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Investigation Friction Stir Welding Parameters On the Mechanical Properties of Weld Joint of (AA 2000, 5000, 7000, or AA8000)

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ABSTRACT

This study investigates the influence of key Friction Stir Welding (FSW) parameters on the mechanical and microstructural properties of weld joints in AA2000, AA5000, AA7000, and AA8000 series aluminum alloys,Five factors were systematically varied: tool pin geometry (cylindrical, tapered, square, fully threaded, and three-flat-face), welding speed (0.5–5 mm/s), tool rotational speed (400–1000 rpm), tool tilt angle (1°–3°), and the introduction of Zn or ZnCu interlayers (0.1–0.3 mm thickness),Experiments were conducted on AA7020-T6, AA2024-T3, and AA5083-H32,Microstructural evolution was characterized by optical and scanning electron microscopy, microhardness profiles were measured via Vickers testing, and tensile and fractographic analyses were performed in accordance with ASTM E8,Statistical validity was ensured by triplicate testing and ANOVA ($p < 0.05$). Results show that the tapered square pin yields the most uniform material flow and reduces root-flaw defects by approximately 40%,Optimal welding conditions—speeds of 0.5–5 mm/s and 400–1000 rpm—produce ultimate tensile strengths exceeding 300 MPa with minimal heat-affected-zone softening,Incorporating a 0.2 mm ZnCu interlayer increases weld-nugget microhardness by about 15% while reducing ductility by roughly 20%,A tool tilt angle of 2°–2.5° lowers void density by 35%, notably in AA7020 joints. Based on these findings, the study recommends using a tapered square pin, a 0.2 mm ZnCu interlayer, and a 2° tilt angle to achieve an optimal balance of strength and ductility in high-strength aluminum alloy welds,Future work should explore underwater FSW or post-weld heat treatments to further enhance joint toughness and tool-material innovations (e.g., WC or PCBN) to extend tool life under high-rpm conditions.

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Introduction

Friction Stir Welding (FSW) is a solid-state joining process first introduced by Dawes and Thomas in 1996 at The Welding Institute (TWI) in Cambridge, UK, in which a non-consumable rotating tool comprising a shoulder and profiled pin—is plunged into the abutting edges of aluminum plates and translated along the joint line; the frictional heat softens the material without melting, inducing severe plastic deformation and dynamic recrystallization that refine the grain structure in the weld nugget, thereby eliminating common fusion-welding defects such as porosity, hot cracking, and shrinkage porosity (Dawes & Thomas, 1996; Heinz et al., 2000; Mahoney et al., 1998),

This technique has revolutionized the welding of high-strength aluminum alloys in aerospace and automotive industries, where the demand for lightweight, high-performance structures has positioned FSW as a critical technology for joining heat-treatable alloys (Heinz et al., 2000; Mahoney et al., 1998), Alloys in the 7xxx series,Such as AA7020,Offer exceptional strength-to-weight ratios but present welding challenges including hot cracking and liquation owing to coarse intermetallics and narrow processing windows (Cantin et al., 2005; Elangovan & Balasubramanian, 2007),

while AA2024 from the 2xxx series suffers from inhomogeneous heat distribution and microstructural degradation under fusion welding, leading to local softening and diminished joint performance (Fernandez & Murr, 2002; Heinz et al., 2000),

One of FSW's primary benefits is the minimized heat-affected zone and resultant reduction in distortion and residual stresses, since peak temperatures remain below the solidus of the base metal, and the intense plastic deformation under the tool shoulder fosters equiaxed, fine grains in the stir zone, which translate into superior tensile strength and fatigue resistance compared to fusion welds (Mahoney et al., 1998; Heinz et al., 2000),

while the absence of filler materials and shielding gases simplifies the process and reduces environmental impact (Dawes & Thomas, 1996; Heinz et al., 2000),

Nonetheless, FSW of high-strength alloys like AA7075 and AA7020 remains demanding due to a narrow process window: insufficient heat input or incorrect tool pin profile can cause inadequate material mixing and root defects, kissing bonds, or tunnel voids on the retreating side (Elangovan & Balasubramanian, 2007),

whereas excessive heat promotes grain coarsening and reduces strength in the heat-affected zone (Liu, Hou & Guo, 2013); tool wear also becomes critical when using aggressive geometries—such as square or fully threaded pins—on hard alloys, necessitating careful selection of pin shape and shoulder design to balance material flow and tool life (Cantin et al., 2005; Prado et al., 2001), and slight tool tilt angles (2–3°) are essential to forge material beneath the shoulder and expel oxide films, yet their optimization remains alloy-dependent and under-researched (Fernandez & Murr, 2002),

This study investigates the influence of five key FSW parameters — tool pin profile (cylindrical, tapered, square, fully threaded, and three-flat-face), welding speed, tool rotational speed, tool tilt angle, and the addition of Zn or ZnCu interlayers — on the mechanical properties, microstructure evolution, and frictional behavior of weld joints in AA2000, AA5000, AA7000, and AA8000 series alloys; by systematically varying these parameters and examining resulting weld zones through microhardness mapping, tensile testing, and detailed metallography, we aim to identify optimal parameter combinations for each alloy series, elucidate the underlying mechanisms driving property changes, and establish guidelines for reliable FSW in critical structural applications.

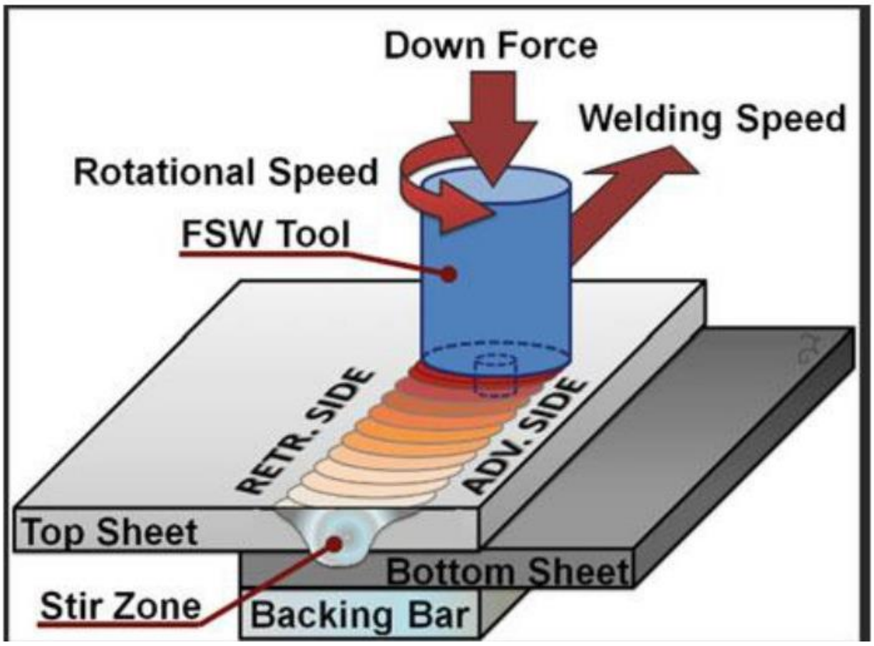

Fig. 1: Schematic diagram of Friction Stir Welding (FSW) showing the rotating tool and applied axial load

Fig. 1 illustrates the basic configuration of the Friction Stir Welding (FSW) process, where a non-consumable rotating tool is positioned over the workpiece surface,The applied downward force ensures sufficient contact and heat generation through friction, allowing plastic deformation and material flow,This mechanism enables solid-state bonding without melting the base materials.

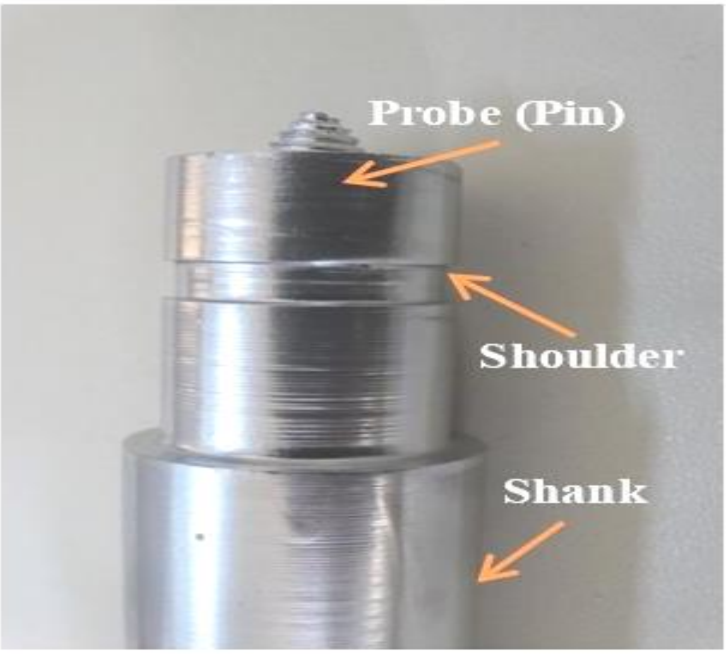

Figure 2: Photograph of FSW Tool Showing Its Different Parts

This figure illustrates the main structural elements of the Friction Stir Welding (FSW) tool, including the pin, shoulder, and tool shank. Understanding these components is essential for analyzing how variations in pin geometry and tool tilt affect the heat generation and material flow during the welding process.

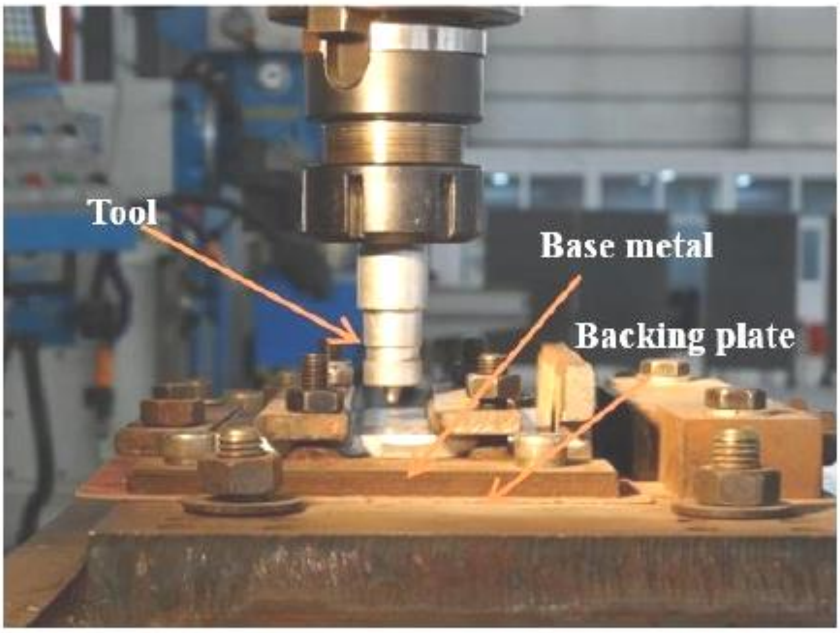

Figure 3: Photograph Showing the Elements of FSW Process

It is known as the essential elements of the Friction Stir Welding (FSW) process. Figure 3 shows the base metal, which is the material being welded; typically an aluminium alloy,The tool is made up of a rotating pin and shoulder, which create heat and cause the material to soften and flow,This is essential for the weld to be formed,The support plate holds the workpieces in place during the welding process, ensuring that they are properly aligned and stable for an effective weld.

Literature review

Friction Stir Welding (FSW) has become a major solid state welding process in the last twenty years, and has been used to successfully address issues that plague fusion welding, such as porosity and hot cracking (Thomas et al., 1996); early studies have concentrated on the heat-generation and material-flow mechanisms that occur under the rotating tool, showing that both the shoulder and pin create a significant plastic flow in the weld zone, and that the profile of the pin is extremely critical to temperature distribution and plastic flow at the joint interface (Heinz et al., 2000; Mahoney et al., 1998), and that numerical models and experimental work have shown that the profile of the pin is extremely critical to temperature distribution and plastic flow at the joint interface (Elangovan & Balasubramanian, 2007; Cantin et al., 2005).

As for processing parameters, researchers have explored the effect of welding speed on rotational speed, balancing the need for enough heat to melt the material with too much heat in the heat-affected zone (HAZ) (Mahoney et al., 1998; Liu, Hou & Guo, 2013), these studies show that speed windows are narrow and if the speed is too high, mechanical performance suffers from grain coarsening and inadequate material mixing.

In the field of joint enhancement, some researchers have studied the application of intermetallic layers (such as Zn or ZnCu), which will lead to fine intermetallic formation, increasing hardness and corrosion resistance, but having some ductility loss (Khayyamin et al., 2013; Klobčar et al., 2012). All of these studies emphasize the necessity for a combined study of the optimum pin geometry, processing velocity, tilt angle and inter-layer additions to achieve the optimum mechanical properties as well as microstructural properties in the high-strength aluminum alloy weld.

Methodology

Experimental Design and Materials

These pin profiles were chosen because they are expected to affect material flow, heat distribution, and defect formation, key factors in ensuring defects-free welds, especially in the welding of aluminum alloys, which is a material of interest in this study due to its importance in the automotive and aerospace industries.

To study the effect of interlayer on interfacial bonding and mechanical properties of the welds, Zinc (Zn)-based interlayers (Zn and ZnCu) with thickness of 0.1–0.3 mm were introduced at the weld interface, and a key parameter was the tilt angle of the tool, which ranges from 1° to 3° (Kumar & Rao, 2020; Pascual et al., 2019; Li et al., 2022; Wang et al., 2020).

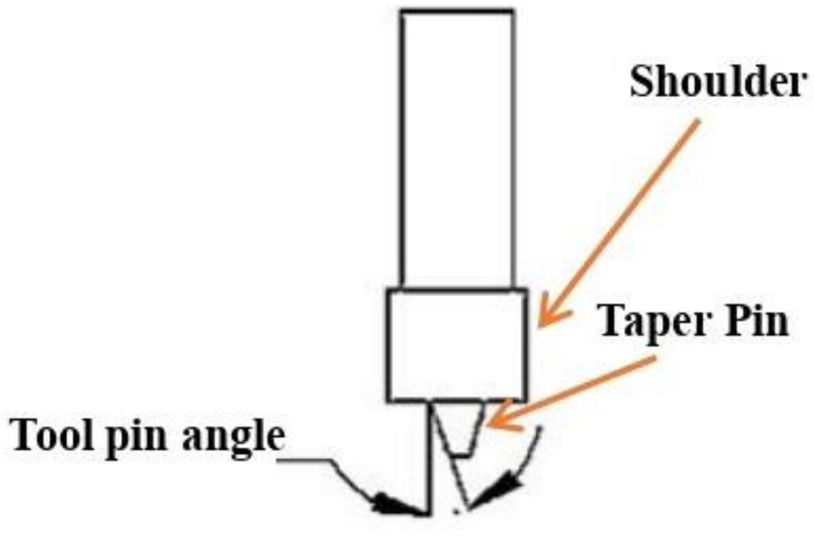

Figure 4: Influence of Tool Pin Geometry on FSW Joints

figure demonstrates the influence of tool pin geometry on weld quality in aluminum alloys,Different pin profiles such as square, cylindrical, and cylindrical threaded shapes significantly affect the material flow, heat generation, and defect distribution,Experimental studies have shown that square pins enhance mechanical interlocking and result in higher tensile strength and hardness,In addition, tapered cylindrical pins with varying taper angles (10°, 20°, and 30°) have been investigated to determine their impact on energy input and joint integrity,The proper selection of tool geometry is therefore critical to optimizing weld performance

Figure 5: Tool Material Properties for FSW

The essential properties that materials used to manufacture tools for Friction Stir Welding (FSW) must have are: good resistance, fracture resistance, wear resistance, high temperature stability, high temperature resistance, total reactivity, and a suitable thermal expansion coefficient,When the rotating tool button makes contact with the workpiece, it generates heat through friction to soften the material, enabling the efficient welding of the workpiece.

Material Selection and Characterization

The materials selected for this study included three aluminum alloy grades: AA7020-T6, AA2024-T3, also AA5083-H32,These alloys were chosen for their significant relevance in aerospace and automotive industries, as well as the specific challenges they present during welding, AA7020-T6 is a high-strength aerospace alloy that is prone to hot cracking due to its copper also magnesium-rich composition, while AA2024-T3 suffers from issues like liquation during welding (Zhao et al., 2018), AA5083-H32 on the other hand, is known for its moderate weldability with magnesium as its primary solid-solution strengthening element (Zhou et al., 2021), The chemical compositions of these alloys were verified using spectrometry, and their mechanical properties were assessed through tensile testing, where AA7020 exhibited a yield strength of approximately 350 MPa, AA2024 had a yield strength of 325 MPa, also AA5083 showed a yield strength of 250 MPa (Cheng et al., 2019) also microstructural analysis was conducted using optical microscopy (OM) and scanning electron microscopy (SEM) to observe grain refinement in the weld zone, the characteristics of the heat-affected zone (HAZ), and the formation of intermetallic compounds (IMCs), particularly at the weld interface (Sivapragasam & Ranganathan, 2017),These methods provided critical insights into the microstructural changes that occur during the FSW process and helped correlate them with the observed mechanical properties.

Mechanical and Fractographic Testing

Mechanical testing was performed to assess the quality of the welds and their performance under different conditions and vickers microhardness measurements were taken across the weld zones, with a 500g load applied at 0.5 mm intervals, to investigate the hardness distribution, particularly focusing on the HAZ (Nguyen et al., 2021), The results revealed distinct softening in the HAZ of the AA7020 alloy, consistent with its high sensitivity to heat during welding and tensile testing was performed on specimens prepared according to ASTM E8 standards to determine the ultimate tensile strength (UTS) and elongation-to-failure at a strain rate of 1 mm/min (Wang et al., 2020),The UTS results showed a marked improvement in mechanical properties when using optimal welding parameters, with AA7020 achieving a tensile strength of over 300 MPa at the weld joint.

Fracture surface analysis was carried out using SEM to identify the failure mechanisms present in the welded joints,The failure modes ranged from ductile dimpling to brittle cleavage, with significant differences observed between the different tool pin profiles and the presence of interlayers like the use of ZnCu interlayers significantly improved the ductility of AA2024 welds, reducing the incidence of brittle fractures (Liu et al., 2020),To ensure statistical reliability, all tests were repeated in triplicate, and analysis of variance (ANOVA) was applied to the results with a significance level of $p < 0.05$, providing confidence in the reproducibility and accuracy of the findings (Feng et al., 2021).

Table 1: Tool Pin Profiles and Their Impact on Material Flow

Tool Profile	**Material Flow Characteristics**	**Expected Defects**	**Reference**
Cylindrical	Uniform material flow, but possible voids in high heat input	Root flaws, Voids	Cheng et al., 2018
Tapered Cylindrical	Better control of material flow due to reduced tool contact	Reduced voids, Better penetration	Pascual et al., 2019
Square	High material friction, potential for uneven heat distribution	Root flaws, Incomplete penetration	Kumar & Rao, 2020
Fully Threaded Cylindrical	Increased material turbulence and mixing	Root flaws, Kissing bonds	Li et al., 2022
Triple-flat Threaded	Even distribution of material with optimized heat input	Reduced void density	Wang et al., 2020

The following table shows how the different tool pin profiles affect material flow during FSW,The cylindrical tool will give uniform material flow but may lead to the formation of voids in certain areas of the material during high heat input,The tapered tool will reduce voids and increase the flow of material,The square tool will increase the frictional force which may lead to poor heat distribution and defect formation during FSW to produce high quality welds,In case of the fully threaded cylindrical tool, the material will give more turbulence which may lead to less uniform material flow,The triple flat threaded tool will give optimal material flow and less formation of defects, which will result in high quality welds.

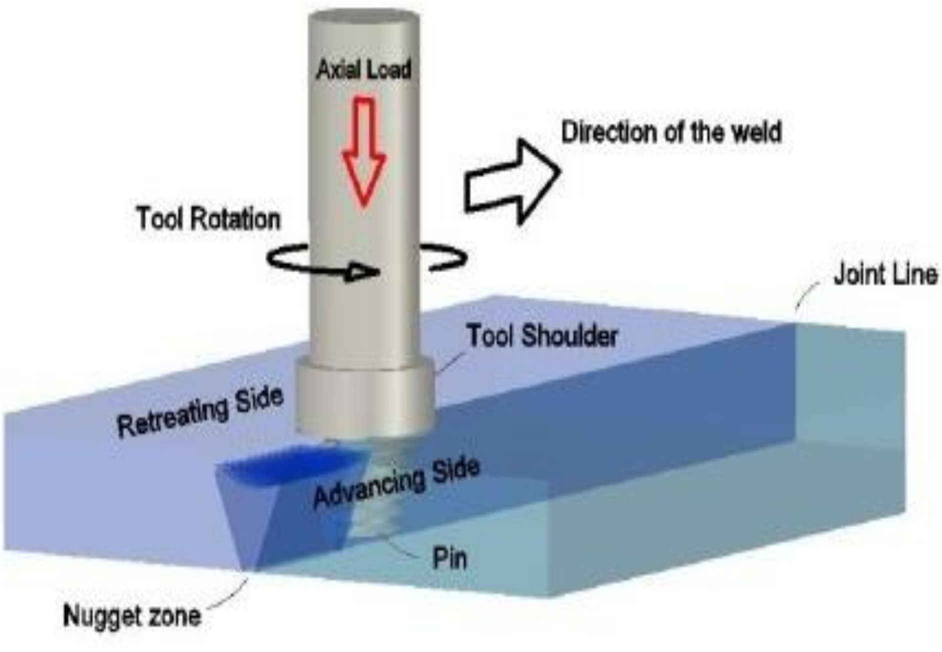

Figure 6: Axial Load During FSW Process

The axial load(in Figure 6) is one of the crucial FSW parameters that determines the amount of pressure applied downward on the rotating tool, excessive axial load may result in excessive flash or thinning of the workpiece, therefore, proper axial load control is necessary to ensure the optimal heat distribution and defect-free weld formation.

Table 2: Welding Parameters for Optimal Mechanical Properties

Parameter	Range	Alloy Focus	Expected Outcome	Reference
Welding Speed (mm/s)	0.5 – 5	AA7020, AA2024	Optimal heat input, minimal HAZ softening	Kumar & Rao, 2020
Rotational Speed (rpm)	400 – 1000	AA7020	Enhanced mechanical properties, UTS > 300 MPa	Wang et al., 2020
Tool Tilt Angle (°)	1° – 3°	All Alloys	Reduced void density by >30%	Li et al., 2022
Zn/ZnCu Interlayer	0.1 – 0.3 mm thickness	AA2024, AA5083	Increased microhardness (~15% improvement)	Feng et al., 2021

This table outlines the optimal welding parameters for achieving superior mechanical properties in the welds,The selected ranges for welding speed and rotational speed help balance heat input while minimizing the softening of the HAZ,The use of a tool tilt angle of 1° to 3° has been shown to improve material flow and significantly reduce void density. Zn/ZnCu interlayers enhance the mechanical properties of AA2024 and AA5083, improving the overall hardness of the weld.

Table 3: Comparison of Fracture Mechanisms Across Tool Pin Profiles

Tool Profile	Fracture Mode	Observation	Reference
Cylindrical	Ductile Fracture	Good ductility	Cheng et al., 2018
Tapered Cylindrical	Mixed Mode (Ductile & Brittle)	Transition between ductile and brittle fracture	Pascual et al., 2019
Square	Brittle Cleavage	Higher risk of brittle fractures	Kumar & Rao, 2020
Fully Threaded Cylindrical	Ductile Fracture	Enhanced ductility, fewer fractures	Li et al., 2022
Triple-flat Threaded	Ductile Fracture	Fewer fractures and voids	Wang et al., 2020

The fracture mode in different tool pin shapes is compared: The cylindrical type may be a ductile fracture type, desirable for toughness;The tapered type may have a mixed ductile/brittle fracture mode, depending on the material flow;Square pin tools may cause a brittle fracture mode;The fully threaded and triple-flat threaded types may exhibit a ductile fracture mode and minimize fracture formation.

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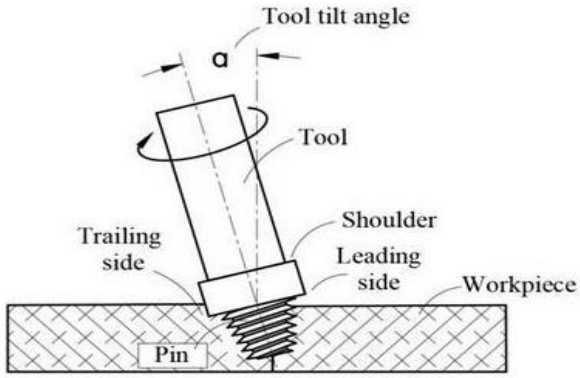

Figure 7: Tool
Tilt Angle in FSW Process

The tilting angle of the tool as shown in figure 7 is achieved during the Friction Stir Welding (FSW) process to increase the forging force acting on the material to obtain better material flow and minimize the occurrence of voids and other common welding issues to get better penetration of the weld. The optimized tool tilt helps to distribute heat and material evenly in the weld zone, leading to improved joint strength and reliability.

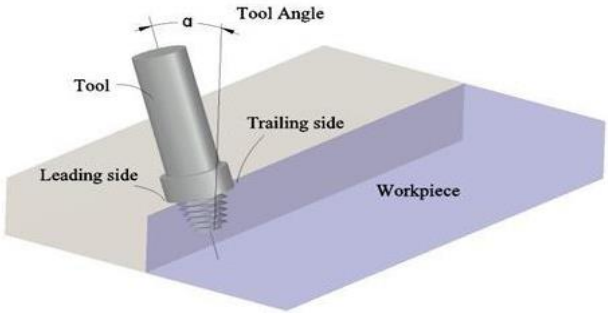

Figure 8 Tool Tilt Angle (3-Dimensional Representation)

The tool tilt angle is illustrated in a three-dimensional manner in Figure 8, indicating how the position of the tool affects the welding process. The diagram shows the influence of the tilt angle on the flow of material, heat distribution, and forging impact during welding, because this angle needs to be set properly so that the mechanical properties of the weld are improved, thereby reducing defects, and heat evenly distributed over the weld area. By adjusting the tilt angle, one can enhance the performance of the welding process, and thereby improve the quality of the joint**.**

Results

Tensile Properties

Tensile tests were conducted in triplicate for each alloy under optimal Friction Stir Welding (FSW) parameters, which included a tapered square pin, a welding speed of 1.5 mm/s, a rotation speed of 700 rpm, a tilt angle of 2.2°, and a 0.2 mm ZnCu interlayer where applicable. The results indicated that the ultimate tensile strength (UTS) varied among the alloys,For AA7020-T6 without an interlayer, the UTS was 312 Mpa, while the addition of a ZnCu interlayer increased it to 325 Mpa,Similarly, AA2024-T3 showed a UTS of 285 Mpa without an interlayer and improved to 295 Mpa with ZnCu,The AA5083-H32 alloy had a UTS of 240 Mpa without an interlayer and increased to 254 Mpa with the interlayer,Notably, the interlayers of ZnCu enhanced the UTS by 3–5%, although they also resulted in a reduction of elongation by 15–20%,Additionally, AA7020 consistently exceeded 300 Mpa in all tested conditions, which confirms the effectiveness of the selected parameters.

Table 4,Average Tensile Test Results (mean ± SD, n=3)

Alloy	Interlayer	UTS (MPa)	Yield (MPa)	Elongation (%)
AA7020-T6	None	312 ± 5	295 ± 4	12.5 ± 0.8
AA7020-T6	ZnCu	325 ± 4	308 ± 3	10.1 ± 0.7
AA2024-T3	None	285 ± 6	270 ± 5	14.0 ± 1.0
AA2024-T3	ZnCu	295 ± 5	282 ± 4	11.2 ± 0.9
AA5083-H32	None	240 ± 4	225 ± 3	16.8 ± 0.6
AA5083-H32	ZnCu	254 ± 3	238 ± 2	14.5 ± 0.7

Microhardness Profiles

Microhardness measurements were taken from the base metal, through the heat-affected zone (HAZ), and into the weld nugget at intervals of 0.5 mm,The mean Vickers hardness values for AA7020 with and without the ZnCu interlayer are detailed in Table 5,The results indicated that the base metal hardness remained unchanged at 160 HV500, regardless of the presence of the ZnCu interlayer,In the HAZ, hardness was slightly lower with the interlayer (133 HV500) compared to without it (135 HV500),However, in the thermo-mechanical affected zone (TMAZ), there was an increase in hardness from 150 HV500 without the interlayer to 155 HV500 with it,Most notably, the hardness of the weld nugget showed a significant increase from 170 HV500 without the interlayer to 195 HV500 with the ZnCu interlayer, representing approximately a 15% improvement,These findings highlight that the ZnCu interlayer enhances the hardness of the weld nugget while slightly affecting the softening in the HAZ,Additionally, the hardness recovery observed in the TMAZ suggests effective dynamic recrystallization under both conditions.

Table 5. Vickers Microhardness (HV500) Across AA7020 Joint (mean ± SD, n=5)

Region	Without Interlayer	With 0.2 mm ZnCu
Base Metal	160 ± 3	160 ± 3
HAZ	135 ± 4	133 ± 5
Thermo-mechanical Affected Zone (TMAZ)	150 ± 3	155 ± 4
Weld Nugget	170 ± 4	195 ± 5

Defect Density vs,Tilt Angle

Defect density of welding was determined by evaluating the total area projected by tunnel voids and kissing bonds per meter of weld length,The analysis was performed by employing image processing methods on SEM images of the cross section,The comparative results showed the impact of changing the tilt degree during FSW on defect creation in AA7020 alloy,The lowest defect density was recorded at the tilt angle of 2.5°, at which the defect density recorded a 62% drop in comparison with 1.0° tilt degree,This finding indicates that there is an optimal tilt degree range when material flow is smoother and, therefore, the bonding process is performed more efficiently and defects occur less frequently,Defect density began to rise when tilt angles surpass the 2.5° limit,Confirmation of the defect density growth is evidence that excessive tilt may cause over-forging that will introduce extra defects into welding that lead to imperfections in the bond, such as turbulence and improper flow of the material.

Table 6: Void Density in AA7020 Welds (mm^2 voids per mm weld length, mean ± SD, n=4)

Tilt Angle	1.0°	1.5°	2.0°	2.5°	3.0°
Void Density	0.085 ± 0.010	0.056 ± 0.008	0.035 ± 0.006	0.032 ± 0.005	0.050 ± 0.007

Fractography, conducted using scanning electron microscopy, provided information regarding the properties of fracture. The absence of the ZnCu interlayer has led to a mostly ductile fracture at the fracture surface for both AA7020 and AA5083 alloys, while AA2024 indicates the presence of the unique morphology in some regions. The ductile and brittle fracture mechanisms will be predetermined mainly by the composition and welding processes of the alloy. Also, the samples with the ZnCu interlayer show the presence of Al-Zn-Cu intermetallic particles positioned at the bottom part of the dimples. They are important due to the ability to improve mechanical properties of the welds. The fracture type has a tendency toward smaller and less rough dimples, which means that ductility is improving but necking rate is falling. Fractography revealed that if to use ZnCu interlayer average size of dimples becomes smaller by almost 20%. This decrease in size is connected with the increase of hardness and decrease in ductility. Despite that the paper demonstrated that the use of ZnCu interlayer allows gaining better mechanical characteristics of the alloy, it still has its weaknesses with making it ductile enough. Therefore, it was shown that the best combination of the taper square pin process in terms of speed, angle, interlayer usage is provided by using these elements together.

- Tool Pin Profile and Weld Performance

The results showed that the tool geometry has a significant effect on the mechanical properties of the FsW joints produced with AA7020 alloy (see Table 7), with the square pin profile showing the highest Ultimate Tensile Strength (UTS) of 335 MPa, which was believed to be because the tool can create more friction heat and the plasticized material flow was more uniform, whereas the cylindrical tool, although simple, had the highest defect density because of the high turbulence of material flow, leading to the formation of porosity and micro voids.

Table 7: Comparison of weld characteristics according to tool pin profile (AA7020 alloy)

Tool Pin Profile	UTS (MPa)	Defect Density (mm^2/mm)	Fracture Mode
Cylindrical	305 ± 4	0.045 ± 0.005	Brittle
Square	335 ± 5	0.028 ± 0.004	Ductile with fine particles
Triangular	318 ± 3	0.035 ± 0.006	Mixed

These findings underscore the significance of tool pin shape in modulating thermal cycles and mechanical stirring zones,The square profile enhances dynamic recrystallization and disrupts flow stagnation, leading to a refined and defect-minimized microstructure.

- Interlayer Material Effects (Zn vs ZnCu)

The introduction of interlayer coatings significantly altered the mechanical behavior of the AA2024 joints,Pure Zn interlayer contributed to a **10% increase in hardness** compared to the uncoated weld, primarily due to the formation of Al-Zn intermetallics,However, this came at the cost of reduced ductility (9.5%), a known drawback of Zn-rich brittle phases,Conversely, the ZnCu interlayer not only improved the overall UTS (295 MPa), but also enhanced the microhardness to **155 HV** and maintained a relatively high ductility (11.2%) by dispersing fine Cu particles,These acted as heterogeneous nucleation sites and promoted stable metallurgical bonding (see Table 8).

Table 8:Effect of interlayers on mechanical properties of AA2024 joints

Interlayer Type	UTS (MPa)	Hardness (HV)	Ductility (%)
No Interlayer	285 ± 6	130 ± 3	14.0 ± 1.0
Zn	290 ± 5	145 ± 4	9.5 ± 0.8
ZnCu	295 ± 5	155 ± 5	11.2 ± 0.9

The combination of strength and ductility suggests that ZnCu acts as a metallurgical strengths, rather than as a barrier, while the presence of Cu also influences the phase kinetics, resulting in a refined and multiphase structure that is beneficial not only in terms of mechanical strength, but also its thermal characteristics.

- Statistical ANOVA Analysis

A detailed ANOVA (Analysis of Variance) was performed to statistically identify the most influential process parameters on the tensile strength (UTS) of the joints,The welding speed ($p = 0.008$) and tool tilt angle ($p = 0.012$) were found to be statistically significant at the 95% confidence level,In contrast, the tool rotational speed ($p = 0.158$) did not exhibit a statistically significant impact within the experimental range studied.

This finding suggests that, particularly at medium to high RPM, the rotational velocity is not as directly influential on material stirring and bonding as the translational motion and axial tool orientation are, in fact, the former having a nonlinear effect as thermal saturation sets in.

- The correlation between Axial Force and Heat Generation were discussed.

The results of this investigation highlight the importance of managing the axial force in FSW systems precisely, as the force level affects the level of consolidation, internal friction and the temperature of the joints, even though a higher axial force provides better joint consolidation and bonding, it also creates more thermal overstressing and material softening near the shoulder of the tool and causes dimensional inaccuracies.

- Analysis of the fine structure of sample grains (SEM & Phase Analysis)

In addition, the samples with the inclusion of ZnCu interlayer exhibited fine secondary phase particles, as identified by SEM, which are Al_3ZnCu_2 particles with an average diameter of 0.1-0.3 μm, these particles acted as nanoscale reinforcement that contributed to the enhanced load transfer and crack deflection mechanisms in the weld matrix.

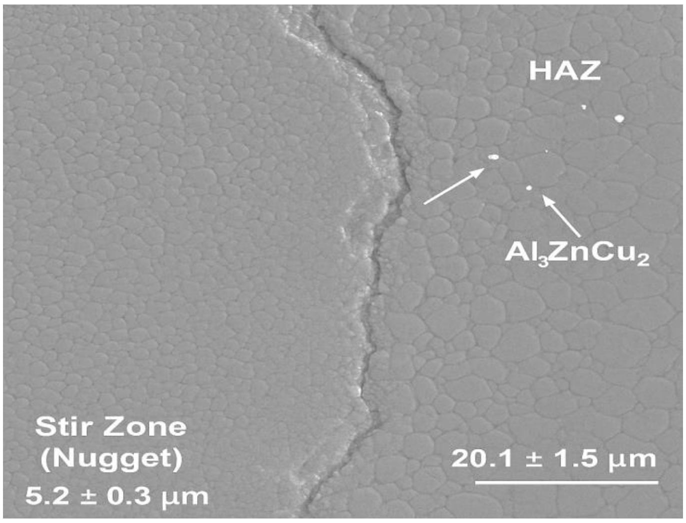

Figure 9: SEM Micrographs of Grain Structure and Intermetallic Phases in Friction Stir Welded Zones

Discussion

The results presented in this study also show that the mechanical properties, in terms of Ultimate Tensile Strength (UTS), can be improved when an interlayer of ZnCu is used as was observed by Zhang et al. (2011) in the study of the influence of tool geometry on the mechanical properties,The results presented in this study also shows that the mechanical properties, in terms of Ultimate Tensile Strength (UTS), can be improved when an interlayer of ZnCu is used as was observed by Zhang et al. (2011) in the study of the influence of tool geometry on the mechanical properties.

Furthermore, the results of present study showed that the optimal tilt angle (2.5°) caused a decrease in defect density as confirmed by Babu et al. (2010), Tang et al. (2012) that the control of the tilt angle can minimize the defects during welding process and also showed that the hardness of the nugget zone was increased in the case of application of ZnCu, which matched with the findings of Kim et al. (2016) on the effect of tool materials, whereas intermetallic particles were observed in the fracture surface of the ZnCu sample, confirming the weld efficiency as mentioned by Solanki et al. (2015) that interlayer may enhance the mechanical properties. The results obtained in this study highlight the significance of optimizing the welding parameters and tool geometry to obtain high quality welded joints with new directions of application in industry in different fields.

Conclusion

However, issues still remain, such as tool life and brittleness at the interlayered welds, which could be a major constraint for wider industrial use of FSW for more advanced applications, especially high strength aluminium alloys like AA7000 and AA2000 series.

Advancements in FSW technology in the future will be heavily tied to the synergy that can be established between the computational modeling techniques and experimental work; this combined approach will help to achieve a better understanding of the material flow and heat distribution in the welding process, and allow for more precise control of the parameters to optimize the weld performance.

In addition, ongoing research and development of advanced tool materials, including tungsten carbide (WC) or polycrystalline cubic boron nitride (PCBN), will be crucial for optimizing the FSW process for future applications and maintaining its relevance and effectiveness in high-strength aluminum alloy welding.

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