Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 2 (2024)

A Comparative Study of Friction Stir Welding and Friction Stir Scribe Welding for Dissimilar Metal Joining

Sapna A Solanki[1], Dr. Anand B. Dhruv[2]

[1]*Research Scholar, Gujarat Technological University, Chandkheda, Ahmedabad, Gujarat.*

[2]*Professor, Government Engineering College, Patan. Gujarat*

Abstract:-Friction stir welding (FSW) has emerged as a novel method for joining similar and dissimilar ferrous and non-ferrous materials. This solid-state welding process utilizes frictional heat generated between a tool shoulder and the base material. The stirring action facilitates the movement and consolidation of the material, resulting in localized fusion and the formation of a joint. This review paper examines the effectiveness of FSW joints through various experimental investigations, considering multiple variables. Furthermore, it explores the application of scribed tool FSW as a recent advancement in the field of joining materials. The review draws upon existing literature to analyze the factors influencing the quality of FSW joints and presents the results of weld quality investigations.

Keywords: *Welding, Friction stir scribe welding, Friction stir welding*

1.1 Introduction

People and materials have always been closely linked throughout history. The materials that people have used played a big role in shaping civilization. From the first basic stone tools to the modern materials used in building and transportation today, materials have allowed us to construct and advance the world. The industrialization was a foremost reason in developing new materials, like steel and plastics. These new materials let us make stronger, lighter, and cheaper things. In turn, this led to huge changes in our society[1].

However, integrating different materials with diverse properties into a single structure has presented challenges for designers. While mechanical fastening has been commonly used, the focus has shifted to welding for high-performance structures. Yet, welding dissimilar materials remains a difficult task that researchers are working to overcome [2].

1.2 Conventional Joining Techniques

In the world of joining materials together, there are various techniques commonly used, as shown in Figure 1.1. Welding is a popular method that brings several benefits, like being cost-effective, saving time, allowing for flexible designs, reducing weight, making structures stronger, creating tight seals, and enabling wide welding areas. Traditionally, fusion welding and solid-state welding techniques, such as friction stir welding (FSW), ultrasonic welding, explosion welding, and diffusion welding, have been used to join different types of materials. Additionally, attempts have been made to use brazing and soldering to prepare joints between dissimilar materials[3].

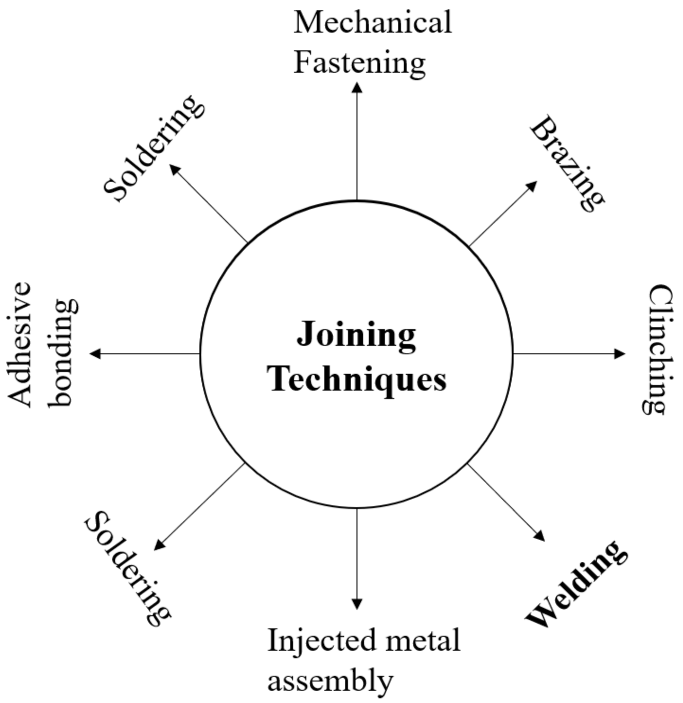

Figure 1.1 Different techniques used to join the different types of materials (similar and dissimilar)[2].

1.3 Friction Stir Welding (FSW)

Friction acts as a useful source of the thermalenergy needed for the welding, depositing, and handling important metals and alloys. Friction stir processes work based on common principles in which factors such as the rate of rotation and axial force of the instrument produce friction at the contact point between the instrument and workpiece. This friction has the ability to plasticise the material in the welded area[1]. The study of Friction stir technique is critical, as it could provide researchers with detailed insights (on the process, variables, operating ranges, orbital friction[4], materials [5], tool profiles[6], tool-work interfaces[7], benefits, drawbacks, properties, etc.) that may expand applications across a wide range. Friction stir techniques have already been widely adopted in many industrial applications including surface coating, surface cladding, component repair, fabrication of automotive structural components (tailored blanks, driveshafts, frames, suspension links, etc.)[8], aerospace components (thrust frames, fuselages, aircraft landing gear), ship-building, vacuum vessels, and more[9].

The solid-state joining process known as Friction Stir Welding (FSW) was established at the welding institute in the UK in 1991. It is an effective and easy method that utilizes a reusable rotating instrument with a uniquely designed shoulder and pin to connect two plates. The instrument is inserted into the adjoining edges of the plates and moved along the joint line. The heat and plastic deformation produced by the instrument soften the surrounding material, causing it to flow around the instrument and form a joint between the plates. The terminology used in FSW, including advancing side and retreating side, is illustrated in the diagram[10][11].

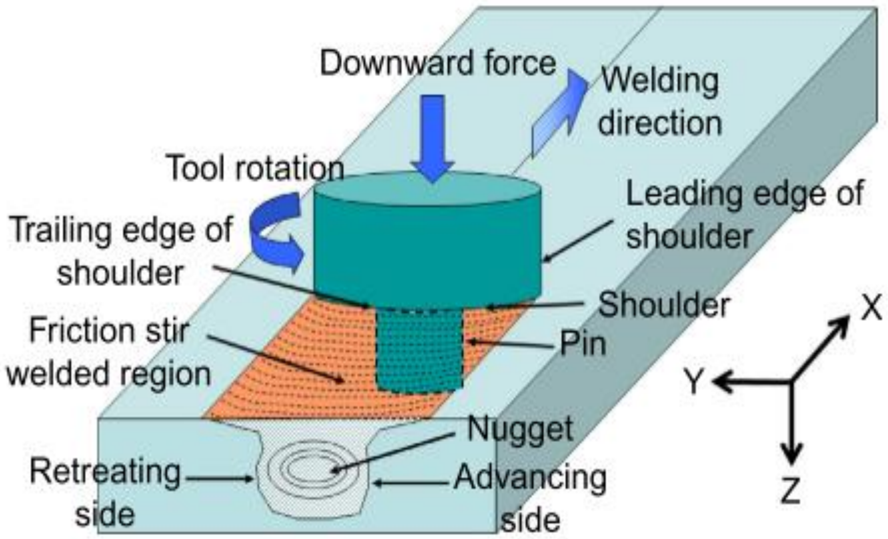

Figure 1.2 Schematic view of Friction Stir Welding

The Friction Stir Welding (FSW) takes place at temperatures lower than the alloy's melting point, preventing the challenges linked with fusion welding. In Figure 1.2, various microstructural zones within friction stir welds are depicted. The nugget zone symbolizes the region undergoing dynamic recrystallization, whereas the thermo-mechanically affected zone (TMAZ) encounters plastic deformation under elevated temperatures[12].

Friction StirWelding have valuable benefits which make the method special. It's a process that doesn't involve melting, which results in less distortion, stable sizes, and consistent repetition. FSW maintains the essential elements in the material, shows excellent strength properties, and creates a very fine reorganized microstructure[13]. It gets rid of issues like cracks that can happen during cooling and allows for the replacement of multiple parts joined with fasteners. FSW can be used with all sorts of aluminum and can be shaped after welding [14]. In terms of the environment, it doesn't need special gases, requires minimal cleaning, and eliminates the production of grinding waste and the need for extra cleaning agents. FSW also brings energy-saving benefits by using materials more effectively, consuming less energy, and reducing fuel usage in lightweight applications[15] .

Friction stir scribe (FSS) is a technique for joining different materials together. It's a improved version of friction stir welding (FSW), where the tool used has a scribe at its tip.A groove is cut in the bottom sheet by the scribe, creating a mechanical interlock between the two different metals.The FSS development is similar to FSW, but there are some key differences[6]. The scribe tool is inserted into the bottom sheet, and the rotational speed and welding speed are decided. The tool is then moved along the joint line, and the scribe cuts a groove in the bottom sheet. The friction and heat generated by the tool plasticizes the materials, and the tool stirs the materials together. The mechanical interlock created by the scribe helps to hold the materials together, and the weld is completed when the tool is removed. The FSS process has several advantages over other joining techniques for dissimilar materials. This is a development that happens in the solid state, meaning the materials don't melt or fuse together. This can be beneficial for materials with different melting points or for materials that are sensitive to heat. The FSS process also produces a narrow heat-affected zone, which can help to preserve the properties of the parent materials. The FSS process has been used to join a variety of dissimilar materials, including aluminum[16][17], steel[18], titanium[19], and magnesium[20]. This method has been employed for joining materials exhibiting variations in melting points, strengths, and thermal properties.The FSS process has also been used to join materials with different thicknesses. The FSS process is a promising joining technique for dissimilar materials. It is a solid-state process that produces a narrow heataffected zone. This makes it a good choice for materials with different melting points or for materials that are sensitive to heat. The FSS process has been utilized to join a variety of dissimilar materials, and it is a promising technology for future applications[6].

1.4 Comparison between welded joints made using conventional welding processes and Friction Stir Welding

Gite et al. performedexperiments using Friction Stir Welding (FSW) and found this process is a promising substitute for traditional fusion-based welding methods. This article offers a comprehensive review of contemporary research on FSW, with the objective of outlining notable contributions in this domain. It emphasizes the approaches employed, materials used, tool characteristics, workpiece dimensions, and typical operational factors. The research also incorporates a succinct overview of numerical simulations pertaining to the FSW technique. Furthermore, the research shows the practical applications and potential future advancements of FSW, furnishing valuable perspectives into this inventive welding methodology [21][22][23].

Dwivedi et al. compared friction stir welding (FSW) with autogenous TIG welding. FSW produced fine-equiaxed grains, resulting in higher weld strength (approximately 20% more) compared to ATIG welding with coarse grains. Higher rotational speeds in FSW increased grain size but decreased tensile strength. FSW samples exhibited greater hardness, with hardness increasing at higher rotational speeds. FSW demonstrated favorable mechanical properties, including low distortion, absence of spatter and fume, and high-strength welds[24].

S. Malarvizhi et al. conducted study on the FSW joint demonstrated 20% higher strength than the GTAW joint and 12% higher than the EBW joint. However, its fatigue strength was 10% less than the base material (BM) joint, while EBW and GTAW joints exhibited 25% and 45% less fatigue strength. FSW components had lower corrosion resistance compared to EBW and GTAW components. The enhanced tensile and fatigue capabilities of FSW joints were ascribed to the formation of equiaxed fine grains, a reduced precipitate-free zone, and numerous dislocation cells in the weld area. However, this led to a deterioration in pitting corrosion resistance[25].

P. Carlone et al. examined the welding of magnesium ZE41A alloy plates using TIG welding and friction stir welding. Optical and SEM analyses, along with EDX analysis and microhardness measurements, revealed varying elements and grain sizes. The FSW joints exhibited smaller recrystallized grains due to dynamic recrystallization during welding, in contrast to TIG welding, which showed grain nucleation and growth from molten metal. The results provided valuable insights into the microstructural differences between the two welding processes and their effects on grain size in the welds[26].

S. Rajakumar et al.compared AZ-61A-Mg alloy plate welding using pulsed current gas tungsten arc welding (PiGTAW) and friction stir welding (FSW) as shown in Figure 1.3. FSW joints demonstrated significantly better mechanical properties, with 84% higher strength coefficient than PiGTAW joints. FSW also resulted in higher tensile and yield strength, increased by 12% and 18% respectively, due to the cold-worked microstructure. FSW joints exhibited a smaller heat-affected zone, leading to increased strength, reduced distortion, and void-free welds [27][28].

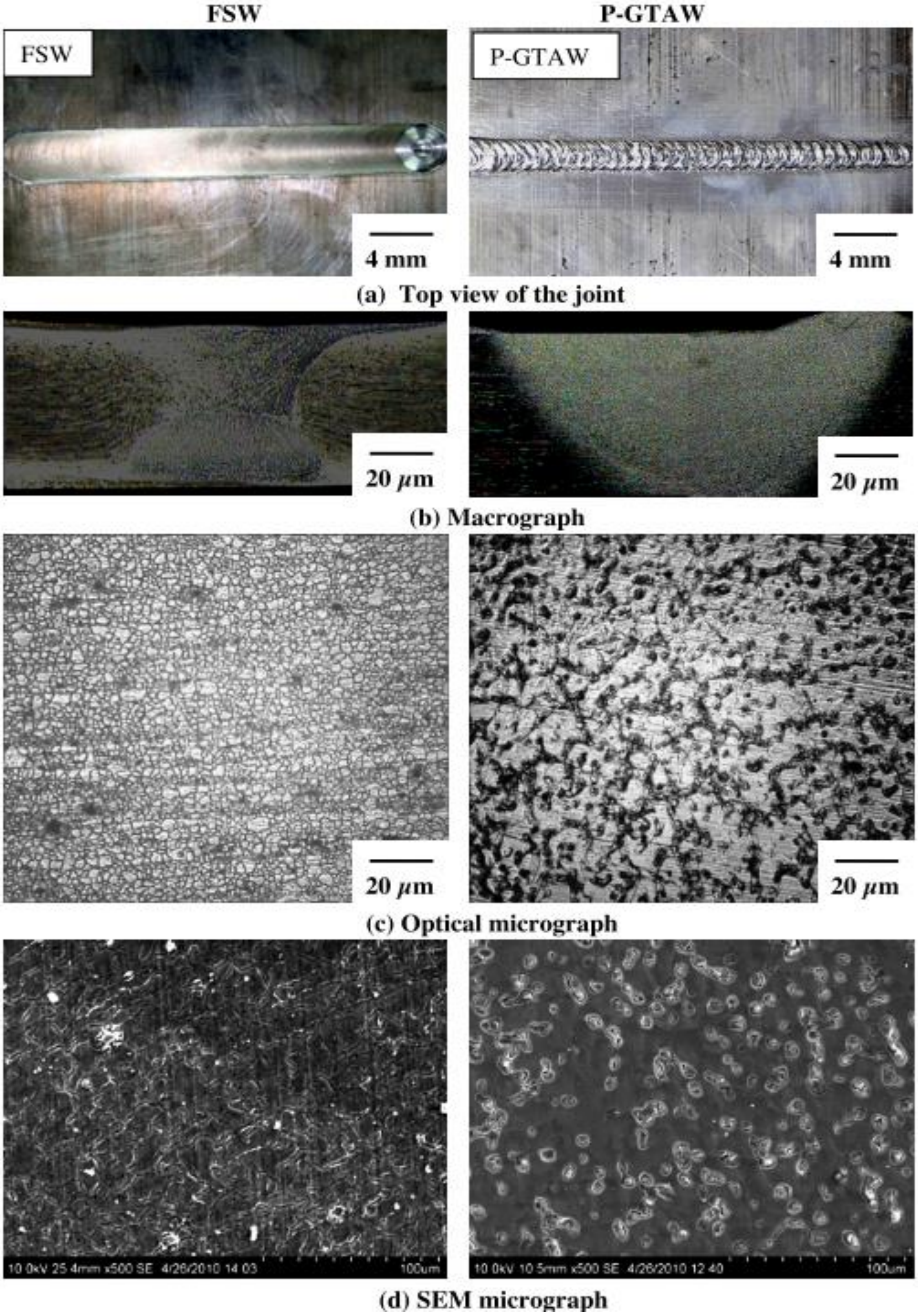

Figure 1.3 Comparison based on macro and microstructure of FSW and P-GTAW weld joints

Ericsson et al. experimentally studied how the welding speed impacts the fatigue durability of friction stir welds (FSW). They contrasted these findings with the outcomes of MIG and TIG welding. The team conducted FSW on Al Mg Si 6082 under T6 and T4 states, performed MIG-pulse and TIG welding under T6, and carried out MIG-pulse and TIG welding under T6 conditions followed by post-weld aging. Lower welding speeds improved fatigue efficiency, attributed to higher heat production during welding. FSW showed higher static and dynamic strengths compared to MIG-pulse and TIG welds. Among traditional arc welding methods, fatigue efficiency favored TIG welds, but FSW exhibited the highest fatigue strength in Al Mg Si alloy 6082 [29].

The research conducted by Dehghani et al. focused on friction stir welding (FSW) joints between Al-5186 and MS plate. A study analyzed how varying friction stir welding parameters like tool speed, plunge depth, tilt angle, and tool pin design impacted weld quality and strength. At slower welding velocities, thick layers of intermetallic compounds like Al_6Fe and Al_5Fe2 formed in the stir zone, reducing tensile strength and promoting tunnel defects. However, increasing the tool's travel speed reduced intermetallic formation and improved tensile properties. Using a threaded M3 tool pin configuration prevented tunnel defects and created a bell-shaped stir zone that yielded joint strength equal to 90% that of the parent aluminum alloy. Based on these results, the researchers defined an optimal friction stir welding parameter window for maximizing joint strength and quality[30].

A recent study by researchers including Kai Chen investigated using friction stir spot welding to join aluminum 6061 alloy and transformation-induced plasticity (TRIP) 780/800 steel. They explored how key process parameters like plunge speed and dwell time affected weld strength through experimental design and analysis of variance. The result illustrated that dwell time had a greater impact on weld strength compared to plunge speed. The welded samples displayed a distinct hooked, swirling pattern with alternating thin layers of steel and aluminum-iron intermetallic compounds. During tensile shear testing, the main failure mode was cross-nugget fracture. Cracks initiated in the swirling structure on the tension side of the weld and propagated with a cleavage-like morphology. The initial study illustrates that friction stir spot welding can effectively join dissimilar aluminum and steel alloys, with optimized process parameters for strength[31].

Friction stir welding considered as an optimal method to join the lightweight aluminum alloys used in transportation and aerospace applications. A study sought to optimize friction stir welding factors to increase the strength of 5mm thick butt joints in 6061-T6 aluminum alloy plates. The researchers employed Grey relational analysis and L9 orthogonal arrays to systematically optimize the process. The optimized parameters produced joint efficiencies reaching 91.3% of the base metal strength. In summary, the study demonstrated that friction stir welding can maximize joint strength in aluminum alloys while minimizing cost and material waste. This makes it an attractive environmentally-friendly joining solution to meet industry demands for lightweight structural joints[32].

1.5 Various materials welded by Friction Stir Welding

In sectors like automotive and aerospace, where weight is crucial, researchers and industrial engineers seek a reliable welding operation that can produce defect-free welds on high-strength-to-weight ratio materials[33]. Friction stir welding (FSW) has emerged as a solid-state welding technique, particularly for nonferrous materials like aluminum[34,35]. FSW revolutionized aluminum welding, addressing previous challenges[36]. Now, FSW has become a topic of extensive research for welding high-strength and high-temperature materials and alloys such as steel, Ti 6Al 4V, Nickel, and Tungsten, opening up new possibilities in the field[3][37].

Friction stir welding (FSW) has been extensively studied for various materials and applications[38]. P. Lin et al. (2020) investigated the effect of tool rotating speed on FSW of an FCC phase Al0.3CoCrCu0.3FeNi high-entropy alloy, revealing improved hardness and grain refinement in the stir zone [39]. R. Giorjão et al. (2019) examined FSW of super duplex stainless steel pipes, achieving high-quality welds with increased hardness in the stir zone[40]. R. Ramesh et al.explored FSW on HSLA butt joint plates, obtaining a microstructure with higher hardness and adequate ductility[41]. R. Mohammed et al. (2016) compared welding methods, highlighting FSW's superior mechanical properties[42]. T. Küçükömeroğlu et al. (2015) studied FSW on cast Nickel-Aluminum Bronze alloy, obtaining grain refinement and improved proof stresses. Overall, these studies underline the versatility and potential of FSW as an efficient welding technique with enhanced mechanical properties and microstructural characteristics for diverse industrial applications[43].

Kaygusuz et al. conducted a review on FSW method and observed its exceptional results in joining properties, especially for lightweight and durable materials like aluminum alloys in various industries. Conventional welding methods encounter challenges with such materials due to their high thermal conductivity and low melting point. FSW overcomes these limitations by welding below the materials' melting point, preserving the mechanical structure. The study comprehensively examined the FSW process, its advantages and disadvantages, as well as its diverse application fields.[15].

The research papers on friction stir welding (FSW) provide valuable insights into the process and its impact on different materials and welding conditions. In the study by S.J. Barnes et al.HSLA-65 steel FSW was produced with varying traverse speeds and two different tool alloy, W-Re and PCBN. The researchers found that the use of a PCBN tool at a specific welding speed resulted in the maximum hardness of 323 Hv(10) in the weld nugget, indicating a superior microstructure [44]. T. Saeid et al. investigated FSW of SAF 2205 duplex stainless steel at different welding speeds and observed that higher welding speeds led to increased mechanical properties as the size of the stir zone and grains reduced [45]. F. Ye et al. produced an FSW joint with recrystallized stir zone and excellent mechanical properties, including over 35% joint elongation [46]. C. Chen et al. explored the fusion-solid-state welding combination for Al 6061 and AISI 1018 steel, utilizing the AE sensing technique to detect tool failure during welding [47]. P. Konkol et al. reported on welding with a PCBN tool in 0.29C-Mn-Si-Mo-B quenched and tempered steel, revealing FSW's advantages over GMAW in terms of toughness [48]. These research findings contribute significantly to the advancement and optimization of FSW techniques for various industrial applications, offering valuable knowledge for improving weld quality and mechanical performance in different materials and welding conditions.

Isa et al. reported an review on the possibilities presented by friction stir welding (FSW) for connecting different aluminum and copper metals. The paper discusses various aspects, including FSW process variables, the analysis of microstructure, mechanical attributes, electrical traits, and novel methods for improving joint quality. Additionally, the study delves into numerical modeling to better comprehend process influences, thus offering valuable perspectives for driving future advancements in this area of research[49].

Liu et al. conducted experimental study butt weld joining of thin sheets of aluminum alloy 6061-T6 and TRIP steel using friction stir welding (FSW). The resulting joint exhibited up to 85% of the base aluminum alloy's ultimate tensile strength. The strength of the joint was influenced by the existence of an intermetallic compound (IMC) layer, either FeAl or Fe3Al, at the interface between aluminum and iron. Within the weld nugget, there was an aluminum matrix composite identified, which was strengthened by steel fragments that had been sheared off and a delicate layer of intermetallic compound. The research extended its focus to the effects of process variables on the development of the joint's microstructure. This examination involved analyzing data collected during the friction stir welding (FSW) process, including welding force and temperature measurements[50].

Friction stir welding (FSW) has revolutionized welding for high-strength-to-weight ratio materials like aluminum, addressing previous challenges and improving joint quality. Extensively studied, FSW showcases versatility and potential for diverse applications, offering defect-free welds and enhanced mechanical properties[51]. Researchers have explored FSW's impact on various materials, including super duplex stainless steel, high-strength aluminum alloys, and nickel-aluminum bronze, revealing improved microstructural characteristics and hardness. Numerical modeling aids in understanding process effects and guides future advancements. FSW's ability to join dissimilar metals like aluminum and copper enhances joint properties, while its application in aerospace components demonstrates remarkable tensile shear fracture loads. FSW continues to hold promise for industrial sectors seeking efficient and reliable welding solutions[30].

1.6 Tool geometry

Friction stir welding (FSW) is a technique that joins materials without melting them. Heat is generated through friction by a special rotating tool in this process, which is used to soften the materials being joined. The tool comprises a cylindrical pin and a larger shoulder, and as it rotates, the pin and shoulder produce friction heat that softens the surrounding material without complete melting. This allows the materials to be welded together by the mechanical mixing action of the pin and shoulder. FSW has advantages over traditional fusion welding methods when working with hard alloys like steel and titanium. Fusion welding can cause cracks and holes in the welded joint, while FSW avoids these defects[6]. However, the high temperatures and forces involved still place significant demands on the FSW tool, especially when welding hard alloys[52][53]. The high stresses and wear limit the commercial viability and lifespan of FSW tools. Ongoing research aims to develop lower cost, more durable FSW tools to enable broader use of this technology with challenging materials like steel and titanium. The geometry and dimensions of the FSW tool play a key role in the process. Factors like the shoulder diameter, shoulder angle, pin shape and size, and tool surface characteristics all influence important aspects of FSW. These include the heat input, forces generated, material flow patterns, and thermomechanical conditions experienced by the tool. Finding the optimal tool geometry is crucial for producing high quality and efficient welds. Further research and development of improved tool designs is still needed to fully realize the potential of friction stir welding across various alloy systems[1,54]

Alkhafaji et al. conducted an experimental study on the effects of tool geometry in friction stir spot welding (FSSW) of aluminum alloy AA6061-T6 sheets. They used four different FSSW tools made of AISI H13 steel to join 1.8 mm thick aluminum sheets for lap-shear testing. The tools had cylindrical or conical pin profiles and shoulder diameters of either 12 mm or 16 mm, as illustrated in Figure 1.4. The FSSW process was performed at room temperature with four specimens produced for each tool configuration. The results revealed that a conical pin and larger shoulder diameter improved the weld mechanical properties and microstructure over the cylindrical pin and smaller shoulder diameter tools. The conical pin and larger shoulder induced greater strain hardening and frictional heat input during welding. This demonstrates the significant role of FSSW tool geometry factors like pin profile and shoulder size in determining aluminum weld quality[55].

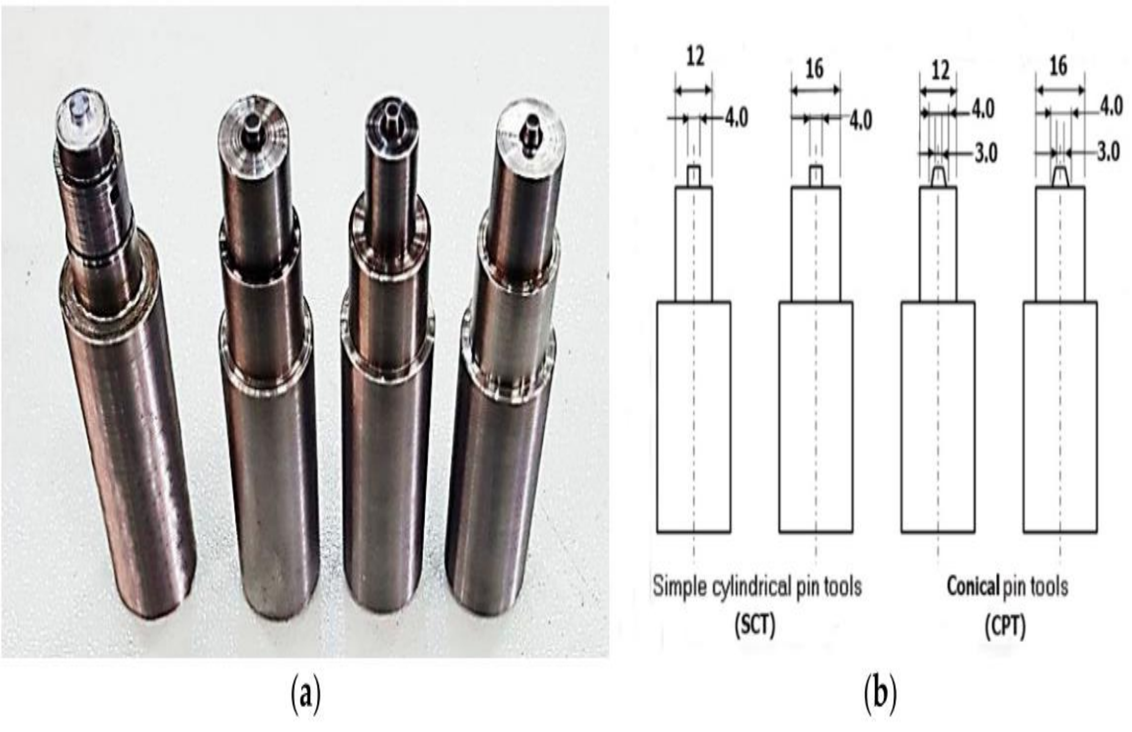

Figure 1.4 The FSSW tool: (a) cylindrical and conical pin tools with simple geometries; (b) a schematic illustration of the tools depicting their shared constant pin length

Movahedi et al. investigated friction stir lap welding of Al-5083 and St-12 alloy sheets with different tool travel (7–23 cm/min) and rotation (750–1125 rev/min) speeds as shown if Figure 1.5. Decreasing travel speed enhanced joint strength, with 11 cm/min identified as the optimal speed. Higher rotation speed slightly improved joint strength, tends to the form an intermetallic phase layer with a hardness of around 335 HV [56][6].

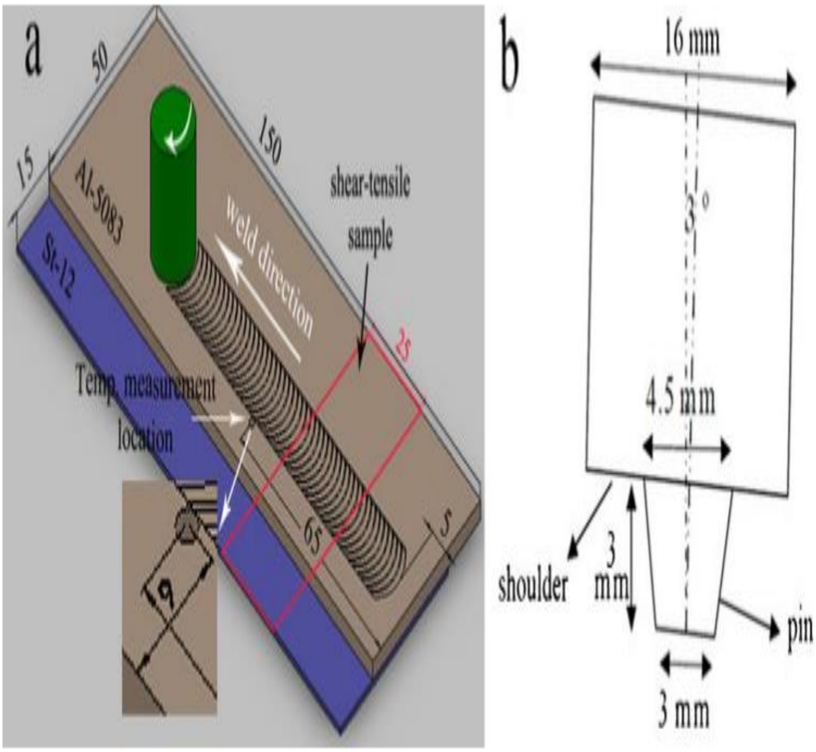

Figure 1.5(a) a diagram of the joint design showing the locations where interface temperatures were measured, with dimensions in millimeters; (b) a schematic illustration of the welding tool configuration.

Rajendran et al. experimentally stud focused on utilizing friction stir welding (FSW) to join high-strength aluminum alloys, specifically 2xxx series like 2014, commonly used in aircraft components. Conventional fusion welding methods face challenges due to oxide layer disruption, causing issues like solidification cracking and porosity. Lap joints were created with varying tool tilt angles (0° to 4°) while keeping other parameters constant. Experimentally, the tensile shear fracture load and microstructure properties were investigated. A tool tilt angle of 3° yielded defect-free friction stir lap welding with a remarkable maximum tensile shear fracture load of 14.42 kN, making it a promising technique for high-strength aircraft applications, offering enhanced joint strength and reliability[57][58].

A recent study by Correia et al. examined friction stir welding of glass fiber reinforced polyphenylene ether polymer to 6082-T6 aluminum alloy in an overlapping joint configuration. They studied how tool penetration depth, adjusted through pin length, and process control mode impacted joint performance. Tensile testing revealed joint strengths ranging from 5.5 to 26.1 MPa and efficiencies from 10.1% to 47.4%, depending on pin length. Joints made with higher tool penetration and position control showed poorer performance, while a 2 mm pin under position control achieved comparable strength with less variability, making it promising for industry use. The study also found process control mode had a minor influence. This initial work demonstrates friction stir welding can join polymer composites and aluminum in overlap joints, with properties optimized by controlling tool penetration and process parameters[59].

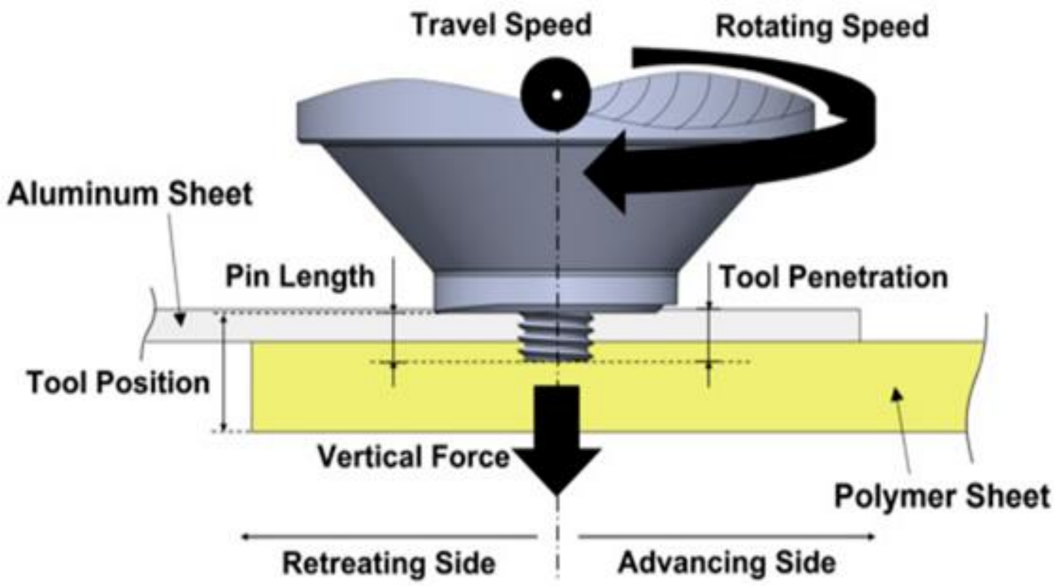

Figure 1.6 depicts the friction stir welding of dissimilar materials in an overlap configuration. The figure shows the phases of the joining process, including tool plunging (1), dwelling (2), welding (3), and tool extraction (4)

The investigation of the microstructure and mechanical properties of AA1050 alloy friction stir welds (FSW) was carried out by Abdullah et al., focusing on the effect of the partial-contact tilt angle of the tool (TTA).They tested three TTA levels: 0°, 1.5°, and 3°, and observed that higher TTA reduced heat generation but increased FSW tool wear, contrasting total-contact TTA joints. A strength of 45% of the alloy, along with a maximum heat of 336°C, tensile strength of 33 MPa, and 75% elongation, was observed in welds with a 0° TTA. Fracture analysis revealed a brittle fracture mode for 0° TTA welds[60].

Balos et al. experimetnally studied the application of bobbin tool friction stir welding (BTFSW), which simplifies the friction stir welding (FSW) process using a two-shoulder toolThe research centered on examining the interference between the square pin tool and convex shoulders in an aluminum-magnesium alloy. The findings indicated that an optimal interference of 0.4 mm yielded the best mechanical properties, comparable to the base metal. Additionally, higher impact strength was observed, attributed to grain refinement in the nugget zone.Additionally, specimens with 0.4 mm interference exhibited fewer defects. [20].

In a recent study, Wang et al. experimentally investigated single-pass friction stir lap welding of 6061-T651 aluminum alloy to JAC270 45/45 galvanized steel sheets. They found that an intermediate tool plunge depth of 0.2 mm produced lap joints with the highest strength. This optimized plunge depth minimized defects and intermetallic compounds forming at the aluminum-steel interfaces.Furthermore, the development of a double-pass welding method eliminated critical area flaws, significantly improving the weld strength and creating a robust interfacial bond. These crucial findings provide valuable insights for optimizing lap weld designs and material integration in high-integrity structural components, enhancing lightweight and energy-efficient hybrid structures across diverse industries [61].

A recent study by Cavalierea et al. investigated how friction stir welding parameters affected the mechanical properties and microstructure of AA6082 aluminum alloy joints. Specimens were produced at a constant tool rotation speed of 1600 rpm and a range of welding speeds from 40 to 460 mm/min. Mechanical characterization included room temperature tensile testing and fatigue tests up to 250 Hz under constant amplitude loading.Microstructural analysis was performed via optical observations of jointed cross-sections, and SEM observations were used to characterize weld performance on fractured surfaces. The findings provide valuable insights for optimizing friction stir welding parameters and enhancing joint quality [62].

1.7 Friction stir scribe welding

Friction stir scribe welding (FSSW) is an innovative solid-state joining technique designed to overcome the challenges of joining materials with vastly different melting points, such as dissimilar metals and metal-polymer composites. The process involves using a modified tool pin with a cutting-scribe at its bottom, inducing localized deformation to create a groove at the material interface. The tool then stirs the materials together, forming continuous overlap joints with mechanical interlocks at the interface. These interlocks significantly enhance joint strength and integrity. FSSW offers great potential in lightweighting efforts and joining dissimilar materials[63], making it particularly relevant in industries like automotive and aerospace[64][36].

Figure 1.7 Friction stir scribe tool geometry[65]

Wang et al. conducted an experimental study on joining automotive aluminum and steel sheets using Friction Stir Scribe (FSS) welding, which resulted in a hook-like structure at the interface as shown in Figure 1.7. However, the bond formation mechanism remains unclear. Through microstructure analysis, they discovered simultaneous mechanical interlocking and interfacial bonding during FSS welding. The advancing side exhibited a higher diffusion driving force, and thermally activated diffusion played a significant role in interfacial bond formation. TEM analysis revealed a thin intermetallic compound (IMC) layer with compositional variations (Fe_2Al_5 or Fe_4Al_{13}) dependent on weld regions[66]. These findings advance the understanding of FSS welding for automotive applications[65].

Shen et al. explored lap joint friction stir welding (FSW) between Al5754 aluminum and DP600 steel. The study analyzed how friction stir welding parameters such as travel velocity and depth of tool penetration into the steel sheet influenced the joints. At the aluminum-steel interface, the intermetallic compound Fe4Al13 was observed to form.Increasing penetration depth significantly enhanced weld strength, regardless of travel speed. For penetration depths >0.17 mm, premature failure occurred through the aluminum substrate, while depths <0.17 mm resulted in shear fracture. These insights aid in optimizing FSW parameters for dissimilar alloy joints, with potential applications in automotive and aerospace industries, where reliable and robust joints are essential for structural integrity[21].

Barker et al. explored the potential of friction stir scribe technology to join materials with dissimilar melting regimes, such as aluminum and steel as shown in Figure 1.8. This technology creates a mechanical interlocking interface at the material junction using the scribe portion of the welding pin, resulting in promising joint strength. However, the hook-like morphology of the interface varies along the weld and is affected by different joining and tooling parameters. The research aims to understand the influence of hook interface morphology on joint strength and develop a predictive model based on key morphology parameters, thus advancing the application of this technique. [67].

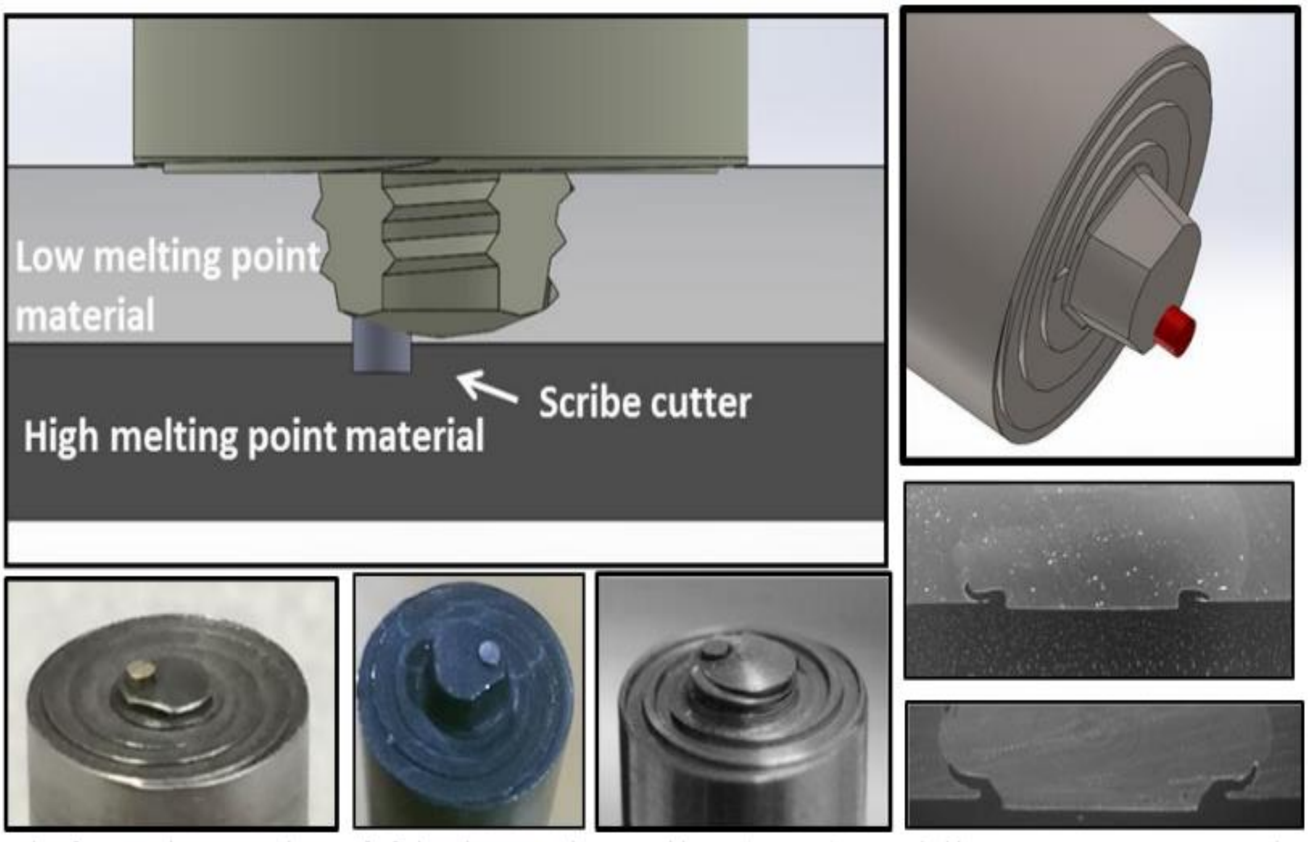

Figure 1.8 FSW tool plunged into dissimilar material lap joint

Friction stir welding (FSW) can join dissimilar materials in the solid state, making it suitable for lap welds between different metals. A recent study introduced a cutting scribe at the bottom of the FSW tool pin to create mechanical interlocks at the material interface. Researchers developed a thermo-mechanical model using a Coupled Eulerian-Lagrangian approach that accurately simulated the morphology of these interlocks during welding, validated experimentally. This modeling aids in predicting post-weld microstructure and joint strength, which is crucial for optimizing FSW parameters for diverse industrial applications. Overall, this work demonstrates how FSW can be utilized to lap weld dissimilar metals, with process modeling enabling further improvements[68].

Upadhyay et al. performed experimental study on the friction stir scribe welding as shown in Figure 1.9. The friction stir scribe (FSS) technique shows promise in joining materials with significantly different melting points, like Al to MS plate and polymer composites to metals. Developed by Pacific Northwest National Laboratory with support from the U.S. Department of Energy Vehicle Technologies Office and automotive stakeholders, FSS employs an offset cutting tool to create overlap joints with in situ mechanical interlocks. The study discussed welding trials, challenges, mitigation strategies, characterization, including mechanical properties and performance of welding [69].

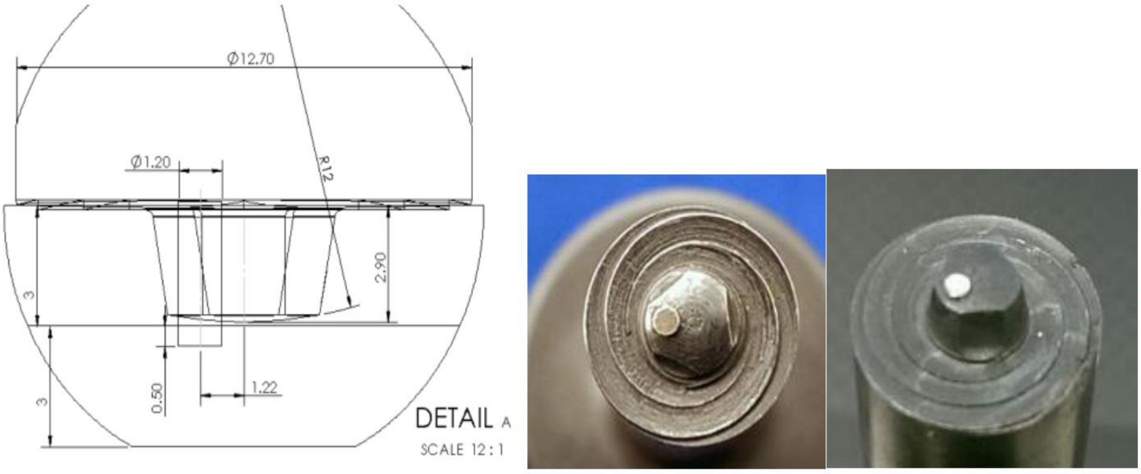

Figure 1.9. FSW tool (W-C-Co) applied for welding 1 mm thick AA6022 to 3 mm thick cast aluminum.

In a recent study, Kulkarni et al. used a friction stir-assisted scribe technique to join AZ31 Mg alloy to uncoated DP590 steel. They thoroughly characterized the resulting joint's properties and behavior using finite element modeling and electron microscopy. The researchers identified two primary factors contributing to joint strength - mechanical interlocking from hook-shaped features created by the scribe, and metallurgical bonding formed at the magnesium-steel interface. This study provides insights into joining dissimilar magnesium and steel alloys using this friction stir-based method.A computational model with a cohesive zone was used to quantify the contributions of these factors. A sensitivity analysis also evaluated the effect of hook geometry on joint strength. EDX analysis verified the formation of complex aluminum oxides at the interface, confirming metallurgical bonding between the materials. This multi-faceted approach provided insight into the bonding mechanisms enabling viable friction stir-assisted joints between magnesium alloy and steel. The mechanical interlocking and metallurgical bonding were both found to be critical for achieving sufficient joint strength [70].

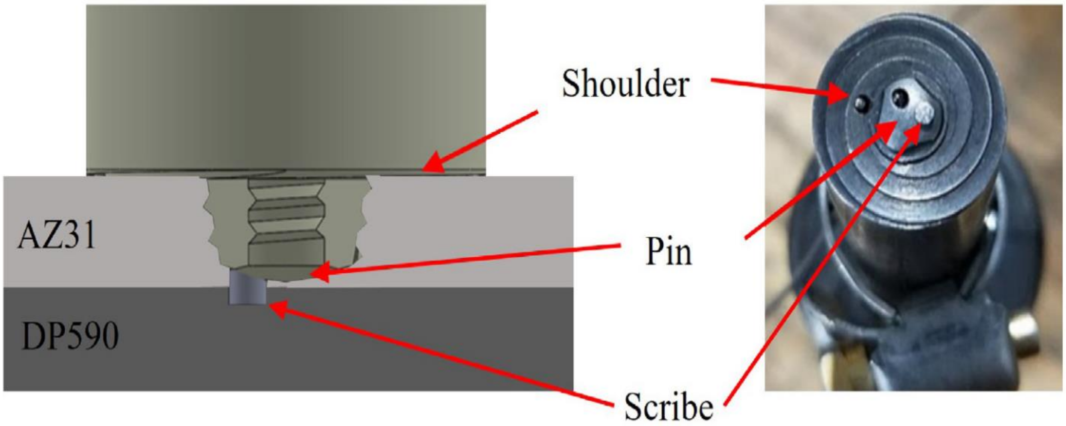

Figure 1.10 (a) Schematic view of FaST setup, (b) Scribe Tool Table

Syafiq et al. investigated the effect of welding parameters on temperature of welding during friction stir method of AA6061-T6 and S275JR mild steel. The study utilized thermocouples in the aluminum metal alloy plate to measure temperatures under different welding parameters. The appearance and defects of the joints were examined, including excessive flash, tunnels, and incomplete welding. These were caused by effects on material flow and heat generation. The highest temperature occurred with the greatest tool plunge depth, resulting from increased downward pressure. Microhardness profiles were similar across all joints, exhibiting a "plateau" of lower values corresponding to the thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). The plateau region was wider for larger tool plunge depths. The results demonstrate the effect of FSSW parameters like tool depth on temperatures, weld defects, and microstructural changes in aluminum-steel dissimilar joints[23].

Curtis et al. investigated friction stir scribe welding to join dissimilar aluminum and steel materials, which is increasingly desired in the automotive and aerospace sectors. Conventional fusion welding between aluminum and steel is challenging due to the formation of hard and brittle intermetallic compounds. FSSW aims to overcome these issues by utilizing a specialized tool to mechanically interlock the distinct materials without melting. This study explores the feasibility and characteristics of FSSW for aluminum-steel joints, given the growing demand for a robust dissimilar welding technique in high-performance applications.The research focuses on assessing the feasibility of using FSSW to join 1.0 mm thick 6022 Al and 0.7 mm electro-galvanized steel sheets in a dissimilar lap weld configuration. The study employs an H13 steel pin tool with a tungsten carbide scribe insert and examines the optimal size of the scribe insert, studying its impacts on mechanical properties and microstructure of the joints[71].

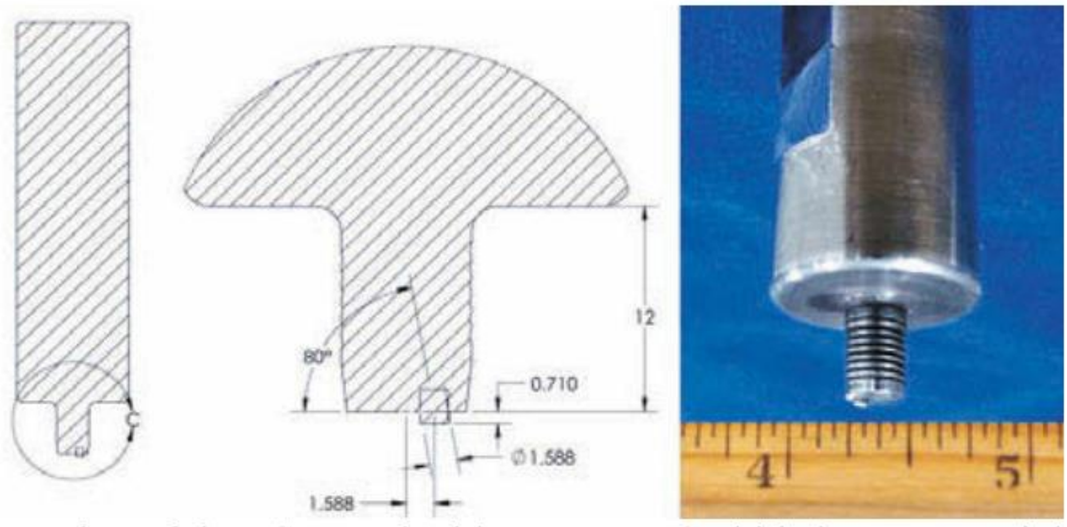

Figure 1.11 On the left is an illustration of the FSW tool, showcasing the Tungsten Carbide insert positioned in both straight and tilted orientations. On the right is a photograph of the actual tool utilized for welding, featuring a tilted scribe configuration.

Upadhyay et al. developed a novel variant of friction stir welding called friction stir scribe (FSS) to join dissimilar materials with large differences in melting points and high temperature flow properties. As shown in Figure 1.11, FSS incorporates a cutting feature on the pin of a traditional FSW tool. This allows the high melting point material to be mechanically scribed, creating an interlocking geometry between the dissimilar materials. The scribe cutter enables joining of materials that cannot be welded by conventional FSW alone. In this work, FSS was applied to join polymer materials like HDPE with aluminum alloy sheet. The research analyzed how the scribe feature shape and length affected the interlock and lap shear strength. FSS successfully produced welds between the polymer and aluminum. The scribe geometry strongly influenced the mechanical interlock and joint strength. This demonstrates the potential of FSS technology to expand friction stir welding to new dissimilar material pairs with very different properties[72].

Yuri et al. utilized friction stir scribe (FSS) technology to join dissimilar aluminum and steel materials with different melting temperatures. FSS uses a cutting feature on the pin tool to mechanically interlock the distinct materials. The researchers demonstrated the capability of FSS to produce aluminum-steel lap joints through both chemical and mechanical bonding. Lap shear testing showed the joint efficiency exceeded 75% of the bearing strength of the weaker joined material. They also implemented a non-rotating shoulder fixture with the FSS tooling. This reduced surface roughness compared to traditional FSW where the shoulder rotates. The study highlights the potential of FSS to join challenging material combinations like aluminum and steel. Key advantages include high joint strength and improved surface finish[73].

Wang et al. studied Friction Stir Scribetechnique to perform different material welding between aluminum metal and galvanized mild steel. They considered effects of welding parameters on hook height and joint strength, establishing a strong correlation between hook height and fracture position. Furthermore, the research delved into the impact of zinc coating on joint strength, shedding light on the overall performance and behavior of the FSS-welded joints in this novel dissimilar material joining application[18].

	Title of paper	Top and Bottom Plate	Shoulder and PIN material	Scribe Material	FSW Tools Dimension	Scribe height and Scribe offset	Welding Parameters
1	Friction stir scribe welding of dissimiliar Aluminum to steel Lap joints.	TOP - 6022 T4 Aluminum alloy sheets (1mm)	Shoulder and Pin : H13 tool Steel	Tungsten Carbide	Shoulder Diameter 9.5 mm	Height : 0.15 mm 0.23 mm	RPM : 1200
		Bottom : Low Carbon Electro galvanized mild steel Sheets (0.7mm)				offset : 1.5 mm	Travel Speed : 40PM Tool tilt : 0.5 degree
2	Linking process and structure in the friction stir scribe joining of dissimilar materilas: A computational approach with experimental support	TOP - 3.15mm 60-61 - T6 Aluminum	Shoulder and Pin : H13 tool Steel	Tungsten Carbide	Shoulder Diameter 12.17 mm	Height : 1.2 mm	RPM : 850
		Bottom : 1.8mm thick mid steel Sheets			Pin hieght: 2.7 mm Pin Diameter: 5mm	offset : 1.2 mm	Travel Speed : 500mm/min Plunge depth : 0.10mm
3	Evaluation of intermetallic compound layer at aluminum/steel interface	TOP - Aluminum alloy (1.0 mm)	Shoulder and Pin : H13 tool Steel	Cobalt Steel	Shoulder Diameter 12.8 mm	Height : 0.1 mm	RPM : 2000

	joined by friction stir scribe technology	Bottom : steel Sheets (1.2 mm)			Pin Diameter: 4.2mm	offset : 1.13 mm	Travel Speed : 1000mm/min 1500/mm/min 1700/mm/min Tool Tilt 0.5 degree
	Investigation of interfacial layer for friction stir scribe welded Aluminum to steel joints	TOP - Aluminum alloy (1.1 mm)	Shoulder and Pin : H13 tool Steel	Cobalt Steel	Shoulder Diameter 12.7 mm	Height : 0.32 mm	RPM : 1600
4		Bottom : steel Sheets (1.2 mm)			Pin Diameter: 4.2mm	offset : 1.1 mm	Travel Speed : 0.4 mm
	Friction stir scribe welding technique for dissimilar joining of aluminium and galvanised steel	TOP - 6022 - T4 Aluminum alloy Sheets (300 mm* 100mm *1mm)	Shoulder and Pin : H13 tool Steel	M42 Cobalt Steel	Shoulder Diameter 12.8 mm	Height : 0.3 mm	Rotation rate: range from (2000 to 2800) min-1
		Bottom : Electro galvanized mild steel Sheets (300mm * 100mm * 0.7mm)			Pin Height: 0.8mm	offset : 1.5 mm	Traverse Speed: range from (1000 to 2400) mm min-1
							Plunge depth : 1.10 to 1.20 (mm)
5							Tool kit : 0.5 degree

1.8 Conclusions and Future Scope

In conclusion, the studies on friction stir scribe weldingand friction stir welding have demonstrated their potential as innovative and efficient solid-state joining techniques for dissimilar materials, with particular relevance in the automotive and aerospace industries.By employing modified tool pins and a stirring process, FSSW creates localized deformation and mechanical interlocks, resulting in overlap joints with enhanced strength and integrity. Researchers have investigated various welding parameters' effects, such as traverse speed and plunge depth, revealing insights into optimizing joint strength. FSW and FSSW exhibit both mechanical interlocking and interfacial bonding, contributing to the formation of hook-like structures with intermetallic compounds, which enhance joint mechanical properties. These advancements hold potential for achieving energy savings and lightweighting objectives in diverse engineering applications, making them vital for addressing the growing demand for diverse material combinations in modern industries. The continuous development and optimization of FSSW and FSW will drive innovation and contribute to superior product design and performance across various industrial sectors.

The future scope for friction stir scribe welding (FSSW) holds immense potential in advancing the field of dissimilar material joining. Optimizing welding parameters for specific material combinations and joint configurations will be crucial for achieving superior joint strength and quality. Further exploration of a wider range of dissimilar material combinations and the development of automated systems can enhance the practicality and adoption of these techniques in industrial settings. Understanding and mitigating weld defects, such as tunneling and flash formation, will be important for ensuring consistent and reliable joint quality. Additionally, advanced characterization techniques and hybrid approaches that combine FSSW or FSW with other joining methods can lead to novel and improved joining techniques. The industrial applications of FSSW and FSW, particularly in automotive, aerospace, and maritime sectors, will validate their practicality and economic viability, while a focus on sustainable joining practices can align them with environmentally friendly manufacturing trends. The continuous development and exploration of these solid-state joining techniques hold the potential to revolutionize dissimilar material joining and drive innovation across various engineering applications.

References

[1] Rai R, De A, Bhadeshia HKDH., et al. Review: Friction stir welding tools. Sci Technol Weld Join. 2011;16:325–342.

[2] Kumar N, Yuan W, Mishra RS. Introduction. Frict Stir Weld Dissimilar Alloy Mater. 2015;1–13.

[3] Martinsen K, Hu SJ, Carlson BE. Joining of dissimilar materials. CIRP Ann - Manuf Technol. 2015;64:679–699.

[4] Ferreira FB, Felice I, Brito I, et al. A Review of Orbital Friction Stir Welding. Metals (Basel). 2023;13:1055.

[5] Mehta KP. A review on friction-based joining of dissimilar aluminum-steel joints. J Mater Res. 2019;34:78–96.

[6] Rajendran C, Srinivasan K, Balasubramanian V, et al. Effect of tool tilt angle on strength and microstructural characteristics of friction stir welded lap joints of AA2014-T6 aluminum alloy. Trans Nonferrous Met Soc China (English Ed. 2019;29:1824–1835.

[7] Saeed M, Khan MU. Mechanical characterization of friction stir welded joint of dissimilar aluminum alloys AA6061and AA7050. Int J Res Eng Innov. 2021;05:236–243.

[8] Gupta V, Upadhyay P, Fifield LS, et al. Linking process and structure in the friction stir scribe joining of dissimilar materials: A computational approach with experimental support. J Manuf Process. 2018;32:615–624.

[9] Prabhakar DAP, Shettigar AK, Herbert MA, et al. A comprehensive review of friction stir techniques in structural materials and alloys: challenges and trends. J Mater Res Technol [Internet]. 2022;20:3025–3060. Available from: https://doi.org/10.1016/j.jmrt.2022.08.034.

[10] Kumar N, Yuan W, Mishra RS. Friction Stir Welding of Dissimilar Alloys. Frict Stir Weld Dissimilar Alloy Mater. 2015;319:43–69.

[11] Kumar N, Yuan W, Mishra RS. A Framework for Friction Stir Welding of Dissimilar Alloys and Materials. Frict Stir Weld Dissimilar Alloy Mater. 2015;15–33.

[12] Beygi R, Galvão I, Akhavan-Safar A, et al. Effect of Alloying Elements on Intermetallic Formation during Friction Stir Welding of Dissimilar Metals: A Critical Review on Aluminum/Steel. Metals (Basel). 2023;13.

[13] Ahmed MMZ, Seleman MME, Albaijan I, et al. Stir Spot-Welded AA5052-H32 : Influence of Tool Rotation Rate. Materials (Basel). 2023;16:1–24.

[14] Cook R, Handboy T, Fox SL, et al. 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. 2005;35–42.

[15] Kaygusuz E, Karaomerlioglu F, Akinci S. A review of friction stir welding parameters, process and application fields. Turkish J Eng. 2023;7:286–295.

[16] Hassan HA. Study friction stir welding regions of similar (AA6061-T6) aluminum alloys. Int J Mech Eng Technol. 2018;9:1535–1546.

[17] Di Bella G, Favaloro F, Borsellino C. Effect of Process Parameters on Friction Stir Welded Joints between Dissimilar Aluminum Alloys: A Review. Metals (Basel). 2023;13:1176.

[18] Wang T, Sidhar H, Mishra RS, et al. Friction stir scribe welding technique for dissimilar joining of aluminium and galvanised steel. Sci Technol Weld Join. 2018;23:249–255.

[19] Dias F, Cipriano G, Correia AN, et al. Joining of Aluminum Alloy AA7075 and Titanium Alloy Ti-6Al-4V through a Friction Stir Welding-Based Process. Metals (Basel). 2023;13.

[20] Balos S, Labus Zlatanovic D, Kulundzic N, et al. Influence of Tool–Base Metal Interference on the Performance of an Aluminium–Magnesium Alloy Joined via Bobbin Tool Friction Stir Welding. Metals (Basel). 2023;13:1215.

[21] Shen Z, Chen Y, Haghshenas M, et al. Role of welding parameters on interfacial bonding in dissimilar steel/aluminum friction stir welds. Eng Sci Technol an Int J [Internet]. 2015;18:270–277. Available from: http://dx.doi.org/10.1016/j.jestch.2014.12.008.

[22] Gite RA, Loharkar PK, Shimpi R. Friction stir welding parameters and application: A review. Mater Today Proc [Internet]. 2019;19:361–365. Available from: https://doi.org/10.1016/j.matpr.2019.07.613.

[23] Syafiq WM, Afendi M, Mazlee MN. Influence of friction stir welding parameters on joint defects, temperature and hardness of AA6061-T6 and S27JR mild steel FSW joint. J Phys Conf Ser. 2021;2051.

[24] Dwivedi U, Tiwari S, Mishra A, et al. Comparative Study of Weld Characteristics of Friction Stir Welded Joints on Aluminium 7075 with Autogenous TIG. Mater Today Proc. 2020;22:2532–2538.

[25] Malarvizhi S, Balasubramanian V. Effect of welding processes on AA2219 aluminium alloy joint properties. Trans Nonferrous Met Soc China. 2011;21:962–973.

[26] Carlone P, Astarita A, Rubino F, et al. Microstructural Aspects in FSW and TIG Welding of Cast ZE41A Magnesium Alloy. Metall Mater Trans B [Internet]. 2016;47:1340–1346. Available from: https://doi.org/10.1007/s11663-015-0536-2.

[27] Rajakumar S, Balasubramanian V, Razalrose A. Friction stir and pulsed current gas metal arc welding of AZ61A magnesium alloy: A comparative study. Mater Des [Internet]. 2013;49:267–278. Available from: http://dx.doi.org/10.1016/j.matdes.2013.01.051.

[28] Luo Z, Sun Y, Li W, et al. Evolution of Microstructures, Texture and Mechanical Properties of Al-Mg-Si-Cu Alloy under Different Welding Speeds during Friction Stir Welding. Metals (Basel). 2023;13:1120.

[29] Ericsson M, Sandström R. Influence of welding speed on the fatigue of friction stir welds, and comparison with MIG and TIG. Int J Fatigue. 2003;25:1379–1387.

[30] Dehghani M, Amadeh A, Akbari Mousavi SAA. Investigations on the effects of friction stir welding parameters on intermetallic and defect formation in joining aluminum alloy to mild steel [Internet]. Mater. Des. Elsevier Ltd; 2013. Available from: http://dx.doi.org/10.1016/j.matdes.2013.01.013.

[31] Chen K, Liu X, Ni J. Effects of process parameters on friction stir spot welding of aluminum alloy to

advanced high-strength steel. J Manuf Sci Eng Trans ASME. 2017;139.

[32] Asmare A, Al-Sabur R, Messele E. Experimental investigation of friction stir welding on 6061-t6 aluminum alloy using taguchi-based gra. Metals (Basel). 2020;10:1–21.

[33] Liu X, Chen G, Ni J, et al. Computational Fluid Dynamics Modeling on Steady-State Friction Stir Welding of Aluminum Alloy 6061 to TRIP Steel. J Manuf Sci Eng Trans ASME. 2017;139.

[34] Carlson BE, Ollett D, Kleinbaum S. Final Technical Report-Friction Stir Scribe Joining of Carbon Fiber Reinforced Polymer (CFRP) to Aluminum (General Motors). 2016;

[35] Carlson BE, Ollett D, Kleinbaum S. Friction Stir Scribe Joining of Carbon Fiber Reinforced Polymer (CFRP) to Aluminum. 2018; Available from: https://www.osti.gov/biblio/1464600.

[36] Upadhyay P, Reynolds AP. Effects of forge axis force and backing plate thermal diffusivity on FSW of AA6056. Mater Sci Eng A [Internet]. 2012;558:394–402. Available from: http://dx.doi.org/10.1016/j.msea.2012.08.018.

[37] Kalemba-Rec I, Kopyściański M, Miara D, et al. Effect of process parameters on mechanical properties of friction stir welded dissimilar 7075-T651 and 5083-H111 aluminum alloys. Int J Adv Manuf Technol. 2018;97:2767–2779.

[38] Chumaevskii A, Amirov A, Ivanov A, et al. Friction Stir Welding/Processing of Various Metals with Working Tools of Different Materials and Its Peculiarities for Titanium Alloys: A Review. Metals (Basel). 2023;13.

[39] Lin PT, Wu CS, Peng CH, et al. Effects of rotational speed on the Al0.3CoCrCu0.3FeNi high-entropy alloy by friction stir welding. High Temp Mater Process [Internet]. 2020 [cited 2023 Jul 17];39:556–566. Available from: https://tohoku.elsevierpure.com/en/publications/effects-of-rotational-speed-on-the-alsub03subcocrcusub03subfeni-h/fingerprints/.

[40] Giorjão RAR, Pereira VF, Terada M, et al. Microstructure and mechanical properties of friction stir welded 8 mm pipe SAF 2507 super duplex stainless steel. J Mater Res Technol [Internet]. 2019;8:243–249. Available from: https://doi.org/10.1016/j.jmrt.2018.01.002.

[41] Ramesh R, Dinaharan I, Kumar R, et al. Microstructure and mechanical characterization of friction stir welded high strength low alloy steels. Mater Sci Eng A. 2017;687:39–46.

[42] Mohammed R, Madhusudhan Reddy G, Srinivasa Rao K. Welding of nickel free high nitrogen stainless steel: Microstructure and mechanical properties. Def Technol. 2017;13:59–71.

[43] Küçükömeroğlu T, Şentürk E, Kara L, et al. Microstructural and Mechanical Properties of Friction Stir Welded Nickel-Aluminum Bronze (NAB) Alloy. J Mater Eng Perform [Internet]. 2016;25:320–326. Available from: https://doi.org/10.1007/s11665-015-1838-x.

[44] Barnes SJ, Bhatti AR, Steuwer A, et al. Friction Stir Welding in HSLA-65 Steel: Part I. Influence of Weld Speed and Tool Material on Microstructural Development. Metall Mater Trans A [Internet]. 2012;43:2342–2355. Available from: https://doi.org/10.1007/s11661-012-1110-z.

[45] Saeid T, Abdollah-zadeh A, Assadi H, et al. Effect of friction stir welding speed on the microstructure and mechanical properties of a duplex stainless steel. Mater Sci Eng A. 2008;496:262–268.

[46] Ye F, Fujii H, Tsumura T, et al. Friction stir welding of Inconel alloy 600. J Mater Sci. 2006;41:5376–5379.

[47] Chen CM, Kovacevic R. Joining of Al 6061 alloy to AISI 1018 steel by combined effects of fusion and solid state welding. Int J Mach Tools Manuf. 2004;44:1205–1214.

[48] Ozekcin A, Jin H-W, Koo J, et al. A Microstructural Study of Friction Stir Welded Joints of Carbon Steels.

Int J Offshore Polar Eng. 2004;14.

[49] Isa MSM, Moghadasi K, Ariffin MA, et al. Recent research progress in friction stir welding of aluminium and copper dissimilar joint: a review. J Mater Res Technol [Internet]. 2021;15:2735–2780. Available from: https://doi.org/10.1016/j.jmrt.2021.09.037.

[50] Liu X, Lan S, Ni J. Analysis of process parameters effects on friction stir welding of dissimilar aluminum alloy to advanced high strength steel. Mater Des [Internet]. 2014;59:50–62. Available from: http://dx.doi.org/10.1016/j.matdes.2014.02.003.

[51] Zheng Q, Feng X, Shen Y, et al. Dissimilar friction stir welding of 6061 Al to 316 stainless steel using Zn as a filler metal. J Alloys Compd [Internet]. 2016;686:693–701. Available from: http://dx.doi.org/10.1016/j.jallcom.2016.06.092.

[52] Jedrasiak P, Shercliff HR, Reilly A, et al. Thermal Modeling of Al-Al and Al-Steel Friction Stir Spot Welding. J Mater Eng Perform. 2016;25:4089–4098.

[53] Justman R, West M. Friction Stir Lap Welding Aluminum to Steel Using Scribe Technology. 2013;

[54] Zlatanovic DL, Balos S, Bergmann JP, et al. Influence of tool geometry and process parameters on the properties of friction stir spot welded multiple (Aa 5754 h111) aluminium sheets. Materials (Basel). 2021;14:1–26.

[55] Alkhafaji A, Camas D, Lopez-Crespo P, et al. The Influence of Tool Geometry on the Mechanical Properties and the Microstructure of AA6061-T6 Aluminum Alloy Friction Stir Spot Welding. Materials (Basel). 2023;16.

[56] Movahedi M, Kokabi AH, Seyed Reihani SM, et al. Effect of tool travel and rotation speeds on weld zone defects and joint strength of aluminium steel lap joints made by friction stir welding. Sci Technol Weld Join. 2012;17:162–167.

[57] Long L, Chen G, Zhang S, et al. Finite-element analysis of the tool tilt angle effect on the formation of friction stir welds. J Manuf Process. 2017;30:562–569.

[58] Rajendran C, Srinivasan K, Balasubramanian V, et al. Effect of tool tilt angle on strength and microstructural characteristics of friction stir welded lap joints of AA2014-T6 aluminum alloy. Trans Nonferrous Met Soc China (English Ed [Internet]. 2019;29:1824–1835. Available from: http://dx.doi.org/10.1016/S1003-6326(19)65090-9.

[59] Correia AN, Santos PAM, Braga DFO, et al. Effects of Friction Stir Welding Process Control and Tool Penetration on Mechanical Strength and Morphology of Dissimilar Aluminum-to-Polymer Joints. J Manuf Mater Process. 2023;7:106.

[60] Abdullah ME, M. Rohim MN, Mohammed MM, et al. Effects of Partial-Contact Tool Tilt Angle on Friction Stir Welded AA1050 Aluminum Joint Properties. Materials (Basel). 2023;16.

[61] Wang X, Lados DA. Optimization of aluminum-to-steel friction stir lap welding for the fabrication of high-integrity structural components. J Adv Join Process [Internet]. 2022;5:100114. Available from: https://doi.org/10.1016/j.jajp.2022.100114.

[62] Cavaliere P, Squillace A, Panella F. Effect of welding parameters on mechanical and microstructural properties of AA6082 joints produced by friction stir welding. J Mater Process Technol. 2008;200:364–372.

[63] Kumar N, Yuan W, Mishra RS. Friction Stir Welding of Dissimilar Materials. Frict. Stir Weld. Dissimilar Alloy. Mater. 2015.

[64] Schwartz M. Friction stir welding. Innov Mater Manuf Fabr Environ Saf. 2010;87–122.

[65] Wang K, Upadhyay P, Wang Y, et al. Investigation of Interfacial Layer for Friction Stir Scribe Welded Aluminum to Steel Joints. J Manuf Sci Eng Trans ASME. 2018;140.

[66] Kulkarni SS, Gupta V, Ortiz A, et al. Determining cohesive parameters for modeling interfacial fracture in dissimilar-metal friction stir welded joints. Int J Solids Struct [Internet]. 2021;216:200–210. Available from: https://doi.org/10.1016/j.ijsolstr.2021.01.023.

[67] Barker EI, Upadhyay P, Hovanski Y, et al. Predicting Lap Shear Strength for Friction Stir Scribe Joining of Dissimilar Materials. Miner Met Mater Ser. 2017;261–267.

[68] Gupta V, Upadhyay P, Fifield LS, et al. Linking process and structure in the friction stir scribe joining of dissimilar materials: A computational approach with experimental support. J Manuf Process. 2018;32:615–624.

[69] Upadhyay P, Hovanski Y, Carlson B, et al. Joining Dissimilar Material Using Friction Stir Scribe Technique. Miner Met Mater Ser. 2017;147–155.

[70] Kulkarni SS, Das H, Tamayo DR, et al. A Combined Experimental and Modeling Approach to Investigate the Performance of Joint Between AZ31 Magnesium and Uncoated DP590 Steel Using Friction Stir-Assisted Scribe Technique. J Mater Eng Perform. 2021;30:8296–8308.

[71] Curtis T, Widener C, West M, et al. Friction stir scribe welding of dissimilar aluminum to steel lap joints. Frict Stir Weld Process VIII. 2016;163–169.

[72] Upadhyay P, Hovanski Y, Fifield LS, et al. Friction stir lap welding of aluminum - polymer using scribe technology. Frict Stir Weld Process VIII. 2016;153–161.

[73] Hovanski Y, Upadyay P, Kleinbaum S, et al. Enabling Dissimilar Material Joining Using Friction Stir Scribe Technology. Jom. 2017;69:1060–1064.