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Comparative Evaluation of Weld Quality, Mechanical Performance, and Feasibility in Dissimilar Friction Stir Welded AA 8090–CFRP and AA 8090-PP Joints

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Abstract:

Friction stir welding (FSW) joins materials without melting them during the process. It is often used for aluminum because it is more effective than conventional welding methods.

Friction Stir Welding (FSW) can be utilized in the fabrication of thermoplastic polymers and dissimilar hybrid structures, resulting in joints with significant mechanical strength. Nevertheless, the process may occasionally lead to defects, such as voids or incomplete bonding, which could potentially compromise the overall strength and reliability of the joint.

This study presents an experimental investigation into the dissimilar joining of AA 8090 aluminum alloy with carbon fiber reinforced (CFR) polymer and polypropylene (PP) under comparable friction stir welding (FSW) conditions. This study evaluated the joint feasibility, tensile performance, and weld defect characteristics of both material combinations.

The AA 8090 Al–CFR polymer joint produced structurally weak results. The primary cause was identified as poor interfacial adhesion between the aluminum surface and the epoxy resin binder within the CFR polymer, which restricted effective mechanical interlocking and offered little chemical affinity at the interface. In contrast, the AA 8090 Al–PP combination yielded a more viable joint, with the tensile strength reaching approximately 20% of the PP base material, which is consistent with mechanical interlocking as the governing bonding mechanism. Defects, including interfacial voids, incomplete bonding zones, and material flow irregularities, were recorded in both combinations, which were largely attributed to the pronounced mismatch in thermal conductivity, melting behavior, and flow properties between aluminum and each polymer.

The findings indicate that thermoplastic polymers, such as polypropylene (PP), exhibit superior compatibility with aluminum in friction stir welding (FSW) compared with thermosetting fiber-reinforced systems. The epoxy resin matrix in CFR polymers poses challenges in dissimilar FSW joints with aluminum owing to its thermal degradation, poor thermal conductivity, and incompatibility with the frictional heat generated during the welding process, leading to delamination and weakened interfacial bonding. Although the AA 8090 aluminum–PP joint demonstrates limited strength, it is feasible and sufficiently strong for practical applications; it is adequate for non-critical lightweight structures, such as automotive interior panels and aerospace secondary components, where weight reduction takes priority over maximum mechanical performance. Future research should prioritize the development of improved tool geometries, surface preparation techniques prior to welding, and effective heat management strategies to enhance the reliability of Al–polymer FSW joints.

Keywords: Friction stir welding, AA 8090 Aluminium, polypropylene, carbon fiber reinforced polymer, dissimilar joining, tensile strength, interfacial defects, joint feasibility, mechanical interlocking

1. Introduction

Manufacturing industries across the aerospace, automotive, and electronics sectors have increasingly pushed toward multi-material structures - assemblies that combine the structural efficiency of metals with the weight savings of polymers and composites. This shift is not merely a trend but a response to the mounting pressure for lighter, more fuel-efficient, and structurally optimized products. However, realizing the full potential of such combinations requires reliable joining techniques, and this is precisely where conventional welding falls short. Fusion-based processes, built on the premise of melting base materials together, struggle fundamentally when asked to unite materials with vastly different thermal properties, melting points, and chemical compatibility.

Friction Stir Welding (FSW) is a solid-state joining process invented by The Welding Institute in 1991, which uses a rotating tool to generate heat through friction without melting the material. This frictional heat softens the surrounding material just enough to plasticize it, allowing the tool to mechanically forge a strong and continuous joint in a fully solid form. FSW generates significantly less heat than conventional fusion welding processes, making it far more suitable for temperature-sensitive materials, such as polymers and polymer-based composites. This reduced thermal input effectively prevents degradation, delamination, and matrix burning, which would otherwise occur under the intense temperatures of traditional fusion methods.

This study focuses on material pairing involving Al 8090, an aluminum-lithium alloy initially developed for rigorous aerospace applications. AA 8090 is approximately 10% lighter than conventional aluminum alloys while still offering higher specific stiffness and competitive tensile strength. These properties have established it in airframe structures, helicopter components, and lightweight spacecraft panels, where mass reduction has direct operational consequences. What becomes genuinely interesting is how this alloy performs when joined via FSW with materials that sit at the opposite end of the material spectrum.

Carbon Fiber Reinforced Polymer (CFRP), the first dissimilar partner considered here, is a composite that has become nearly synonymous with high-performance structural engineering. Its exceptional stiffness-to-weight ratio has led to its adoption in aircraft fuselage panels, automotive chassis reinforcements, wind turbine blades, and high-end sporting equipment.

Polypropylene (PP), the second material pair, operates in a different application space. As a semi-crystalline thermoplastic, PP is inexpensive, chemically resistant, and widely used in automotive door panels, under-bonnet components, battery housings in electric vehicles, and certain medical device enclosures.

This study conducted a systematic experimental investigation of FSW joints between Al 8090 and CFRP and Al 8090–PP, with three primary objectives: to characterize the tensile behavior of each joint type, to identify and describe defect formations within the weld zone, and to evaluate the overall feasibility of achieving structurally functional joints in each case. The aim is not merely to confirm the occurrence of bonding but to develop an evidence-based understanding of the mechanical and morphological behaviors that either support or limit the use of FSW as a viable joining method for these dissimilar combinations.

2. Literature Review: Dissimilar Friction Stir Welding of Aluminium and Polymer

The use of friction stir welding (FSW) to join aluminum alloys with polymers and composite materials has gained significant research interest in recent years. This interest mainly stems from the growing need in the industry for lightweight hybrid structures, which are difficult to achieve using conventional fusion welding or mechanical fastening methods.

Joining dissimilar materials is challenging because their properties, including thermal conductivity, melting characteristics, and chemical behavior, differ significantly. As a result, selecting suitable process parameters and understanding how bonding occurs at the interface have become more critical than in typical metal-to-metal joining systems.

The Welding Institute introduced friction stir welding (FSW) in 1991 as a solid-state joining technique that avoids melting and relies on the plastic deformation of the material. In this process, a rotating, non-consumable tool produces frictional heat that softens the material without turning it into a liquid, allowing the joint to form in the solid state.

The Key process parameters are tool rotational speed, traverse speed, tool design, and tilt angle, which directly affect the heat input and the manner in which the materials mix and bond, ultimately determining the quality and characteristics of the joint formed between dissimilar materials.

Tool design has emerged as a particularly consequential variable in dissimilar FSW applications. Patel et al. [6] joined AA6061-T6 and polycarbonate at rotational speeds from 500 to 1400 rpm, recording a maximum tensile strength of 14.91 MPa at 500 rpm and 40 mm/min. A tool tilt angle of 1.5° produced the most favorable stir zone morphology and peak temperature distribution, with microstructural examination confirming mechanical interlocking as the dominant bonding mechanism. Huang et al. [7] extended this understanding to 6061-T6 aluminium and PEEK via friction stir lap welding using a triple-facet tapered threaded pin, achieving a maximum shear bond strength of 20 MPa. Increasing the traverse speed reduced the aluminum anchor size and adhesion area, directly deteriorating the mechanical interlocking, confirming that the pin geometry and welding speed require simultaneous optimization rather than independent adjustment.

Research involving aluminum alloys in dissimilar FSW configurations has spanned a wide range of alloy systems, with the 5xxx and 6xxx series dominating the published literature. Khodabakhshi et al. [1] achieved a defect-free FSW joint between AA5059 and HDPE at 710 rpm with a pin offset of 1.4 mm toward the aluminium side, yielding 50% joint efficiency relative to HDPE. Higher rotational speeds produced wider metal fragments alongside tunnel defects and microvoids, which progressively deteriorated the strength. A subsequent interface characterization study by the same group [4] using FE-SEM and TEM revealed macro-, micro-, and nanoscale mechanical interlocks between aluminum fragments and the re-solidified polymer, with a 30-nm-thick semi-crystalline interfacial aluminum layer enriched in oxygen. This multi-scale interlocking architecture, rather than any chemical reaction product, was confirmed as the structural basis of joint load transfer, a finding with implications well beyond the specific alloy–polymer pair studied.

Investigations into aluminum–CFRP and aluminum–polymer joining have collectively mapped the process parameter space with increasing resolution. Derazkola and Elyasi [5] joined AA5058 with polycarbonate, identifying 1600 rpm and 45 mm/min as the optimum combination; excessive heat caused PC thermal degradation and void-type defects, whereas insufficient heat produced incomplete bonding, together defining a narrow viable process window. Shahmiri et al. [3] reported an analogous thermal constraint in AA5052–PP lap joining, where low rotational speeds caused poor interface contact and voids, and excessive heat generated polymer overflow and surface degradation. Ashong et al. [11] produced AA6014–CFRP joints by refill friction stir spot welding with a peak tensile shear load of 1.6 kN, and XPS analysis confirmed the simultaneous formation of Al–O–C, C–C, and C=O bonds at the fracture surfaces, which is a dual bonding mechanism that distinguishes CFRP-based joints from most thermoplastic systems, where chemical bonds are absent. Choi et al. [12] further demonstrated in Ti–CFRP FSW that sound joints formed only within a narrow thermal band between the matrix melting point and its decomposition temperature, with fracture shifting from the interface into the CFRP stir zone at elevated rotational speeds.

Tensile behavior and defect characterization have received increasing attention as the field has matured beyond feasibility demonstration toward structural performance evaluation. Moghanian et al. [13] achieved a peak tensile shear strength of 22.5 MPa in Mg–PP lap joints at 700 rpm and 75 mm/min, which was attributed to an optimum mechanical interlocking fraction of 48% and interfacial MgO formation. Alhatti et al. [14] recorded 3.8 MPa in AA5052–PP friction stir lap welding, with SEM confirming a chip–PP composite microstructure reinforced by metallic hooks; joint strength decreased consistently as interaction layer thickness increased, establishing excess heat input as counterproductive. Hosny et al. [15] subsequently defined the operative temperature window for AA5052–PP joining as 156°C to 316°C, with over-melting and bubble nucleation appearing above this threshold. Correia et al. [10] modelled joint strength in AA6082-T6–glass fibre reinforced polymer joints as a combined contribution from mechanical interlocking, chemical bonding, and Van der Waals interactions, noting that excessive temperature caused polymer degradation while insufficient temperature produced tunnel defects from inadequate material stirring. Yuan et al. [17] further reported depth-dependent microstructural asymmetry in Al–carbon fibre reinforced thermoplastic lap welds, where smaller metal fragments at the lower interface recombined into larger entities - a redistribution that renders surface tensile measurements insufficient for characterising load transfer through the full joint thickness.

Review contributions have synthesized these findings into broader frameworks. Huang et al. [8] identified back support, weld thinning, and keyhole formation as the three inherent structural challenges of polymer–metal FSW, while confirming that short carbon-fiber-reinforced PEEK joined with aluminium can achieve tensile shear strengths up to 33 MPa. Haghshenas and Khodabakhshi [9] identified rotational speed, welding speed, tool geometry, and material placement on the advancing or retreating side as the most influential variables, with hybrid techniques combining FSW and adhesive bonding offering joint efficiency gains beyond conventional optimization. Asmael et al. [18] documented the strongest metal–CFRP FSSW joint at 7.1 kN for AA5182–CFRP at 3000 rpm, while noting that pore formation beneath the tool centre- driven by localised resin decomposition - persisted across systems regardless of parameter refinement. Barakat et al. [19] confirmed across multiple alloy–polymer combinations that interaction layer thickness correlates inversely with joint strength, a relationship now sufficiently replicated to constitute a general principle of dissimilar FSW rather than a material-specific anomaly. Melaku and Tomków [16] further attributed interfacial bubble and pore formation to trapped moisture in the polymer expanding as vapor during processing, a degradation mechanism distinct from thermal decomposition and one that complicates defect prediction from temperature data alone. Malaske et al. [20] assessed friction stir joining of aluminium with CF-PPS, demonstrating that macro-mechanical interlocking through aluminium nub insertion produced structurally coherent joints without adhesives, with the solid-state process confining metallurgical changes to a comparatively small heat-affected zone.

Existing studies have clearly shown that researchers have developed a good understanding of how process parameters affect friction stir welding (FSW) in individual systems, such as metal–polymer and metal–CFRP joints. However, there is still a lack of direct experimental comparison between two different types of polymer-based materials under the same welding conditions. This gap is particularly evident for aluminum–lithium alloys, such as Al 8090, which have not been sufficiently explored in this context in either experimental or review studies.

To address this limitation, the present study investigates Al 8090–CFRP and Al 8090–PP joints produced by FSW under identical conditions. This study focuses on the tensile properties, defect analysis, and overall joint feasibility, providing material-specific insights that are currently lacking in this research area.

3. Experimental Methodology

This experimental study was designed to evaluate the mechanical performance and weld quality of dissimilar friction stir welded (FSW) joints made between an aluminum and lithium alloy, AA 8090, and two different polymer-based materials: carbon-fiber-reinforced polymer (CFRP) and polypropylene (PP). As joining metals with composite materials in the solid state is inherently complex, this study followed a carefully controlled experimental approach.

The methodology included systematic steps, such as material preparation, selection of welding parameters, microstructural examination, tensile testing, and defect evaluation. Each stage of the procedure is clearly outlined and discussed in the following subsections.

3.1 Materials and Specimen Preparation

3.1.1 Base Materials

The metallic constituent employed in this study was AA 8090, a third-generation aluminum–lithium alloy distinguished by its reduced density, elevated specific stiffness, and moderate precipitation-hardening capability. This alloy is widely used in aerospace structural applications and serves as an appropriate candidate for solid-state joining research owing to its sensitivity to thermal cycles and well-documented susceptibility to liquation and solidification cracking under fusion-welding conditions. Plates of AA 8090 were prepared in the workpiece form with nominal dimensions of 100 mm × 50 mm × 5 mm.

The first polymeric material selected was a woven carbon-fiber-reinforced polymer (CFRP) composite, consisting of a cross-ply carbon-fiber fabric embedded within an epoxy matrix. CFRP panels with dimensions of 100 × 50× 5 mm. The second polymeric material was a polypropylene (PP) sheet of the same planar dimensions with a thickness of 5 mm.

3.2 Friction Stir Welding Setup and Process Parameters

3.2.1 Machine Configuration

All welding trials were performed on a 3-axis CNC friction-stir welding machine (spindle torque capacity: 120 N·m; axial force capacity: 25 kN) operated in position-control mode.

3.2.2 Tool Design

A bespoke FSW tool fabricated from H13 tool steel (hardness: 50 HRC) was used throughout the study. The tool comprised a concave shoulder of 18 mm diameter and cylindrical pin of 6 mm diameter and 4.8 mm length, chosen to penetrate the aluminum plate by approximately 95% of its thickness. A conical shoulder angle of 2° was selected

3.2.3 Process Parameter Matrix

The study examined three levels of spindle speed—500, 1200, and 1700 rpm—together with welding speeds of 20, 30, and 50 mm/min, to determine suitable conditions for producing high-quality joints. Each combination produced different results; some settings led to visible defects, whereas others showed improved bonding performance.

An increase in the spindle speed enhanced the frictional heat at the tool–workpiece interface, which improved the material softening and flow. Simultaneously, the welding speed had a strong influence on joint formation, as both very low and very high traverse rates tended to cause defects such as incomplete bonding or material disturbance.

Butt joint configuration is used

The tool is 1 mm offsetted to aluminium side and aluminium at advancing side.

3.3.1 Joint Feasibility and Interfacial Behaviour: Al 8090–CFR Polymer

Dissimilar FSW of Al 8000 series aluminum alloy and CFR polymer was conducted under the selected process parameters, and joint formation was visually confirmed across all trial specimens. As shown in Fig.1, a weld joint was physically produced along the interface between the two materials. However, visual examination and mechanical assessment both indicated that the joint was structurally weak and lacked the integrity needed for any meaningful load-bearing application.

Fig1: CFR Polymer and AA 8090 Dissimilar Joint Formation

3.3.2 Joint Feasibility and Interfacial Behavior: Al 8090–Polypropylene

When different material combinations were evaluated, it was observed that joining aluminum with polypropylene (PP) using friction stir welding (FSW) was more practical and easier to control than joining with carbon-fiber-reinforced polymer (CFRP) (epoxy resin matrix). The simpler softening behavior of polypropylene, together with the good thermal conductivity of aluminum, allowed better process stability and control.

Consequently, the aluminum–PP joints exhibited more consistent quality and higher reliability, whereas the aluminum–CFRP combination presented greater challenges during welding.

When the spindle speed was set to 1700 rpm and the welding speed to 30 mm/min, the process generated sufficient frictional heat at the tool–workpiece interface to properly soften the Aluminum AA 8090 and polypropylene (PP). This adequate heat input enabled a smooth and uniform material flow within the joint region, leading to a well-formed and defect-free weld.

The chosen combination of rotational and traverse speeds maintained a proper thermal balance, avoiding both overheating and insufficient softening during the welding. Consequently, this parameter set produced the most reliable joint, exhibiting the highest strength and best structural quality among all conditions evaluated in this study.

Fig.2: CFR Polymer and AA 8090 Dissimilar Joint Formation

Fig.3: CFR Polymer and AA 8090 Dissimilar Feasible Joint Formation

4. Testing and Discussions

4.1 Tensile Testing

4.1.1 Specimen Geometry

After welding, strong and feasible joint was sectioned transversely to the welding direction using a precision water-cooled diamond saw to produce tensile specimens conforming to a modified ASTM E8. The specimen dimensions are shown in fig.

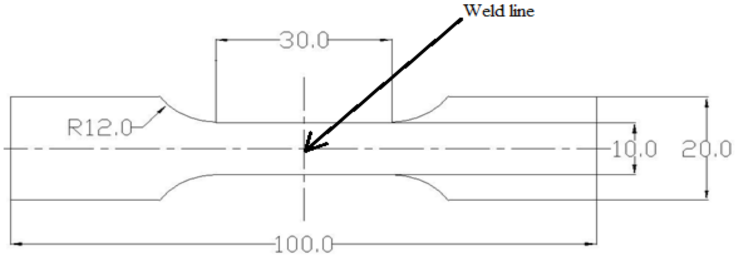

Fig.4: Tensile testing specimen [21]

4.1.2 Test Configuration

Uniaxial tensile tests were conducted on a precision electromechanical universal testing machine (Instron 5966, load cell capacity: 2 kN)

Among all parameter combinations examined, a spindle speed of 1700 rpm combined with a welding speed of 30 mm/min produced the most reliable results, yielding joints with superior strength and improved structural soundness compared to other conditions.

Friction stir welding (FSW) experiments were conducted on an FSW machine under well-controlled conditions, specifically optimized for the AA 8090 aluminum–lithium alloy. The selected process parameters were as follows:

- Tool design: a straight cylindrical pin with a concave shoulder
- Rotational speed: 1700 rpm
- Welding (traverse) speed: 30 mm/min
- Tool tilt angle: maintained between 2° and 3° in the backward direction

These settings were chosen to prepare tensile test specimen.

4.2. Results and Discussion

4.2.1 Tensile Test Analysis

Joint Efficiency

When dissimilar friction stir welding (FSW) was performed between AA 8090 series aluminum and polypropylene (PP) at a traverse speed of 30 mm/min and a rotation speed of 1700 RPM, a sound and feasible joint was successfully produced. The joint exhibited an efficiency of approximately 20% compared to the polypropylene base material. Although bonding was achieved with limited defects, the overall strength of the joint remained relatively lower than that of the parent PP material. FSW joints achieved a tensile strength of 12 MPa (>20% joint efficiency)

4.2.2 Macrostructural and defects Analysis:

Fig. 5 shows the macrostructure of the AA 8090 aluminum joint of two different combinations. Shows similar structure. The tool was offset by 1 mm to the aluminum side and aluminum at the advancing side. The figure shows that the welded-joint region between aluminum and polymer clearly reveals the characteristic surface appearance produced through the friction stir welding process. The central weld zone displayed a textured, consolidated mass where the frictional heat successfully softened and intermixed the two dissimilar materials during tool traversal. Closer observation revealed slight irregularities along the weld edges, which are typical in aluminum–polymer FSW joints and reflect the contrasting thermal and mechanical properties of the two materials involved. Overall, the joint appears reasonably well-formed and continuous along its length, suggesting that the selected process parameters facilitated adequate material flow and bonding between the aluminum and polymer interfaces.

Fig.5: Macrostructure of Disimilar FSW joint Aluminium AA 8090 and PP

4.2.3 Defects:

Tunnel Defect

Fig. 6A clearly shows a continuous hollow channel running through the weld interior, which developed owing to inadequate heat generation and poor material flow during FSW. This subsurface void visibly reduces the effective bonding area within the joint, directly weakening its ability to withstand the mechanical loading.

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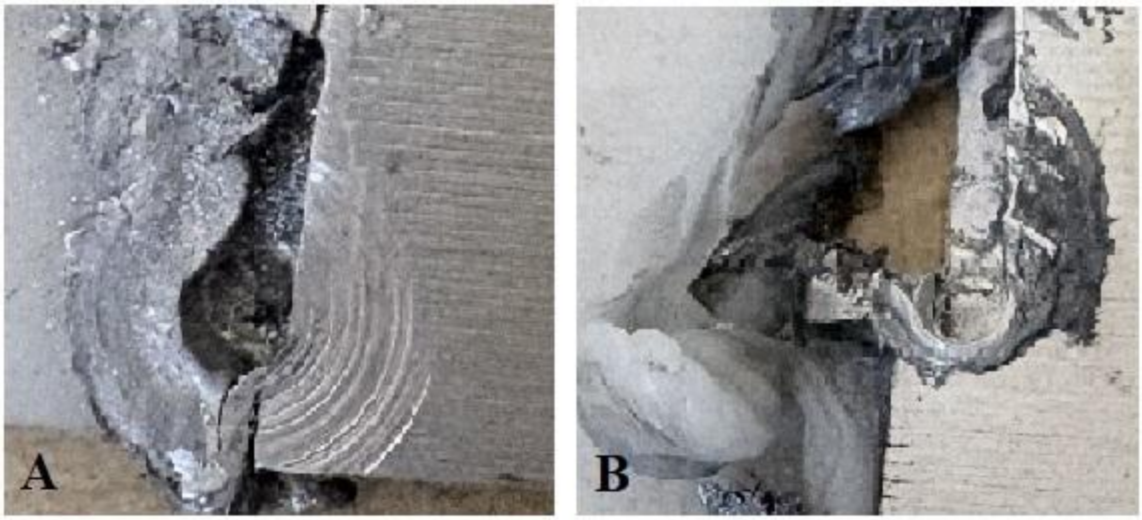

Fig.6: A: Tunnel Defect, B: Flash Defect

Flash Defect

As seen in Fig.6B, excess softened material has been expelled outward along the edges of the weld path, forming the characteristic flash deposits typical of over-heated FSW conditions. This visible material loss from the weld zone indicates that the heat input exceeded the optimal level, ultimately affecting the dimensional accuracy and strength of the joint.

Kissing Bond Defect

The photograph (Fig.7) reveals a weld interface that appears visually intact and continuous on the surface, yet closer examination suggests that the two materials have made only superficial contact without achieving true metallurgical bonding. This subtle but critical defect, visible as a faint boundary line at the joint interface, typically arises from insufficient downward forging force or inadequate heat input during the welding process.

Fig.7: Kissing Bond

4.2.4 Joint Feasibility and Interfacial Behavior: AA 8090 - CFR polymer

The core issue lies in the nature of the matrix binding the carbon fibers. The CFR polymer used in this study contained an epoxy resin binder, which is a thermosetting polymer. Unlike thermoplastic polymers, which soften and flow reversibly upon heating, thermosetting epoxy resins undergo an irreversible crosslinking cure during manufacturing and cannot be remolded or reflowed. When subjected to frictional heat during FSW, the epoxy resin begins to pyrolyse rather than softening into a workable state that supports material flow and bonding. Published literature confirms that the pyrolysis temperature of epoxy resin in CFRP is approximately 300°C 400^{0}C— a threshold readily approached or exceeded in the weld zone during FSW of aluminum. Beyond this point, the resin decomposes irreversibly, losing its structural role as a binding matrix. When carbon fibers are exposed to high temperatures, they undergo thermal oxidation. The loss of structural integrity and thermal shielding is called Thermal Degradation.

The resulting interface was characterized by weak contact, scattered bonding zones, and an absence of continuous interlocking features required for effective load transfer. The Al 8090–CFR polymer joint produced structurally weak results not only because of parameter selection, but also because of a fundamental incompatibility between the thermosetting nature of the epoxy binder and the thermomechanical demands of the FSW process. This finding has important implications for material selection: CFR polymers bound with thermosetting epoxy resins are inherently unsuitable for conventional FSW without significant modifications, such as thermoplastic interlayers, surface pre-treatment, or alternative low-heat joining strategies.

4.2.4 Joint Feasibility and Interfacial Behavior: Al 8090–Polypropylene

In contrast to the Al 8000–CFR polymer trials, the dissimilar FSW of Al 8090 aluminum alloy and polypropylene (PP) produced considerably more encouraging results. As shown in Fig. 3, a well-formed weld joint was achieved along the Al–PP interface, and both visual inspection and tensile testing confirmed that the joint was structurally sound. The tensile strength reached approximately 20% of the PP base material value, which is consistent with the results reported in the broader Al–thermoplastic FSW literature and confirms that a functional, reproducible joint was established.

The more favorable response of PP under FSW conditions stems from its thermoplasticity. Unlike epoxy-bound CFR polymers, PP softens and flows reversibly upon heating. During FSW, the frictional heat generated at the tool–workpiece interface raised the local temperature sufficiently to plasticize the PP, enabling it to deform and partially intermix with the Al 8090 surface. Upon cooling, the re-solidified PP formed mechanical interlocks with the aluminum surface asperities and embedded metal fragments, which is the primary and essentially sole bonding mechanism in Al–PP FSW joints, as chemical interaction at the PP–metal interface is considered negligible owing to the non-functional surface chemistry of polypropylene macromolecules.

Despite the feasibility of the joint, the weld was not defect-free. As shown in Fig.6A, 6B cross-sectional examination revealed interfacial voids and localized regions of incomplete bonding within the weld zone. These are characteristic defects in dissimilar Al–polymer FSW, arising from the significant mismatch in the thermal conductivity and material flow behavior between the two materials. Aluminum conducts heat rapidly and remain structurally rigid throughout the process, whereas PP softens at comparatively low temperatures. Where the thermal conditions were locally insufficient, the PP did not fully plasticize, leaving unbonded pockets along the interface. In some areas where the heat input was slightly excessive, polymer overflow at the weld edges reduced the effective bonded area. Nonetheless, the bonded regions provided sufficient load transfer to produce a consistent tensile response, and fracture occurred within or near the PP material rather than at the bare interface, indicating that the interface had developed genuine mechanical interlocking. Therefore, the presence of defects is best understood as a consequence of process parameters that require further optimization rather than a fundamental incompatibility between the materials. The Al 8090–PP combination is a feasible dissimilar FSW candidate, with scope for meaningful improvement in joint efficiency through refined tool geometry and controlled heat input.

5. Conclusions

This study investigated the friction stir welding of dissimilar material combinations, specifically CFRP–AA 8090 and Polypropylene (PP)–AA 8090 joints. Of the two configurations, the PP–AA 8090 pairing consistently demonstrated greater structural reliability and process feasibility, attributed to the cooperative thermal behavior of polypropylene and its compatibility with the frictional heat generated during FSW. The PP–AA 8090 joint achieved approximately 20% of the polypropylene base metal strength, which is an encouraging outcome given the substantial differences in the thermal and mechanical properties of the two constituent materials. Macrostructural examination confirmed that carefully optimized process parameters produced several sound, well-consolidated joints with only limited defects, demonstrating the potential of this material combination. However, some samples displayed significant flaws, such as tunnel defects, flash formation, and kissing bond defects, highlighting the sensitivity of the FSW process to even slight changes in welding conditions. Among all parameter combinations explored, a spindle speed of 1700 RPM paired with a welding speed of 30 mm/min was the most effective setting for achieving a strong, defect-minimal joint. These findings collectively underscore the potential of friction stir welding as an effective method for joining polymer–metal hybrid structures in the future. However, to enhance joint uniformity and achieve greater strength, further advancements in tool design, optimization of process parameters, and improvement in surface preparation are required.

5.1 Future Scope

Future studies should explore a broader range of tool geometries, shoulder diameters, and pin profiles to enhance the material flow and interfacial bonding in PP–aluminum FSW joints. Employing systematic parameter optimization through response surface methodology or the Taguchi design of experiments can yield a more profound understanding of the interaction effects that influence joint strength and defect formation. The application of surface pre-treatment techniques may further enhance adhesion at the polymer–metal interface. In addition to butt joint configurations, exploring lap joint arrangements could be beneficial, as they may provide an increased contact area and improved bonding efficiency for polymer–metal combinations. Advanced nondestructive evaluation methods, including phased-array ultrasonic testing and X-ray computed tomography, should be employed to characterize internal defect morphology with greater precision

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