioned fusion welding issues.

2. FRICTION STIR WELDING

Friction Stir Welding (FSW) is a solid-state autogenous joining technique in which the term *friction* refers to the application of frictional heat necessary to soften the workpiece materials, and the term *stir* refers to the rotational movement of the material brought (by heating) to plastic deformation state. W.M.Thomas of The Welding Institute (TWI) in Cambridge, United Kingdom, created and patented the FSW technique [8]. The method was first used to combine low-strength materials such as aluminium alloys and magnesium alloys. Even on a vertical milling machine, the procedure is straightforward.

2.1. Principle of FSW

The procedure involves inserting a non-consumable spinning tool into the joint line and stirring it to construct the joint. The shoulder and pin (probe) are two crucial parts of the instrument. The tool's role is to heat and soften the base materials while extruding the workpiece materials from the tool's top to bottom and front to rear and then consolidate the softened material to produce the solid-state junction [9]. The tool shoulder is the area of the tool that comes into contact with the workpiece surface. The tool shoulder is the most significant element for heat generation, with rubbing action between the shoulder and the workpiece producing roughly 87% of the heat. Negative or positive scrolls can be carved into the tool shoulder to facilitate material flow. Positive scrolls are like protrusions on the shoulder surface, whereas negative scrolls are like depressions where the workpiece materials fill in the scrolls [10]. Figure 1 depicts the fundamental friction stir welding technique.

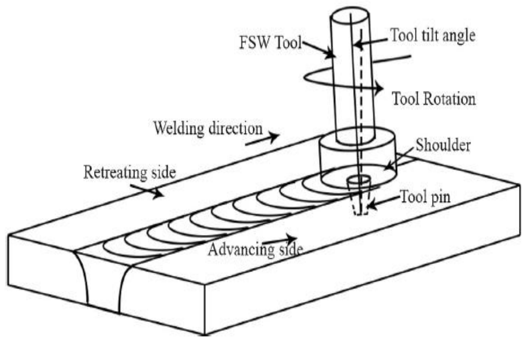


Fig. 1. The basic FSW process [11]

The tool pin, also known as a probe, is responsible for allowing plasticized material to move around in the joint line by agitating it. The diameter and length of the tool pin that regulates material churning are significant characteristics. The length of the pin has an impact on the penetration of the plasticized material, thus, it should be kept 0.2 to 0.3 mm shorter than the thickness of the workpiece [12]. By applying adequate axial plunge force after full diving, the shoulder can make suitable contact with the base material.

2.2. Parameters of FSW Process

Friction Stir Welding has a limited number of process parameters that are divided into machine and tool-related factors that govern the weld quality and various mechanical characteristics of the welded connection. Figure 2 depicts the different FSW parameters. Tool rotational speed, tool traverse speed, axial load or plunge force, and tool tilt angle are all machine-related metrics. Shoulder diameter, pin or probe length, the contour of the pin, and shoulder-to-pin ratio are some of the tool’s characteristics [13]. All of these variables may be easily managed, which in turn affects the welded joint's quality.

Table 1. Invention of different welding process [5]

Name of the Welding Process	Year	Inventor	Country
Electric Welding	1865	Henry Wilde	England
Electric Arc welding	1885	N.N.Benardos	Russia
Resistance welding	1886	Elihu Thomson	USA
Oxyacetylene welding	1903	Edmond Fouche and Charles Picard	France
Thermit Welding	1903	Hans Goldschemidt	Germany
Metal arc welding	1907	Oscar Kjellberg	Sweden
Electroslag joining	1940	R.K.Hopkins	USA
Gas Metal arc welding (Inert Gas)	1948	Air Reduction Company	USA
Submerged arc welding	1935	National Tube Company	USA
Gas metal arc welding (CO_2)	1953	Lyubavskii and Novoshilov	USSR
Friction welding	1956	Chudikov	USSR
Ultrasonic welding	1957	James Byron and his team	USA
Electron beam welding	1957	J.A.Stohr of French Atomic Energy Commission	France
Plasma Arc welding	1957	Robert Gage	USA
Explosive welding	1960	Dupont company	USA
Robotic Resistance spot welding	1964	Unimation Company of General Motors	USA
Laser cutting	1966	Peter Houldcroft	England
Laser Beam Welding	1970	Martin Adams	England
Magnetic Pulse Welding	1988	Tamaki and Kojima	Japan
Friction Stir Welding	1991	Wayne Thomas and his team	England

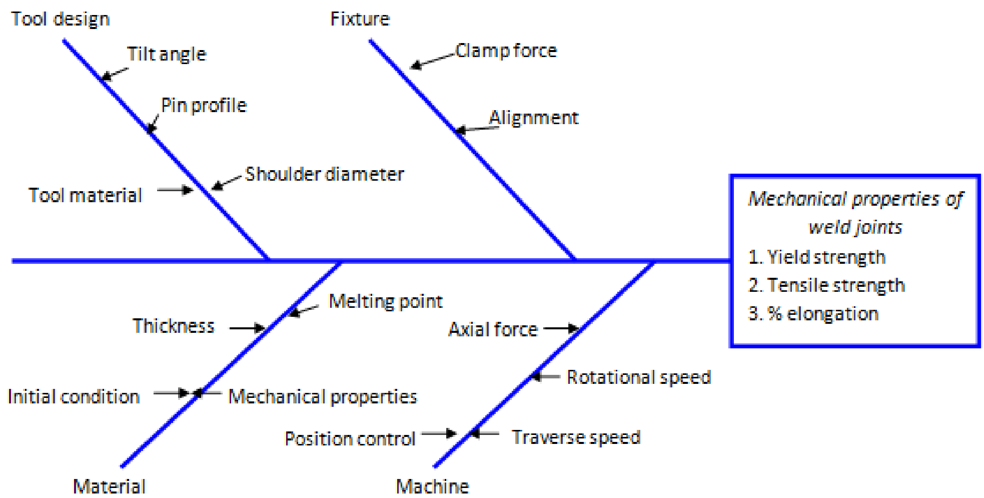


Fig. 2. Fishbone diagram containing various parameters of FSW process [13]

Machine-related process factors have an impact on certain output qualities. A few have a direct impact on weld quality, while others have an indirect impact on weld quality and mechanical properties. The torque of the tool is directly influenced by the tool's rotational speed, while the welding force and axial force are indirectly influenced by the tool's rotational speed. Plunge depth is affected by axial and welding forces in both direct and indirect ways. The tool's tilt angle is also important. When the tool is slanted towards the workpiece's trailing edge, some of the tool's leading edge does not make contact with the workpiece, reducing the creation of a flash. Due to decreased heat generation, this will also avoid excessive softening in the heat affected zone [14]. The diameter and shape of the tool shoulder (concave, convex, flat and scrolling), as well as the profile of the tool pin, have a significant impact on the weld quality. The tool pin profile may directly regulate the welding force, whereas the shoulder diameter can impact the axial force. The generation of the flash can be reduced by increasing the tool shoulder’s diameter to a certain extent.

The profile of the tool pin also has an impact on the stirred materials. Different researchers experimented with square, cylinder, taper, cylinder with threads, hexagonal, and many more pin profiles for various material combinations. The majority of the findings showed that a square tool pin shape has a superior influence on material stirring and, as a result, weld quality. It is recommended that the optimal ratio of shoulder diameter to pin diameter to be between 2.5 and 3 for good quality weld [15], [16]. Tool material, fixture material, and various ambient factors influence heat dissipation during the operation. Good heat-conductive materials can be used as fixture materials to connect titanium and other hard materials. The low-heat conductive material can be used to link aluminium and copper components to prevent unwanted heat loss during the process. Several academicians have conducted detailed reviews on the subject of FSW during the last two decades. The relevance of FSW in connecting aluminium alloys was discussed by Threadgill et al. [17]. R. S. Mishra and Z. Y. Ma [18] reviewed the literature on friction stir welding and friction stir processing in great detail. The numerous tools employed and their impact on various output responses to the FSW process were discussed by W. M. Thomas et al. [19] and Y. N. Zang et al. [20] Several researchers (D. Wang et al. [21], O. S. Salih et al. [22], and M. A. Fenoel [23]) evaluated the joining of aluminium metal matrix composites by friction stir welding and submitted their findings to the scientific community.

2.3. FSW of Aluminium Alloys

Aluminium-based alloys are widely utilised in the vehicle industry because of their low density, higher specific strength, improved corrosion resistance, higher thermal conductivity, inherent recyclability, and appealing look [24], [25]. P. L. Threadgill et al. [17] conducted a review of friction stir welding of aluminium alloys and came to the conclusion that the amount of heat generated and how well the materials are consolidated are the most important factors in weld quality. The procedure may be used to join any type of aluminium alloy, including 2XXX, 7XXX, and 8XXX, which would be difficult to combine with traditional fusion welding. The temperature attained for aluminium friction stir welding was about 500^0C, according to the study. The causes and corrective measures for flaws such as kissing bonds, flash, tunnel, and root faults are also discussed in the review article [26]. Figure 3 depicts the weldability of several aluminium alloys. Y. E. Ma et al. [27] attempted to combine AA2198–T8 aluminium sheets with a thickness of 2 mm. The ratio of rotation speed to transverse speed was used to examine the tensile strength, hardness, and microstructure in this study. The findings show that by raising the speed ratio, the size of the joint's stir zone increases, which further increases heat generation. Recrystallization resulted in the formation of fine equiaxed grains. The hardness results revealed that the hardness of the stir zone was low as compared to the base material. The maximum tensile strength of the material was roughly 70% greater than that of the basic material.

A few researchers performed comparable work on alternative materials such as AA7075 and AA2024, as well as different combinations [28–30]. C. Sharma et al. [31] were interested in investigating the influence of tool rotation speed and welding speed on the mechanical characteristics of AA7039 – T6 aluminium alloy. Various tests were performed, including root bend, tensile, hardness, and microscopic analyses. The joint efficiency of welded joints was estimated to have a directly proportional relationship with the spindle speed and an inverse relationship with the welding speed. The spindle speed had a greater effect on weld quality. Higher welding speeds and lower spindle speeds reduced the grain size.

Dehghani. K et al. [32] used a threaded tool pin to combine AA7075-O aluminium alloys with a consistent rotating and welding speed. The welded specimen had a 15% higher tensile strength than the base material, and the nugget zone had the highest hardness, with the base material having the lowest. Precipitates were fine at the weld nugget and coarse in the heat-damaged zone, according to microstructural analysis.

To investigate the strength and hardness of the welded junction, J. A. Al-Jarrah et al. [33] attempted to combine cast aluminium alloys. Five different spindle and transversal speeds were used in the studies. When the tool rotation speed and shoulder diameter were raised, the grain size was increased because of the high heat input. When the spindle speed increases to a particular level, the ultimate tensile strength increases to its maximum value, but when the speed further increases, the tensile strength decreases. The hardness of the stir zone was lower than that of the foundation material. L. N. Tufaro et al. [34] examined 3 mm thick AA5052 – H32 aluminium alloys to see how important heat is for the material to flow plastically. The impact of shoulder diameter on heat generation was investigated, and it was discovered that by raising the shoulder diameter, the size of the stir zone, the quantity of generated heat, and material flow increased. Hardness values increase when reducing the shoulder diameter at the stir zone.

Z. Yan et al. [35] evaluated the mechanical and metallurgical properties of connecting A7N01 aluminium alloy using FSW and MIG welding techniques. The grains generated by FSW were significantly smaller than those produced by MIG welding, and grain refining was seen in the stir zone. The joint created by FSW had an ultimate tensile strength of 73.2% of the base material, which was much lower than that of MIG welding. G. Singh et al. [36] joined AA6082 aluminium alloy through FSW and TIG and evaluated the weld properties, it resulted that friction stir welded joints have more strength and hardness than TIG welded joints. The fine grains were achieved through the FSW process.

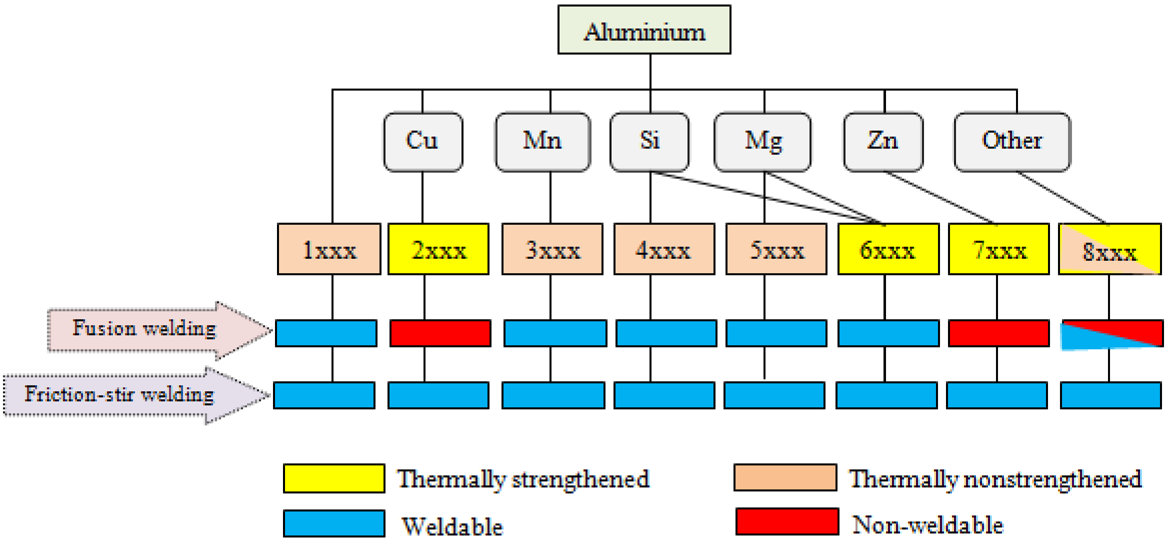


Fig. 3. Weldability of different aluminium alloys [25]

S. Tikader et al. [37] want to know how tool pin shape affects the quantity of heat input and the mechanical characteristics of AA1100 aluminium alloy. Two straight cylinders and two conical pin tools were used to prepare the joints. The findings revealed that joints made using conical pins had greater strength and hardness with less heat input. S. Bayazid et al. [38] investigated the influence of tool pin shape on defect generation while welding AA 7075 – T6 aluminium alloy. For this study, several tool pin profiles such as cylindrical, square, and triangular pins were chosen. The results of the experiments demonstrated that when utilising square tools, no faults were found. AA2014, aluminium MMC, and other basic materials combinations were used in similar experiments [39- 41]. In a study of the effect of tool rotation speed on intergranular and pitting corrosion behaviour of AA7075 aluminium alloy, M. Navaser et al. [42] discovered that as the speed rises, the size of the grains grows, intergranular corrosion reduces and pitting corrosion increases. P. V. Kumar et al. [43] investigated the influence of post-weld heat treatment on corrosion behaviour and discovered that post-weld heat treatment improves the welded samples' corrosion resistance.

The pitting and intergranular corrosion properties of AA 6061 aluminium alloy were investigated by F. Gharasi et al. [44]. The findings revealed that the base material's corrosion resistance is superior to that of other weld locations. Intergranular corrosion attack was more likely in the heat affected zone. The influence of tool pin geometry on pitting corrosion of FSW of AA2219 aluminium alloy was studied by C. V. Rao et al. [45]. According to the experimental test findings, the corrosion resistance at the stir zone was superior to the base material. The hexagonal profiled tools outperformed the other profile tools in terms of corrosion resistance. G. Durso et al. [46] looked at the impact of process factors on the mechanical characteristics and corrosion resistance of AA2024–T3 and AA7075–T6 aluminium alloy dissimilar joining. Experiments were carried out by altering the material on the retreating and advancing sides. It was discovered that in AA2024, pitting corrosion was evident in the stir zone. Corrosion attack exfoliation was seen on AA7075.

2.4. FSW of Magnesium Alloys

Magnesium and its alloys are exceptionally light metals with high specific strength, sound-dampening properties, improved castability and formability, superior electromagnetic interference shielding, and recyclability [47], [48]. A. R. Rose et al. [48] investigated the effect of axial downward force on the tensile and microstructural behaviour of 6 mm thick AZ61A magnesium alloy during friction stir welding. By increasing the axial force from 3 to 7 kN while keeping the other parameters constant, a total of five welded joints were created. The test findings revealed that a vertical force of 5 kN had a maximum and ultimate tensile strength of 224 MPa, indicating that the vertical downward force had a significant impact on the grain size of the weld nugget and material flow [49]. While connecting 3 mm thickness AZ31B magnesium alloys, P. Motalleb-Nejad et al. [50] attempted to study the impact of the tool pin shape on microstructural and mechanical parameters. Three distinct tool pin geometries were tested: screw threaded cylinder, straight cylinder, and taper cylinder with a 30° taper angle. The microstructure of the taper pin welds was the finest and had the best mechanical qualities.

To analyse the fatigue behaviour of the welded specimen, D. R. Ni et al. [51] produced welded joints of AZ91D-type magnesium alloys. The fatigue test revealed that the welded joints' fatigue life was similar to that of the parent material and that all specimens failed at the base material throughout the test. The nugget zone's microstructural investigation revealed a recrystallized and fine-grained structure. The ultimate tensile test resulted in a 245 MPa result with an elongation of 7.6 %. Fusheng Pan et al. [52] attempted to fuse Mg-5Al–3Sn magnesium alloys together and evaluated the microstructural and mechanical features of the welded joints, concluding that FSW may generate defect-free welds in magnesium alloys [52]. P. Sevvel and V. Jaivignesh [53] were interested in learning more about the impact of tool pin profile on the mechanical characteristics of AZ31B alloy and discovered that welds made with taper cylindrical pins had the best quality and mechanical attributes. B. Ratna Sunil et al. [54] used friction stir welding to link two magnesium alloys, AZ31 and AZ91, in order to investigate the influence of welding process parameters on fracture development.1400 rpm and 25 mm/min were two of the parameters that generated sound welds with fine grain development. Because of the grain refinement, the weld area's microhardness was increased.

2.5. FSW of Steel

Normal tool materials, such as high-speed steel and tool steels, were not suited for connecting hard materials such as steel and tungsten. In general, the hardness of the workpiece material to be connected influences the tool material selection. Polycrystalline cubic boron nitride (PCBN) and tungsten-based alloys have been discovered to be more appropriate materials for joining hard materials like steel. Initially, tungsten was employed as a tool material because of its higher heat strength. This was suitable to be used as a friction stir welding tool, but the high ductile to brittle transition temperature caused problems when plunging the tool. Later, 25% rhenium was added to increase wear resistance and fracture toughness. Molybdenum was employed as a tool metal, as well. [55]. Steel is generally friction stir welded at temperatures that correspond to the temperature of crystal structure change between BCC and FCC. For combining steel materials, process factors, such as tool rotating speed, which is principally responsible for heat input, and welding speed, which regulates the pace at which the heated weld metal cools, must be carefully selected [56]. By altering the tool rotation speed and welding speed, Karami et al. investigated the mechanical characteristics and microstructural changes that occur while connecting steel materials. The findings revealed that raising the welding speed while lowering the rotation speed resulted in insufficient heat input, tunnel defects and flaky surfaces.

For increased tool rotation speed and lower welding speed, a fine-grained microstructure was created. The results of the tensile tests revealed that there was a larger quantity of yield strength and less elongation [57]. Lakshminarayanan et al. attempted to combine 409 M ferritic stainless steel by using a 1000 rpm rotating speed and a 50mm/min welding speed. The microstructure and mechanical characteristics of the welded joints were examined and it was determined that they had adequate impact toughness and ductility [58]. Cho et al. studied the microstructural development of high-strength welded API X 100 grade line pipe steel with a 10 mm thickness. In an inert gas atmosphere, the tool was manufactured of PCBN with a shoulder diameter of 16 mm and a pin diameter of 4 mm. During the phase change, acicular-shaped bainitic ferrites were generated in most sections of the stir zone, according to the microstructural analysis. A fine-grained microstructure was found in the thermo-mechanically affected zone (TMAZ), and the hardness in the stir zone was substantially greater than in the other areas [59].

Ragunathan et al. investigated the impact of process factors on the microstructure and mechanical characteristics of naval grade High Strength Low Alloy (HSLA) steel. Due to grain refinement in the nugget zone and strain-induced deformation, the manufactured joints had a 13% increase in strength. The nugget zone had a hardness value of roughly 410 HV, which was greater than other areas of the weld metal. This was due to extreme plastic deformation in the nugget zone and the rapid cooling rate of the FSW process[60]. While welding 18Cr – 2 Mo ferritic stainless steel, Han et al. investigated the microstructural and mechanical parameters of the welded specimens. The examples were made with various welding speeds and a constant spindle speed. The fine-grained microstructure was preserved and resulted in a high level of hardness and impact toughness [61]. Sabooni et al. examined the outcomes of welding ultrafine-grained AISI 304 L by using the GTAW and FSW processes. According to mechanical characteristics, the welding efficiency of FSW samples was about 70%, which was more than 20% greater than the GTAW welding.. The microstructure of FSW and GTAW differed significantly, according to SEM examination. For the FSW, the minimum hardness was measured at the heat affected zone, while for the GTAW, the minimum value was taken at the weld centerline [62].

Mahdi Mahmoudinium et al. used a constant spindle speed and three variable welding speeds of 100, 150, and 200 mm/min to connect dual-phase advanced high-strength steel. At speeds of 100 and 150 mm/min, the trial findings revealed defect-free, high-quality welds. Because of the lower peak temperature and faster cooling rate, the greater welding speed created finer and tougher microstructure in the nugget zone. When the transverse speed is increased from 100 to 150 mm/min, the breadth of the softened zone shrinks [63]. Matsuhita and colleagues welded a variety of DP steel grades. The primary goal was to determine the range of welding conditions that resulted in excellent quality sound welds [64]. Friction stir welding of steel has advanced to the point where welds up to 30 metres long may be welded in a variety of engineering steel alloys, according to TWI. The generated welds had outstanding mechanical qualities and their fatigue strength and corrosion resistance were superior to those of fusion welding. Some steels, such as Oxide Dispersion Strengthened (ODS) steels, can be welded using the technique, which is currently considered unweldable using the fusion welding procedure. TWI revealed that the joint efficiency of several plates of steel, such as HSLA – 65, 304 L, and Duplex 2205, was greater than 100%. The joint efficiency of the welded specimen is normally a ratio of the ultimate tensile of the welded joint to ultimate tensile strength of the parent material [65].

2.6. FSW of Composite Materials

Composite materials, particularly metal matrix composites (MMC), are recognized as promising prospective materials in the aerospace and automotive sectors owing to their increased mechanical qualities [66]. The difficulty in linking composite materials with other composite materials or unreinforced materials is a challenge connected with their extensive usage in the industry [67]. Traditional fusion welding creates consequences such as coarse microstructure, ceramic particle disintegration, segregation, and the creation of brittle intermetallic compounds [68]. C.Devanathan et al. [69] used a TiAlN coated tool to assemble MMC. The impact of process variables on ultimate tensile strength was studied. ANOVA was used to examine the influence of process factors, and it was discovered that axial force was the most important process parameter, followed by welding speed and spindle speed. During the procedure, there was no visible tool wear due to the tool coating. K.Kalaiselvan et al. [70] connected 6 mm thick Boron carbide reinforced AA6061 plates. The researcher experimented with several tool pin profiles and found that the square pin tool provided a joint efficiency of 93.4 %, which was considerably superior to other tool pin profiles. The impact of process parameters was investigated by modifying four elements with five levels and concluding that tool rotational speed and tool material had a substantial impact on tensile characteristics [71].

S.J.Vijay et al. [72] studied the mechanical and metallurgical parameters of a welded junction made of 10% TiB_2 reinforced aluminium alloy utilising various tool pin shapes. The experimental findings demonstrated that the square tool pin profile had better mechanical qualities than the other profiles. The weldability of AA2124 augmented with 25% silicon carbide particles (SiC) was investigated by Yahya Bozkurt et al. [73]. The microhardness, tensile strength, surface roughness, and microstructure of the welded specimens were all evaluated. From HAZ to TMAZ, the hardness value was enhanced on both the advancing and retreating sides. During testing, the welded joint's highest efficiency was 73%, and a ductile mode of fracture occurred.

I. Dinaharan et al. [74] sought to determine the optimal parameters for achieving high tensile strength, wear resistance, and ductility. The process parameters were adjusted by using the general reduced gradient approach, and the improved process parameter was evaluated by welding the specimen. Using an ultra-hard tool, D. Wang et al. [75] welded AA2009 reinforced with 15% SiC particles. In the nugget zone, the SiC particles were distributed more evenly and homogeneously. The material was heat treated to a T4 state, and it failed in the nugget zone, while it had previously failed in the base material zone. Tracie Prater [76] investigated the suitability of the FSW technique for welding MMCs utilised in the aerospace industry, as well as the impact of tool wear during the joining process. The test findings on tool wear revealed that employing a tougher tool material rather than reinforced particles is a superior way to combat wear.

The mechanical and metallurgical characteristics of AlB_2-reinforced aluminium matrix composites were examined by P. Ponesakki Raja et al. [77]. Six experiments were undertaken in order to find the optimal process parameters. A value of 152.7 MPa was the greatest strength obtained. The base material's hardness and wear resistance were superior to that of the weld region due to the aggregation of reinforcement particles. Halil Ibrahim kurt et al. [78] studied the influence of process parameters on particle distribution, ultimate tensile strength, hardness, and joint efficiency using AA2124-reinforced 25 % SiC particles. The temperature was measured four times during the procedure, 15 mm distance from the centre of the weld, on each side of the weld. At the farthest location from the centre line, the greatest temperature achieved was 270^0C, and the maximum joint efficiency was about 73%.

2.7. FSW of Polymer Materials

Because polymers have various chain lengths and molecular weights, the FSW of polymer materials is not considered a true solid-state process. Materials with shorter chain may readily achieve their melting point during the joining process, but materials with longer chain cannot reach the needed temperature. According to Shayan Eslami et al. [79], the traditional friction stir welding tool may not be suited for welding polymer materials due to the limited heat conductivity, melting temperature, and hardness of the polymer materials. During friction stir welding, polymer materials respond differently than metallic ones. New tools must be created efficiently to provide high-quality sound welds. A. Mustafa Aydin et al. [80] were interested in investigating the effect of preheating during the friction stir welding of Ultra High Molecular Weight Polyethylene (UHMWPE).

Plastic materials can easily be stirred thanks to the impact of preheating, and the maximum joint efficiency of 89 % of the base material was reached. While welding 4 mm polypropylene composite plates reinforced with 20% carbon fibers, H. Ahmadi et al. [81] studied the influence of probe shape on tensile strength and appearance of the weld bead. The findings revealed that the tool shape has a significant impact on heat generation, material flow, and weld strength. The surface quality of the threaded probe was the best, with no flaws such as porosity or cavities. Reduced probe height was achieved by plunging more of the tool into the workpiece, which required a more axial process and resulted in an excessive flash in the weld bead. K. Pannerselvan et al. [82] used grooved square and triangular pins to attach 10 mm polypropylene plates with minimal linear applied force. The welding beam had minimal blow holes and the square pin tool generated excellent quality weld.

The influence of tool rotational speed, welding speed, and axial force on friction stir welding of Acrylonitrile Butadiene Styrene (ABS) was investigated by N. Mendes et al. [83]. With a greater tool rotating speed and an excellent weld look, the maximum strength was achieved. V.Jaiganesh et al. [84] performed high-density polypropylene (HDPP) welding with the purpose of optimising the process parameters for high-quality welds. Imad M.Hussain et al. [85] used friction stir welding on Nylon 66 to determine the ideal parameters for producing a junction with acceptable mechanical qualities but at a lower cost than base materials.

A.Paoletti et al. [86] made use of FSW to join polycarbonate sheets to investigate the influence of process parameters on generating high-quality welds. They discovered that plunge rate, rotating speed, and dwell duration all affect the mechanical qualities of the welded junction. Low heat conductivity of the polymer materials, deformation, and softening were all difficult to achieve with high transverse speed, and joining with a low welding speed allows enough time for the parent material to be stirred [87]. S.Hosein laghab et al. [88] investigated the creep qualities of the joint and the look of the weld while investigating the effect of friction stir welding on Polyethylene (PE) sheets. According to the findings, the creep resistance of the welded samples was equal to that of the base materials. A. Zafar et al. [89] employed pins with screw threads to link a 9 mm Nylon 6 sheet and discovered that low rotating speed can form the joints better, whereas high rotational speed with high tool tilt angle easily increases temperature, resulting in molten material overflow.

To investigate the influence of tool geometry on mechanical characteristics and microstructure, M. Razaee Hajideh et al. [90] welded two different polymer materials, such as polyethylene and polypropylene sheets. When compared to various tool pin profiles such as square, triangular, and cylinder, the tool with the cylindrical threaded pin provided higher mechanical qualities. When connecting nylon 6, N. Ethiraj et al. [91] investigated the effect of process factors on microstructural and mechanical qualities. Excessive flash was seen on both sides of the weld line, according to the testing data. The highest tensile strength was 26% of the parent material, while the yield strength was 18% of the base material. The value obtained was significantly lower than that of the original material [91]. V. K. Parikh et al. [92] reviewed the publications on the FSW of MMCs. The researcher went over all of the articles on multi-objective optimization of process parameters and concluded that merging MMC with FSW will increase the usage of composites in the manufacturing industry. Tool wear at the pin part was substantial, and the tool wear had to be combated. It was also suggested that the tool should be coated to prevent tool wear. Several other studies experimented with different process parameters to connect different metal matrix composites and found that FSW is a promising choice for joining metal matrix composites.

2.8. FSW of Dissimilar Materials

Many industries, including automotive, shipbuilding, electronics, and others, need the joining of different materials. Due to variances in the chemical and physical characteristics of the materials being connected, the fusion procedure was not suitable [93]. The connecting of dissimilar welding can take a variety of forms, as seen in Figure 4. B. Fu et al. [94] linked the same materials by altering the tool spindle speed and welding speed, with a maximum efficiency of roughly 70%. Anil Kumar Deepati et al. [95] used H13 tool steel to connect several aluminium alloys ranging from AA5083 to AA1100 and discovered that friction was the predominant source of heat production, and tensile strength was impacted by the welding speed and tool rotating speed. M. Koilraj et al. [96] used varied tool pin shapes to fuse AA6061 with AA2024. When the results of the experiments were analysed, it was discovered that the square pin tool generated the highest ultimate tensile strength when compared to other tool pin profiles. M. Dehghani et al. [97] used a mild steel sheet to link 3 mm thick cold rolled AA3003–H18 aluminium alloy. The trial findings revealed defect-free welds and a maximum ultimate tensile strength of 96 MPa, which was higher than that of the aluminium base material.

Yael Templeman et al. [98] investigated the corrosion resistance and microstructural properties of AM50 and AZ31 magnesium welded joints. Rotational speed and welding speed were the process parameters that were examined. It was observed from microstructural examination results that aluminium enrichment and beta phase were dissolved into the interior of the alpha magnesium grains in the nugget zone, resulting in an increase in aluminium concentration and higher corrosion resistance in the nugget zone. When connecting AA5754 with AZ31 magnesium alloy of 3 mm thickness, Y. Zhao et al. [99] investigated the effect of welding speed on metallurgical and mechanical characteristics. Excessive flash, groove, and surface peeling off were noticed in the welded joints, which were generated by inserting an aluminium workpiece on the advancing side and a magnesium sheet on the retreating side. The existence of intermetallic compounds and microstructural cracks were discovered using SEM and EDX analysis, resulting in a loss in tensile strength and an uneven distribution of hardness values. A. Dorbane et al. [100] looked at the microstructural and mechanical characteristics of connecting AA6061-T6 and AZ31B magnesium alloys and discovered the occurrence of grain refinement and a very thin layer of intermetallic compounds in the stir zone. The findings revealed that keeping the aluminium material on the advancing side resulted in better welding. The tensile strength of the welded joint was 18% and 55% at room temperature, and 58% and 78% at a higher temperature of roughly 200ºC.

To combine AA5052 alloys with HSLA steel, K. Ramachandran et al. [101] improved friction stir welding with external water cooling. The impact of spindle speed on mechanical qualities was studied and compared to the traditional friction stir welding method. In both procedures, raising the spindle speed increases the tensile strength to a certain point, beyond which the tensile strength declines as the spindle speed is further increased. TWI had designed a butt joint arrangement with a length of 2 metres and a thickness of 6 mm in S275 carbon steel and S32205 Duplex stainless steel. FSW and conventional methods were used to weld these materials. When compared to traditional welding, the heat affected zone for the FSW technique was smaller, and the material flow in the weld zone was evident [102].

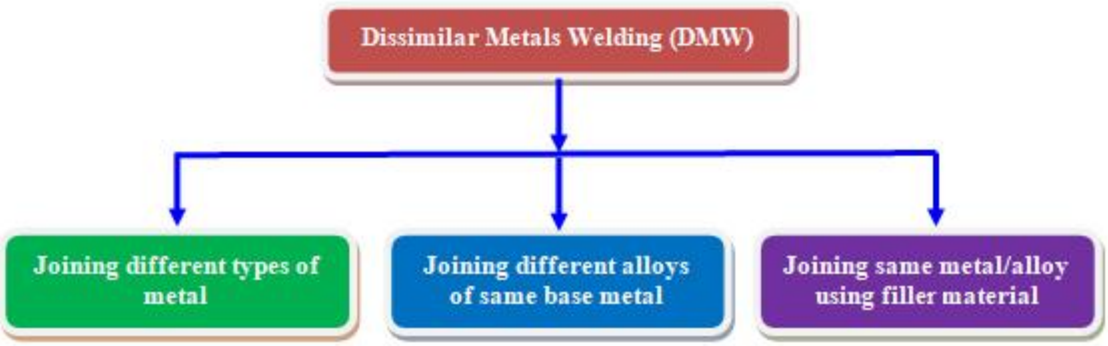
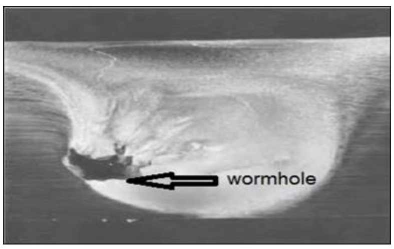


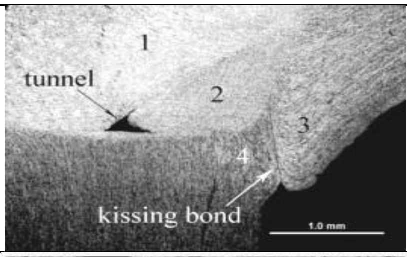
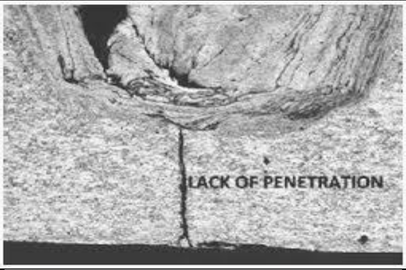
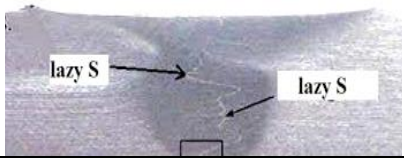
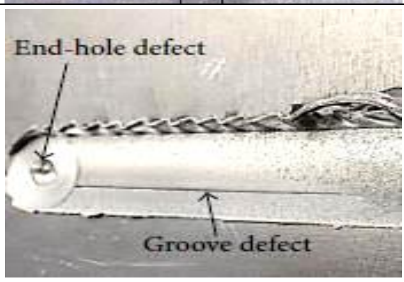
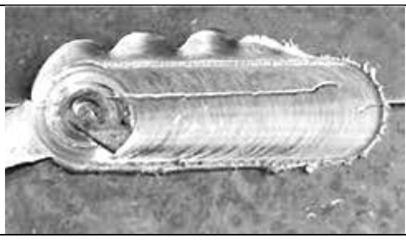
Fig. 4. Types of dissimilar metals welding [95]

2.9. Defects in FSW

Friction Stir Welding is susceptible to defects that are different from fusion welding defects. The selection of improper welding process parameters leads to insufficient heat input, excessive heat input, abnormal stirring, and insufficient pressure underneath the shoulder. Some of the defects are controllable during the process by means of controlling the heat input and some welding defects are controlled by the proper design of the tool. Due to the insufficient heat input, the defects such as tunnel, kissing bond, and lack of fill were induced during the welding. On the other hand, due to excessive heat input, flash, nugget collapse, surface galling, and sticking were produced during welding. Lack of penetration and excessive indentation occurred due to the improper tool design. Table 2 shows some of the FSW defects with their causes.

Table 2. Defects developed during FSW [106], [107]

Name of the defect	Example	Causes
a) Worm hole		• Excessive heat input due to high rotation speed (or) low traverse speed. • Insufficient butting surfaces.

Name of the defect	Example	Causes
b) Kissing bond		Low heat generation due to low rotation speed (or) high traverse speed.
c) Lack of penetration		Length of the pin is not long enough.
d) Lazy S		Originated from oxides.
e) End-hole and Groove defects		Very low / High tool tilt angle, Insufficient pin plug depth.
f) Flash formation		Excessive heat input.

3. APPLICATIONS OF FSW

Up to the present-day scenario, FSW has been selected as a process for the development of components by approximately 231 organizations in 24 countries. Among these, half of the organizations are end users and the rest of the users are research organizations, equipment suppliers, and educational institutions. Most of the process beneficiaries are from the USA, Japan, Germany, Norway, and Sweden [103]. To manufacture the hollow aluminium deep freezer panels for ship decks, Scandinavian aluminium extruders applied a friction stir welding process, in 1995. Norwegian Extrusion Company Hydro aluminium reported that friction stir welding can be used to prepare prefabricated panels and consequently, labour costs were reduced by 15%. Another shipbuilding business, Norwegian Fjellstrand, claimed a 10% cost savings due to improved ship design. FSW is utilised in Japan to manufacture honeycomb panels and seawater-resistant panels.

The aluminium panels for a military ship were successfully manufactured by the Nichols Brothers' boat builders in Freeland, Washington, USA, using the friction stir welding procedure. FSW is used for building massive tanks for satellite launch vehicles using high-strength aluminium alloys in the US aerospace industry. The first rocket featuring the FSW inter-stage module was launched in August 1999. The strength of the weld was raised from 30 to 50% and the cycle time was lowered by approximately 80% when FSW was utilised for the Delta IV common booster core tanks. In 2001, Delta II rockets received a total length of 2100 m of defect-free friction stir welds, whereas huge Delta IV rockets received a length of 1200 m of defect-free welds. The toenails of the Boeing's C17 cargo ramp were the first commercially produced FSW components. After a 100% NDT examination, Advanced Joining Technology Inc. declared a scrap rate of zero in 2006. FSW was chosen by Eclipse Aviation Corporation of Albuquerque, New Mexico, to replace traditional riveting and bonding procedures. This is the first time when a joining procedure has been used in the building of an aircraft, with the benefit of decreased assembly time and manufacturing costs. About 7000 fasteners and rivets were replaced with FSW for Eclipse 500 [106]. Table 3 lists the various industrial applications of friction stir welding. Figure 5 depicts the most common industrial uses of friction stir welding.

Table 3. Industrial applications of FSW [104]

No.	Company	Applications	Year of use
1	Marine Aluminum, Norway	Heat Exchangers, Ship building	1995, 1996
2	Boeing, United States	Delta II rockets	1998
3	SAPA, Sweden	Ship building, Automotive Components	1999, 2000
4	General Tool, United States	Laser System housing	2000
5	Hydro Aluminum	Motor housing	2001
6	Alstom, Germany, and Hydro Marine	Suburban trains	2001
7	Showa, Japan	Automotive Components	2001
8	Hitachi, Japan	Train bodies	2001
9	Tower Automotive, USA	Automotive components	2002
10	Advanced Joining Technology, USA	Ship building	2003
11	Lockheed Martin, USA	Space shuttle external tank	2004
12	RIFTEC, Germany	Food trays	2004
13	Friction Stir Link, United States	Ship building	2006
14	Honda Motor Company	Automotive Components	2012

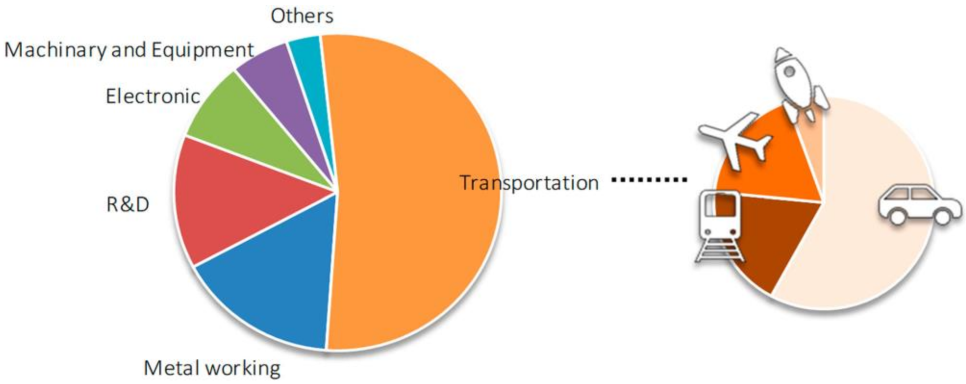


Fig. 5. The main industrial applications of FSW [105]

Apple has used a friction stir welding procedure to attach the smooth metal surfaces of their new iMac model. Traditional welding methods including spot welding were originally used to attach the front and rear components of the iMac model, resulting in incorrect welds. For the 2005 GT model, Ford used the FSW technique. T

The electrical industry has expressed interest in employing the FSW technique for a variety of applications, including motor housing, bus bars, and electronic encapsulation, among others [105].

4. CONCLUSIONS

The consequences of FSW research are presented here. The observations based on the gathered publications from the previous decade are that the FSW is simple to use and is a strong joining technology with a small number of process parameters that are easy to control and optimise. This friction method is one of the best processes for joining lightweight materials like aluminium and magnesium and to join dissimilar materials like a joint of ferrous-non-ferrous combination. The pin profile also has an impact on the mechanical properties. While considering the process parameters, axial force dominates the properties compared to others. Literature informed that FSW is suitable not only for joining composites but also polymers, and it successfully unites incompatible materials with fewer flaws. Since this welding technique has been successfully adopted by several businesses, there is still a lot of research to be done in the area of temperature monitoring, parameter optimisation for welding thin plates, joining semi-cylindrical parts and temperature control during the process.

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