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REVIEW ARTICLE

Pilot Hole Study in Friction Stir Welding Processes: A Review

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ABSTRACT – This paper reviews the progress of research on the use of pilot holes in metal joints during welding, focusing on Friction Stir Welding and Friction Stir Spot Welding (FSSW) processes. The impact of pilot holes on the mechanical behaviour and macrostructure of metal joints under various welding conditions was thoroughly evaluated. The incorporation of pilot holes in FSSW processes, particularly for similar aluminum alloy joints, can increase mechanical performance by up to 50%. This technique also enhances tool longevity, improves joint quality, and optimizes surface finish. Several factors influenced by pilot hole optimisation are discussed, including the significance of the pilot-hole-to-keyhole (PTK) diameter ratio. Notably, pilot holes with a PTK ratio below 1 have demonstrated superior results. In dissimilar material FSSW, pilot hole conditions significantly influence material flow and intermixing, thereby affecting joint strength. Additionally, the diameter of the pilot hole plays a critical role in the welding process, significantly affecting joint integrity. Based on these findings, several recommendations are offered to guide future research and application in this field, including an exploration of the relationship between the PTK ratio and its influence on material flow to enhance mechanical performance and joint quality.

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1. INTRODUCTION

Welding is the process of joining two or more parts of a material by applying heat and/or pressure, forming a joint as the parts cool [1]. There are two primary types of welding: fusion welding and solid-state welding. Fusion welding involves melting the two parts to be joined, typically with the addition of a filler metal, to create coalescence. In contrast, solid-state welding uses heat or pressure to join parts without melting the material or adding a filler metal [2][3]. Friction Welding (FRW) is a solid-state welding technique that includes four primary processes: Friction Stir Welding (FSW), Friction Stir Spot Welding (FSSW), linear friction welding, and rotary friction welding [4][5]. One of the most commonly used processes is FSW owing to its versatile application, automation capabilities, and high metal joining rate. This process is mostly used to join aluminium alloys [6].

Thomas et al. from 'The Welding Institute' in England originally developed FSW in 1991 [7]. It has gained wide recognition as a pioneering technique for bonding a diverse range of materials, including metals, ceramics, and polymers, and for joining different materials together to form dissimilar joints [7][8]. Figure 1 shows the schematic diagram of the FSW process.

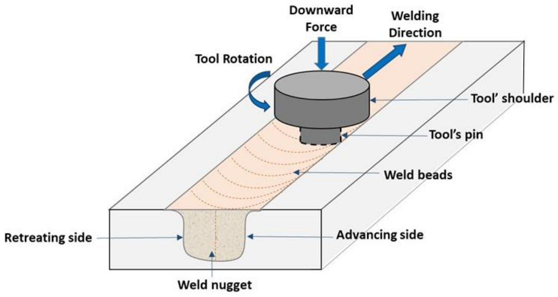

Figure 1. Schematic diagram of the friction stir welding

No external heat source is utilized during the FRW process; instead, the connection forms as a result of frictional heat generated along the tool's length and plastic deformation at the interface surfaces under high pressure. Throughout the welding process, the heat generated by the friction of the tool's rapid rotation makes it possible for the tool pin to plunge slowly through the thickness of the workpiece, subsequently moving linearly to join the two workpieces together [7][9]. However, excessive force and heat may occur due to the high-pressure force used to produce metal-to-metal joints [9][10]. The outcome may lead to the emergence of defects and lower mechanical properties in the workpiece while also diminishing the lifespan of the tool [10][11]. Consequently, one of the most effective ways to reduce the amount of excessive force and heat during the process is by making a preexisting pilot hole since it is designed to reduce the force imposed on the tool [11][12]. The pilot hole also known as a pre-hole or clearance hole is a through hole usually made or machined at the beginning of a weld [13].

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Table 1. Pilot hole optimisation in chronological order from 2013 to 2023 [18-37]

No.	Authors	Year	Method	Material and Thickness (mm)	Parameter	Findings
1	Amit Kumar Sinha [18]	2013	Laser Welding	Galvanized Steel (1.4 & 1.8)	Heat and gas input	Pilot holes are used to prevent welding defects such as porosity and spatter caused by the accumulation of zinc vapor.
2	Yunxia Huang [19]	2013	Friction Stir Welding	Aluminium (5)	Tool material Tool dip angle	New self-support FSW eliminates root flaws, adapts to thickness variations, and does not require predrilled pilot holes or backing bars.
3	Jingjing Li [20]	2014	Ultrasonic welding, friction stir blind riveting and Frictions stir spot welding	Aluminium (3), copper (1) and magnesium (1)	Dwell time Welding method	Pilot hole size influences the formation of IMC at the interface between dissimilar materials in friction-stir-forming joints
4	Galya Duncheva [21]	2015	Welding and mandrel cold working method	S355 steel welded stiffened plate (3)	PTK = (< 1) Interference fit Working scheme	The study focused on the use of cold working on pre-drilled holes in noncircular openings' corners welded steel plates.
5	Xinjiang Fei [22]	2016	Laser-assisted FSW	Q235 steel (3) and 6061-T6 aluminium alloy (3)	PTK = (< 1) Laser power Rotational speed Transverse speed	Optimal pilot hole offset distance is crucial for joint strength and inter-metallic compound formation.
6	Hossein Karami [23]	2017	Threaded Hole Friction Spot Welding (THFSW)	AA5052 Aluminium (2) Polymer composite hybrid (2)	PTK = (< 1) Melt flow index Thermal conductivity Rotational speed Dwell time Temperature	Pilot holes help achieve robust mounting, enough joint strength, and complete filling of the hole with melt polymer when using THFSW
7	Andre Carlos Ferreira Silva [24]	2017	Friction Stir Welding	Aluminium alloy (3)	PTK = (< 1) Thermocouple Rotational speed Transverse speed Axial force Tool design	Using pilot holes for temperature measurement on small FSW tools is risky.
8	Moslem Paidar [25]	2019	Friction-Stir-Spot-Welding (FSSW)	AA2219 (1.7) and PP-C30S Sheets (2)	PTK = (< 1) Rotational speed Dwell time Tool design Plunge depth	A suitable pilot hole size and tool shoulder design contributed to the improved fracture load of the weld.

Table 1. (cont.)

No.	Authors	Year	Method	Material and Thickness (mm)	Parameter	Findings
9	Oluwaseun John Dada [26]	2020	Friction stir welding	AA5083-H111 (2.8)	Rotational speed Transverse speed Tool shoulder design	The presence of a pilot hole will help eliminate the pinhole at the weld nugget, significantly reducing tensile properties.
10	Tinu P. Saju [27]	2020	Dieless friction stir spot lap joining	AA 5050 H32 with AA 6061-T6 (0.93 to 2mm)	PTK = (< 1 >) Tool features Too; plunge depth Welding method Rotational speed	For joint formation to be successful, the stir tool's center and the pilot hole center had to be collinear.
11	Yang Gao [28]	2020	Pre-hole Friction Stir Spot Welding (PFSSW)	AA2219 (1.7) and AA3003 Sheets (1.5)	PTK = (< 1) Rotational speed Dwell time Plunge depth	PFSSW process leads to keyhole-free welds, excellent metallurgical bonding, and improved joint strength.
12	Joshi Gaurang [29]	2020	Friction Stir Welding	Copper (2) and Stainless Steel (2)	PTK = (> 1) Pre-heating current Cooling medium	A pilot hole reduces the load on the (FSW) tool during the plunge phase, increasing its reliability.
13	Moslem Paidar [30]	2021	Friction spot extrusion welding-brazing	AA5083-H112 aluminium alloy (1.5) and pure copper (2)	PTK = (< 1) Shoulder geometry Rotational speed Dwell time Plunge depth	The triangle shape tool's effect is better on pre-hole filling than the cylindrical shape tool.
14	Venkadesh Samykannu [31]	2021	Friction stir welding	AA2024 (6) and AA6061 (6)	PTK = (1) Rotational speed Transverse speed Pin diameter Shoulder diameter	A pilot hole formed at the end of the weld helps to prevent cracks and control excessive temperature distribution.
15	Miguel Costas [32]	2021	Flow-drill screw joints	AA6060-T6 (2.5) and AA6063-T4 (2)	PTK = (1) Pilot hole and joint configuration	A pilot hole can increase a connection's ductility and decrease its maximum shear force in loading conditions with a high shear force component.
16	Pabitra Maji [33]	2022	Friction stir welding	Al (6), Mg (6) and Cu alloys (6)	Tool material and geometry	A modified bobbin tool design effectively reduces root defects and torque exerted on the tool thus eliminating the need for pilot holes in FSW.

Table 1. (cont.)

No.	Authors	Year	Method	Material and Thickness (mm)	Parameter	Findings
17	Osamah Sabah Barrak [34]	2022	Friction Stir Spot Welding	Pure Copper (C11000) (2) and AA5052 (2)	PTK = (< 1) Rotational speed Pin inserting rate Dwell time Plunge depth Pilot hole diameter	The pre-hole in the plate was filled with aluminium, and the extruded copper in almost all of the joint samples showed that the heat and pressure of the friction process were sufficient for reliable filling.
18	Timo Nonnenmann [35]	2023	Friction-Stir-Spot-Welding (FSSW)	AlMg6–H18 (1.5) and a Mild Steel (1.5)	PTK = (< 1) Rotational speed Dwell time Tilt angle	The pre-drilled holes helped to relieve the pressure during the plunging stage and reduce the vibrations of the spinning tool.
19	Francisco Dias [36]	2023	Friction Stir Welding	AA7075 (3) and Ti-6Al-4V (2)	PTK = (< 1) Rotational speed Transverse speed Connection points	Pilot holes improved aluminium and titanium alloy joints and increased joint strength and reliability.
20	Qiaoying Zhou [37]	2023	Flow-drill screw and friction stir welding joints	AA6061-T6 (1.8) and DP590 high strength steel plates (2.7)	PTK = (< 1 >) Rotational speed Axial force Torque Test Configuration	The pre-hole wall influenced the plastic strain distribution in the component, concentrating the equivalent plastic strain mostly on the left-side boss.

Accordingly, a drill operation is used to make a pilot hole, where a drill bit is used to make a circular hole on the workpiece. Besides reducing excessive force, this method also offers other benefits such as reducing the risk of delamination, which indirectly helps improve the surface finish, increase the tool life, and reduce the energy consumption in a joining process [13][14].

Table 1 highlights the recent progress of pilot hole optimization in various joining processes, mainly focusing on the FRW processes chronologically. The number of publications in this field has risen consistently over the past decade. Although the FSW process is one of the most popular in the FRW family, another joining method that utilizes the pilot hole technique is FSSW [5][15]. FSSW is a variant of FSW that rotates, plunges, and retracts a two-piece material in an overlapping configuration to create “spot" welds Figure 2. The tool has no linear movement through the part during FSSW [15]. Previous researchers in joining processes, especially in FSW and FSSW, have shown great interest and are studying the optimization of the pilot hole. This method suits many metal types well and combines dissimilar metals effectively [16][17]. Thus, Table 1 presents the papers related to the pilot hole optimization study in chronological order from 2013 to 2023.

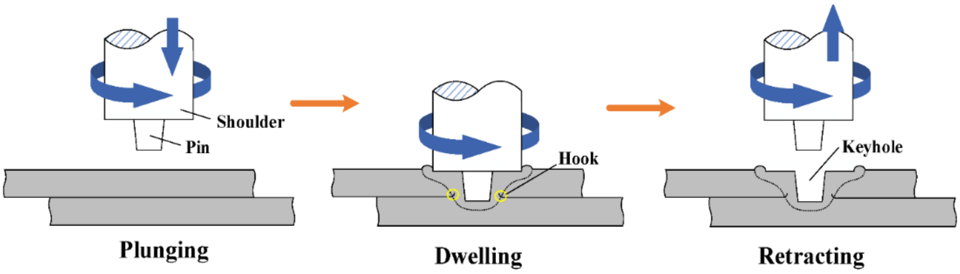


Figure 2. Schematic diagram of the FSSW process [38]

Based on the growing use of pilot-hole techniques in previous studies, thus this paper examines the advancements in pilot-hole research, their impact on the mechanical response and macrostructural changes of metal joints under various welding parameters, and the various aspects that can be enhanced by optimizing the pilot-hole diameter during the joining process. The scope of the review will mainly focus on implementing pilot holes in FSW and FSSW processes. This paper examines, in a critical manner, the impact of welding parameters on various process variables and material properties, while also providing recommendations for future research.

2. PILOT HOLE DIAMETER AND ITS VARIATION

As mentioned earlier, a pilot hole is drilled before the welding process, where the initial plunging stage of the rotating tool will be made. Conventionally, no pilot hole is pre-drilled, imposing a large downward force from the tool during its plunging stage [39][40]. Once the temperature of the workpiece has been elevated due to the frictional heat, the plasticized workpiece is gradually extruded from the top until the tool pin completely penetrates the workpiece, creating a permanent keyhole. The keyhole follows the shape and diameter of the tool pin [41][42].

The pilot hole technique is utilized to mitigate the large force and excessive heat generation. Several works report that the diameter of the pilot hole could influence the welding outcome [32][43]. Previous work conducted by J. C. Roukema et al. examined the stability of the drilling process with various parameters including pilot hole diameters ranging from 4mm to 12mm by using a drill with a diameter of 16 mm [44]. To clarify, the pilot holes are not drilled using the 16 mm bit. Instead, smaller drill bits are employed to create pilot holes of various sizes (4 mm, 8 mm, 10 mm, and 12 mm). These pilot holes are designed to ready the workpiece for the larger 16 mm drill bit. Using smaller bits to create these preliminary holes ensures that the 16 mm bit is properly guided and stabilized during the final drilling operation. The drill’s diameter continuously increased until it reached a steady state, matching the hole’s diameter. They found that a small pilot hole allowed for easier deflection but caused interference from the cutting lips near the hole. At the same time, the larger pilot holes will mostly interfere with the drill’s progress. Thus, the appropriate pilot hole size is vital since it affects the process and joint quality.

Correspondingly, prior studies by Tor et al. suggested that using a smaller pilot hole during the drilling operation helps to improve hole accuracy and lengthen the bit’s lifespan. While a relatively larger pilot hole could further reduce the plunging force and mitigate the wear of the tool pin, the pilot hole should not be too large to ensure no worm hole or void defects will form due to lack of plasticized material in the weld zone [43][45]. Although the use of pilot holes offered few advantages, improper selection of pilot hole criteria in FRW can reduce joint strength, create stress concentrations, and alter heat distribution. Consequently, it adds complexity, increases costs and generates material waste. Therefore, analyzing the optimal pilot hole-to-keyhole diameter (PTK) ratio from previous works is of utmost importance. Henceforth, a PTK ratio of one signifies that the pilot hole diameter is similar to the keyhole diameter. In contrast, a ratio larger than one or lower than one signifies that the pilot hole diameter is larger or lower than the keyhole diameter, respectively. Based on the study mentioned, a PTK ratio of <1 is suggested. The details of the PTK criteria selection or guideline will be discussed in the next few sections.

3. MECHANICAL AND MACROSTRUCTURAL ANALYSIS OF THE METAL JOINTS

A critical aspect when evaluating the influence of the pilot hole in the FRW process is its impact on the mechanical and microstructural properties of the welded joints [46][47]. Several aspects, such as surface finish and mechanical performance, will be discussed below. Those effects are interconnected with metallurgical changes that directly influence mechanical properties, and the optimal pilot hole diameter balances these factors for specific materials and applications.

3.1 Surface Finish of the Joint

As shown in Figure 3, K. Kimapong and T. Watanabe conducted the FSW process with various pilot hole diameters from 10 mm to 20 mm on the aluminium plate [48]. Illustrated in Figure 3(a), the surface appearance of the weld using a 1 PTK ratio showed a smooth surface with minimal defects. However, when 1.3 and 1.5 PTK ratios were used, an incomplete part occurred at the starting point, as seen in Figures 3(b) and 3(c). There was not enough agitated aluminium volume to form a weld at the starting point, consequently affecting the joint quality since the weld joint forms worm hole defects, which weakens the joint and make it more susceptible to fracture [48].

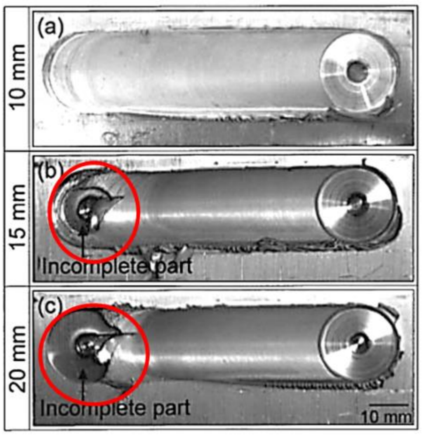
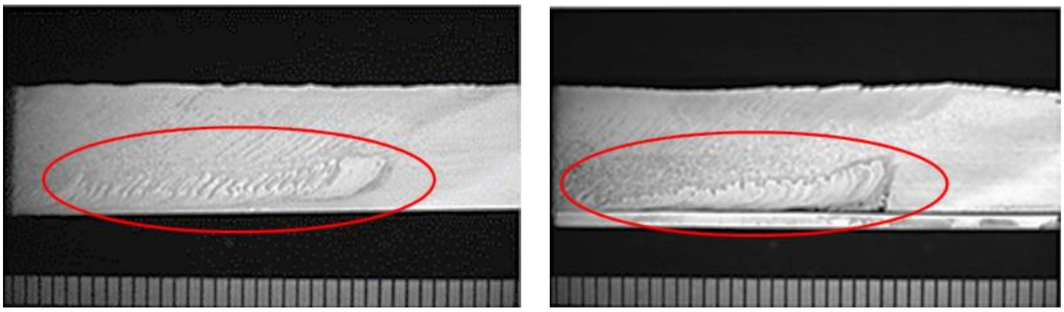


Figure 3. Surface finish of weld joint with different pilot hole sizes [48]

W. M. Thomas et al. also demonstrated that when a pilot hole is drilled smaller than the pin (<1 PTK ratio) depicted in Figure 4(a), sufficient backfilling of the hole can be accomplished. An incomplete backfilling is produced when a pilot hole with a diameter greater than the pin diameter (>1 PTK ratio), as Figure 4(b) [49] illustrates. It has also been demonstrated that the pilot hole plays a role in the plasticization-assisted filling process, which reduces external flash [49][50].



(a) (b)

Figure 4. Macrosections of backfilled pilot holes (a) Showing complete backfilling of a pilot hole with a hole smaller than the pin diameter, and (b) Showing partial backfilling of a pilot hole made with a hole slightly larger than the pin diameter [47]

3.2 Force and Torque

Force and torque are process variables strongly related to the FRW and friction drilling processes [12][51][52]. Figure 5 and Figure 6 show the comparison of the force induced during the friction drilling process with and without a pre-drilled pilot hole with 0.5 and 0.85 PTK ratio respectively [51]. The material used in the study is aluminium alloy. Both studies presented by the authors revealed that the pilot-hole setup plays a significant role in the force imposed on the setup. Mutually, pilot-hole samples facilitated the lowering of the initial plunging force up to 50% compared to those without a pilot hole [49, 50, 52]. Since torque and force are directly proportional, the torque imposed during the process will also decrease, potentially enhancing tool and machine life [12][51][53][54].

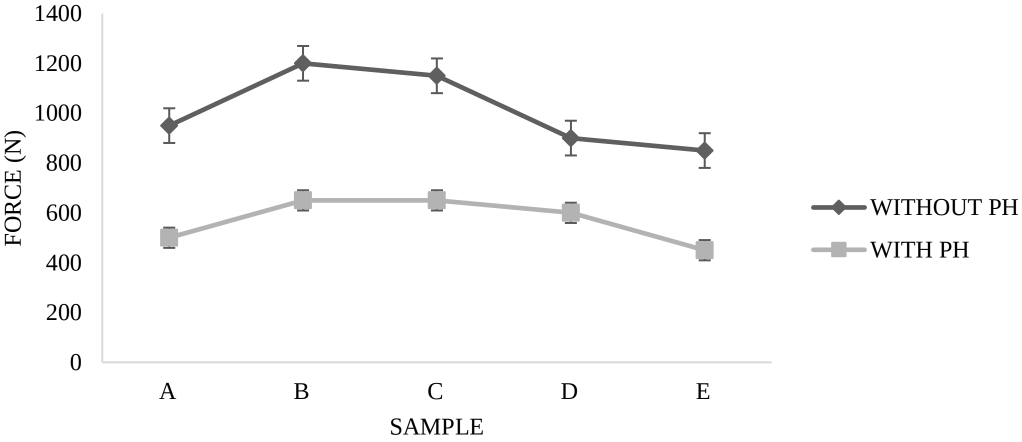


Figure 5. Comparison of force with and without pre-drilled pilot hole

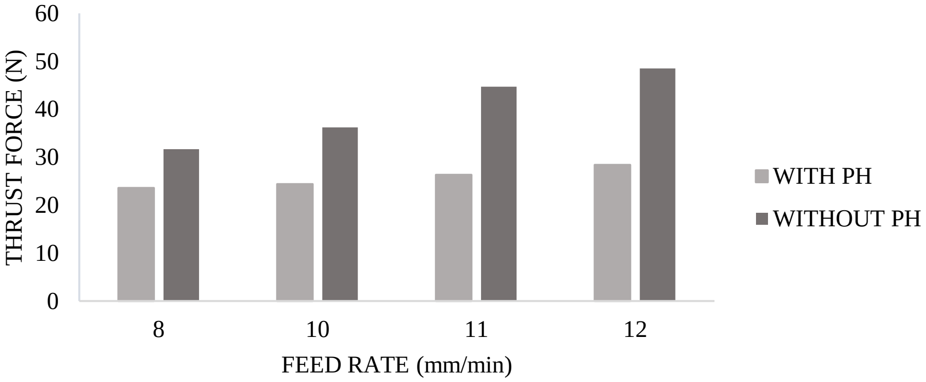


Figure 6. Comparison of force with and without pre-drilled pilot holes

3.3 Shear Strength and Elongation

Miguel Costas et al. have thoroughly studied the mechanical performance of a flow drill screw connection (FDS) between two aluminum plates with and without pilot holes [13]. The FDS process generates heat and experiences significant plastic deformation, similar to the FSW process. Both processes utilize the friction between the plates and tools to soften the material, pass through the workpiece, and form a sold or threaded connection. [37][55][56]. Therefore, mechanical performance testing on the FDS samples can also be used as a reference to compare the FSW process done towards aluminium plates with and without a pilot hole. Material behavior, microhardness, thermal cycle temperature, and microstructure of FSW compounds were measured and compared with FDS compounds. Although the process differs from FSW, the core principles of stress analysis and testing methods share similarities, particularly concerning the impact of various testing approaches or reinforcement strategies on mechanical properties like shear strength[13][14]. Figure 7 shows the force-displacement curve obtained from the FDS cross-shear experiment. Note that the original length of the specimen is 120 mm. The samples with pilot holes elongated more [13].

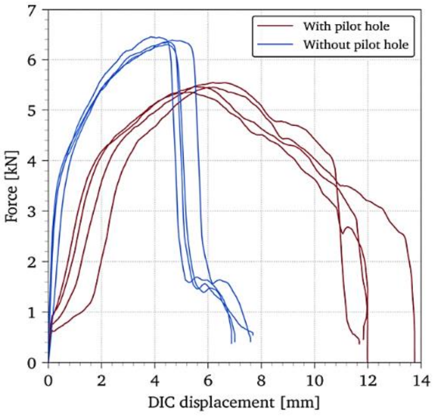


Figure 7. Force-displacement curves of FDS cross shear tests with and without pilot hole [13]

The works on FDS by Miguel Costas et al. involved two different aluminum plate joints with varying parameters such as the joint configuration and different test modes. To support the result shown in Figure 7, another experiment was conducted using a cross-joint configuration as illustrated in Figure 8. The joint samples underwent two loading angle tests: a mixed-mode test (Figure 9(a)) at 45 degrees and a normal shear test (Figure 9(b)). Every test was run at a steady crosshead speed of 5 mm/min. The data is presented in Table 2 and Figure 10.

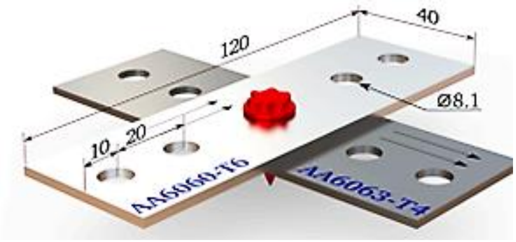
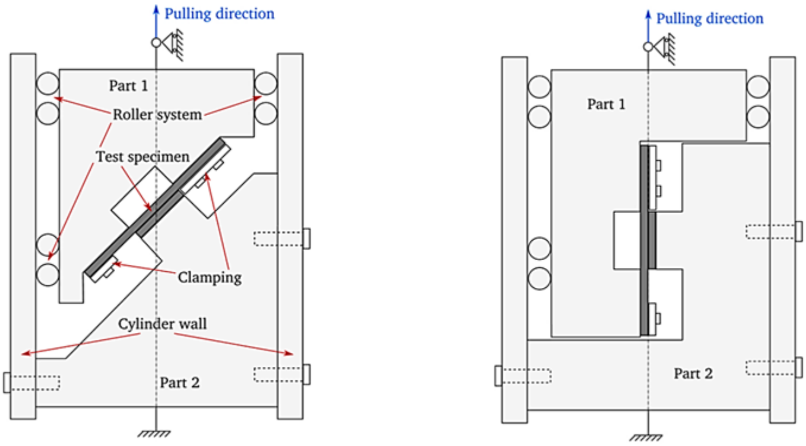


Figure 8. Cross-joint configuration [13]



(a) (b)

Figure 9. (a) Mixed mode test at 45 degrees and (b) normal shear test [13]

Table 2. Cross-joint shear test data

Sample	Test and Description	Elongation with Pilot Hole (mm)	Elongation without Pilot Hole (mm)
A	Normal Shear (center top plate)	20	14
B	Mixed Mode (center top plate)	20	10
C	Normal Shear (adjusted top plate position)	15	7
D	Mixed Mode (adjusted top plate position)	14	11

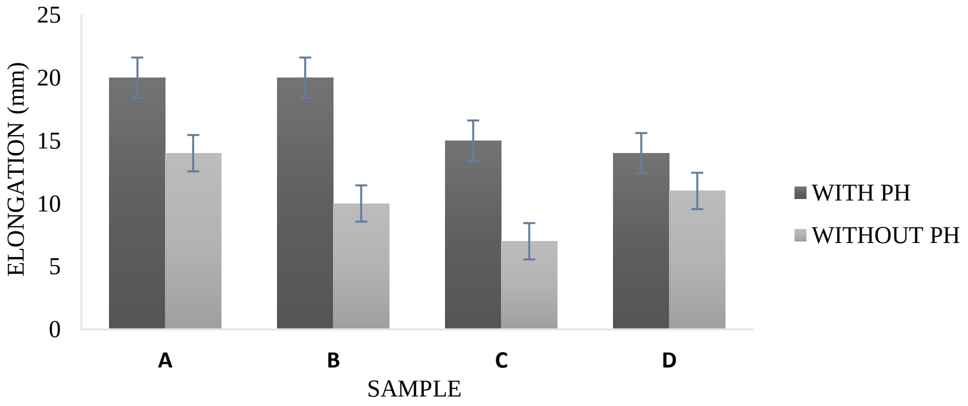


Figure 10. Cross-joint test with vs. without pilot hole

The findings demonstrate how the pilot hole affects the connection's mechanical performance. The specimens with a pilot hole using 0.6 PTK ratio experienced more elongation up to 53%, which showed higher ductility than those without it. This may be due to the hole's ability to hold the screw while it rotates. Since the increased flexibility of screw rotation is different due to its limitation, then the maximum force in the pilot hole design is less. The greater stiffness of the configuration in the experiment without the pilot hole produced a greater force, which eventually led to screw failure [13]. As mentioned earlier, the pilot hole proportionally contributes to the reduction of the external flash through the filling process, aided by plasticization [49][50][57][58]. According to works by Yang Gao et al., utilizing a 0.3 PTK ratio in the pre hole friction stir spot welding (PFSSW) procedure results in a bigger bonded region (stir zone), which may have an impact on the spot weld's shear strength [28].

As shown in Figure 11, they found that the shear strength of the weld produced between dissimilar AA2219 and AA3003 aluminium plates using the PFSSW process is much higher (156 MPa) than the weld made by the conventional FSSW process (103.56 MPa), with an increase up to 50.6 % elongation. It has been attributed to the mechanical interlocking and material mixing between these alloys [28].

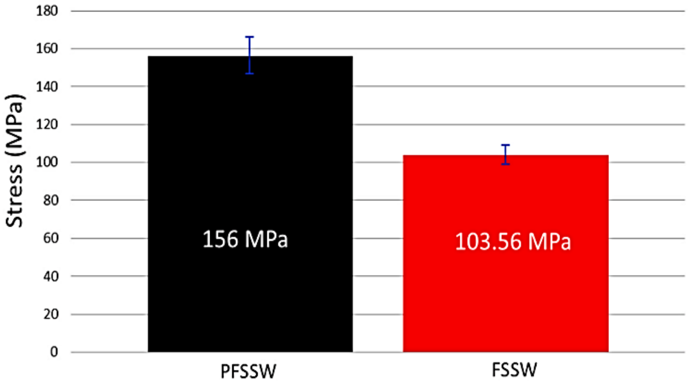


Figure 11. Comparison of PFSSW and FSSW shear strength [28]

On the other hand, Aliff et al. compared the shear strength between aluminium (AA7075) and magnesium (AZ31B) dissimilar joints using 1 PTK ratio under different pilot hole conditions [59]. The samples were stacked in a lap joint configuration, with the aluminium workpiece consistently on the top. Samples with the label 'ph' are workpieces that have been pre-drilled with a pilot hole. All tests were performed at a constant dwell time of 5 seconds and rotational speed of 1000 rpm. The data is tabulated in Table 3 and summarised in Figure 12.

Table 3. Summary of USS, Young's modulus, and standard deviation of all sample

Samples	Ultimate shear strength USS (MPa)
Al-Mg(ph)	187.62 ± 17.41
Al(ph)-Mg(ph)	190.72 ± 22.41
Al-Mg	160.58 ± 11.42
Al(ph)-Mg	168.53 ± 10.58

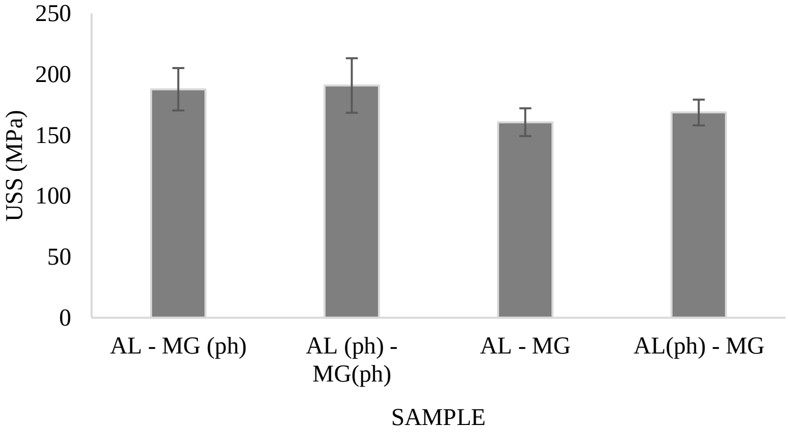


Figure 12. USS for different types of welding conditions

Based on the bar graph, the ultimate shear strength (USS) for aluminium magnesium (Al-Mg) dissimilar joints, the highest USS is 190.72 MPa. Other Al-Mg specimens also show approximately the same (USS) value, except for the aluminium magnesium joint, when no pilot hole was applied [59]. While the presence of pilot holes generally contributes to better mechanical properties for similar welds, the study shows that pilot holes can increase or decrease the USS based on the pilot hole condition (on both workpieces, only one or none at all).

To summarise, the effect of pilot holes with PTK ratios <1 on the mechanical properties of the load joint offers better mechanical performance than conventional joints. Shear strength for joints with a pilot hole has been increased up to 50% and experienced enhanced elongation of 56% compared to joints without a pilot hole [13][28][59].

3.4 Material Flow

In the case of FRW processes such as FSSW, the weld strength relies heavily on the material mixing to form mechanical interlocking between both materials [27]. The presence or absence of a pilot hole has been shown to affect the material flow of the weld zone. The study by Aliff et al. mentioned earlier examined the material intermixing of the specimens, comparing the specimens with the highest and lowest USS values. Figure 13 shows the macrostructure of weld zones for specimens produced where pilot holes have been pre-drilled in both (Al-Mg) plates. This condition facilitates the plunging process, i.e., lowering the plunging force helps the material intermix well during welding. Once proper material plasticisation and mixing are achieved, no voids or porosity are observed in the specimen producing high-quality joints with higher USS values [27][59][60][61]. For the specimen where the pilot hole is only drilled at the magnesium plate (Figure 14), there is only partial mixing, resulting in an incomplete consolidation. This leads to premature cracking and fracture during the shear test, resulting in the lowest USS value among all specimens. [59][62].

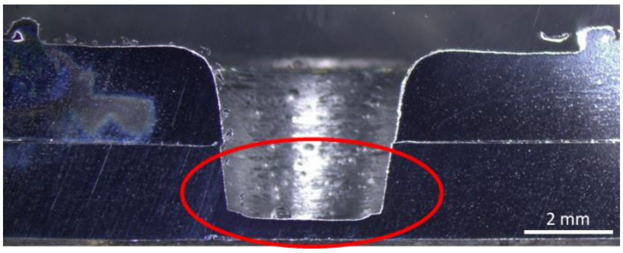


Figure 13. Macrosections of complete back-filled specimens with pilot holes at both plates

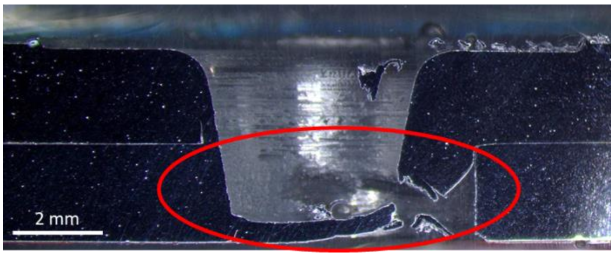


Figure 14. Macrosections of incomplete back-filled specimens with pilot holes at magnesium plate only

Prior studies by T. P. Sajua and R. G. Narayanan also examined the material flow using a pinless FSW joining process with various pilot hole diameters ranging from 2.5 mm to 5 mm with a few types of load performance tests [50]. Figure 15 provides a general overview of the macrostructure comparison for various hole diameters, highlighting distinctive zones and providing a schematic representation of the metal flow directions. As previously stated, joints are created when mechanical interlocking and metallurgical bonding coincide. The formation of an internal collar on the lower sheet metal, intended for pinless stir weld friction joining processes limits the production of extruded upper sheet metal. It affects the mechanical interlocking of the joint [50][63][64][65]. This occurs when the top sheet is plastically deformed owing to the stirring action and downward plunge of the tool. In contrast, the bottom sheet is plastically deformed owing to the transmitted frictional heat flow and tool impact force. Thus it was not completely penetrated since there was no tool pin. The central part of the junction shown in this section is formed by an extruded pin that surrounds the adhesive area between the two sheets.

In all loading performance analysis tests, the samples manufactured with a pilot hole diameter of 3 mm (Figure 15(b)) were found to have significant overall performance. Samples with a pilot hole diameter of 3 mm exhibit 95% of the greatest peel-breaking load recorded (1.05 kN), 83% of the maximum transverse tension-breaking load (2.89 kN), and 95% of the maximum tensile shear-breaking load (7.42 kN) [50]. The optimal mechanical performance was found from the macrostructural analysis at 2.5 mm pilot hole diameter samples (Figure 15 (a)). Since the hole is quite small, thus there is a noble chance for the pilot hole to close rapidly. The upper sheet material partially extended into the pre-drilled hole owing to the plastic deformation in the surrounding area. As a result, the metal that was extruded is separated from the top sheet. Thus, that particular specimen inhibits collar development and the ensuing pin formation [50].

Figure 15(b) shows a pin extruded from the upper sheet metal interlocks with collar growth within the joint, with a pilot-hole width of 3.5mm. Additionally, these joints have metallurgical bonding, and no hook defects are visible. Nevertheless, there is a lower chance of pre-drilled hole closure as the hole diameter increases. No major improvement was observed in the mechanical interlocking with a 5 mm pilot hole diameter [50] [66]. To summarise, elements such as the joint interface's substantial metallurgically bonded region and the potential of the hole closure are present due to macrostructure analysis. The extruded pin's neck grew along with the pilot hole diameter, indicating a lower probability of hole closure [50][67][68]. Nevertheless, the development of these internal joint features did not significantly boost strength when the pilot hole diameter was increased further, up to 5 mm [50].

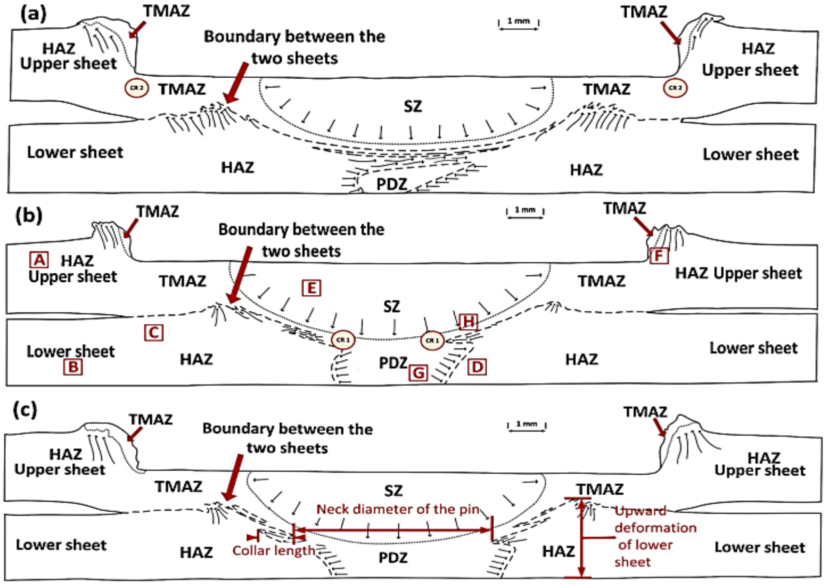


Figure 15. Schematic illustration of the cross-section of pinless friction joints at (a) 2.5 mm hole diameter, (b) 3.5 mm hole diameter, and (c) 5 mm hole diameter with direction of metal flow [50]

To conclude, the diameter of the pilot hole is critical for the mechanical and microstructure properties of dissimilar aluminum joints welded using FSW and FSSW [69]. In terms of mechanical properties, an optimal diameter maximizes tensile strength, while deviations reduce joint strength. Yield strength is influenced by heat input and material flow, both affected by hole size. Ductility depends on the level of plastic deformation during welding, and fatigue resistance relates to stress concentrations and residual stresses, which vary with hole diameter [70][71]. Hardness distribution across the weld zone changes with heat input and cooling rates, while toughness is modified by the microstructural changes due to different pilot hole sizes. The residual stress distribution is also impacted by hole size, affecting heat distribution and material flow during welding [72][73].

The diameter of the pilot hole also significantly influences the metallurgical properties of dissimilar aluminum joints in FSSW. Smaller holes result in finer grains due to increased forging, whereas larger holes produce coarser grains. The heat-affected zone (HAZ) is impacted by hole diameter, which controls heat generation and distribution [74][75]. Recrystallization of the weld region occurs with heat input, with hole size affecting the type of recrystallization. Hole size also affects cooling rates, influencing phase transformations and precipitation in the alloy. The formation of intermetallic compounds is governed by interface temperatures and materials, both related to hole size [76][77]. Those effects are interconnected with changes in the metallurgical properties that often directly influence the mechanical properties. The optimal pilot hole diameter aims to balance these factors for specific materials and application requirements.

4. RELATIONSHIP BETWEEN PILOT HOLE RATIO AND JOINT EFFICIENCY

T. P. Sajua and R. G. Narayanan analyzed the relationship between the pilot hole ratio and joint efficiency by using a few FRW methods. Researchers found that the optimal mechanical performance and macrostructure analysis occurred when the pilot hole size was between 0.2 and 0.3 PTK ratio, with an average pilot hole diameter 75% smaller than the tool diameter, resulting in successful overall performance [50].

The larger size of the pilot hole compared to the tool or diameter with a 1.5 PTK ratio was not too effective due to severe frictional heat generation during the plunging or welding process which led to incomplete welding or voids. Smaller or equal-sized pilot holes, compared to the tool diameter range from 0.8 to 1 PTK ratio offer better performance where the joint efficiency can reach up to 50% [50][59][61][78]. On the other hand, few studies have used pinless tools during the pinhole-assisted welding process, and the results show that joint efficiency reaches up to 90% [50][79][80][81]. Although it offers high joint efficiency, using a pinless tool during the welding process needs extra attention, especially during the dwelling stage of the stir tool. Proper control of dwelling and plunging processes can prevent rapid plastic deformation and severe frictional heat generation in dieless friction-stir lap (DFSL) joints, potentially causing damage to mechanical interlocking and metallurgy bonding [50]. It is thus evident that, while adding pilot holes offers better performance compared to conventional FSW and FSSW, the PTK ratio is one of the parameters that should be considered and chosen wisely.

5. RELATIONSHIP BETWEEN PILOT HOLE SIZE AND MATERIAL THICKNESS

The relationship between pilot hole size and material thickness in friction welding (FRW) is crucial for optimal weld quality and efficiency. The material thickness affects heat input requirements, with thicker materials needing more heat for proper plastic deformation [64][82][83]. Pilot hole size ensures proper tool-material fit and influences material displacement during welding. In processes like FSW, this relationship is determined by several factors, balancing heat input, material flow, and tool engagement [84][85][86].

Thicker materials typically require larger pilot holes to manage the heat generation and material flow, allowing better tool penetration and stronger bonding [82][87][88]. The pilot-hole size affected the material flow and heat distribution during welding [73][89]. While larger holes may be necessary for thicker materials to ensure mechanical interlocking and heat management, excessively large holes can weaken joints, especially in thin materials [90][91]. The literature study suggests that the pilot hole diameter is smaller than the material thickness, often by 70-80%, [92][93]. This guideline helps avoid excessive heat and deformation from too-small holes or insufficient friction and poor welds from large holes. The relationship between hole size and weld quality is also influenced by factors such as material characteristics (including hardness and thermal conductivity), welding variables (such as rotational speed and axial force), and the desired weld properties [84][94][95][96].

To conclude, the size of the pilot hole should increase proportionally with the material thickness to balance heat input, material flow, and mechanical strength of the joint [96][97][98]. This proportional relationship ensures that sufficient heat is generated to facilitate proper material mixing while avoiding excessive heat that could degrade the joint's properties [83][93][99][100]. However, the exact relationship often requires experimentation and may be adjusted based on specific application requirements.

6. CONCLUSION

The following conclusions can be made based on the results and discussions given above.

a) Incorporating a pilot hole can increase the mechanical performance of similar aluminium FSSW by up to 50%.
b) The pilot hole decreases the load and force onto the FSW tool during the plunging phase potentially offering better tool life.
c) Optimization of the pilot hole in the joining process especially in FRW processes has positive impacts on joining process quality and surface finish. It is suggested that a pilot hole with a PTK ratio of less than one is utilized since it has been shown to yield the best results.
d) The pilot hole size should increase proportionally with the material thickness to balance heat input, material flow, and joint strength, and it is recommended that the pilot hole diameter be 70-80% of the material thickness.
e) Varying the pilot hole conditions in incompatible dissimilar FSSW can change the material flow and intermixing, resulting in an increase or decrease in the joint strength.
f) The optimal pilot hole diameter balances metallurgical and mechanical factors, tailored to specific materials and application requirements.

In summary, though pilot holes provide useful criteria, they are limited by the lack of research on the subject. The effects of welding parameters and setup are complex making it challenging to draw definitive conclusions. For instance, the study on how pilot holes can alter the material flow in the weld zone is still lacking. Thus, it is recommended that future work looks further into the relationship between the PTK ratio and its effect on the material flow toward better mechanical performance and joint quality.

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REFERENCES

[1] A.A.Y. Al-Qenaei, “Fusion welding techniques,” *Journal of Engineering Research and Applications*, vol. 6, no. 2, pp. 78–83, 2016.

[2] Y.M. Zhang, Y.P. Yang, W. Zhang, and S.J. Na, “Advanced welding manufacturing: A brief analysis and review of challenges and solutions,” *Journal of Manufacturing Science and Engineering. ASME,* vol. 142, no. 11, p. 110816, 2020.

[3] H. Dahlan, A.K. Nasution, S.A. Zuhdi, and M. Rusli, “Study of the effect of friction time and preheating on the joint mechanical properties of friction welded SS 316-Pure Zn,”*Applied Sciences*, vol. 13, no. 2, p. 988, 2023.

[4] D. Kumar Rajak, D.D. Pagar, P.L. Menezes, and A. Eyvazian, "Friction-based welding processes: friction welding and friction stir welding," *Journal of Adhesion Science and Technology*, vol. 34, no. 24, pp. 2613–2637, Dec. 2020.

[5] W. Li and V. Patel, "Solid state welding for fabricating metallic parts and structures," in *Encyclopedia of Materials: Metals and Alloys*, Elsevier, vol. 1, pp. 246–259, 2022.

[6] A. Heidarzadeh, S. Mironov, R. Kaibyshev, G. Çam, A. Simar, A. Gerlich, et al., "Friction stir welding/processing of metals and alloys: A comprehensive review on microstructural evolution," *Progress in Materials Science,* vol. 117, p. 100752, 2021.

[7] R.S. Mishra and Z.Y. Ma, "Friction stir welding and processing," *Materials Science and Engineering R: Reports*, vol. 50, no. 1–2, pp. 1–78, 2005.

[8] K.N. Uday and G. Rajamurugan, "Influence of process parameters and its effects on friction stir welding of dissimilar aluminium alloy and its composites – a review," *Journal of Adhesion Science and Technology,* vol. 37, no. 5, pp. 767–800, 2023.

[9] N.S. Abtan, A.H. Jassim, and M.S. Marmoos, "Study on the effects of rotational and transverse speed on temperature distribution through friction stir welding of AA2024-T3 aluminium alloy," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 53, no. 2, pp. 234–248, 2019.

[10] B. Kusharjanta, "Effect of friction stir welding process on crystallinity," *Journal of Southwest Jiaotong University,* vol. 55, no. 2, pp. 1–15, 2020.

[11] H. Papahn, P. Bahemmat, M. Haghpanahi, and I.P. Aminaie, "Effect of friction stir welding tool on temperature, applied forces and weld quality," *IET Science, Measurement & Technology,* vol. 9, no. 4, pp. 475–484, 2015.

[12] C.C. Tsao, "The effect of pilot hole on delamination when core drill drilling composite materials," *International Journal of Machine Tools and Manufacture,* vol. 46, no. 12–13, pp. 1653–1661, 2006.

[13] M. Costas, D. Morin, J.K. Sønstabø, and M. Langseth, "On the effect of pilot holes on the mechanical behaviour of flow-drill screw joints. Experimental tests and mesoscale numerical simulations," *Journal of Material Processing Technology,* vol. 294, Art. no. 117133, 2021.

[14] B. Rüstem, K. Mustafa, P. Danil Yu, A.U. Üsame, G. Munish Kumar, and K. Mehmet Erdi, "Advance monitoring of hole machining operations via intelligent measurement systems: A critical review and future trends," *Measurement: Journal of the International Measurement Confederation*, vol. 201, p. 111757, 2022.

[15] S.R. Yazdi, B. Beidokhti, and M. Haddad-Sabzevar, "Pinless tool for FSSW of AA 6061-T6 aluminum alloy," *Journal of Material Processing Technology*, vol. 267, pp. 44–51, 2019.

[16] W.H. Khalafe, E.L. Sheng, M.R. Bin Isa, A.B. Omran, and S. Bin Shamsudin, "The effect of friction stir welding parameters on the weldability of aluminum alloys with similar and dissimilar metals: Review," *Metals (Basel),* vol. 12, no. 12, Art. no. 2099, 2022.

[17] Z. Shen, Y. Ding, and A.P. Gerlich, "Advances in friction stir spot welding," C*ritical Reviews in Solid State and Materials Sciences,* vol. 45, no. 6, pp. 457–534, 2019.

[18] A.K. Sinha, D. Y. Kim, and D. Ceglarek, "Correlation analysis of the variation of weld seam and tensile strength in laser welding of galvanized steel," *Optics and Lasers in Engineering,* vol. 51, no. 10, pp. 1143–1152, 2013.

[19] Y.X. Huang, L. Wan, S.X. Lv, and J.C. Feng, "Novel design of tool for joining hollow extrusion by friction stir welding," *Science and Technology of Welding and Joining,* vol. 18, no. 3, pp. 239–246, 2013.

[20] J. Li, "The characteristics of interface microstructures in dissimilar materials joints through ultrasonic welding and friction stir processes," *IWMF2014, 9th International Workshop on Microfactories,* pp. 1–23, 2014.

[21] G. Duncheva, J. Maximov, N. Ganev, and M. Ivanova, "Fatigue life enhancement of welded stiffened S355 steel plates with noncircular openings," *Journal of Constructional Steel Research,* vol. 112, pp. 93–107, 2015.

[22] X. Fei, X. Jin, Y. Ye, T. Xiu, and H. Yang, "Effect of pre-hole offset on the property of the joint during laser-assisted friction stir welding of dissimilar metals steel and aluminum alloys," *Materials Science and Engineering,* vol. 653, pp. 43–52, 2016.

[23] H. Karami Pabandi, M. Movahedi, and A.H. Kokabi, "A new refill friction spot welding process for aluminum/polymer composite hybrid structures," *Composites Structure,* vol. 174, pp. 59–69, 2017.

[24] A.C.F. Silva, J. De Backer, and G. Bolmsjö, "Temperature measurements during friction stir welding," *International Journal of Advance Manufacturing and Technology,* vol. 88, no. 9–12, pp. 2899–2908, 2017.

[25] M. Paidar, O.O. Ojo, A. Moghanian, H.K. Pabandi, and M. Elsa, " Pre-threaded hole friction stir spot welding of AA2219/PP-C30S sheets," *Journal of Material Processing and Technology,* vol. 273, p. 116272, 2019.

[26] O.J. Dada, "Fracture mechanics and mechanical behaviour in AA5083-H111 friction stir welds," *Scientific African,* vol. 8, p. 00265, 2020.

[27] T. P. Saju and R. G. Narayanan, "Dieless friction stir lap joining of AA 5050-H32 with AA 6061-T6 at varying pre-drilled hole diameters," *Journal of Manufacturing Processes,* vol. 53, pp. 21–33, 2020.

[28] Y. Gao, Y. Liang, X. Ren, and M. Paidar, "Pre-hole Friction Stir Spot Welding (PFSSW) for dissimilar welding of AA2219 to AA3003 sheets," *Vacuum,* vol. 182, p. 109688, 2020.

[29] J.G.R, "Evaluating the Tensile Fracture Mechanism of Friction Stir Welded Cu to SS Material," *Journal of Mineral Science and Materials,* vol. 1, no. 4, p. 578, 2020.

[30] M. Paidar, K.S.A. Ali, V. Mohanavel, S. Mehrez, M. Ravichandran, and O.O. Ojo, "Weldability and mechanical properties of AA5083-H112 aluminum alloy and pure copper dissimilar friction spot extrusion welding-brazing," *Vacuum,* vol. 187, p. 110080, 2021.

[31] S. Venkadesh and M. Shunmathi, "Friction stir welding of AA2024 and AA6061 using various pin profile," *International Journal of Machine Tools and Maintenance Engineering,* vol. 2, no. 1, pp. 5-12, 2021.

[32] M. Costas, D. Morin, J.K. Sønstabø, and M. Langseth, "On the effect of pilot holes on the mechanical behaviour of flow-drill screw joints. Experimental tests and mesoscale numerical simulations," *Journal of Materials Processing Technology*, vol. 294, p. 117133, 2021.

[33] P. Maji, R. Karmakar, R. Kanti Nath, and P. Paul, "An overview on friction stir welding/processing tools," *Material Today Proceeding*, vol. 58, pp. 57–64, 2022

[34] O.S. Barrak, M.M. Hamzah, and S.K. Hussein, "Friction stir spot welding of pure copper (C11000) with pre-holed threaded aluminum alloys (AA5052)," *Journal of Applied Science and Engineering,* vol. 26, no. 8, pp. 1105–1112, 2023.

[35] T. Nonnenmann, R. Beygi, R. Carbas, L. da Silva, and A. Öchsner, "Feasibility study on hybrid weld-bonding between dissimilar material for automotive industry," *International Journal of Adhesion and Adhesives*, vol. 121, p. 103316, 2023.

[36] F. Dias, G. Cipriano, A.N. Correia, D.F.O. Braga, P. Moreira, and V. Infante, "Joining of aluminum alloy AA7075 and titanium alloy Ti-6Al-4V through a friction stir welding-based process," *Metals (Basel),* vol. 13, no. 2, p. 249, 2023.

[37] Q. Zhou, Z. Yao, C. Xu, D. Zhou, W. Liu, and L. Li, "Shared mechanism between flow drill screw and friction stir welding and its impact on failure prediction of steel-aluminum joints," *Journal of Materials Processing Technology*, vol. 311, p. 117796, 2023.

[38] M. Li, C. Zhang, D. Wang, L. Zhou, D. Wellmann, and Y. Tian, "Friction stir spot welding of aluminum and copper: A review," *Materials (Basel),* vol. 13, no. 1, p. 156, 2020.

[39] B. Suresh Kumar, N. Baskar, and K. Rajaguru, "Drilling operation: A review," *Material Today Proceedings*, vol. 21, pp. 926–933, 2020.

[40] D. Biermann, F. Bleicher, U. Heisel, F. Klocke, H. C. Möhring, and A. Shih, "Deep hole drilling," *CIRP Annals*, vol. 67, no. 2, pp. 673–694, 2018.

[41] E. Maleki, "Artificial neural networks application for modeling of friction stir welding effects on mechanical properties of 7075-T6 aluminum alloy," *IOP Conference Series: Materials Science and Engineering*, vol. 103, no. 1, p. 012034, 2015.

[42] X. Meng, Y. Huang, J. Cao, J. Shen, and J. F. dos Santos, "Recent progress on control strategies for inherent issues in friction stir welding," *Progress in Materials Science*, vol. 115, p. 100706, 2021.

[43] A. Chaudhari, S. Malarvizhi, K. S. Woon, A. Senthil Kumar, and M. Rahman, "The effects of pilot hole geometry on tool-work engagement efficacy in deep hole drilling," *Journal of Manufacturing Processes*, vol. 19, pp. 135–141, 2015.

[44] J.C. Roukema and Y. Altintas, "Generalized modeling of drilling vibrations. Part I: Time domain model of drilling kinematics, dynamics and hole formation," *International Journal of Machine Tools and Manufacture*, vol. 47, no. 9, pp. 1455–1473, 2007

[45] O. Tor, "Effects of pilot hole diameter on screw-driving torques in medium density fiberboard," *Cerne: Journal of Structural Engineering*, vol. 25, no. 1, pp. 54–59, 2019.

[46] Y. Wang, P. Li, H. Jiang, K. Yang, Z. Chen, H. Chuai, et al., "Microstructure and Mechanical Properties of Refill Friction Stir Spot-Welded Joints of 2A12Al and 7B04Al: Effects of Tool Size and Welding Parameters," *Materials*, vol. 17, no. 3, p. 716, 2024.

[47] J. Torzewski, M. Łazińska, K. Grzelak, I. Szachogłuchowicz, and J. Mierzyński, "Microstructure and mechanical properties of dissimilar friction stir welded joint AA7020/AA5083 with different joining parameters," *Materials*, vol. 15, no. 5, p. 1910, 2022.

[48] K. Kimapong and T. Watanabe, "Effect of welding process parameters on mechanical property of FSW lap joint between aluminum alloy and steel," *Materials Transactions*, vol. 46, no. 10, pp. 2211–2217, 2005.

[49] W.M. Thomas, C.S. Wiesner, D.J. Marks, and D.G. Staines, "Conventional and bobbin friction stir welding of 12% chromium alloy steel using composite refractory tool materials," *Science and Technology of Welding and Joining,* vol. 14, no. 3, pp. 247–253, 2009.

[50] T.P. Saju and R.G. Narayanan, "Dieless friction stir lap joining of AA 5050-H32 with AA 6061-T6 at varying pre-drilled hole diameters," *Journal of Manufacturing Processes,* vol. 53, pp. 21–33, 2020.

[51] S. Nama, N. Namer, and I. Abdullah, "Effect of pre-hole diameter on bushing dimensions for friction drilling process of A6063-T6 aluminum alloy," *Journal of Al Rafidain University College,* no. 1, pp. 373–387, 2021.

[52] U. Acharya, B.S. Roy, and S.C. Saha, "Torque and force perspectives on particle size and its effect on mechanical property of friction stir welded AA6092/17.5SiC p -T6 composite joints," *Journal of Manufacturing Processes*, vol. 38, pp. 113–121, 2019.

[53] C.C. Tsao, "Effect of a pilot hole on thrust force by saw drill," *International Journal of Machine Tools and Manufacture*, vol. 47, no. 14, pp. 2172–2176, 2007.

[54] G. Joshi and V. Badheka, "Evaluating the tensile fracture mechanism of friction stir welded Cu to SS material,"*Journal of Mineral Science and Materials*, vol. 1, no. 4, pp. 1–6, 2020.

[55] A. Chumaevskii, A. Amirov, A. Ivanov, V. Rubtsov, and E. Kolubaev, "Friction Stir Welding/Processing of Various Metals with Working Tools of Different Materials and Its Peculiarities for Titanium Alloys: A Review," *Metals (Basel).*, vol. 13, no. 5, p. 970, 2023

[56] M.P. Mubiayi, "Current developments in Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) of aluminium and titanium alloys," in *The 4th International Electronic Conference on Applied Sciences, Engineering proceedings*, vol. 56, no. 1, p. 184, 2023.

[57] H. Luo, T. Wu, P. Wang, F. Zhao, H. Wang, and Y. Li, "Numerical simulation of material flow and analysis of welding characteristics in friction stir welding process," *Metals*, vol. 9, no. 6, p. 621, 2019.

[58] Y. Sun, W. Liu, Y. Li, W. Gong, and C. Ju, "The Influence of Tool Shape on Plastic Metal Flow, Microstructure and Properties of Friction Stir Welded 2024 Aluminum Alloy Joints," *Metals*, vol. 12, no. 3, p. 408, 2022.

[59] A. Haiqal and L.A. Shah, "Dissimilar welding of aluminum and magnesium alloy using friction stir spot welding," Final year project thesis, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia, 2022.

[60] L.H. Shah, N.H. Othman, and A. Gerlich, "Review of research progress on aluminium–magnesium dissimilar friction stir welding," *Science and Technology of Welding and Joining*, vol. 23, no. 3, pp. 256–270, 2018.

[61] D. Ambrosio, Y. Morisada, K. Ushioda, and H. Fujii, "Material flow in friction stir welding: A review," *Journal of Materials Processing Technology*, vol. 320, no. July, p. 118116, 2023.

[62] G. Lakshmi Balasubramaniam, E. Boldsaikhan, G.F.J. Rosario, S.P. Ravichandran, S. Fukada, M. Fujimoto, et al., "Mechanical properties and failure mechanisms of refill friction stir spot welds," *Journal of Manufacturing and Materials Processing*, vol. 5, no. 4, p. 118, 2021.

[63] J. Liu, R. Guo, P. Gong, Y. Yue, Z. Yu, and Y. Zhang, "Interface characteristics and mechanical properties of 2024 aluminum alloy and 304 stainless steel dissimilar alloys FSLW joint with Ni interlayer," *Metals*, vol. 12, no. 10, p. 1574, 2022.

[64] A.N. Correia, P.A.M. Santos, D.F.O. Braga, R. Baptista, and V. Infante, "Effects of friction stir welding process control and tool penetration on mechanical strength and morphology of dissimilar aluminum-to-polymer joints," *Journal of Manufacturing and Materials Processing*, vol. 7, no. 3, p. 106, 2023.

[65] M.A.R. Pereira, I. Galvão, J.D.M. Costa, A.M. Amaro, and R.M. Leal, "Production of aluminium-polymer joints by friction stir spot welding," *Journal of Manufacturing and Materials Processing*, vol. 8, no. 4, p. 179, 2024.

[66] X. Chu, M. Yin, J. Gao, X. Wang, and Y. Wang, "Effects of shoulder geometry on microstructures and mechanical properties of probeless friction stir spot welded aluminum 7075-t651 sheets," *Metals*, vol. 10, no. 12, p. 1605, 2020,

[67] X. Meng, J. Gao, Y. Xie, T. Huang, J. Dong, X. Ma, et al., "Extrinsic-riveting friction stir lap welding of Al/steel dissimilar materials," *Materials*, vol. 17, no. 8, p. 1830, 2024.

[68] M. Li, C. Zhang, D. Wang, L. Zhou, D. Wellmann, and Y. Tian, "Friction stir spot welding of aluminum and copper: A review," *Materials*, vol. 13, no. 1, p. 156, 2019.

[69] N. Muhayat, S. G. Ramasamy, M.R.A. Azmi, M.N.R. Al-Hadidi, R.T.S. Kadir, S.M. Sapuan, et al., "Friction stir welded AA5052-H32 under dissimilar pin profile and preheat temperature: Microstructural observations and mechanical properties," *Metals*, vol. 12, no. 1, p. 4, 2021.

[70] G. Sun, X. Wei, J. Niu, D. Shang, and S. Chen, "Influence of residual stress on fatigue weak areas and simulation analysis on fatigue properties based on continuous performance of FSW joints," *Metals*, vol. 9, no. 3, p. 284, 2019,

[71] Y. Xia, J. Yue, J. Lei, K. Yang, and Y. Garbatov, "Re-Distribution of welding residual stress in fatigue crack propagation considering elastic–plastic behavior," *Journal of Marine Science and Engineering*, vol. 11, no. 12, p. 2378, 2023.

[72] G. Mohammed, M. Ishak, S. Aqida, and H. Abdulhadi, "Effects of heat input on microstructure, corrosion and mechanical characteristics of welded austenitic and duplex stainless steels: A review," *Metals*, vol. 7, no. 2, p. 39, 2017.

[73] Z. Fei, Z. Pan, D. Cuiuri, H. Li, B. Wu, D. Ding, et al., "Effect of heat input on weld formation and tensile properties in keyhole mode TIG welding process," *Metals*, vol. 9, no. 12, p. 1327, 2019.

[74] M.M.Z. Ahmed, M.M. El-Sayed Seleman, E. Ahmed, H.A. Reyad, K. Touileb, and I. Albaijan, "Friction stir spot welding of different thickness sheets of aluminum alloy AA6082-T6," *Materials*, vol. 15, no. 9, p. 2971, 2022.

[75] A. Alkhafaji, D. Camas, P. Lopez-Crespo, and H. Al-Asadi, "The influence of tool geometry on the mechanical properties and the microstructure of AA6061-T6 aluminum alloy friction stir spot welding," *Materials*, vol. 16, no. 11, p. 4135, 2023.

[76] V.V. Marchenkov, S.M. Emelyanova, and E.B. Marchenkova, "Martensitic transformation temperatures and hall effect in Ni47−xMn41+xIn12 (x = 0, 1, 2) alloys," *Materials*, vol. 16, no. 2, p. 672, 2023.

[77] T. Artaza, T. Bhujangrao, A. Suárez, F. Veiga, and A. Lamikiz, "Influence of heat input on the formation of laves phases and hot cracking in Plasma Arc Welding (PAW) additive manufacturing of inconel 718," *Metals*, vol. 10, no. 6, p. 771, 2020.

[78] M. Cabibbo, A. Forcellese, M. Simoncini, M. Pieralisi, and D. Ciccarelli, "Effect of welding motion and pre-/post-annealing of friction stir welded AA5754 joints," *Materials & Design*, vol. 93, pp. 146–159, 2016.

[79] P. Gong, Y. Zuo, S. Ji, D. Yan, and Z. Shang, "A novel non-keyhole friction stir welding process," *Journal of Manufacturing and Materials Processing*, vol. 73, pp. 17–25, 2022.

[80] M. Simoncini, D. Ciccarelli, A. Forcellese, and M. Pieralisi, "Micro- and macro- mechanical properties of pinless friction stir welded joints in AA5754 aluminium thin sheets," *Procedia CIRP*, vol. 18, pp. 9–14, 2014.

[81] W. Li, J. Li, Z. Zhang, D. Gao, W. Wang, and C. Dong, "Improving mechanical properties of pinless friction stir spot welded joints by eliminating hook defect," *Materials & Design*, vol. 62, pp. 247–254, 2014.

[82] A. Alhourani, J. Sheikh-Ahmad, F. Almaskari, K. Khan, S. Deveci, and I. Barsoum, "Thermal modeling of friction stir welding of thick high-density polyethylene plates," *Journal of Materials Research and Technology*, vol. 28, pp. 4186–4198, 2024.

[83] M.M.Z. Ahmed, S. Ataya, M.M. El-Sayed Seleman, A.M.A. Mahdy, N.A. Alsaleh, and E. Ahmed, "Heat Input and Mechanical Properties Investigation of Friction Stir Welded AA5083/AA5754 and AA5083/AA7020," *Metals*, vol. 11, no. 1, p. 68, 2020.

[84] S. Bharti, M. Singh, R.S. Singh, A. Yadav, N. Yadava, P. Kumar, et al., "A review of recent developments in friction stir welding for various industrial applications," *Journal of Marine Science and Engineering*, vol. 12, no. 1, p. 71, 2023.

[85] H. Wei, A. Latif, G. Hussain, B. Heidarshenas, and K. Altaf, "Influence of tool material, tool geometry, process parameters, stacking sequence, and heat sink on producing sound Al/Cu lap joints through friction stir welding," *Metals*, vol. 9, no. 8, p. 875, 2019.

[86] E. Hoyos and M. C. Serna, "Basic tool design guidelines for friction stir welding of aluminum alloys," *Metals*, vol. 11, no. 12, p. 2042, 2021.

[87] M.M.Z. Ahmed, R.A.A. Kadir, M.S.A. Rahman, R.S. Al-Boghdadi, M.R.Z. Ali, M.A. Rahim, et al., "Bobbin tool friction stir welding of aluminum thick lap joints: Effect of process parameters on temperature distribution and joints' properties," *Materials*, vol. 14, no. 16, p. 4585, 2021.

[88] D.A.P. Prabhakar, A. Korgal, A.K. Shettigar, M.A. Herbert, M.P.G. Chandrashekharappa, D.Y. Pimenov, et al., "A review of optimization and measurement techniques of the Friction Stir Welding (FSW) process," *Journal of Manufacturing and Materials Processing*, vol. 7, no. 5, p. 181, 2023.

[89] M. Hossfeld, "On friction, heat input, and material flow initiation during friction stir welding: Tool and process optimization,"*Journal of Manufacturing and Materials Processing*, vol. 7, no. 1, p. 34, 2023.

[90] M.A.R. Pereira, A.M. Amaro, P.N.B. Reis, and A. Loureiro, "Effect of friction stir welding techniques and parameters on polymers joint efficiency—A critical review," *Polymers*, vol. 13, no. 13, p. 2056, 2021.

[91] Z. Sun, X. Yang, and S. Li, "Characteristics of friction plug joints for AA2219-T87 FSW welds," *Materials*, vol. 15, no. 4, p. 1525, 2022.

[92] M.M.Z. Ahmed, M.M. El-Sayed Seleman, D. Fydrych, and G. Çam, "Friction stir welding of aluminum in the aerospace industry: The current progress and state-of-the-art review," *Materials*, vol. 16, no. 8, p. 2971, 2023.

[93] B. Abnar, S. Gashtiazar, and M. Javidani, "Friction stir welding of non-heat treatable Al alloys: Challenges and improvements opportunities," *Crystals*, vol. 13, no. 4, p. 576, 2023.

[94] X. Liu, W. Li, Y. Zhen, L. Jia, Y. Li, and X. Pei, "Effect of process parameters on weld quality in vortex- friction stir welding of 6061-T6 aluminum alloy," *Materials*, vol. 16, no. 2, p. 873, 2023.

[95] D. Labus Zlatanovic, S. Balos, J. Bergmann, S. Rasche, M. Pecanac, and S. Goel, "Influence of tool geometry and process parameters on the properties of friction stir spot welded multiple (AA 5754 H111) aluminium sheets," *Materials*, vol. 14, no. 5, p. 1157, 2021.

[96] W.H. Khalafe, E.L. Sheng, M.R. Bin Isa, A.B. Omran, and S. Bin Shamsudin, "The effect of friction stir welding parameters on the weldability of aluminum alloys with similar and dissimilar metals: Review," *Metals*, vol. 12, no. 12, p. 2099, 2022.

[97] X. Ma, S. Xu, F. Wang, Y. Zhao, X. Meng, Y. Xie, et al., "Effect of temperature and material flow gradients on mechanical performances of friction stir welded AA6082-T6 joints," *Materials*, vol. 15, no. 19, p. 6579, Sep. 2022.

[98] M. Abboud, L. Dubourg, G. Racineux, and O. Kerbrat, "Experimental methodology to identify optimal friction stir welding parameters based on temperature measurement," *Journal of Manufacturing and Materials Processing*, vol. 8, no. 4, p. 137, 2024.

[99] H.I. Khalaf, R. Al-Sabur, M.E. Abdullah, A. Kubit, and H.A. Derazkola, "Effects of underwater friction stir welding heat generation on residual stress of AA6068-T6 aluminum alloy," *Materials*, vol. 15, no. 6, p. 2223, 2022.

[100] S. Cui, W. Cao, Q. Zhang, L. Wang, Y. Sun, and S. Guan, "Material flow and microstructural evolution in friction stir welding of LAZ931 duplex Mg-Li alloys," *Metals*, vol. 14, no. 11, p. 1305, 2024.