

*Review*

# Recent Advances and Future Perspectives in Friction Stir Welding and Processing: A Review

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## Abstract

Friction stir welding (FSW) began as a fairly specialized joining method, but over the past three decades it has evolved into something considerably more versatile, a manufacturing platform that now handles complex multi-material assemblies and solid-state additive processes with reasonable reliability. This review follows this evolution, paying particular attention to friction stir additive manufacturing (FSAM) and the persistent difficulties that arise when joining dissimilar systems, such as aluminum to steel or metals to polymers, where the fate of the joint is largely decided by how well the intermetallic compounds are kept under control. Machine learning, artificial intelligence, and high-fidelity numerical models are reducing the reliance on trial-and-error that once dominated parameter selection and defect prediction, bringing FSW closer to the operating principles of Industry 4.0. Hybrid variants, including ultrasonically assisted and underwater FSW, also receive attention here, as they offer researchers finer control over heat generation and plastic flow than the standard process allows. Throughout the study, microstructural observations are directly connected to mechanical results, with the aim of analyzing the current state of solid-state manufacturing and identifying the questions that most urgently need answering.

**Keywords:** friction stir welding (FSW); dissimilar joining; microstructural evolution; process optimization; hybrid welding

## 1. Introduction

### 1.1. Background and Industrial Context

Since its invention at the Welding Institute (TWI) in 1991, friction stir welding has emerged as one of the most important developments in solid-state joining [1]. Early investigations by Dawes and Thomas [2] confirmed that this solid-state approach was particularly well-suited for aluminum alloys, which tend to develop porosity and hot cracking when welded by conventional fusion methods. The process, described in the seminal patents by Thomas et al. [3], operates by means of a profiled, non-consumable rotating tool that is inserted into the interface between two workpieces. No melting of the material occurs during the process; instead, friction between the spinning tool and the substrate generates localized heat, reducing the yield stress of the material until it reaches a highly plasticized state. The tool then advances along the joint line, mechanically extruding and forging the softened material behind the pin into a consolidated joint, one

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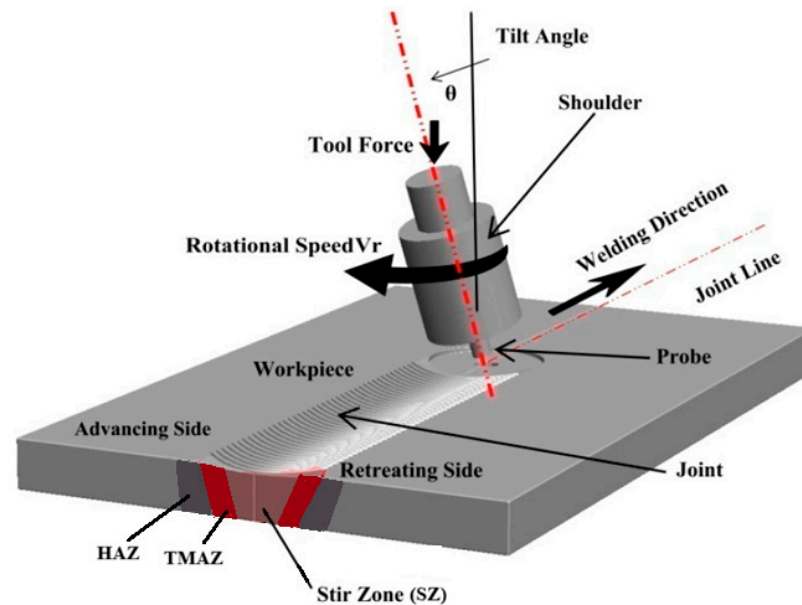
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formed entirely below the melting point. An FSW process schematic can be observed in Figure 1 in this manuscript, with the following labeling of all elements of the process: tool rotation direction, traverse direction, advancing side (AS) and retreating side (RS), stir zone (SZ/NZ), thermomechanically affected zone (TMAZ), and heat-affected zone (HAZ).

The aerospace industry has played a significant role in transforming friction stir welding from a specialized procedure into mainstream manufacturing, as highlighted by Ahmed et al. [4], who note that the FSW process serves as a leading weight-reducing alternative to mechanical fastening in aviation. The basic process and its variants, including stationary shoulder and coil configurations, allow for the defect-free assembly of advanced aluminum- and lithium-based structures. However, wider industrial adoption remains constrained by tool wear during high-temperature operations and the significant capital investment required for purpose-built multiaxis machines.



**Figure 1.** A schematic of the FSW process indicates the process's main characteristic features. The FSW tool is shown with the exit hole just below the tool after extraction [4].

The marine industry has followed a similar trajectory to the aerospace industry. The assembly of large structural components, which must withstand persistent moisture exposure and cyclic mechanical loading, has led marine manufacturers to move towards optimized joining parameters and hybrid bolted and soldered configurations. Delzendeurooy et al. [5] have studied how these approaches address the long-term integrity requirements faced by marine assemblies. In the automotive sector, the shift to electric propulsion systems has significantly accelerated FSW innovation. Patel et al. [6] show that high-speed FSW is suitable for the production of lightweight battery trays on a large scale. The joining is performed at higher traverse speeds that limit the heat-affected zone (HAZ) in aluminum extrusions, preserving the hardness of the base metal and shortening cycle times without significantly degrading impact strength.

These cross-industry requirements continue to drive research in the field of aluminum joining, as noted by Dada et al. [7]. Dynamic thermal management and microstructural refinement have proven to be effective tools for limiting HAZ degradation in high-strength structural alloys, while real-time monitoring and adaptive control are increasingly seen as prerequisites for defect-free joining in complex disparate systems. However, Prabhakar et al. [8] acknowledge that there are still significant barriers to

adapting friction stir welding (FSW) to a wider range of materials. Overcoming these requires reliable statistical optimization and continuous process monitoring to manage the variability inherent in thermomechanical processing. In the long term, expanding the industrial footprint of FSW will depend on the development of durable and cost-effective tools capable of withstanding extreme mechanical and thermal stresses while maintaining consistent joint quality, a challenge that has not yet been fully resolved.

### *1.2. Scope and Emerging Trends*

Although a substantial number of review articles have been published on friction stir welding in recent years, the present work occupies a distinct position in the literature. Most existing reviews focus on a single material system, such as dissimilar aluminum–steel joints, aluminum–magnesium combinations, or friction stir additive manufacturing, or on a single process variant such as underwater FSW or ultrasonically assisted FSW. Reviews that address digitalization in FSW tend to treat numerical modeling, machine learning, and statistical optimization as isolated topics. The contribution of the present review lies in its integrative framing: rather than treating dissimilar material systems, hybrid process variants, and digital process tools as separate research threads, this work examines them as a unified manufacturing system oriented toward the operating principles of Industry 4.0. The dissimilar material challenges described in Section 2 motivate the hybrid process solutions reviewed in Section 3, which in turn generate the experimental complexity that drives the digitalization approaches covered in Section 4. The microstructural analysis in Section 5 serves as a cross-cutting validation layer connecting all three pillars. This three-part architecture, materials, processes, and digitalization, distinguishes the present review from narrower surveys of the FSW literature and reflects the increasing integration of these domains in modern manufacturing research.

Dissimilar material joining has become one of the most active areas of current FSW research, driven by the demand for components with spatially tailored mechanical properties that single-material designs simply cannot provide. Even joining dissimilar aluminum grades presents complications not encountered in single-material configurations. Cam et al. [9] point out that preventing brittle intermetallic phases at the interface and ensuring adequate material flow across it depend largely on tool placement, positioning of the harder alloy on the advancing side, and careful thermal management throughout the welding cycle. Kilic et al. [10] found that an inadequate ratio between rotation speed and traverse speed promotes volumetric defects, such as tunnel voids and bonding, either of which degrades tensile and fatigue strength in ways that are difficult to repair later.

Beyond aluminum–aluminum combinations, friction stir welding (FSW) has been gradually extended to more complex multi-material associations, and Shankar and co-workers [11] have shown that joining aluminum to non-aluminum metals is possible due to the solid-state nature of the process, which eliminates many of the incompatibilities associated with solidification and which make conventional fusion welding impractical for such combinations. Managing differences in thermal conductivity, expansion coefficient, and yield stress requires tight control over heat input and tool kinematics, with particular attention to limiting intermetallic growth. In the case of ferrous alloys, Khedr et al. [12] reviewed FSW applied to steels, noting that while this method successfully avoids solidification defects and brittle phase transformations, it imposes severe demands on tool design and durability. Shravan et al. [13] emphasize that thorough microstructural and mechanical testing is indispensable for establishing reliable correlations between process variables and structural performance.

Specific alloy classifications introduce their own processing constraints. Non-heat-treatable aluminum alloys, studied by Abnar et al. [14], respond to thermomechanical loading quite differently from heat-treatable ones, and achieving acceptable joint efficiency typically requires specialized tool geometries and some form of active cooling to limit grain growth and softening of the heat-affected zone (HAZ). Di Bella et al. [15] noted that the different configurations add an additional level of complexity and that process parameters must be carefully calibrated to account for the different flow stresses between aluminum grades, with adjustments to rotation speed, tool tilt, and material placement all necessary to ensure adequate mixing and prevent non-uniform thermal gradients.

Underlying all of this is the fundamental importance of thermal control, a theme that Khalafe et al. [16] repeatedly state that the balance between frictional heat input and subsequent cooling rate governs microstructural evolution, which in turn determines mechanical performance. Ambrosio et al. [17] provide the physical basis for this relationship, describing how surface heating from the tool shoulder and internal agitation from the pin together create the extrusion and forging conditions necessary to strengthen the joint and close residual voids. More recently, solid-state welding (FSW) has been extended to material classes that once seemed inaccessible. Sonar et al. [18] report on solid-state welding of high-entropy alloys (HEAs), showing that the process can preserve complex multicomponent microstructures without elemental segregation, a promising outcome for next-generation structural applications.

Engineering strategies originally developed to manage thermal softening in conventional aluminum alloys are adapted, with appropriate modifications, to the joining of increasingly harder materials. By completely eliminating the liquid–solid phase transition from the equation, FSW provides a thermomechanical framework flexible enough to accommodate both commercial alloys and advanced high-entropy systems, provided that the process parameters are chosen with sufficient care.

The remainder of this review is organized as follows. Section 1.3 describes the literature search methodology and presents a brief bibliometric overview of publication trends in the FSW field. Section 1.4 establishes the thermomechanical fundamentals of FSW as a shared conceptual framework that is referenced throughout the review, avoiding repetition of these principles in individual material-system sections. Section 2 examines advances in dissimilar material joining across four principal combinations: aluminum–steel, aluminum–magnesium, aluminum–copper, and metal-to-polymer systems, with an additional subsection on high-entropy and specialty alloys. Section 3 reviews hybrid and derivative FSW variants, underwater FSW, ultrasonically assisted FSW, stationary shoulder FSW, and laser/induction-assisted hybrid processes, discussing the specific metallurgical limitations each variant is designed to address. Section 4 covers the digitalization of FSW, encompassing numerical modeling and simulation, machine learning and artificial intelligence, and statistical optimization techniques. Section 5 addresses microstructural challenges and defect characterization, with an emphasis on the process–structure–property relationships that govern mechanical reliability. Finally, Section 6 synthesizes the main findings, identifies unresolved scientific challenges, and proposes a future research roadmap oriented toward AI-integrated and Industry 4.0-enabled solid-state joining.

### *1.3. Literature Search Methodology*

This review was conducted as a critical narrative review rather than a formal systematic review in the PRISMA sense; nevertheless, in response to peer review feedback, full transparency regarding the literature selection strategy is provided here to

allow readers to assess the comprehensiveness and potential biases of the surveyed evidence.

### 1.3.1. Database Sources and Search Strategy

The primary literature search was conducted in Scopus and Web of Science (WoS) Core Collection, supplemented by targeted searches in Engineering Village and Google Scholar for gray literature verification. These databases were selected for their comprehensive coverage of materials science, manufacturing engineering, and mechanical engineering journals relevant to FSW research. For each database, both keyword and subject-category searches were performed, see Table 1.

**Table 1.** Search terms used.

| Keyword Group            | Search Terms Used                                                                                                                                                                 |
|--------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Process core             | "friction stir welding" OR "FSW" OR "friction stir processing" OR "FSP"                                                                                                           |
| Dissimilar joining       | "dissimilar joining" AND ("aluminum" OR "aluminium") AND ("steel" OR "magnesium" OR "copper" OR "polymer" OR "CFRP")                                                              |
| Intermetallic compounds  | "intermetallic compound" AND "FSW" OR "IMC layer" AND "friction stir"                                                                                                             |
| Additive manufacturing   | "friction stir additive manufacturing" OR "FSAM" OR "solid-state additive"                                                                                                        |
| Hybrid FSW variants      | "underwater friction stir" OR "UFSW" OR "ultrasonically assisted FSW" OR "UaFSW" OR "stationary shoulder FSW" OR "SSFSW" OR "induction-assisted FSW" OR "laser shock peening FSW" |
| Digitalization           | "machine learning" AND "friction stir welding" OR "artificial neural network" AND "FSW" OR "finite element" AND "FSW" OR "CFD" AND "friction stir" OR "digital twin" AND "FSW"    |
| Microstructure & defects | "dynamic recrystallization" AND "FSW" OR "tunnel defect" AND "friction stir" OR "kissing bond" OR "hook defect" AND "FSW"                                                         |
| Advanced alloys          | "high-entropy alloy" AND "friction stir" OR "titanium" AND "FSW" OR "Al-Li alloy" AND "friction stir" OR "Inconel" AND "FSW"                                                      |

### 1.3.2. Time Range and Publication Scope

The primary coverage window was January 2017 to December 2025, a period that captures the most significant recent advances in dissimilar FSW, FSAM, and the integration of machine learning into process optimization. This window was deliberately broad to reflect the multidisciplinary scope of the review. Seminal contributions published before 2017, including the original TWI patent [1], the foundational characterization studies for Al–steel and Al–Mg systems, and the first systematic FEM approaches to FSW, were retained regardless of publication date because they remain the primary references against which more recent work is contextualized. No restriction was placed on journal impact factor, but conference proceedings were included only where they reported original experimental or computational results not subsequently published as journal articles.

### 1.3.3. Inclusion and Exclusion Criteria

To ensure that the body of literature surveyed in this review reflected methodologically sound and technically relevant contributions, a structured set of inclusion and exclusion criteria was defined prior to source screening (Table 2). The selection framework was designed to balance breadth of coverage with analytical rigor, prioritizing sources that contribute quantifiable insight into the physical, microstructural, and mechanical behavior of friction stir welding (FSW), friction stir processing (FSP), and friction stir additive manufacturing (FSAM).

**Table 2.** Inclusion and exclusion criteria.

| Inclusion Criteria                                                                                                                                    | Exclusion Criteria                                                                                           |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|
| Peer-reviewed journal articles (any language, English abstract required)                                                                              | Studies without quantitative experimental or simulation results (purely descriptive)                         |
| Studies reporting original experimental, numerical, or hybrid results on FSW/FSP/FSAM                                                                 | Duplicate publications or translations of previously published work                                          |
| Review articles from the same period, retained for contextualization (not as primary sources for experimental claims)                                 | Studies on rotary friction welding or linear friction welding not directly applicable to FSW process physics |
| Seminal pre-2017 works cited in multiple recent studies, retained for foundational context                                                            | Preprints without peer-reviewed equivalent (accepted but not yet published excepted)                         |
| Studies on closely related solid-state processes (friction stir spot welding, stationary shoulder FSW) where directly relevant to the reviewed themes | Studies focused exclusively on non-metallic joining without any metal-side characterization                  |

#### 1.3.4. Quality Assurance

Reference quality was ensured through a multi-step process. Primary searches in Scopus and WoS were followed by backward citation tracing of the fifty most-cited papers in each keyword group, to capture foundational works that may have predated the primary time window or used different terminology. The resulting reference pool was cross-checked against the reference lists of fifteen recent FSW review articles identified in the initial search, to identify frequently cited studies absent from our keyword-based results. Papers were excluded when they lacked quantitative data, when their experimental conditions were too poorly described to contextualize (e.g., no reporting of tool geometry or welding speed), or when independent replication of their findings could not be located. It is explicitly acknowledged that no keyword-based search strategy is exhaustive; studies published in non-English languages, or indexed only in regional databases, may not be fully represented.

#### 1.3.5. Bibliometric Overview

A bibliometric analysis of the recovered literature provides useful context for the review. As shown in Figure A1, annual publication counts for FSW-related research indexed in Scopus rose sharply between 2017 (1078 publications) and 2019 (1646), after which total output stabilized at roughly 1500–1670 publications per year through 2025. This pattern points to a maturing field that has reached a high but broadly steady level of activity, rather than one undergoing continued exponential expansion. Against this stable baseline, three sub-fields display distinct dynamics: (i) dissimilar FSW, particularly Al-steel and Al-Mg systems, has shown no sustained growth, fluctuating between approximately 75 and 135 publications per year with no clear trend; (ii) machine learning and AI-assisted FSW grew from a small base of 16 publications in 2017 to 122 in 2025, increasing from roughly 1.5% to about 8% of annual FSW output; and (iii) FSAM exhibited the steepest relative growth of any FSW sub-field since 2020, rising nearly nine-fold from

25 publications in 2020 to 219 in 2025, consistent with the broader surge in solid-state additive manufacturing research.

Keyword co-occurrence analysis of titles and abstracts identified the dominant active research clusters: intermetallic compound control, process parameter optimization (rotation speed, traverse speed, axial force), microstructural evolution and dynamic recrystallization, hybrid process variants, and numerical/FEM modeling. Emerging clusters with high recent growth include digital twins, in-process monitoring, and high-entropy alloy joining. By contrast, publication rates on conventional similar-material aluminum FSW show signs of maturation, with declining marginal novelty in parameter optimization studies, a pattern consistent with the field's shift toward more complex material systems and digitalized process management.

The leading contributing countries by publication volume are China, India, South Korea, the United States, and Germany. China dominates in absolute output, particularly in dissimilar joining and hybrid process variants. India has emerged as a major contributor in statistical optimization and composite joining. European institutions lead in FSAM and advanced modeling. This geographic distribution reflects broader industrial priorities: lightweight structural joining for automotive and aerospace in Europe and North America, battery and EV applications in Asia, and marine applications distributed across all regions.

It is noted that the present review does not reproduce the full bibliometric output (co-citation maps, country collaboration networks) as these are available in dedicated bibliometric analyses of FSW cited elsewhere. The purpose of this subsection is to provide the reader with a quantitative sense of the field's trajectory and to contextualize the topic priorities selected for in-depth coverage in the following sections.

#### 1.4. Thermomechanical Fundamentals of FSW: A Shared Framework

Because subsequent sections discuss multiple material systems and process variants, it is useful to establish a common thermomechanical framework here and reference it throughout, rather than re-explaining the same physical principles each time. The following subsections describe the three governing phenomena, heat generation, material flow, and thermal cycle evolution, that underpin all FSW processes discussed in this review.

##### 1.4.1. Heat Generation Mechanisms

Heat in FSW is generated by two concurrent mechanisms: frictional dissipation at the tool–workpiece interface and viscous (plastic) dissipation within the shear-deforming material volume. The relative contribution of each depends on the interfacial contact condition, full sliding, partial sliding/sticking, or full sticking, which is itself a function of tool rotational speed, axial force, and material flow stress. Under the partial sliding/sticking regime that dominates in most practical FSW conditions, the total heat flux  $q$  at the tool shoulder contact can be approximated as

$$q \approx \mu \cdot P \cdot \omega \cdot r$$

where  $\mu$  is the interfacial friction coefficient,  $P$  is the contact pressure,  $\omega$  is the angular velocity, and  $r$  is the radial distance from the tool axis. Numerical studies (see Section 4.1) confirm that the shoulder accounts for approximately 70–85% of total heat input, while the pin contributes the remainder through internal shear deformation, a distinction with direct consequences for defect formation, as pin-generated heat governs material flow in the lower portion of the weld where root defects originate. The friction coefficient is not constant: it varies with temperature and slip rate, increasing during plunge (cold material, high friction) and decreasing once the material softens (reduced contact pressure). Models

that ignore this temperature dependence systematically overestimate peak temperatures and underestimate torque in the early stages of the weld.

#### 1.4.2. Material Flow and the Stir Zone

The plasticized material around the rotating tool is subject to three superimposed velocity components: rotational (circumferential), translational (in the welding direction), and vertical (through-thickness extrusion). The resultant material transport path is asymmetric: on the advancing side (AS), the tool rotation direction and travel direction are aligned, producing higher local velocities and temperatures; on the retreating side (RS), they oppose, producing a cooler, lower-velocity flow field. This asymmetry governs the distribution of heat, plastic strain, and microstructural refinement across the weld cross-section, and is particularly consequential in dissimilar joints where the two materials have different flow stresses, the harder material placed on the AS experiences greater mechanical mixing, while material on the RS is more susceptible to flow defects if insufficient heat is generated. The stir zone (SZ, also termed nugget zone, NZ) forms where all three velocity components produce sufficient deformation to induce complete dynamic recrystallization; its boundaries define the transition to the thermomechanically affected zone (TMAZ) and the heat-affected zone (HAZ). The TMAZ experiences plastic deformation without full recrystallization, while the HAZ experiences thermal cycling without plastic deformation, the latter being the weakest zone in precipitation-hardened alloys because strengthening precipitates coarsen or dissolve without the compensating grain refinement present in the SZ.

#### 1.4.3. The Thermal Cycle and Its Microstructural Consequences

The FSW thermal cycle is non-isothermal and spatially heterogeneous. Peak temperatures in the SZ typically reach 70–90% of the melting temperature for aluminum alloys (450–530 °C for 2xxx and 7xxx series), while the HAZ experiences lower peak temperatures (250–380 °C) for longer durations. The traverse speed is the primary variable controlling the heating rate and dwell time: higher traverse speeds reduce peak temperature and dwell time at temperature, which limits precipitate dissolution in heat-treatable alloys and restricts grain growth in non-heat-treatable alloys, but also reduces the degree of plastic flow and increases the risk of tunnel void formation on the AS. Lower traverse speeds produce higher heat inputs, broader HAZ softening, and greater IMC growth rates in dissimilar systems. The rotation speed governs the maximum temperature and the intensity of plastic deformation; its ratio to traverse speed, the so-called pitch or heat index ( $\omega/v$ ), is commonly used as a single-parameter descriptor of heat input, though it does not capture the effects of axial force or tool geometry. The cooling rate following the peak temperature determines the final precipitate state: in 7xxx alloys, rapid cooling (achieved by active cooling or high traverse speed) suppresses coarsening of the  $\eta$  and  $\eta'$  phases that provide yield strength; in 2xxx alloys, it limits the formation of continuous grain-boundary precipitates that promote stress corrosion cracking. These relationships are elaborated for each specific alloy system in Section 2 and for the modified thermal cycles produced by hybrid process variants in Section 3.

This framework, heat input governed by  $\omega$  and tool geometry, material flow governed by the AS/RS asymmetry and  $\omega/v$  ratio, and microstructural outcome governed by peak temperature and cooling rate, is referenced throughout the remainder of this review. Wherever a specific material system or process variant introduces deviations from this general picture, those deviations are highlighted explicitly.

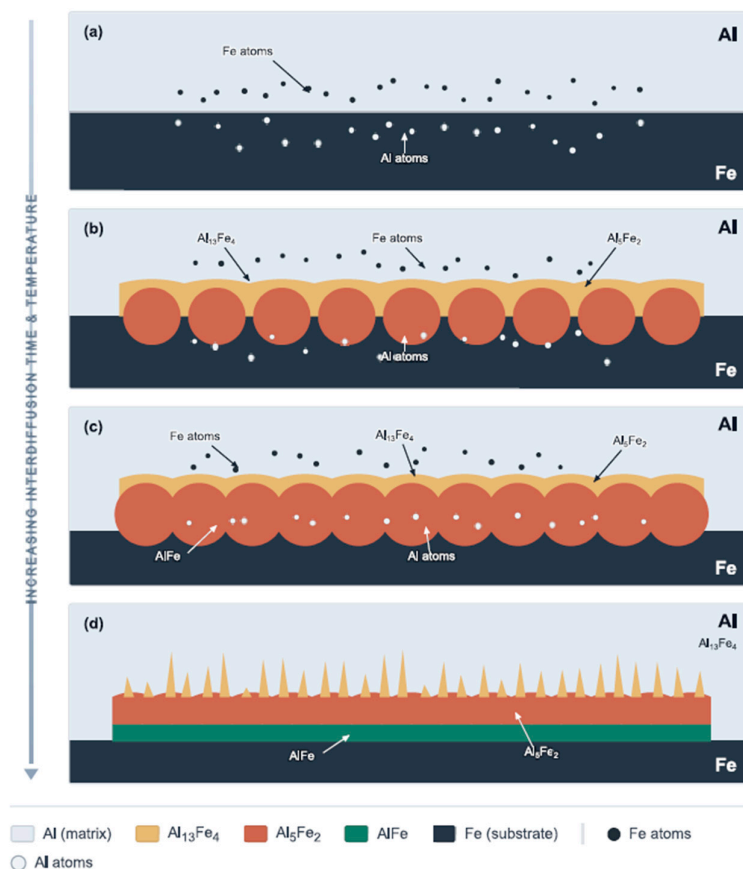
## 2. Advances in Dissimilar Material Joining

### 2.1. Aluminum-to-Steel Joining

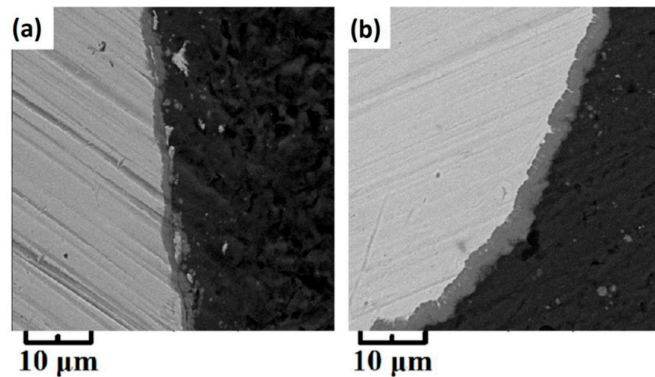
The combination of aluminum alloys with steel in transportation applications is justified by the fact that steel provides structural rigidity and strength, aluminum reduces the mass of the structure, and a well-made joint between them provides both benefits simultaneously. The metallurgical reality, however, is considerably more complicated. The large differences in melting points and coefficients of thermal expansion between the two materials make conventional fusion welding practically impractical, and solid-state joining techniques have consequently become the main focus of research efforts in this field.

### 2.1.1. Process Mechanisms and Interfacial Characteristics

The intermetallic compound (IMC) layer that forms at the aluminum–steel interface is the product of both thermodynamic driving forces and kinetic diffusion processes, and its development follows a recognizable physical sequence. Yang et al. [19] proposed a conceptual model of this progression that begins with the interdiffusion of Fe and Al atoms across the initial contact plane, proceeds through the localized nucleation of the first intermetallic phases, and culminates in the rapid, continuous growth of a brittle, multilayered reaction zone. Figure 2 presents a schematic reconstruction of this four-stage sequence, redrawn by the present authors, in which the  $\text{Al}_{13}\text{Fe}_4$  and  $\text{Al}_5\text{Fe}_2$  layers form preferentially at the interface and progressively coalesce, alongside the appearance of  $\text{AlFe}$ , into a continuous intermetallic band with a characteristic serrated morphology separating the aluminum matrix from the steel substrate. Thermodynamically, the phases that nucleate first are those with the lowest Gibbs free energy barriers under typical fusion welding (FSW) thermal conditions. Beygi et al. [20] showed that  $\text{Fe}_4\text{Al}_{13}$  and  $\text{Fe}_2\text{Al}_5$  meet this criterion under standard FSW thermal cycles, preferentially precipitating at the interface before other phases have an opportunity to form (see Figure 3).



**Figure 2.** Stage-wise formation of Fe–Al intermetallic compounds at the aluminum–steel interface with increasing interdiffusion time and temperature: (a) interdiffusion; (b) nucleation; (c) growth; (d) continuous reaction layer. Redrawn by the authors after Yang et al. [19].



**Figure 3.** IMC layer at the interface of Al (AA5005)–St in butt joints made (a) underwater and (b) in air. Al is seen in the dark contrast, and St (steel) is seen in the white contrast. IMCs are observed as gray contrast [20].

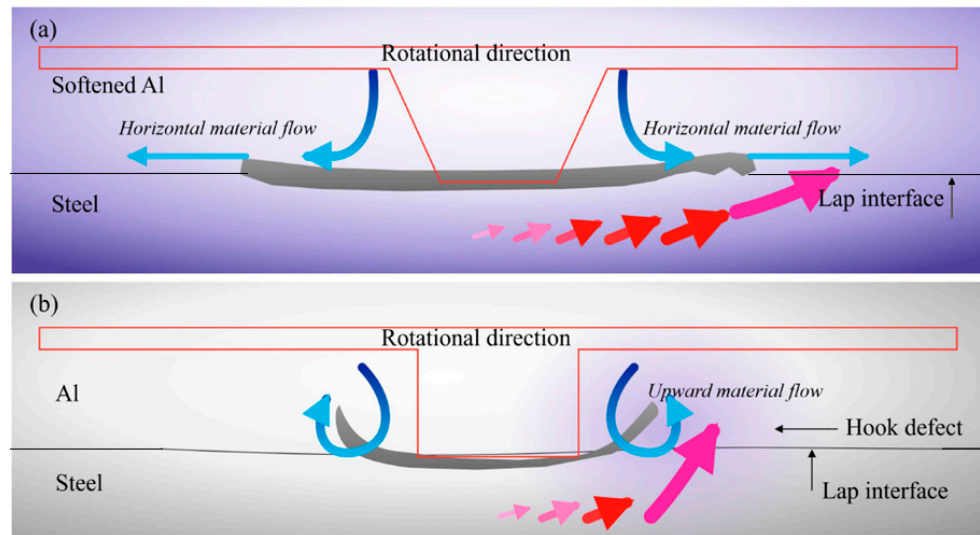
As established in Section 1.4, tool rotation speed simultaneously governs interfacial temperature and material flow rate, and Geng et al. [21] demonstrated that this dual dependency creates a particularly narrow operating window for Al–steel systems: too little heat input produces incomplete bonding defects where the interface lacks metallurgical interaction, while too much heat leads to reaction layers thick enough to act as preferential crack initiation sites. The complexity of this operating window, where both insufficient and excessive heat input compromise joint integrity, underscores the need for predictive modeling approaches. Sekban et al. [22] addressed this challenge by developing an artificial neural network (ANN) trained on experimental data to model the formability of high-strength steel joints, allowing for the upfront optimization of process parameters and reducing the risk of cracking during post-weld forming.

Taken together, the studies reviewed in this subsection establish a coherent picture of Al–steel interfacial behavior, yet several questions remain open. The consensus is clear on the identity of the dominant phases,  $\text{Fe}_2\text{Al}_5$  and  $\text{FeAl}_3$  are consistently the primary IMC species, with preferential nucleation driven by Gibbs free energy minimization, but the precise critical thickness below which these phases can be tolerated without significant embrittlement remains a subject of ongoing debate, with reported values ranging from approximately 3 to 10  $\mu\text{m}$  depending on the joint geometry, loading mode, and alloy combination. Equally unresolved is the extent to which AI-based predictive models trained on laboratory-scale data can generalize to industrially relevant process conditions, where thermal boundary conditions differ substantially from the controlled laboratory environment. These gaps represent the most productive targets for future experimental and computational work in Al–steel FSW.

### 2.1.2. Strategies for Controlling Intermetallic Compounds (IMCs)

Since the excessive growth of brittle IMC layers represents the main structural vulnerability in aluminum–steel joints, mitigation strategies have converged in two complementary directions: interface engineering and thermal management. In terms of tooling, pin geometry has proven to be a particularly effective variable. As illustrated schematically in Figure 4, replacing a conventional cylindrical pin with a circumferentially notched pin fundamentally alters the material flow pattern at the lap interface. With the notched pin (Figure 4a), the plasticized aluminum is driven predominantly in the

horizontal, in-plane direction along the bond line, producing a mechanical stirring action that yields a planar, essentially defect-free interface. By contrast, the conventional cylindrical pin (Figure 4b) promotes an upward material flow that draws the interface into the stir zone, generating the stress-concentrating hook defect characteristic of lap configurations, as seen in Liu et al. [23].



**Figure 4.** Material flow and interface formation for (a) a circumferentially notched pin (horizontal flow, planar bond) and (b) a conventional cylindrical pin (upward flow, hook defect). Redrawn by the authors after Liu et al. [23].

Parallel efforts have focused on the thermal conditions that determine the kinetics of IMC growth. Sahu et al. [24] coupled three-dimensional thermomechanical simulations with atomic-scale characterization to examine how frictional heat distribution patterns relate to IMC thickness. Their results indicate that controlling the directionality of heat dissipation across the joint thickness is the critical variable: restricting downward thermal diffusion reduces interfacial temperatures, thereby limiting the atomic diffusion kinetics responsible for excessive IMC growth and preventing localized thickening of brittle phases.

The identity and behavior of the dominant intermetallic phases were examined in more detail by Geng et al. [25], who identified  $\text{Fe}_2\text{Al}_5$  and  $\text{FeAl}_3$  as the main phases in 5052-Al/DP590 steel joints. Their microstructural analysis revealed a direct and concerning relationship: increasing the tool rotation speed produces a monotonic increase in interfacial heat input, which in turn causes an approximately linear growth of the extremely brittle  $\text{Fe}_2\text{Al}_5$  layer. Since fractures propagate predominantly through this specific phase, the authors argue that process parameters must be tightly controlled or the process window must be narrowly defined to suppress the growth of the brittle  $\text{Fe}_2\text{Al}_5$  layer.

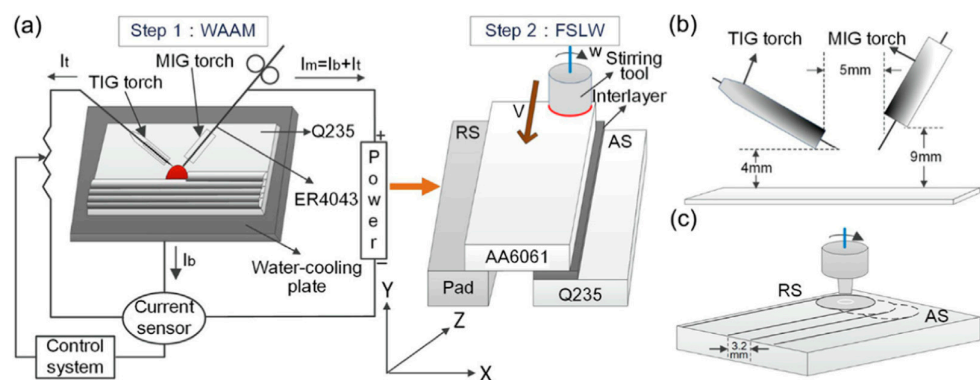
The IMC control strategies reviewed here converge on a consistent engineering principle: the most reliable joints are those in which the brittle intermetallic layer is kept thin, discontinuous, and mechanically isolated through a combination of tool geometry modification, directed heat dissipation, and process hybridization. Pin geometry changes that increase in-plane plastic flow, directional thermal management that restricts through-thickness heat diffusion, and the use of ultrasonic or arc-assisted variants that fragment continuous reaction layers all operate through fundamentally different mechanisms, yet achieve the same structural outcome. The key unresolved question is which combination of these strategies is most transferable to production conditions, specifically, whether the

thermal management precision required to consistently maintain IMC layers below the critical thickness can be sustained on industrial platforms where machine stiffness, thermal boundary conditions, and fixturing variability are all less well-controlled than in laboratory experiments.

### 2.1.3. Hybrid Approaches and Mechanical Performance

Conventional friction stir welding (FSW) sometimes is limited by the formation of thick, brittle intermetallic layers when joining metallurgically incompatible materials such as aluminum and steel, which has sparked interest in hybrid process variants, as highlighted by Liu et al. [26], who showed that superimposing ultrasonic vibrations on the FSW process significantly improves the quality of the joint. The high-frequency acoustic energy promotes the fragmentation of continuous IMC layers and leads to grain refinement. By reducing the flow stress of the material, ultrasound assistance widens the defect-free processing window and changes the failure mechanism from a mixed ductile–brittle mode to a purely ductile fracture, with a corresponding increase in the ultimate load capacity.

The introduction of a secondary heat source has been shown to be equally effective. Liu et al. [27] investigated a hybrid arc–FSW technique in which flow stress is reduced and atomic diffusion is enhanced at the interface, thereby promoting metallurgical bonding during the subsequent FSW pass. By depositing an initial intermediate aluminum layer using a bypass current MIG (BC-MIG) arc, the method restricts the brittle IMC layer to a thickness of less than  $1.5\ \mu\text{m}$ . As a result, tensile failure is redirected away from the vulnerable interface and toward the softer aluminum base metal. The hybrid arc–friction stir welding (AFSHW) process, illustrated in Figure 5, operates in two stages: an initial BC-MIG heat pretreatment to coat the galvanized steel surface, followed by substantial thermomechanical deformation by a multi-pass FSW tool. The approach illustrates the main advantage of hybrid systems: the use of sequential thermal and mechanical energy fields to design a resistant interface with minimal brittle phase formation.



**Figure 5.** Schematic diagram of (a) the AFSHW process (step 1-SS, step 2-FSLW), (b) welding torch location in the step 1, (c) the position and relationship between adjacent pass in step 2 [27].

Pankaj et al. [28] observed that controlling the flow of immiscible materials is equally important for preventing internal defects and applied multiphase Computational Fluid Dynamics (CFD) to model the mixing behavior of aluminum and steel. Their simulations show the distribution of steel fragments in the aluminum matrix, a dispersion that strengthens the joint when uniform but triggers premature failure when the fragments agglomerate. The models show that insufficient rotation speeds generate insufficient material flow on the advancing side or stagnant or poorly mixed flow regions on the

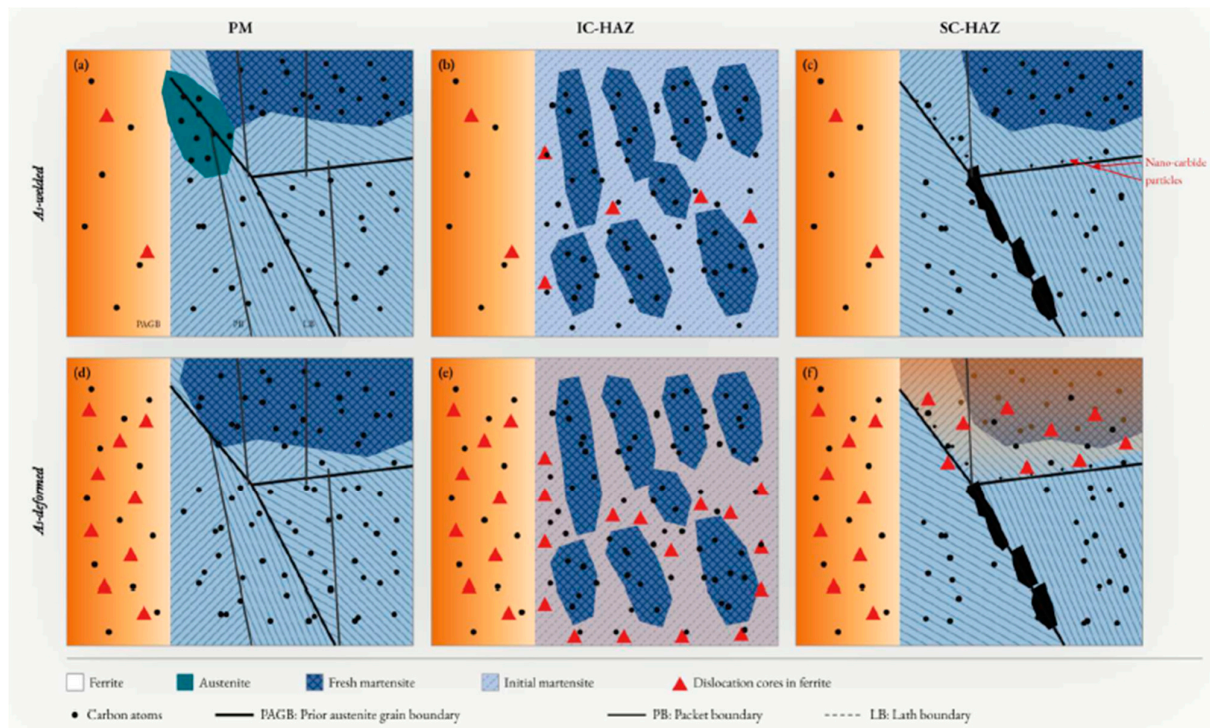
advancing side, while optimized heat inputs produce more uniform flow fields or promote homogeneous material transport and suppress macroscopic voids. Coupling auxiliary energy sources with predictive fluid dynamics represents a significant step towards resolving the inherent incompatibilities of Al–steel systems.

The hybrid approaches reviewed here collectively demonstrate that the metallurgical incompatibility of aluminum and steel is not a fundamental barrier to strong joint formation, but rather a process design problem that can be overcome when thermal, acoustic, or chemical energy inputs are appropriately combined with the FSW tool's mechanical action. The key finding is that no single hybrid strategy dominates across all joint configurations: ultrasonic assistance is most effective at fragmenting IMC layers in lap joints, arc predeposition is most effective at modifying interfacial thermodynamics in butt configurations, and CFD-guided optimization is most effective at suppressing void formation through material flow management. The outstanding challenge is the development of unified process design frameworks capable of selecting the optimal hybrid combination for a given joint geometry, material pair, and performance target, rather than relying on empirical trial-and-error optimization of each configuration individually.

#### 2.1.4. Microstructural Evolution of the Steel Substrate

The mechanical integrity of a dissimilar joint depends not only on the interfacial bond but also on how the steel substrate responds to intense thermal cycling and severe plastic deformation. Ahmed et al. [29] examined mild steel for shipbuilding and found that thermomechanical processing causes substantial grain refinement, increasing local hardness. Their work shows that the traverse speed directly controls the cooling rate: higher speeds promote a refined bainitic microstructure that maximizes hardness, while lower speeds produce a softer matrix of polygonal ferrite and pearlite.

Advanced high-strength steels behave differently, as observed by Qiao et al. [30], who investigated the deformation mechanisms in twin-induced plasticity (TWIP) steel during FSW, finding that intense shear forces transform pre-existing annealing twins into regular high-angle grain boundaries, simultaneously causing the nucleation of nano-deformation twins. These microstructural changes govern the heterogeneous partitioning of plastic deformation across the weld in ways that are not easily predicted based on the properties of the base metal alone. In ultrahigh-strength quenching and partitioning (Q&P) steel, Wang et al. [31] documented a more complex phase evolution involving martensite and retained austenite. Rapid cooling in the stir zone produces fresh, untampered martensite and localized hardening, while the subcritical heat affected zone undergoes significant softening due to the decomposition of metastable retained austenite and subsequent precipitation of nanoscale carbides along the prior austenite grain boundaries. As illustrated schematically in Figure 6, which contrasts the microstructure of the parent material (PM) with that of the intercritical (IC-HAZ) and subcritical (SC-HAZ) heat-affected subregions in both the as-welded and post-weld deformed states, this interplay between localized hardening and softening governs the overall stress distribution across the steel side of the joint. The decomposition of martensitic laths and retained austenite at subcritical temperatures triggers the precipitation of nano-carbides and the formation of ultrafine ferrite grains with dense dislocation tangles, a microstructural configuration that provides strain hardening capability and helps protect against premature failure in the softened HAZ region.



**Figure 6.** Schematic microstructural evolution of Q&P steel during welding and post-weld tensile deformation across the PM, IC-HAZ and SC-HAZ regions: (a–c) As-welded; (d–f) as-deformed. Redrawn by the authors after Wang et al. [31].

The thermomechanical framework established in Section 1.4 governs the microstructure of the steel substrate as much as the aluminum side, ensuring that localized phase transformations contribute to joint performance rather than undermine it. Boumerzoug et al. [32] demonstrated that varying the traverse speed at a constant rotation rate directly affects microstructural evolution and shear load in 6061-T6 aluminum welded to ultra-low carbon steel, while Dehghani et al. [33] determined that the joint strength in 3003-H18 aluminum and mild steel configurations is fundamentally related to the heat input and tool shoulder diameter. Among the process variables examined, tool offset proves particularly critical: Zandsalimi et al. [34] found that an optimal offset during welding of 6061 aluminum to 430 stainless steel prevented void formation and generated a serrated interface characterized by robust mechanical interlocking.

Mitigating tool wear while maintaining joint strength has been another persistent research challenge, as studied by Watanabe et al. [35], who observed that shifting the tool offset toward the softer side of the aluminum effectively limited pin degradation while allowing the frictional action to remove the oxide layer from the steel surface. Zhang et al. [36] went further, protecting an H13 steel tool from direct contact with SUS304 stainless steel using a thickened aluminum interfacial plate. Meng et al. [37] proposed a friction stir lap welding with rivet reinforcement specifically designed to improve the load-bearing capacity of Al–steel assemblies through mechanical reinforcement. At the extreme end of thermal management, Li et al. [38] applied rotational speeds of up to 18,000 rpm to join 6061-T6 aluminum to 316L stainless steel, a pair also examined by Newishy et al. [39]. Under these specific conditions, the resulting intermetallic phases contributed to both mechanical bonding and improved corrosion resistance, a finding that warrants further investigation given the typically detrimental electrochemical role of IMC layers. The industrial scalability of such lap joints was demonstrated by Campanella et al. [40], who successfully integrated AA6016 aluminum with low-carbon steel for automotive body

panels, demonstrating that tight parameter control can overcome the physical disparities and poor wetting behavior that complicate large-scale fabrication. Perhaps the most unexpected discovery in this area comes from Kasai et al. [41], who demonstrated that a controlled Fe-Al intermetallic layer can serve as a metallurgical bridge even for completely immiscible systems. The introduction of aluminum as an alloying element allowed the joining of steel and magnesium, with the Fe-Al intermetallic compensating for the fundamental lack of chemical affinity between iron and magnesium.

The following paragraphs draw together the principal findings from Sections 2.1–2.3 into a comparative cross-system synthesis. Before comparing the three material systems, three methodological caveats must be stated. First, joint efficiency, defined as the joint UTS relative to the weaker base material UTS, is cited only where the reviewed studies report it explicitly; it is not inferred for studies that record only qualitative or relative performance, because normalization to unreported base metal values would introduce unverifiable assumptions. Second, the three systems face qualitatively different primary constraints: Al-steel joints are limited by Fe-Al IMC brittleness above a critical layer thickness of approximately 5  $\mu\text{m}$ ; Al-Mg joints are bounded by the 437 °C eutectic temperature that defines the upper limit of the thermal process window; and Al-Cu joints carry a dual structural–electrical performance requirement in which a thin but crack-free IMC layer is desirable rather than simply minimal. These distinct constraint structures mean the systems cannot be meaningfully ranked by a single metric. Third, joint configuration, butt, lap, or spot, substantially affects IMC development and the most relevant performance metric, and comparisons across configurations within a system should be interpreted accordingly.

#### Aluminum–Steel: Comparative Performance Summary

In the Al-steel system, the dominant IMC phases are  $\text{Fe}_4\text{Al}_{13}$  and  $\text{Fe}_2\text{Al}_5$ , with  $\text{Fe}_2\text{Al}_5$  consistently identified as the most structurally critical because fractures propagate preferentially through it. The evidence from the studies reviewed in Section 2.1 establishes a clear hierarchy of process strategies ranked by their effectiveness in controlling these phases, with a corresponding progression in fracture behavior from brittle to ductile.

In butt joints produced by conventional or underwater FSW, Beygi et al. [20] demonstrated that submerged welding produces a thinner and more uniform IMC layer compared to welding in air: the rapid heat extraction of the aqueous medium restricts atomic diffusion at the interface, limiting IMC growth and shifting the fracture mode from the mixed ductile–brittle behavior characteristic of air welds toward improved bonding quality. In lap joints, the relationship between IMC thickness and process parameters is more precisely quantified: Geng et al. [25] identified  $\text{Fe}_2\text{Al}_5$  and  $\text{FeAl}_3$  as the main phases in 5052-Al/DP590 steel joints and showed that IMC layer thickness increases approximately linearly with tool rotation speed, because higher rotation speed raises interfacial temperature monotonically. Fracture propagates predominantly through the  $\text{Fe}_2\text{Al}_5$  layer, and joint strength decreases as that layer thickens, establishing a direct and detrimental link between heat input and mechanical performance that requires a narrow rotation speed process window to manage.

The most effective mitigation strategies reviewed are both hybrid approaches. Liu et al. [26] demonstrated that superimposing ultrasonic vibrations on the FSW process fragments continuous Fe-Al IMC layers into a discontinuous morphology, which shifts the fracture mechanism from a mixed ductile–brittle mode in conventional FSW to a purely ductile mode with a corresponding increase in ultimate load capacity. Liu et al. [27] achieved the most aggressive IMC suppression in the reviewed literature through a hybrid arc–FSW technique: by depositing an intermediate aluminum layer using bypass current MIG arc welding before the FSW pass, the method restricts the IMC layer to below

1.5  $\mu\text{m}$  and redirects tensile failure entirely away from the interface and into the softer aluminum base metal, the diagnostic indicator that IMC control has been fully achieved. The process window can also be extended through geometric interventions: Zandsalimi et al. [34] showed that an optimized tool offset in 6061 Al/430 stainless steel butt joints prevents void formation and produces a serrated interface with robust mechanical interlocking, without any hybrid energy source. Collectively, these five studies demonstrate that the fracture mode transition from IMC cleavage to base-metal ductile failure is the most informative single indicator of whether IMC control has been achieved, more diagnostic than absolute UTS values, because it reflects the change in the controlling failure mechanism rather than a shift in the measured load.

In the Al-Mg system, the dominant IMC species are  $\text{Al}_{12}\text{Mg}_{17}$  ( $\gamma$ -phase) and  $\text{Al}_3\text{Mg}_2$  ( $\beta$ -phase), both of which precipitate rapidly when processing temperatures approach or exceed the Al-Mg eutectic at 437 °C. The thermal constraint is therefore more stringent than in Al-steel systems and more precisely defined: rather than a gradual threshold above which IMC growth accelerates, the Al-Mg system imposes a hard upper temperature boundary beyond which localized melting and brittle re-solidification occur regardless of other process conditions.

The broadest process window characterization is provided by Khalafe et al. [42] and Christy et al. [43], who identify 600–1400 rpm as the viable rotation speed range for similar aluminum alloy joints, with the range narrowing further for dissimilar Al-Mg configurations. Exceeding this upper limit triggers grain growth, IMC formation, and a corresponding decrease in tensile strength; operating below the lower limit produces inadequate material flow and cold-weld defects. Within the optimal window, Fu et al. [44] experimentally defined the most effective parameter combination for 6061-T6 Al/AZ31B Mg butt joints as 600–800 rpm with low traverse speed and tool offset toward the magnesium side. This combination maintains processing temperatures below the eutectic threshold, produces IMC layers controlled below the critical thickness, and achieves approximately 70% of the aluminum base metal UTS, the only explicit joint efficiency value reported in the Al-Mg literature reviewed here. The fracture mode at these optimized parameters is ductile; outside the window, brittle IMC cleavage dominates.

Interface geometry modification offers an alternative route to IMC suppression that is independent of thermal control. Xu et al. [45] demonstrated that introducing a serrated multi-groove interface design in 5A06 Al/AZ31B Mg butt joints relocates the metallurgical reaction zones away from the thermal center of the tool, suppressing diffusion kinetics at the most critical interface locations and increasing the load-bearing capacity by more than threefold compared to standard butt configurations, the largest relative performance improvement reported across any single mitigation strategy in the three systems reviewed here. Bandi and Bakshi [46] confirmed in AZ31B-H24 Mg/AA6061-T6 Al lap joints that pin length and rotation speed combination can restrict IMC layer thickness sufficiently to suppress eutectic formation and maintain lapped shear strength, demonstrating that the thermal control principle generalizes across joint configurations. The Al-Mg system is therefore characterized by the tightest thermal process window of the three systems, the most immediate transition from ductile to brittle fracture when that window is exceeded, and the largest single relative performance gain achievable through interface geometry engineering.

#### Aluminum–Copper Comparative Performance Summary

In the Al-Cu system, the dominant IMC phases are  $\text{Al}_2\text{Cu}$  and  $\text{Al}_4\text{Cu}_9$ , whose presence at the joint interface creates the simultaneous structural and electrical performance challenge that distinguishes this system from the other two. A thin, continuous, and crack-free IMC layer is required to maintain conductive path stability;

the same layer must not grow to the thickness that causes embrittlement and sharp increases in electrical resistance. The Al-Cu literature reviewed in Section 2.3 is distinguished from the Al-steel and Al-Mg literature by the availability of precise quantitative IMC thickness measurements that allow performance thresholds to be stated concretely.

In conventional FSSW of AA2024/pure Cu, Bagheri et al. [47] measured an IMC layer thickness of 1.9  $\mu\text{m}$ , which is crack-free and within the acceptable range for both structural bonding and electrical conductivity. Adding SiC nanoparticles to the interface increases this thickness to 3.1  $\mu\text{m}$  due to elevated frictional heat and material agitation, but the extended reaction zone remains free of microcracks, demonstrating that IMC layer thickness and structural integrity are not synonymous: a thicker but crack-free and mechanically sound interface can preserve both structural integrity and conductive path stability. The most effective thermal management strategy for IMC reduction is the stationary shoulder tool: Zhao et al. [48] demonstrated that eliminating shoulder rotation reduces IMC layer thickness from 2.4  $\mu\text{m}$  in conventional FSW to approximately 1.6  $\mu\text{m}$ , keeping the layer below the embrittlement threshold and producing a more ductile fracture mode. Submerged FSW provides an alternative thermal route: Mao et al. [49] showed that rapid aqueous cooling in underwater FSW of Al-Cu plates severely restricts atomic diffusion at the interface, producing a thinner and more uniform IMC layer dominated by  $\text{CuAl}_2$ , a phase with comparatively lower brittleness than the  $\text{Al}_2\text{Cu}$  and  $\text{Al}_4\text{Cu}_9$  phases that form under conventional conditions.

The largest reported performance improvement in the Al-Cu system is achieved through combined process and interlayer modification: Gao et al. [50] proposed a modified friction-stirring technique that fills the residual keyhole of conventional FSSW while simultaneously introducing a zinc interlayer, which acts as a thermodynamic buffer that shifts the IMC phase composition from brittle  $\text{Al}_2\text{Cu}$  and  $\text{Al}_4\text{Cu}_9$  toward ductile lamellar eutectics and Zn-rich  $\text{CuZn}_5$  compounds. This approach achieves a 40% increase in joint strength relative to conventional FSSW, the only explicit absolute performance improvement reported in the Al-Cu literature reviewed—and shifts the fracture mode from brittle interfacial cleavage to ductile failure through the lamellar eutectic structure. The three Al-Cu mitigation strategies thus operate at three distinct levels: nanoparticle addition modifies the interface at the microstructural scale; stationary shoulder and underwater FSW modify the thermal cycle at the process scale; and interlayer introduction modifies the interfacial thermodynamics at the chemical scale. Their combination defines a toolkit whose components address different aspects of the Al-Cu joining challenge and whose application can be tailored to the specific structural–electrical requirements of the target application.

### Cross-System Synthesis

Despite the differences in constraint structure described above, two conclusions hold across all three material systems. First, the fracture mode is the most sensitive and informative indicator of IMC control quality. Joints in which the IMC layer has been successfully suppressed below its system-specific critical thickness consistently exhibit ductile failure in the softer base material; joints where the IMC layer is continuous and above the critical thickness fail by brittle cleavage through the intermetallic, regardless of the material system. This ductile-to-brittle fracture mode transition therefore serves as a practical binary quality criterion that is more diagnostic than absolute UTS values, because it reflects whether the controlling failure mechanism has changed rather than simply whether the measured load has increased. Second, hybrid process strategies, whether acoustic assistance, arc predeposition, submerged welding, or interlayer introduction, consistently outperform parameter-optimized conventional FSW in both

IMC thickness reduction and fracture mode improvement across all three systems, at the cost of increased process complexity. The evidence consistently supports the conclusion that conventional FSW alone operates near the boundary of what is achievable in IMC control for dissimilar metal joints, and that hybrid strategies represent the most productive direction for further performance improvement regardless of which material system is under consideration.

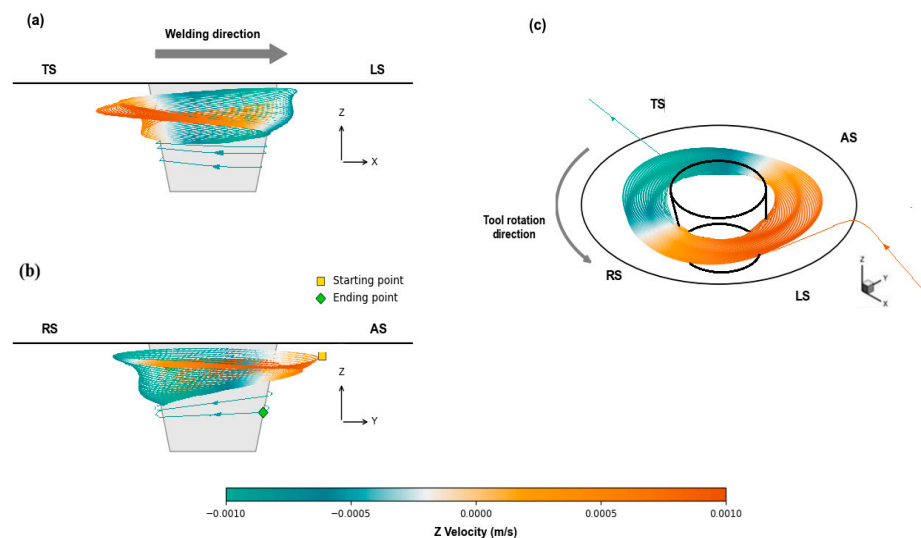
## 2.2. Aluminum–Magnesium Joining

Khalafe et al. and Christy et al. [42] have analyzed in detail how parameter selection governs thermal distribution and weldability in Al-Mg systems. The optimal rotation speed for similar aluminum alloy joints is generally 600–1400 rpm, though dissimilar Al-Mg configurations may require narrower windows; exceeding this range triggers the grain growth and precipitate coarsening described in Section 1.4.3, with a corresponding decrease in tensile strength. The parameter window for a defect-free joint is therefore narrow and specifically dependent on material type and thickness. The combination of aluminum and magnesium alloys is of real interest for the design of lightweight structures in aerospace and automotive applications. The primary challenge arises from their high chemical affinity, which leads to the rapid precipitation of brittle intermetallic compounds, especially  $\text{Al}_{12}\text{Mg}_{17}$  ( $\gamma$ -phase) and  $\text{Al}_3\text{Mg}_2$  ( $\beta$ -phase), which can seriously compromise the integrity of the joint if thermal conditions are not strictly managed. A comprehensive scientometric analysis by Ahmed et al. [43] confirms that friction stir welding (FSW) outperforms conventional fusion methods for Al-Mg systems, but producing reliable joints requires rigorous control of the heat input to prevent eutectic reactions, which initiate at temperatures as low as 437 °C.

### 2.2.1. Material Flow and Mixing Behavior

The structural integrity of different Al-Mg joints depends largely on the dynamics of the material flow around the tool pin. Since aluminum and magnesium have distinct flow stresses and viscosities, their mixing behavior is inherently complex. Khaliq et al. [51] confirmed that, consistent with the AS/RS asymmetry described in Section 1.4.2, positioning the higher-flow-stress material on the advancing side improves material transport and mechanical interlocking in Al-Mg configurations. The severe plastic deformation induced by this arrangement helps to fragment the continuous IMC layers, so that joint strength comes to depend more on macromechanical interlocking than on purely metallurgical bonding. However, when mixing is inadequate, large continuous IMC networks remain intact along the boundaries of the stir zone, with adverse consequences on mechanical performance. A thermodynamic framework is therefore essential for interpreting these microstructural outcomes. Sen et al. [52] confirmed that  $\text{Al}_3\text{Mg}_2$  and  $\text{Al}_{12}\text{Mg}_{17}$  precipitate aggressively in the stir zone and severely compromise mechanical properties when thermal thresholds are exceeded. During severe plastic deformation, localized temperatures can easily exceed the eutectic point, triggering localized melting and brittle re-solidification, which is why maintaining processing temperatures below the solidus line is so important in practice. Nagaraja et al. [53] argue that friction stir welding (FSW) remains a promising route for aerospace Al-Mg structures, provided that flow-induced defects such as tunnel voids are managed through careful parameter optimization. By avoiding the solidification cracking associated with fusion welding, FSW retains a fundamental advantage for this material combination. Predictive modeling provides useful information on the internal dynamics of these joints, as noted by Yang et al. [54], who simulated material flow during different Al-Mg joints, identifying an asymmetric strain rate distribution. The authors applied no transverse offset in their experimental setup, with the tool axis aligned with the initial butt interface. However,

their CFD simulation demonstrates that offsetting the tool toward the magnesium side directionally modulates the volume of mixed material and limits the macroscopic accumulation of brittle phases. The experimentally optimized offset distance for this material combination is reported by Fu et al. [44], whose parameter study of 6061-T6 Al/AZ31B Mg butt joints established the offset toward the magnesium side as part of the optimal processing window. Using a CFD model with a shear boundary coupled with thermomechanical flow, the authors quantitatively mapped the three-dimensional mass transfer. Their results show that although most of the plasticized material follows a relatively straight trajectory, a portion of the magnesium on the advancing side becomes trapped in what they describe as a chaotic vortex, a maelstrom flow that drives the material downward through multiple concentric revolutions around the pin. Figure 7 presents this predicted flow path, colored by the Z-direction velocity, viewed along the welding direction (a) and in transverse section (b), together with a three-dimensional perspective relative to the tool rotation direction (c). This mechanism explains why magnesium accumulates consistently at the root of the weld, while aluminum dominates the upper regions of the agitation zone. This distribution pattern suggests that brittle phase clusters are most likely to concentrate at the weld root, where magnesium accumulation is greatest, making this region the critical site for crack initiation.



**Figure 7.** Typical maelstrom (vortex) flow path of the plasticized material around the pin, colored by Z-direction velocity and predicted by the shear-boundary CFD model: (a) Longitudinal view along the welding direction (X–Z plane); (b) transverse view (Y–Z plane) showing the starting and ending points of the path; (c) three-dimensional perspective view relative to the tool rotation direction. Adapted from [54].

The material flow studies reviewed here reveal a fundamental asymmetry in Al–Mg joints that has direct structural consequences: the maelstrom flow pattern around the pin consistently concentrates magnesium, and therefore brittle IMC clusters, at the weld root, while aluminum dominates the upper stir zone. This distribution is not a defect in the conventional sense, but it creates a predictable location for fatigue crack initiation that is systematically absent from fracture analyses that treat the weld cross-section as macroscopically uniform. The most important open question is whether tool offset toward the magnesium side, which modulates the volume of mixed material and can redistribute the phase distribution, can be consistently tuned to shift IMC accumulation away from the root without introducing advancing-side flow defects, a balance that has been

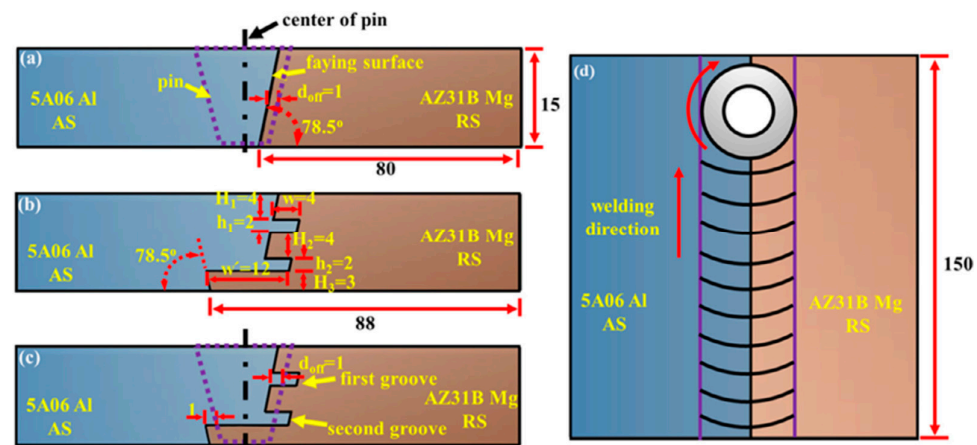
demonstrated in specific laboratory configurations but has not yet been validated across the range of joint thicknesses and alloy tempers relevant to aerospace and automotive applications.

### 2.2.2. Interface Enhancement Techniques

Given the inherent brittleness of Al-Mg intermetallic, recent work has increasingly focused on interface design to modify the fundamental bonding mechanisms. Zhao et al. [55] investigated ultrasonic vibration-assisted FSW, finding that high-frequency acoustic energy breaks continuous IMC layers into discrete dispersed particles, disrupting crack propagation paths and improving joint ductility. Their near-in situ microstructural analysis showed that acoustic softening reduces the flow stress of the material, promoting increased plastic flow and redistributing the magnesium-rich material toward the retreating side and limiting the kinetic conditions favorable for IMC growth by disrupting the continuity of the reaction interface.

The introduction of third-body materials presents another viable strategy, as pointed out by Abdollahzadeh et al. [56], who incorporated a zinc interlayer alongside TiC nanoparticles, the zinc foil acting as a localized diffusion barrier promoting the formation of more favorable Mg-Zn and Mg-Al-Zn compounds at the expense of the brittle Al-Mg intermetallics. The uniformly dispersed TiC nanoparticles provided additional microstructural reinforcement by simultaneously pinning grain boundaries and acting as heterogeneous nucleation sites, promoting significant grain refinement throughout the stir zone.

Beyond chemical and acoustic interventions, Xu et al. [45] demonstrated that modifying the macroscopic geometry of the joint by introducing an interface with multiple interconnected grooves represents another practical route for structural improvement, specifically designed to restrict the effective contact area between the aluminum and magnesium plates. As shown in Figure 8, the serrated profile improves mechanical interlocking while deliberately reducing the metallurgical reaction zone. By relocating the metallurgical reaction zones away from the thermal center of the tool, the design suppresses the diffusion kinetics responsible for excessive IMC proliferation. Xu et al. [45] reported that this design increased the load-bearing capacity by more than threefold compared to standard butt-welding configurations.



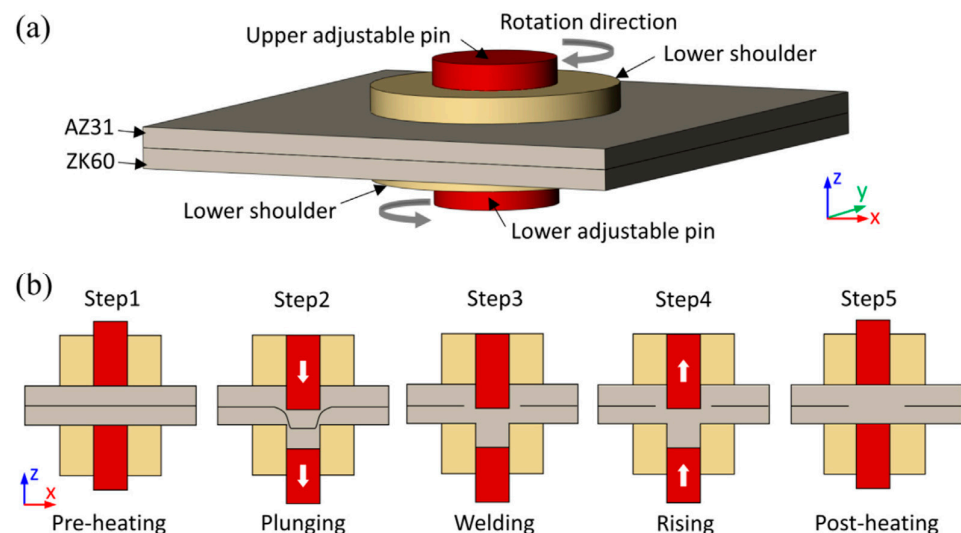
**Figure 8.** Schematic illustration of different joint configurations: (a) Conventional joint; (b,c) innovative joint; (d) Al/Mg FSW process [45].

The interface enhancement strategies reviewed in this subsection—acoustic fragmentation, reactive interlayers, and macroscopic joint geometry modification—each

address the Al-Mg IMC brittleness problem through a distinct physical mechanism, and the literature suggests that they are more complementary than competing. Acoustic softening disrupts the IMC continuity during formation; interlayers redirect the interfacial thermodynamics toward less brittle compound families; and groove geometries relocate the reaction zones away from the thermal center of the tool. Despite these advances, a quantitative comparison of their relative effectiveness remains difficult, because most studies report joint efficiency relative to a different baseline alloy combination or joint geometry, and direct cross-study comparison is confounded by the heterogeneity of testing protocols. Establishing a standardized benchmark dataset for Al-Mg interface enhancement, reporting IMC thickness, tensile joint efficiency, and fracture mode under identical base material conditions, would substantially accelerate the convergence of these strategies toward industrial practice.

### 2.2.3. Influence of Tool Design and Process Variants on Joint Quality

Ke et al. [57] analyzed double-sided friction stir spot welding (FSSW) of magnesium alloys, demonstrating that tool geometry and process variant selection govern the thermal cycle and, consequently, the quality of the resulting joint. Using a coaxial tool system with independently controlled pins, as illustrated in Figure 9, the approach allows for simultaneous symmetrical penetration from both the top and bottom surfaces. This configuration promotes a more uniform thermal distribution across the sheet thickness and directs the material flow towards the midplane, effectively closing the keyhole defect left behind by conventional FSSW and producing a homogeneous stir zone microstructure.



**Figure 9.** (a) Diagram of the Flat DSAT FSSW system; (b) schematic sketch of the welding process [57].

Electrically assisted variants are attracting increasing interest for similar reasons, with Xiaoqing et al. [58] demonstrating that pulsed current applied during FSW for dissimilar Al-Mg joints induces an electroplastic effect that reduces the flow stress of both materials, facilitating adequate mixing at lower temperatures and mechanical loads, thereby restricting the excessive growth of intermetallic compounds. The application of a pulsed current effectively widens the processing window, allowing defect-free joints under conditions that would otherwise lead to failure, and shifts the fracture mechanism from brittle interfacial cleavage to a more ductile mode.

Establishing a rigorous correlation between process parameters and mechanical outcomes remains essential. Using response surface methodology (RSM), Solomon et al. [59] mapped the interactions between rotation speed, traverse speed, and tool tilt angle for magnesium alloys, identifying the optimal parameter windows to maximize tensile strength without extensive empirical iteration or without systematic experimental campaigns. The initial condition of the base material is equally important. Xu et al. [60] showed that prior microstructural refinement of AZ61 magnesium, achieved by a high-load, low-speed FSW strategy, substantially improves the alloy's superplasticity and subsequent weldability. The intense plastic deformation at lower heat inputs causes a fine, equiaxed grain structure that improves both ductility and load-bearing capacity. The shift toward advanced tool configurations and hybrid processes reflects a broader research effort to address the inherent weldability challenges of lightweight alloys in the aerospace and automotive sectors. The thermodynamic tendency of Al and Mg to form brittle intermetallic compounds, especially  $\text{Al}_{12}\text{Mg}_{17}$  and  $\text{Al}_3\text{Mg}_2$  [46,61], represents the primary barrier to joint integrity, operating through the thermal cycle mechanisms described in Section 1.4.3; controlling these networks therefore requires precise microstructural management. For lap joints between AZ31B Mg and AA6061-T6 Al, Bandi and Bakshi [62] showed that they restrict the thickness of the IMC layer, suppress eutectic formation and maintain the lapped shear strength.

In order to disrupt the formation of IMCs, Lv et al. [63] demonstrated that ultrasonically enhanced FSW modifies the local thermal profile and widens the material flow path, improving macroscopic mechanical interlocking, a strategy that researchers are increasingly turning to precisely because of these combined effects. Building on this, Liu et al. [64] applied ultrasonically assisted stationary shoulder FSW to physically break up continuous IMC layers into discrete particles—a structural change that disrupts continuous crack propagation paths and significantly improves the tensile properties of Al-Mg joints.

The microstructural evolution in the agitation zone also determines how the weld holds up in service, with Jayaraj et al. [62] demonstrating that intense mechanical mixing of Al and Mg, combined with IMC precipitation, generates localized galvanic microcells that degrade corrosion resistance. Mitigating these vulnerabilities requires strict thermal control to minimize the IMC volume fraction Mohammadi et al. [65], with Fu et al. [44] experimentally defining this operational window and demonstrating that a moderate rotation rate of 600–800 rpm, combined with a low traverse speed and tool offset towards the magnesium side, reaches up to 70% of the tensile strength of the aluminum base metal or of the weaker base metal. To map these thermomechanical interactions without relying entirely on physical testing, Baruah et al. [66] used three-dimensional finite element modeling to simulate friction stir spot welding of Al-6061 and Mg-AZ31B, clarifying the stress and temperature distributions governing the bond, reflecting the increasing focus of the field on computational modeling. Complementing this approach, Efa et al. [67] combined RSM with artificial neural networks, extending the predictive capability beyond single-response optimization to multi-objective parameter selection. Together, these modeling and optimization tools are progressively reducing the experimental burden of process development for dissimilar Al-Mg systems.

The studies reviewed in this subsection collectively establish that no single process variant or tool configuration is universally optimal for Al-Mg joints; rather, the best outcome in each case reflects a specific balance between thermal input, material flow, and IMC kinetics that depends critically on the alloy grades, section thickness, and target application. Double-sided FSSW, electrically assisted FSW, and ultrasonically enhanced configurations each address a different bottleneck—keyhole elimination, flow stress reduction, and IMC fragmentation, respectively—but introduce their own equipment and

process complexity that must be weighed against the mechanical benefit. The convergence of RSM, ANN, and finite element modeling as complementary optimization tools is a particularly important development, because it suggests a path toward predictive process design for Al-Mg joints that reduces the current dependence on extensive physical trial matrices. The outstanding challenge is validating these models across the alloy and thickness space relevant to aerospace and automotive lightweight structures, rather than for the narrow parameter windows typically investigated in individual studies.

### 2.3. Aluminum–Copper Joining

The joining of aluminum with copper is a well-established requirement in the electrical and power generation sectors. This combination leverages the excellent electrical and thermal conductivity of copper, along with the low weight and cost of aluminum, making it a standard choice for busbars, battery terminals, and heat exchangers. However, as with most dissimilar metal systems, the precipitation of brittle intermetallic compounds poses a persistent challenge to long-term mechanical and electrical reliability.

#### 2.3.1. Electrical and Thermal Performance Considerations

Sun et al. [68] reviewed the current landscape of Al-Cu friction stir welding, noting that while solid-state processing effectively circumvents the high electrical resistance caused by fusion welding defects, management of the IMC layer thickness remains essential. A thin and continuous IMC layer facilitates bonding, while excessive growth sharply increases the electrical resistance and induces embrittlement of the joint.

To address these performance limitations, Bagheri et al. [69] used friction stir spot welding (FSSW) to create Al/SiC/Cu composites, demonstrating that the addition of SiC nanoparticles increases contact surface hardness by approximately 15–20% while reducing electrical conductivity by less than 5%, a decrease considered acceptable for the intended busbar and terminal applications. Bagheri et al. [47] examined the addition of nanoparticles in pure AA2024/Cu joints, finding that the nanoparticles exert a pinning effect that refines the interfacial grain structure and homogenizes the electrical properties across the weld. SiC additions result in a slightly thicker IMC layer, 3.1  $\mu\text{m}$  compared to the conventional 1.9  $\mu\text{m}$ , due to increased frictional heat and material agitation. It is important to note, however, that this extended reaction zone remains free of microcracks, suggesting that even with a higher volume of brittle phases such as  $\text{Al}_2\text{Cu}$  and  $\text{Al}_4\text{Cu}_9$ , structural integrity and conductive path stability are preserved by a mechanically sound interface with preserved diffusion bonding characteristics.

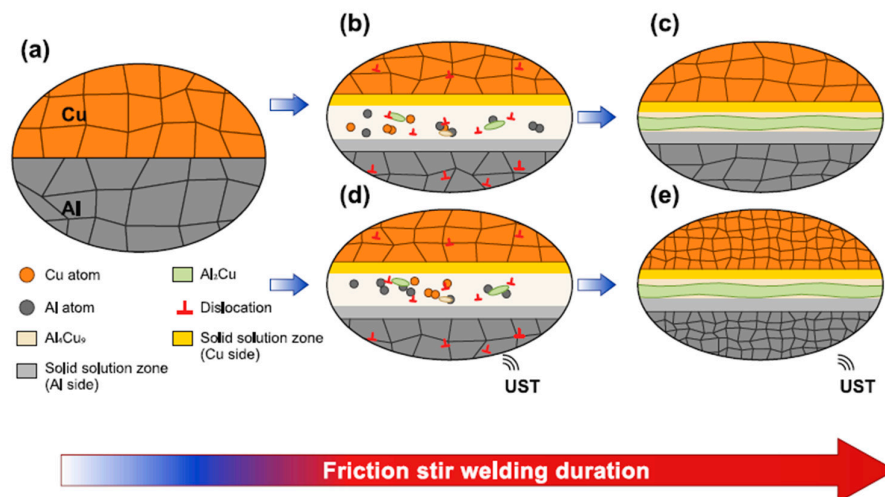
Incorporating reinforcing nanoparticles into the Al-Cu boundary thus offers a dual benefit: it strengthens the joint against wear through particle-induced hardness enhancement and grain boundary pinning, while simultaneously generating the refined, defect-free microstructure required to maintain stable electrical and thermal connections.

The studies on electrical and thermal performance in Al-Cu FSW joints reveal a recurring and important nuance: the same IMC layer that must be minimized to avoid embrittlement is also the primary mediator of electrical bonding at the interface, meaning that the optimization objectives for structural and electrical applications are not identical. For structural lap joints, the IMC layer should be as thin and discontinuous as possible; for electrical busbar and terminal applications, a thin but continuous and crack-free layer may actually be desirable, provided the phases present are those with comparatively lower electrical resistivity. This distinction is not consistently made in the literature, and studies reporting electrical resistance data alongside mechanical performance data remain relatively rare. Establishing a clearer design map that specifies the acceptable IMC phase identity, thickness, and continuity for each application class would represent a significant practical contribution to the field.

### 2.3.2. Microstructural Evolution and Tuning of the IMC Layer

Building on the heat generation and plastic deformation principles established in Section 1.4, Ji et al. [70] introduced a “double friction-stirring” approach in which the coupling of mechanical interlocking with a precisely controlled diffusion layer substantially increases the load-bearing capacity of the joint compared to standard FSSW. The deformation of the copper rivet creates a double anchoring effect, a copper anchor at the top surface and an aluminum anchor at the joint interface, that eliminates kissing defects and ensures a strong metallurgical bond.

Auxiliary acoustic energy has proven to be a reliable tool for controlling microstructural evolution, with You et al. [71] demonstrating that integrating ultrasonic vibrations into a stationary shoulder FSW configuration causes the acoustic field to break continuous IMC layers into isolated particles, halting crack propagation through brittle phases and improving joint ductility. Figure 10 illustrates this interfacial evolution schematically, contrasting the conventional stationary-shoulder process with its ultrasonically assisted variant: initial severe plastic deformation fragments and redistributes the parent-phase constituents, after which the superimposed high-frequency stress waves concentrate cyclic stresses at the brittle IMC interfaces, inducing fracture of the continuous layers and breaking the crack-sensitive IMCs into fine, dispersed particles that interrupt potential fracture pathways.



**Figure 10.** Schematic of the interfacial microstructure evolution during welding: (a) Pre-welding state; (b) DSSFSW intermediate state; (c) DSSFSW final state; (d) U-DSSFSW intermediate state; (e) U-DSSFSW final state. Redrawn by the authors after You et al. [71].

Restricting heat input is another key control strategy, with Zhao et al. [48] demonstrating that the use of a stationary shoulder tool suppresses the thermal gradient along the weld. By eliminating shoulder rotation, frictional heat is significantly reduced, narrowing the heat affected zone and preventing the growth of harmful  $\text{Al}_2\text{Cu}$  and  $\text{Al}_4\text{Cu}_9$  layers. Experimental measurements confirm that this technique reduces the IMC layer thickness from  $2.4\ \mu\text{m}$  in conventional FSW to approximately  $1.6\ \mu\text{m}$ , maintaining the IMC layer below the threshold thickness associated with significant embrittlement. Managing IMCs becomes even more complex in submerged conditions, with Mao et al. [49] demonstrating that the rapid cooling inherent in an aquatic environment severely restricts atomic diffusion in submerged FSW of Al-Cu plates, resulting in a thinner and more uniform IMC layer dominated by phases with comparatively lower brittleness, such as  $\text{CuAl}_2$ .

Producing reliable and diverse Al-Cu joints ultimately requires a comprehensive approach. By combining mechanical interlocking strategies such as friction stir riveting, auxiliary acoustic energy, and strict thermal management through stationary shoulders or active cooling, engineers can confine the brittle intermetallic to a dispersed, discontinuous morphology that preserves both structural and electrical integrity.

The Al-Cu IMC control literature reviewed here demonstrates a higher degree of engineering maturity than comparable work on Al-steel or Al-Mg systems, attributable in part to the more tractable diffusion kinetics of the Al-Cu system and in part to the strong industrial pull from the electrical industry. The convergence of mechanical interlocking strategies, auxiliary acoustic energy, and stationary shoulder thermal management represents a well-developed toolkit, and quantitative targets, such as the 1.6  $\mu\text{m}$  threshold demonstrated by stationary shoulder FSW, provide actionable design criteria. The area most in need of development is the long-term performance of these joints under combined electrical loading and thermal cycling, which simulates the service conditions of battery terminals and power distribution components. Published data on electrical resistance evolution and failure mode under cyclic thermal stress remain scarce, and this gap represents the primary barrier to widespread adoption of FSW Al-Cu joints in electromobility applications.

### 2.3.3. Role of Interlayers and Process Parameters

The introduction of interlayers offers a practical way to manage interfacial reactions in dissimilar welds, with Abdollahzadeh et al. [72] demonstrating both through simulation and experiment that a zinc interlayer acts as a physical buffer in Al-Cu joints, preventing direct contact between the base metals and modifying the thermodynamic driving forces responsible for IMC formation, ultimately resulting in a more ductile interface. Their finite element analysis revealed a critical trade-off: while larger shoulder diameters increase frictional heat and improve material plasticity, they simultaneously reduce the uniformity of stress distribution in the weld zone, requiring a careful balance between thermal generation and mechanical stability.

Since mixing efficiency is directly related to tool geometry, He et al. [73] found that the threaded stud design significantly improved vertical mixing, a downward flow essential for fracturing oxide films and dispersing reaction products, helping to prevent the formation of continuous brittle networks. Their simulations specifically showed that the combination of threaded and flat features generated a high-velocity downward material trajectory, which eliminated the weak bond defects typically observed at the root of the stir zone. The strength of the joint can be further improved by deliberately influencing the IMC phases that precipitate during welding, with Beygi et al. [74] identifying a mechanism whereby intermittent  $\theta$ -phase intermetallic act as crack arresters, a discontinuous reaction layer preventing catastrophic cleavage and forcing propagating cracks to bypass the harder parent materials.

Beyond tool design, Bagheri et al. [75] established a clear empirical link between dwell time and shear strength in Al/SiC/Cu spot welds, with microstructural evaluations confirming that shorter dwell times limit grain growth in the stir zone and produce superior shear strength according to the Hall-Petch relationship, with parameters such as rotation speed and dwell time thus directly controlling the heat input. Vaneghi et al. [76], exploring pinless FSW, observed that pin removal reduces mechanical stir, requiring extremely precise control over the shoulder plunge depth to maintain adequate bonding pressure. Their work also showed that although an intermediate zinc layer aids bonding, prolonged dwell times introduce excessive heat that causes the proliferation of the brittle  $\text{Al}_2\text{Cu}$  phase, ultimately compromising the integrity of the joint.

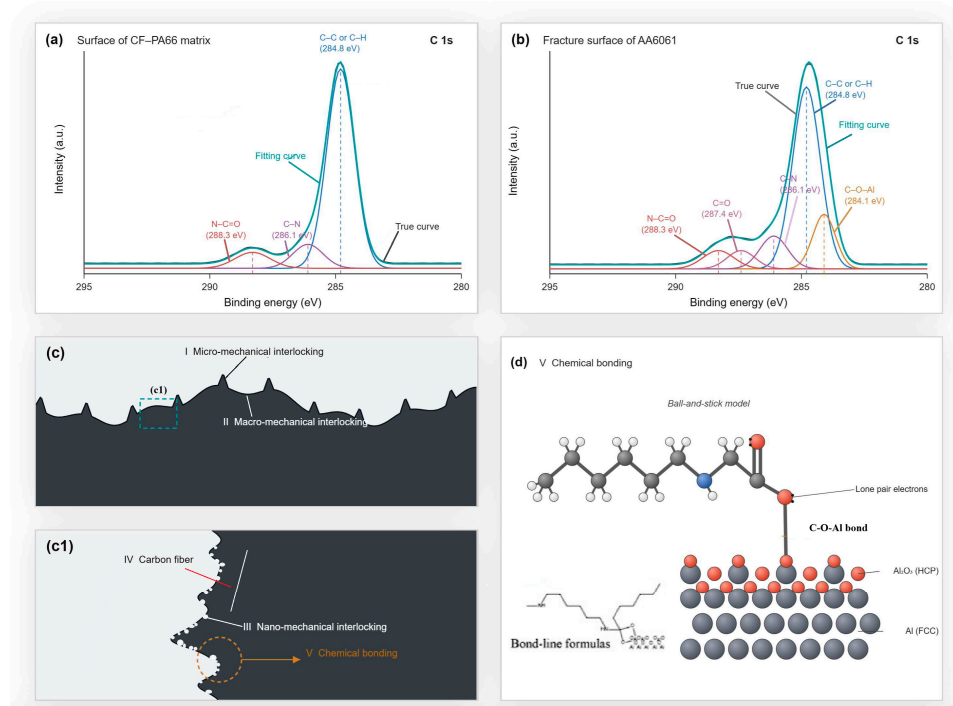
Different alloy combinations require customized analytical approaches. For AA5083 (non-heat-treatable)/Cu joints, Bagheri et al. [77] showed that the optimal processing window differs significantly from that of heat-treatable variants such as AA2024/Cu. Their macrographic analysis revealed a distinct “copper ring” on the advancing side, formed as the copper is extruded into the aluminum matrix, a structure that provides robust macroscopic interlocking, compensating for the limited atomic diffusion at lower processing temperatures. Therefore, thermodynamic modification through interlayer additions or chemical barrier effect of interlayers to ensure that mechanical and metallurgical bonds work together to suppress brittle failure [78]. To mitigate uneven mixing and excessive heat, Bora et al. [79] demonstrated through Analysis of Variance that strategic offset of the tool from the joint line governs material flow and thermomechanical mixing, leading to substantial gains in load-bearing capacity, with spatial parameters such as tool offset being precisely tuned by researchers for this purpose. By embedding thermocouples in AA7075-T6/pure copper joint specimens, Çakan et al. [80] mapped the direct correlation between rotational speeds in the range of 660–1500 rpm and peak temperatures, reinforcing the need for strict thermal management. Wei et al. [81] investigated the influence of tool material and geometry, process parameters, plate overlap sequence, and the use of a heat sink on the quality of Al–Cu joints made by friction stir welding (FSW), aiming to obtain defect-free joints with improved mechanical properties. Specialized FSW variants have been developed for lap joint configurations, with Devarajan et al. [82] identifying tool penetration rate, rotational speed, and dwell time as the main determinants of mechanical interlocking and electrical conductivity in such Al–Cu joints. Since conventional FSW inevitably leaves a residual keyhole defect at the point of tool withdrawal, Gao et al. [50] proposed a modified friction-stirring technique that eliminates this defect through a two-stage tool retraction sequence combined with a pre-placed intermediate zinc interlayer. In the first stage, the rotating pin plasticizes the Al–Cu interface in the conventional FSW manner while the zinc foil is mechanically swept into the stir zone, redistributing as a thermodynamic buffer layer between the two base metals. In the second stage, rather than withdrawing the tool abruptly, a controlled upward retraction under continued rotation forces the plasticized material to flow back into the cavity left by the retracting pin, filling it progressively and consolidating a defect-free top surface. The zinc interlayer simultaneously modifies the interfacial thermodynamics: by introducing a third element at the Al–Cu reaction zone, it shifts the IMC phase composition away from brittle  $\text{Al}_2\text{Cu}$  and  $\text{Al}_4\text{Cu}_9$  toward ductile lamellar eutectics and Zn-rich  $\text{CuZn}_{15}$  compounds. The combined effect of keyhole elimination and IMC phase modification produces a 40% increase in joint strength relative to conventional FSW, with fracture redirected from brittle interfacial cleavage to ductile failure through the lamellar eutectic structure, preserving both structural integrity and conductive path continuity.

The interlayer and process parameter studies reviewed in this subsection collectively highlight a persistent challenge in Al–Cu FSW: the optimal processing window is both narrow and strongly alloy-dependent, making generalization from one alloy combination to another unreliable without targeted experimentation. The use of zinc interlayers as thermodynamic buffers and keyhole repair agents represents one of the most practically promising strategies identified, because it simultaneously addresses two distinct joint quality problems, interfacial brittleness and keyhole defect formation, through a single process modification. However, the quantitative relationship between zinc layer thickness, dwell time, and the resulting IMC phase composition has not been systematically mapped across the range of aluminum alloys used in the electrical and automotive industries, and this is a gap that limits the confident selection of process parameters for new alloy combinations without extensive preliminary experimentation.

#### 2.4. Metal-to-Polymer and Composite Joining

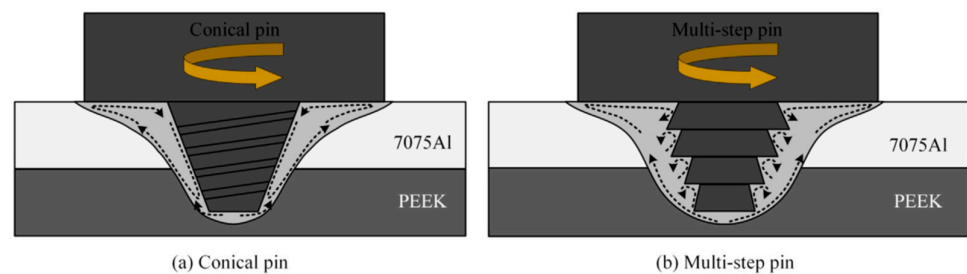
The demand for extreme lightness and corrosion resistance in aerospace and automotive applications has generated considerable interest in metal–polymer hybrid structures. Joining metals to thermoplastics, however, is a fundamentally different problem from metal–metal joining; the severe disparities in melting temperatures and the complete lack of chemical affinity between the two classes of materials preclude most conventional approaches. As presented by Barakat et al. [83], who surveyed FSW of aluminum alloy and steel substrates joined to thermoplastics including high-density polyethylene (HDPE), polyamide (PA6 and PA66), and carbon fiber-reinforced polymer (CFRP) composites, FSW offers a practical solid-state solution in which the metal is plasticized and mechanically pressed into the polymer, with joint integrity relying on macroscopic and microscopic interlocking rather than chemical bonds. Rudrapati [84] notes that excessive heat input readily degrades the polymer matrix or fractures the reinforcing fibers, dramatically reducing joint efficiency, meaning that the operational window for metal–polymer systems is considerably narrower than for metal–metal configurations.

The strength of the joint in these hybrid systems is dictated almost entirely by the quality of the interface. Wang et al. [85], investigating the friction stir lap welding of light metals onto carbon fiber-reinforced polymer (CFRP) composites, demonstrated that the deliberate induction of a hook-like penetration of the plasticized metal into the polymer improves mechanical anchoring, provided that thermal degradation is avoided. To maximize this effect, they introduced a laser ablation pretreatment to establish a multi-scale bonding mechanism. As illustrated in Figure 11, the interface is strengthened at four levels: macromechanical interlocking driven by tool pressure, micromechanical anchoring in laser-ablated grooves, nanomechanical clamping within surface pores, and the formation of C–O–Al chemical bonds. The C 1s X-ray photoelectron spectroscopy (XPS) spectra of the CF-PA66 surface and the fractured AA6061 surface (Figure 11a,b) confirm this chemical contribution through the C–O–Al component, while the schematic diagrams (Figure 11c,d) elucidate the mechanical interlocking across multiple length scales. Laser-induced texturing expands the contact area, allowing the molten polymer to penetrate the metal substrate while facilitating atomic-level reactions between the PA66 matrix and the  $\text{Al}_2\text{O}_3$  surface oxide.



**Figure 11.** XPS analysis and multi-scale interface strengthening mechanism of the hybrid joint: (a,b) C 1s XPS spectra of the CF-PA66 surface and the AA6061 fracture surface, respectively; (c) schematic illustration of macro- and micro-mechanical interlocking at the interface, with (c1) a magnified view of nano-mechanical interlocking around the carbon fiber; (d) ball-and-stick model and structural formulas depicting the C-O-Al bonding formed between the PA66 matrix and the  $\text{Al}_2\text{O}_3$  surface oxide. Adapted from [85].

Driven by the need for improved material transport, Nian et al. [86] introduced a multi-vortex sealing flow lap welding technique for AA7075 aluminum joined to PEEK (polyether ether ketone) polymer matrix composite that induces complex flow patterns, forcing the thermoplastic into surface irregularities on the metal and thereby establishing a robust three-dimensional interlocking network that significantly increases shear strength. As illustrated in Figure 12, while a standard tapered pin generates a defect-prone upward-directed flow, the proposed multi-stage pin geometry creates localized vortex-like circulation at each level. These flow dynamics effectively trap the rising polymer, sealing it within the joint and accelerating mixing to produce a dense, defect-free interlocking zone.



**Figure 12.** Schematic diagrams of material flow behaviors under different pins [86].

The trajectory of metal–polymer bonding research reflects a clear shift away from relying entirely on macroscopic deformation, towards deliberate interfacial engineering

through multi-scale surface texturing and advanced tool geometries designed to provide mechanochemical synergy.

#### 2.4.1. Friction Stir Welding of 3D Printed Polymers

A more recent application of FSW addresses the assembly of additively manufactured polymer sheets, highlighted by Vidakis et al. [87], who optimized process parameters for 3D-printed acrylonitrile butadiene styrene (ABS), showing that FSW can successfully join or repair printed parts while maintaining mechanical properties comparable to those of conventionally processed material. Their work in the context of hybrid additive manufacturing emphasizes that tight control over tool geometry and tilt angle is essential to tune the thermal field and avoid severe material degradation.

In a related study on 3D-printed polylactic acid (PLA), Vidakis et al. [88] used a full factorial design to determine that rotational speed is the dominant factor in suppressing defects such as flash formation and voids in biodegradable polymers. Their comparative microstructural analysis revealed clear morphological differences between a sound joint, marked by a continuous agitation zone and a well-defined onion-ring mixing pattern, and a defective joint containing macroscopic voids and tunnel defects. These findings reinforce the principle that structural integrity in thermoplastic FSW depends on maintaining temperatures within a tightly restricted window, hot enough to allow plastic flow, but cool enough to prevent thermal degradation.

Together, these studies validate hybrid additive manufacturing as a practical industrial approach, demonstrating that solid-state welding can circumvent the dimensional limitations inherent in 3D printing and enable the fabrication of large, structurally robust polymer assemblies.

The studies on FSW of

3D-printed polymers reviewed here are notable for establishing that the process is viable for joining additively manufactured thermoplastic components without requiring the specialized tooling or bonding agents that most alternative repair techniques demand. The dominant finding, that rotational speed is the primary parameter governing defect formation in both ABS and PLA, is consistent with the general FSW principle that thermal input drives viscoplastic flow, but the sensitivity of biodegradable polymers to even moderate excess heat introduces a tighter process window than is typical for semi-crystalline engineering polymers. The most important open question is whether the microstructural integrity demonstrated for simple butt joint configurations can be maintained for the more geometrically complex interfaces that arise when FSW is used to assemble multi-part 3D-printed structures, where local variations in layer deposition direction and residual porosity from the printing process may create unpredictable local variations in flow stress and thermal conductivity.

#### 2.4.2. Tool Design and Surface Pretreatment

Khalaf et al. [89] examined the thermomechanical behavior of high-density polyethylene during FSW using various pin profiles, finding that threaded cylindrical pins significantly improved vertical mixing and heat generation, both of which are necessary for semi-crystalline polymers to reach the correct viscoplastic state. Their CFD models showed that threaded pins reached a peak temperature of 158 °C, higher than that recorded for square or triangular alternatives, establishing a balance between shear stress and frictional heat that avoids both poor consolidation and material degradation. The flow field induced by the threads forces the molten polymer downward, promoting a uniform viscosity distribution in the agitation zone, while polygonal pins tend to generate a pulsating, turbulent flow that frequently introduces internal voids. For more demanding applications, where mechanical interlocking alone is often insufficient, Wang et al. [90]

developed a physicochemical surface pretreatment that modifies the surface energy of the metal prior to welding. This approach generates a hybrid joint based simultaneously on chemical adhesion and mechanical anchoring, thereby doubling the load-bearing capacity compared to untreated specimens. The method creates macroscopic grooves to facilitate resin flow and physical interlocking, while silane molecules are grafted onto the newly micro-roughened surface. The silane functions as a molecular bridge, promoting the formation of interfacial Al-O-Si-C covalent bonds that work in tandem with macroscopic mechanical anchors to resist joint failure.

Further development of hybrid metal–polymer joining depends on a comprehensive manufacturing strategy that synchronizes optimized tool kinematics with advanced surface engineering, enabling multi-scale bonding mechanisms that overcome the deep physical and chemical incompatibilities of the base materials.

The tool design and surface pretreatment studies reviewed in this subsection together map the two complementary degrees of freedom available to the engineer designing a metal–polymer FSW joint: the kinematics of the tool, which determine how the plasticized metal interacts with and penetrates the polymer surface, and the surface chemistry of the metal, which determines the strength of the molecular-scale adhesion that augments the macroscopic mechanical anchoring. The evidence strongly suggests that threaded cylindrical pins are the preferred geometry for most semi-crystalline thermoplastics, because the downward-directed flow field they generate produces a more uniform viscosity distribution than polygonal alternatives. The critical knowledge gap is the durability of the chemical bonds formed at the silane-modified interface under hygrothermal aging and cyclic loading, conditions that are relevant to automotive and aerospace applications but that are not well represented in the current literature, which largely focuses on as-manufactured joint properties.

The introductory studies reviewed here establish the central challenge of metal–polymer FSW: that bonding relies entirely on mechanical interlocking and surface chemistry rather than on the metallurgical diffusion mechanisms that underpin all-metal joints, and begin to identify the multi-scale approach that is necessary to achieve adequate structural performance. The consensus emerging from this body of work is that neither macroscopic mechanical deformation alone nor surface chemistry modification alone is sufficient: only when hook geometry, surface texturing, and chemical pre-activation are combined into a single synchronized strategy do joint efficiencies approach practically useful levels. The unresolved question, with direct implications for manufacturing implementation, is how robustly these multi-scale surface preparation strategies can be maintained under production conditions, where surface cleanliness, pretreatment consistency, and polymer rheology at the time of joining may all vary in ways that the laboratory experiments do not capture.

### *2.5. Joining High-Entropy and Specialty Alloys*

Friction stir welding (FSW) is increasingly applied to advanced materials, including high-entropy alloys (HEAs) and superalloys, which are notoriously difficult to process by conventional fusion welding due to severe elemental segregation and susceptibility to cracking. Do et al. [91] successfully joined a CoCrFeMnNi high-entropy alloy (HEA) to STS304 stainless steel, observing that the solid-state nature of FSW suppressed the formation of deleterious sigma phases and maintained a simple face-centered cubic (FCC) structure at the interface. Subsequent mechanical testing showed that these dissimilar joints exhibit exceptional properties: the HEA side fractured in a ductile manner, while the stainless-steel side failed in a mixed ductile–brittle manner, indicating that joint quality is comparable to, or exceeds, that of the base metals themselves. Similarly, Hu et al. [92] examined the recrystallization behavior of a medium-entropy CoCrNi alloy,

finding that the severe plastic deformation inherent in FSW triggers substantial grain refinement through dynamic recrystallization, with a corresponding increase in material strength. Grain orientation spread (GOS) maps confirmed this: recrystallized grains dominated the microstructure of the agitation zone owing to the high heat input, while deformed grains were relatively rare, confirming dynamic recrystallization as the dominant restoration mechanism driving grain refinement. Significant progress has also been made in highly corrosive environments, with Cao et al. [93] demonstrating that submerged FSW applied to super duplex stainless steel, through rapid cooling provided by the aqueous medium, produces an ultrafine-grained microstructure and a well-balanced austenite–ferrite ratio. The result was a simultaneous improvement in both strength and ductility, a combination notoriously difficult to achieve in duplex steels. Crucially, the submerged process prevented the elemental partitioning that typically accompanies fusion welding, resulting in pitting corrosion resistance comparable to that of the base metal. In a study focused on low-temperature processing, Su et al. [94] analyzed the cooling rates of welds in titanium alloy TA5, concluding that tight control of the  $\beta$ -to- $\alpha$  phase transformation is essential to prevent embrittlement in titanium friction stir joints.

The studies reviewed in this subsection collectively demonstrate that FSW's solid-state character is its key advantage when applied to high-entropy and specialty alloys: the absence of a liquid phase eliminates the elemental segregation, sigma phase formation, and solidification cracking that make these materials so difficult to process by fusion welding. The results for CoCrFeMnNi HEA, CoCrNi medium-entropy alloy, and super duplex stainless steel all confirm that dynamic recrystallization in the stir zone reliably produces refined microstructures with mechanical properties meeting or exceeding base metal specifications. The most significant unresolved challenge, and the primary barrier to industrial adoption, is tool material: no currently available commercial tool can process high-entropy or refractory alloys at the rotational speeds and forces required without sustaining unacceptable wear rates. Progress in this area will likely require purpose-designed ceramic or ultra-hard composite tool materials, and this represents one of the most important open research problems in the field.

## 2.6. Thermodynamic and Kinetic Framework for IMC Growth

The material-system-specific discussions of Sections 2.1–2.5 each describe the formation and control of intermetallic compound layers in qualitative or empirical terms. Taken together, however, they draw on a common thermodynamic and kinetic foundation that is worth making explicit, both to unify the interpretive framework across systems and to provide the physical basis for understanding why the mitigation strategies reviewed in Section 2 and the hybrid process variants discussed in Section 3 are effective. This subsection provides that foundation.

### 2.6.1. Phase Selection: Thermodynamic Driving Force

In any dissimilar metal FSW joint, the question of which intermetallic phases nucleate preferentially at the interface is governed by thermodynamics: the phase that forms first is the one whose nucleation requires surmounting the lowest Gibbs free energy barrier under the prevailing thermal conditions. For a binary system A-B, the Gibbs free energy of formation of a given intermetallic phase  $A_xB_y$  at temperature  $T$  is

$$\Delta G_f(A_xB_y, T) = \Delta H_f - T \cdot \Delta S_f$$

where  $\Delta H_f$  is the enthalpy of formation and  $\Delta S_f$  is the entropy of formation of the phase. Phases with the most negative  $\Delta G_f$  are thermodynamically most stable and nucleate preferentially; the specific FSW thermal cycle, in which interfacial temperatures typically

reach 60–90% of the lower-melting material's solidus, determines which phases in the A-B phase diagram fall within the accessible energy window. In the Al-Fe system, this criterion selects  $\text{Fe}_2\text{Al}_5$  and  $\text{Fe}_4\text{Al}_{13}$  as the preferentially forming phases, consistent with their position on the Al-Fe phase diagram and their negative formation enthalpies of approximately  $-37$  kJ/mol and  $-29$  kJ/mol respectively. In the Al-Mg system,  $\text{Al}_{12}\text{Mg}_{17}$  ( $\Delta H_f \approx -8.5$  kJ/mol) and  $\text{Al}_3\text{Mg}_2$  ( $\Delta H_f \approx -7.2$  kJ/mol) are the equilibrium phases accessible below the  $437^\circ\text{C}$  eutectic temperature; above this temperature, liquid phase formation disrupts the purely solid-state reaction pathway and produces the brittle re-solidified microstructures discussed in Section 2.2. In the Al-Cu system,  $\text{Al}_2\text{Cu}$  ( $\Delta H_f \approx -15$  kJ/mol) and  $\text{Al}_4\text{Cu}_9$  are the primary phases, with  $\text{CuAl}_2$  becoming dominant at lower temperatures, which explains why submerged FSW, by reducing interfacial temperatures, shifts the IMC composition toward the less brittle  $\text{CuAl}_2$  phase.

This thermodynamic phase selection principle provides a direct physical explanation for several empirical observations reviewed in Section 2. The use of interlayers—zinc in Al-Mg and Al-Cu systems, and aluminum pre-deposition in hybrid arc-FSW of Al-steel joints—is effective precisely because it introduces a third element that modifies the local  $\Delta G_f$  landscape, making the formation of less brittle ternary compounds ( $\text{Mg-Zn}$ ,  $\text{Mg-Al-Zn}$ ,  $\text{CuZn}_5$ ) thermodynamically competitive with the binary Al-Mg and Al-Cu intermetallics. The efficiency of this chemical modification strategy is therefore predictable in principle from phase diagram data, and the selection of interlayer composition for a new material pair can be guided by screening ternary phase diagrams for compound families with more negative  $\Delta G_f$  than the binary brittle phases before committing to physical experimentation.

#### 2.6.2. Growth Kinetics: Diffusion-Controlled Thickening

Once a phase has nucleated at the interface, its subsequent thickening is governed by solid-state diffusion of atoms across the growing layer. Under isothermal conditions at temperature  $T$ , the thickness  $x$  of a diffusion-controlled IMC layer grows according to the parabolic rate law:

$$x^2 = 2 \cdot k_0 \cdot \exp(-Q_d/RT) \cdot t = K(T) \cdot t$$

where  $k_0$  is the pre-exponential rate constant,  $Q_d$  is the activation energy for the diffusion process controlling growth,  $R$  is the universal gas constant,  $T$  is the absolute temperature, and  $t$  is the time at temperature. The parabolic dependence on time reflects the progressive increase in diffusion distance as the IMC layer thickens: atomic transport must traverse a growing barrier, so the growth rate  $dx/dt = K(T)/(2x)$  decreases as  $x$  increases. The temperature dependence enters through the Arrhenius exponential, which means that even modest reductions in interfacial temperature produce disproportionately large reductions in the growth rate constant  $K(T)$ : reducing the interfacial temperature by  $50^\circ\text{C}$  in a system with  $Q_d \approx 100$  kJ/mol reduces  $K(T)$  by approximately a factor of 3–4 at typical FSW temperatures.

The activation energies for IMC growth differ substantially between systems and between phases within the same system. In the Al-Fe system, the activation energy for  $\text{Fe}_2\text{Al}_5$  growth is approximately 95–115 kJ/mol, reflecting the relatively sluggish iron diffusion through the growing layer; this is why Al-steel joints require higher heat inputs to form measurable IMC layers than Al-Mg or Al-Cu joints, but also why the heat input sensitivity of  $\text{Fe}_2\text{Al}_5$  thickness is comparatively lower. In the Al-Mg system,  $Q_d$  for  $\text{Al}_{12}\text{Mg}_{17}$  growth is approximately 60–80 kJ/mol, which, combined with the low eutectic temperature of  $437^\circ\text{C}$ , produces the high IMC formation rate that makes Al-Mg thermal process control so critical. In the Al-Cu system,  $Q_d$  for  $\text{Al}_2\text{Cu}$  growth is approximately 80–100 kJ/mol; the tractable diffusion kinetics of the Al-Cu system relative to Al-Fe—a

consequence of copper's higher diffusivity in aluminum compared to iron—contribute to the engineering maturity of Al-Cu FSW control strategies noted in Section 2.3.

### 2.6.3. The Non-Isothermal FSW Thermal Cycle and Its Consequences

The parabolic growth law is derived for isothermal conditions, but the FSW thermal cycle is inherently non-isothermal: the interfacial temperature rises rapidly during tool approach, reaches a peak as the tool shoulder passes, and then falls during cooling. The effective thickness  $x$  of the IMC layer after a complete FSW pass can be estimated by integrating the instantaneous growth rate over the full thermal cycle:

$$x^2(\text{final}) = \int_0^t K(T(t)) dt = \int_0^t 2k_0 \exp(-Q_d/RT(t)) dt$$

This integral is strongly weighted toward the high-temperature portion of the cycle: because  $K(T)$  increases exponentially with temperature, the brief interval near the peak temperature contributes disproportionately more to the final IMC thickness than the much longer cooling phase. The practical implication is that strategies that reduce peak interfacial temperature, including lower rotation speed, higher traverse speed, tool offset toward the softer material, submerged welding, or stationary shoulder configurations, are more effective at limiting final IMC thickness than strategies that accelerate the cooling rate, because the former reduces the integrand at the most heavily weighted part of the integral. This is entirely consistent with the empirical findings reviewed in Sections 2.1–2.3: in every system, the process modifications that most effectively suppress IMC growth are those that limit peak temperature rather than those that promote rapid cooling after the peak.

A further consequence of the non-isothermal integral is that the relationship between process parameters and final IMC thickness is inherently nonlinear, even when the growth kinetics are well-described by a parabolic law. A 10% increase in rotation speed may increase peak temperature by 20–30 °C through the frictional heat generation mechanism of Section 1.4.1, and that temperature increase translates into an exponentially larger growth rate constant  $K(T)$ . This nonlinearity explains why the linear relationship between rotation speed and IMC thickness reported by Geng et al. [25] for 5052-Al/DP590 steel joints is observed over a restricted parameter range: it is an approximation that holds when the temperature variation is small enough that the exponential can be linearized, but breaks down at higher rotation speeds where the temperature sensitivity of  $K(T)$  becomes dominant.

### 2.6.4. Critical IMC Thickness and the Ductile-to-Brittle Transition

The mechanical consequence of IMC layer growth is a ductile-to-brittle fracture mode transition that occurs when the layer exceeds a system-specific critical thickness  $x_{\text{crit}}$ . Below  $x_{\text{crit}}$ , the IMC layer is thin enough that its intrinsic brittleness is mechanically suppressed by constraint from the surrounding ductile metal matrix: any crack that initiates in the IMC layer is arrested at the IMC–metal interface before it can propagate catastrophically. Above  $x_{\text{crit}}$ , the IMC layer is sufficiently thick to sustain a propagating crack across its full width, and fracture becomes brittle and interface-controlled rather than ductile and matrix-controlled. The cross-system synthesis of Section 2 established the following approximate critical thicknesses based on the reviewed experimental evidence:  $x_{\text{crit}} \approx 3\text{--}5 \mu\text{m}$  for  $\text{Fe}_2\text{Al}_5$  in Al–steel joints, above which fracture propagates preferentially through the IMC layer [25];  $x_{\text{crit}} \approx 3 \mu\text{m}$  for  $\text{Al}_{12}\text{Mg}_{17}$  in Al–Mg joints, above which eutectic formation and brittle re-solidification become the dominant failure pathway [44]; and  $x_{\text{crit}} \approx 1.5\text{--}2 \mu\text{m}$  for  $\text{Al}_2\text{Cu}$  in Al–Cu joints, consistent with the embrittlement threshold below which SSFSW maintains acceptable ductility [48]. These values differ between systems primarily because of differences in the intrinsic fracture toughness of the dominant IMC

phase and the degree of elastic mismatch between the IMC and the adjacent metal phases, which governs the stress concentration at the IMC–metal interface.

The parabolic growth law provides a direct route from process parameters to predicted IMC thickness, and from predicted thickness to expected fracture mode, which closes the link between thermomechanical process design and joint mechanical performance. Although the specific values of  $k_0$  and  $Q_d$  must be determined experimentally for each material pair, and data of sufficient precision for all three systems reviewed here are not yet fully consolidated in the published literature, the framework provides a principled basis for parameter selection that is transferable across alloy combinations and joint configurations in a way that purely empirical correlations are not. Connecting this framework to the statistical and machine learning optimization tools reviewed in Section 4, specifically, using the parabolic growth integral as a physics-informed constraint in RSM and surrogate model development, is identified as one of the most productive directions for reducing the experimental burden of process development for new dissimilar FSW material pairs.

The material systems reviewed in Section 2 define the metallurgical challenges that FSW must overcome: brittle intermetallic compound layers in dissimilar metal joints, narrow thermal process windows in Al-Mg systems, dual structural–electrical performance requirements in Al-Cu joints, the fundamental incompatibility of metals and polymers, and the tool material constraints imposed by hard specialty alloys. What unites these challenges is that they all require finer control over heat input, material flow, and interfacial thermodynamics than conventional FSW parameters alone can provide. Section 3 reviews the hybrid and derivative process variants that have been developed specifically to address these limitations, offering the additional degrees of process control that the material systems of Section 2 demand.

Table 3 provides a comprehensive cross-section of the representative FSW studies reviewed in this manuscript, organized across six dimensions for each entry: the material system and joint configuration studied, the representative process parameters reported, the tool type or geometry employed, the main defects observed or predicted, the mechanical performance achieved, and the optimization or modeling technique applied. The table spans Sections 2.1 through 4, covering dissimilar metal joining, metal–polymer joining, hybrid process variants, and digitalization approaches. All data are drawn exclusively from references already cited in the manuscript and no values have been supplemented from external sources. The table is intended as a navigational resource enabling rapid cross-system and cross-methodology comparison and for mechanistic interpretation of any entry, can be directed to the corresponding subsection of the manuscript.

**Table 3.** Comprehensive process parameter summary: material systems, joint configurations, process parameters, tool descriptions, main defects, mechanical performance, and optimization/modeling techniques for representative FSW studies reviewed in Sections 2.1 through 4.

| Material System                        | Joint Config.           | Process Parameters (Representative)                | Tool Description                        | Main Defects Reported                                                          | Mechanical Performance                                                                | Optimization/Modeling Technique                                  |
|----------------------------------------|-------------------------|----------------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|------------------------------------------------------------------|
| Section 2.1—Aluminum-to-Steel Joining  |                         |                                                    |                                         |                                                                                |                                                                                       |                                                                  |
| AA5005/mild steel                      | Butt                    | Conventional FSW; UFSW (submerged)                 | H13 steel; standard shoulder + pin      | Thick IMC layer (air); reduced and uniform (UFSW)                              | UFSW: Thinner IMC, improved fracture mode vs. air                                     | Experimental comparison                                          |
| 5052-Al/DP590 steel                    | Lap                     | Variable rotation speed; key variable: $\omega$    | Standard FSW tool; cylindrical pin      | Fe <sub>2</sub> Al <sub>5</sub> layer thickening; brittle fracture through IMC | IMC thickness~linear with $\omega$ ; fracture through Fe <sub>2</sub> Al <sub>5</sub> | Experimental parametric study                                    |
| Al/galvanized steel                    | Lap (hybrid)            | BC-MIG arc predeposition + multi-pass FSW          | FSW tool + MIG torch; two-stage process | IMC suppressed to <1.5 $\mu$ m                                                 | Failure redirected to Al base metal; ductile fracture                                 | Hybrid arc-FSW (BC-MIG + FSW)                                    |
| Al/steel                               | Lap                     | FSW + superimposed ultrasonic vibrations (~20 kHz) | Standard FSW tool + sonotrode           | IMC fragmented; continuous layer eliminated                                    | Fracture: Mixed ductile–brittle (conv.) → purely ductile (UaFSW)                      | UaFSW; experimental                                              |
| 6061-T6 Al/430 SS                      | Butt                    | Optimized tool offset toward Al side               | Standard FSW tool; offset strategy      | Void formation prevented; serrated interface formed                            | Robust mechanical interlocking; no voids                                              | Experimental tool offset optimization                            |
| Al/galvanized steel                    | Lap                     | Multi-pass FSW; groove pin geometry                | Circumferential groove pin (modified)   | Hook defects eliminated; planar bond achieved                                  | Planar bond free of stress concentrators                                              | Pin geometry modification                                        |
| 6061-T6 Al/316L SS                     | Butt                    | Up to 18,000 rpm; extreme high-speed               | Standard FSW tool                       | IMC contributes to bonding at extreme rpm                                      | Improved mechanical bonding + corrosion resistance                                    | Experimental extreme-parameter study                             |
| Section 2.2—Aluminum–Magnesium Joining |                         |                                                    |                                         |                                                                                |                                                                                       |                                                                  |
| 6061-T6 Al/AZ31B Mg                    | Butt                    | 600–800 rpm; low traverse speed; Mg-side offset    | Standard FSW tool; offset toward Mg     | Tunnel voids if under-parameter; IMC if over-parameter                         | ~70% Al BM UTS at optimum; ductile fracture                                           | Experimental optimization; FEM (Baruah [66]); RSM+ANN (Efa [67]) |
| Al alloys (similar + dissimilar)       | Butt/various            | 600–1400 rpm optimal range                         | Standard FSW tool                       | Grain growth + IMC above 1400 rpm                                              | Strength decreases above optimal rpm window                                           | Experimental review; RSM                                         |
| 5A06 Al/AZ31B Mg                       | Butt (groove interface) | Standard FSW; multi-groove interface design        | Standard FSW tool                       | IMC at reaction zones; suppressed by geometry                                  | Load-bearing capacity >3× standard butt                                               | Joint geometry modification (serrated interface)                 |

|                                                    |                          |                                                      |                                                      |                                                                                                           |                                                               |                                                              |
|----------------------------------------------------|--------------------------|------------------------------------------------------|------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|--------------------------------------------------------------|
| AZ31B-H24<br>Mg/AA6061-T6 Al                       | Lap                      | Variable pin length + rotation speed                 | Variable pin length tool                             | IMC layer; eutectic formation if over temp                                                                | Lapped shear strength maintained at optimum                   | Experimental pin length + rpm optimization                   |
| Al/Mg (dissimilar)                                 | Butt                     | FSW + Zn interlayer + TiC nanoparticles              | Standard FSW tool; interlayer pre-placed             | Al-Mg IMCs suppressed; replaced by Mg-Zn compounds                                                        | Improved ductility; grain refinement throughout SZ            | Interlayer + nanoparticle modification                       |
| Al/Mg (dissimilar)                                 | Butt                     | Pulsed current-assisted FSW (electroplastic)         | Standard FSW tool + pulsed current supply            | IMC growth restricted; processing window widened                                                          | Fracture: brittle (conv.) → ductile (EA-FSW)                  | Electrically assisted FSW; experimental                      |
| AZ31/ZK60 Mg alloys                                | Spot (double-sided FSSW) | Double-sided coaxial tool; symmetrical penetration   | Coaxial tool system; independently controlled pins   | Keyhole eliminated; uniform SZ microstructure                                                             | Homogeneous stir zone; closed keyhole                         | Double-sided FSSW; experimental                              |
| AA2024/pure Cu                                     | Spot (FSSW)              | Conventional FSSW; variable dwell time + rpm         | Standard FSSW tool; SiC nanoparticle addition        | IMC: 1.9 $\mu\text{m}$ (conv.); 3.1 $\mu\text{m}$ (SiC)—crack-free                                        | Hardness + wear resistance increased; conductivity maintained | Experimental FSSW; SiC nanoparticle addition                 |
| Section 2.3—Aluminum–Copper Joining                |                          |                                                      |                                                      |                                                                                                           |                                                               |                                                              |
| Al/Cu                                              | Butt                     | Stationary shoulder FSW (SSFWS)                      | Stationary shoulder tool (non-rotating shoulder)     | IMC: 2.4 $\mu\text{m}$ (conv.) → 1.6 $\mu\text{m}$ (SSFWS)                                                | IMC below embrittlement threshold; improved ductility         | SSFWS; experimental comparison                               |
| Al/Cu                                              | Butt (submerged)         | Underwater FSW; aqueous cooling                      | Standard FSW tool; submerged setup                   | Thinner, $\text{CuAl}_2$ -dominated IMC (lower brittleness)                                               | More uniform, less brittle IMC layer vs. conventional         | UFSW; experimental                                           |
| Al/Cu                                              | Spot (modified FSSW)     | Modified FSSW + Zn interlayer; keyhole elimination   | Modified friction-stirring tool + Zn foil            | $\text{Al}_2\text{Cu}$ , $\text{Al}_4\text{Cu}_9$ suppressed; $\text{CuZn}_5$ + lamellar eutectics formed | Joint strength +40% vs. conventional FSSW; ductile fracture   | Modified FSSW process; interlayer thermodynamic modification |
| AA7075-T6/pure Cu                                  | Butt                     | 660–1500 rpm; embedded thermocouples                 | Standard FSW tool; thermocouple-instrumented fixture | Thermal management critical; rpm directly controls peak temp                                              | Temperature directly correlated with rotational speed         | Experimental thermal mapping; Anova                          |
| AA6061 + CF-PA66 CFRP                              | Lap                      | FSW lap; laser ablation pretreatment of metal        | Standard FSW tool; pre-textured metal substrate      | Thermal degradation of polymer if over-temp                                                               | Multi-scale interlocking: Macro/micro/nano + chemical bonds   | Physicochemical surface pretreatment + FSW                   |
| Section 2.4—Metal-to-Polymer and Composite Joining |                          |                                                      |                                                      |                                                                                                           |                                                               |                                                              |
| AA7075 + PEEK                                      | Lap                      | Multi-stage pin; multi-vortex sealing flow technique | Multi-stage pin (novel geometry)                     | Defect-prone upward flow (conv. tapered pin)                                                              | Dense defect-free interlocking zone; increased shear strength | Pin geometry modification; novel multi-vortex technique      |

|                                                              |                   |                                                                |                                                              |                                                                   |                                                                                  |                                                                 |
|--------------------------------------------------------------|-------------------|----------------------------------------------------------------|--------------------------------------------------------------|-------------------------------------------------------------------|----------------------------------------------------------------------------------|-----------------------------------------------------------------|
| 3D printed ABS                                               | Butt              | Variable rpm; FSW of additively manufactured polymer           | Standard FSW tool; tilt angle critical                       | Flash formation; voids (if comparable to rpm outside window)      | Mech. properties comparable to conventionally processed material                 | Full factorial design; rotational speed as dominant factor      |
| High-density PE (HDPE)                                       | Butt              | Threaded cylindrical pin; peak ~158 °C                         | Threaded cylindrical pin; polygonal alternatives also tested | Internal voids (polygonal pins) avoided with threaded pin         | Uniform viscosity distribution; adequate consolidation                           | CFD pin geometry modeling                                       |
| AA2017 Al (UFSW)                                             | Butt              | ~1400 rpm optimal; Taguchi + ANOVA optimization                | Standard FSW tool; submerged setup                           | Wormhole/incomplete fusion defects below optimal rpm              | Max tensile strength at ~1400 rpm without precipitate dissolution                | Taguchi + ANOVA parameter optimization                          |
| Section 3— Hybrid and Derivative Variants of the FSW Process |                   |                                                                |                                                              |                                                                   |                                                                                  |                                                                 |
| AA5083 Al (UFSW)                                             | Butt + T-joint    | 1800 rpm; 7 mm penetration; conventional vs. UFSW              | Hexagonal profile tool (best result: 302 MPa)                | Weld root hardening risk from rapid cooling                       | 302 MPa (hexagonal tool); best joint efficiency in UFSW                          | Experimental tool profile comparison                            |
| 7003-T4/6060-T4 Al (UFSW)                                    | Butt              | UFSW + post-weld STA heat treatment                            | Standard FSW tool; submerged + oven aging                    | HAZ softening (mitigated by STA)                                  | STA restores hardness to near base-metal levels                                  | UFSW + STA post-weld heat treatment                             |
| Al/Mg dissimilar (UaFSW)                                     | Butt              | FSW + 20 kHz ultrasonic vibrations                             | Standard FSW tool + sonotrode (20 kHz)                       | Residual stress; IMC layers                                       | Peak longitudinal residual stress reduced ~25% vs. conv.                         | UaFSW; FEM residual stress analysis                             |
| 2219 Al (UaFSW)                                              | Butt              | FSW + ultrasonic impact treatment (UIT)                        | Standard FSW tool + UIT post-process                         | Stress corrosion cracking; grain boundary precipitates            | Surface nano-crystallization + compressive layer; improved SCC resistance        | UaFSW + UIT post-processing                                     |
| AA6061 Al (SSFSW)                                            | Butt              | Stationary shoulder; reduced heat input                        | Static shoulder tool (non-rotating)                          | Coarse-grained HAZ (conventional)—eliminated                      | Narrower HAZ; finer crystallographic texture; B/B-bar shear texture              | SSFSW; EBSD texture analysis                                    |
| 2A97 Al-Li (SSFSW)                                           | Butt              | Stationary shoulder FSW of Al-Li alloy                         | Stationary shoulder tool                                     | Surface coarsening of precipitates (conventional)—eliminated      | Mirror-like surface; uniform hardness through thickness; sandwich microstructure | SSFSW; microstructural characterization                         |
| Inconel 718/SS316L (I-FSW)                                   | Butt (dissimilar) | Induction preheating + FSW; local temperature rise before tool | WC-10%Co FSW tool; induction coil ahead of tool              | Laves phase precipitation (conventional)—suppressed by preheating | Corrosion resistance + ductility comparable to base metals                       | Induction-assisted FSW; electrochemical analysis; mech. testing |

|                                                  |                   |                                                      |                                 |                                              |                                                                     |                                                                             |
|--------------------------------------------------|-------------------|------------------------------------------------------|---------------------------------|----------------------------------------------|---------------------------------------------------------------------|-----------------------------------------------------------------------------|
| AA2050-T8 Al                                     | Butt              | Variable $\omega + v$ ; K-Fold cross-validation      | Not specified (ML study)        | Not applicable (ML prediction)               | R <sup>2</sup> up to 0.97 for UTS prediction                        | ML (RF, SVR, ANN) regression; K-Fold cross-validation                       |
| Section 4—Digitalization and Industry 4.0 in FSW |                   |                                                      |                                 |                                              |                                                                     |                                                                             |
| AA7050/AA2014Al                                  | Butt (dissimilar) | Variable $\omega + v$ ; ML temperature prediction    | Not specified (ML study)        | Not applicable                               | R <sup>2</sup> > 0.95 for peak temperature prediction               | ML regression models; peak temperature as output                            |
| AA2024-T3 Al                                     | Butt              | Variable $\omega$ , $v$ , tool parameters            | Not specified (ML study)        | Not applicable                               | XGBoost R <sup>2</sup> = 0.96; MLP R <sup>2</sup> = 0.91 for UTS    | RF, XGBoost, MLP comparison; ensemble methods best for noisy FSW data       |
| AA2024-T351 Al                                   | Butt              | Variable $\omega + v$ ; multi-objective optimization | Not specified (ML study)        | Fatigue failure sites                        | MAPE < 6% for fatigue life prediction                               | ANN + NSGA-II multi-objective optimization (fatigue life + residual stress) |
| AA6082 Al                                        | Butt              | Variable $\omega + v$ + plunge depth; CEL simulation | FEM tool model; CEL formulation | Onion-ring formation; tunnel voids predicted | CEL correctly predicts temperature + material flow distribution     | CEL FEM; tool geometry parametric study                                     |
| Al alloys (general FSW)                          | Butt              | Variable $\omega + v$ + clamping                     | CEL FEM model                   | Tunnel void (wormhole) defect; undercut      | Defect formation predicted; safe process zone defined               | CEL defect prediction; thermal-fluid-structural coupling                    |
| AA6061 + AA7075 composite                        | Butt              | Variable $\omega$ , $v$ , rake angle; RSM + NSGA-II  | Standard FSW tool; lap joint    | Sheet thinning; burr formation               | Max joint strength with min thinning/burr identified                | RSM + NSGA-II multi-objective optimization                                  |
| AA6082 + AA7050 Al                               | Butt (dissimilar) | Variable $\omega + v$ ; RSM optimization             | Standard FSW tool               | IMC if outside window                        | Optimal params identified; 7xxx requires lower heat input than 6xxx | RSM multiple response optimization                                          |
| Marine-grade AA5451                              | Butt              | Variable $\omega + v$ ; Taguchi + RSM                | Standard FSW tool               | Corrosion susceptibility if sensitized       | Precise operational envelope satisfying marine certification        | RSM + Taguchi; marine certification target                                  |

### 3. Hybrid and Derivative Variants of the FSW Process

The development of new hybrid and derivative techniques of the FSW process, designed to address specific metallurgical constraints, has emerged as a response to the limitations of conventional techniques regarding: excessive heat generation, grain coarsening, and the accumulation of residual stresses.

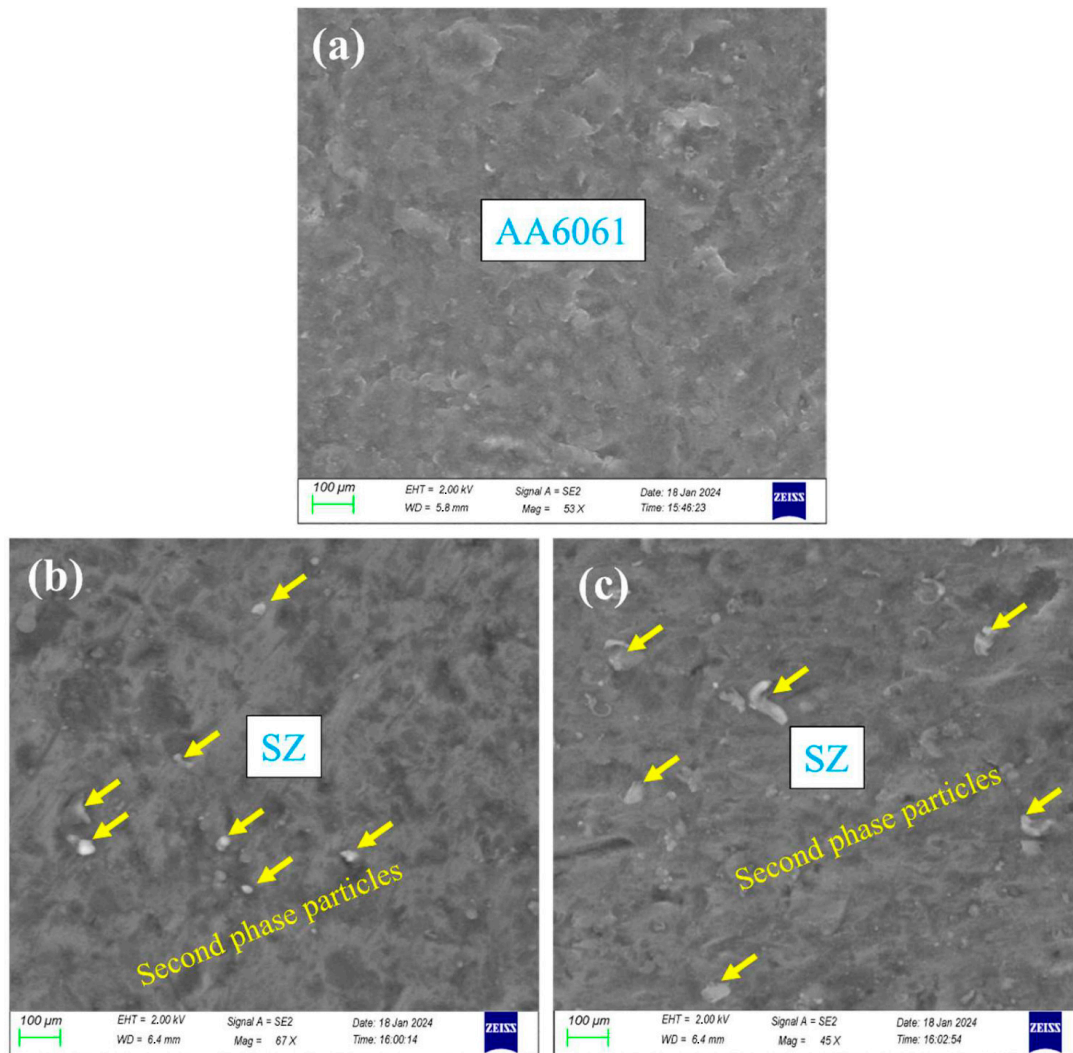
#### 3.1. Underwater Friction Stir Welding (UFSW)

Underwater friction stir welding (UFSW) has proven to be a highly effective hybrid method used for heat-sensitive materials.

Optimizing UFSW parameters requires distinct strategies compared to conventional processing, so Madani et al. [95] applied Taguchi and ANOVA methods to optimize process parameters for welding AA2017 aluminum alloy. They found that the tool rotation speed is the parameter with the greatest influence on joint quality.

To generate sufficient plasticity, high tool rotation speeds are required to compensate for the cooling effect of the water and prevent the occurrence of “wormhole” defects or those caused by incomplete fusion. Using response surface methodology, researchers determined that, although feed rate affects productivity, the rotational speed must be calibrated to be around 1400 rpm. This maximizes tensile strength without introducing excessive heat that would lead to the dissolution of the alloy’s hardening precipitates.

Sabry et al. [96] studied Al-Mg-Si T-joints using both conventional FSW and UFSW, observing that the underwater environment effectively suppressed grain growth in the stir zone, resulting in a significantly finer microstructure. This is evident in the comparative SEM images in Figure 13, where both welding methods refine the elongated grains of the base metal, yet the UFSW specimen exhibits significantly finer and more uniformly distributed equiaxed grains and secondary phase particles, consistent with the rapid-cooling grain refinement mechanism described in Section 1.4.3, reflecting the aqueous environment’s role as an in-process quench medium. A potential concern is that penetration depth must be carefully controlled, as rapid cooling can cause excessive hardening at the weld root, which acts as a stress concentrator if the material is not adequately plasticized.



**Figure 13.** SEM images of welded samples showing second-phase particles: (a) Base metal (BM), (b) SZ of FSW (1800 rpm, 7 mm) and (c) SZ of UFSW (1800 rpm, 7 mm) [96].

Saravanakumar et al. [97,98] demonstrated that different tool profiles, conical, cylindrical and hexagonal, interact in quite different ways with the underwater environment. Since the plasticized material solidifies rapidly underwater, a tool profile that strongly favors vertical flow of the material is essential to ensure adequate mixing before the material actually solidifies. The straight hexagonal profile creates a pulsating stirring action that is quite different from the constant friction of cylindrical designs. This pulsating stirring is extremely effective in fracturing the oxide layers and generating vertical flow in the rapidly cooling plasticized zone. The welded joint of AA5083 armor-grade aluminum alloy made with the straight hexagonal profile tool ultimately produced the highest tensile strength, 302 MPa, and the best joint efficiency. This confirms that maximizing the swept dynamic volume is crucial under UFSW conditions.

Although UFSW improves the properties of welded joints, post-weld heat treatments can further enhance joint performance. The thermal consequence of the aqueous environment must first be understood before selecting an appropriate treatment: Khalaf et al. [99] demonstrated that heat generation during UFSW of AA6068-T6 is significantly lower than in conventional FSW due to the rapid convective extraction of frictional energy by the water medium, producing a compressed thermal cycle with a reduced peak temperature and a steeper cooling rate. This compressed cycle leaves the precipitation

state of the stir zone and HAZ in a condition that differs fundamentally from conventionally welded material of the same alloy, meaning that post-weld treatment protocols developed for conventional FSW cannot be transferred directly to UFSW joints without re-calibration. Dong et al. [100] evaluated the effects of post-weld heat treatment on underwater joints of 7003-T4 and 6060-T4 aluminum and concluded that a subsequent aging treatment is necessary to reprecipitate the strengthening phases that partially dissolved during welding, even though the underwater process successfully minimized the width of the softened zone. Using transmission electron microscopy, it was confirmed that a solution treatment plus artificial aging (STA) regimen successfully repopulated the matrix with fine  $\eta$  and  $\beta$  precipitates, eliminated the characteristic hardness minimum in the HAZ, and restored the material in the joint to levels close to those of the base material. Combining UFSW with targeted heat treatments therefore provides a reliable route to producing high-performance joints in complex, heat-treatable alloys, provided that the post-weld protocol is calibrated to the modified precipitation state produced by the aqueous thermal cycle rather than assumed to follow the conventional FSW response.

The studies on UFSW reviewed in this section establish a consistent set of process–property relationships: the aqueous environment acts as an in-process quench medium, producing finer stir zone grain structures, narrower HAZ widths, and better-retained hardness relative to conventional FSW, but these benefits come at the cost of reduced material plasticity that requires higher rotational speeds and more carefully selected tool profiles to achieve adequate mixing. The consensus finding, that hexagonal or high-swept-volume tool profiles are essential for UFSW because rapid solidification allows less time for material to flow before freezing, is a practically important design rule with direct implications for tool selection. The key limitation of the current literature is that most UFSW studies address a narrow range of aluminum alloys in simple butt or T-joint geometries; the extension of these process–property relationships to dissimilar material pairs, complex joint geometries, and the large-section structural components used in marine applications remains largely unexplored, and this gap must be closed before UFSW can be adopted with confidence at industrial scale.

### 3.2. Ultrasonically Assisted Friction Stir Welding (UaFSW)

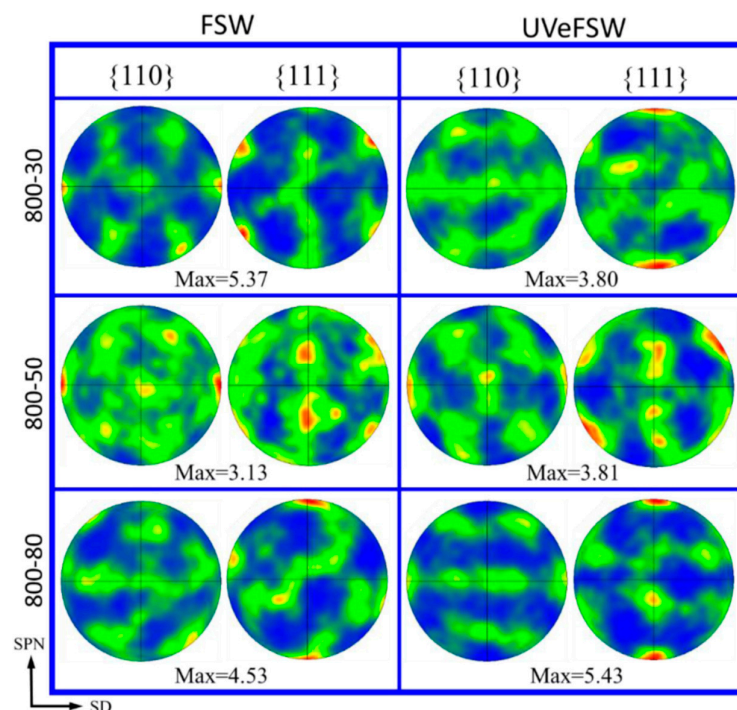
UaFSW emerged specifically to reduce the high reaction forces and severe tool wear that accompany conventional FSW when processing hard alloys. By superimposing high-frequency vibrations (typically ~20 kHz) on either the tool or the workpiece, the technique modifies the frictional and plastic flow behavior described in Section 1.4.1 in ways that cannot be achieved through parameter adjustment alone.

Fan et al. [101] identified the “acoustoplastic effect” which, by introducing ultrasonic energy during the welding process, reduces the static yield stress of the metal, allowing plastic deformation at substantially reduced applied loads. The mechanism operates at the level of the crystal lattice, with dislocations absorbing acoustic energy, facilitating their movement and multiplication, effectively softening the material without additional heat input. Both plunge and traverse welding forces are significantly lower than in standard FSW, which helps to extend tool life and makes it possible to weld much harder alloys. The magnitude of this force reduction is material- and parameter-dependent: Liu et al. [102] demonstrated that UAFSW of 7N01-T4 aluminum alloy reduced the axial force by 9% relative to conventional FSW while simultaneously permitting defect-free joints at traverse speeds 50% higher than the conventional process limit, a direct consequence of the acoustoplastic softening expanding the pin-driven flow zone. The benefit is amplified in harder, higher-melting-point materials where conventional FSW is most force-limited: in Al/Ti dissimilar joints between AA6061-T6 and Ti6Al4V, UaFSW eliminated tool wear and enhanced material flow at the interface, a combination that conventional FSW cannot

achieve on titanium without rapid tool degradation. Modeling of ultrasonic vibration-enhanced FSW further confirmed that superimposing ultrasonic vibration reduces both traverse force and tool torque, and that the percentage reduction in welding loads decreases as tool rotation speed increases, meaning that UaFSW provides the greatest force-reduction benefit precisely in the low-rotation-speed regime required for hard alloys, where thermal softening from frictional heat alone is insufficient.

Muhammad et al. [103] observed that in Al/Mg dissimilar joints welded with ultrasonic assistance, a more homogeneous mixing of the materials and a flattening of the thermal gradient in the weld zone are achieved, which causes the residual stress to decrease. Both numerical models and experimental measurements confirmed that ultrasonic vibrations reduced the peak longitudinal residual stress on the aluminum side by approximately 25% compared to conventional friction stir welding (FSW)—a reduction mainly driven by enhanced dynamic recrystallization, which actively alleviates internal lattice deformations.

Zhao et al. [104] analyzed the microstructural changes at the Al/Mg bonding interface and found that the ultrasonic field actively fragments continuous IMC layers. High-frequency vibrations cause cavitation and acoustic flow in the plasticized metal, breaking the fragile phases into discrete particles and eliminating continuous crack propagation paths that undermine the joint's ductility. As schematically illustrated in Figure 14, acoustic energy propagates through the sonotrode, generating transient cavitation bubbles in the semi-solid material. When these bubbles collapse, the resulting localized shock waves mechanically fracture the continuous layers of  $\text{Al}_{12}\text{Mg}_{17}$  and  $\text{Al}_3\text{Mg}_2$ , while the acoustic flow removes the fragments from the interface.



**Figure 14.** The {110} and {111} pole figures at location A3 (the WNZ in the Al side) under different weld speeds. SPN—Shear plane normal; SD—shear direction [104].

Wu et al. [105] applied a coupled thermomechanical model to investigate tunnel void suppression in UaFSW, a defect type whose formation mechanism is described in Section 1.4.2. Their results show that ultrasonic vibration locally increases both the strain rate and material velocity around the tool pin, ensuring the back cavity is completely filled even at

high welding speeds. Material flow velocity at the tool–workpiece interface increases in direct proportion to the ultrasonic amplitude, confirming that the acoustoplastic effect actively counteracts the advancing-side flow deficit responsible for void formation.

Qian et al. [106] investigated the impact of ultrasonic treatment (UIT) on 2219 aluminum alloy joints, observing that ultrasonic energy refines the grain structure of the agitated zone and redistributes hardening precipitates. This microstructural refinement reduces the electrochemical potential difference between grain boundaries and the grain interior, reducing susceptibility to intergranular corrosion. The treatment also induces a deep layer of compressive residual stress, which, combined with the dissolution of continuous precipitates at the grain boundaries, effectively seals potential corrosion channels.

Ambrosio et al. [107] explored the use of acoustic emission (AE) monitoring in FSW, demonstrating that in hybrid processes, the technique can characterize the real-time interaction between the tool and the workpiece, rather than simply detecting defects. Analysis of the acoustic signature, particularly the burst signals associated with friction and material detachment, provides immediate feedback on the stability of the acoustoplastic flow, allowing adaptive control of welding parameters and allowing operators to correct adverse conditions before they compromise the joint.

The UaFSW literature reviewed in this section collectively demonstrates that the acoustoplastic effect is a genuinely multi-functional tool: it simultaneously reduces processing forces (extending tool life), fragments continuous IMC layers (improving joint ductility in dissimilar systems), suppresses tunnel void formation (enabling higher traverse speeds), and reduces residual stress levels (improving fatigue performance). These benefits are mechanistically distinct and arise from different aspects of the acoustic field—dislocation mobility enhancement, cavitation-induced shock waves, and increased material flow velocity, respectively, which means that the optimal ultrasonic parameters for one objective may not be optimal for another. The most important unresolved question is how to calibrate ultrasonic amplitude and frequency simultaneously for multiple objectives in a production environment, and whether the real-time acoustic emission monitoring demonstrated by Ambrosio et al. [107] can be developed into a practical closed-loop control system that adjusts ultrasonic parameters in response to detected process changes.

### 3.3. Other Variants: Stationary Shoulder and Energy-Assisted FSW

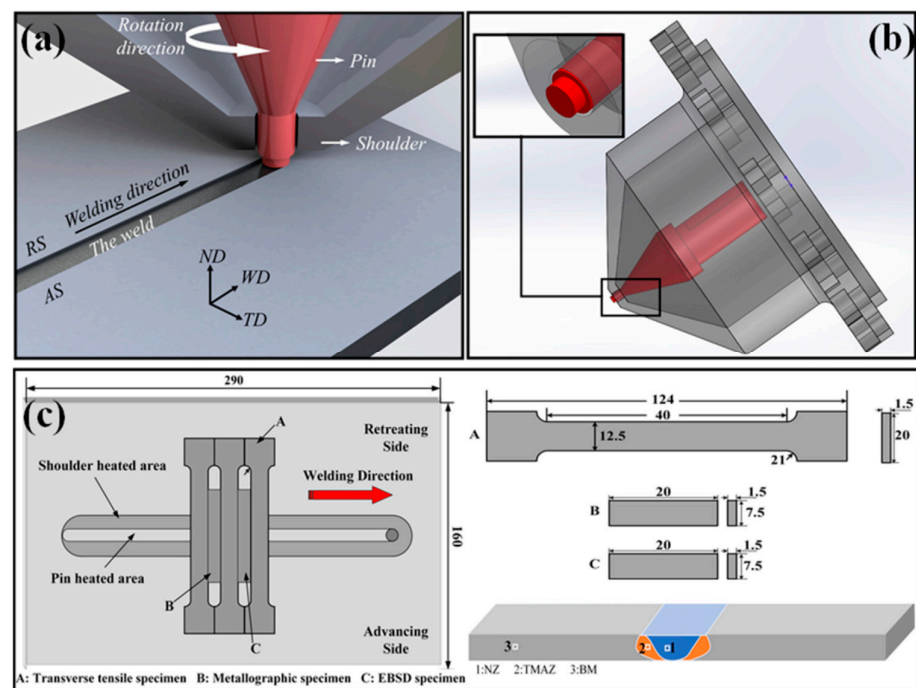
In addition to ultrasonic and underwater welding methods, the field of FSW now includes tool-specific and energy-assisted variants, tailored to address specific metallurgical constraints. Saha et al. [108] analyzed these externally energy-assisted methods, classifying them according to the source of additional heat: laser, induction, or electric arc. Their main argument is that, for high-melting-point materials, preheating the workpiece is essential to reduce the flow stress at the tool face, minimizing tool wear and preventing pin failure. These hybrid techniques effectively disconnect heat generation from the material flow, allowing independent control over the thermal cycle and the rate of plastic deformation.

#### 3.3.1. Stationary Shoulder Friction Stir Welding (SSFSW)

In the conventional FSW process, the rotating shoulder serves both as a heat source and as a forging element. These roles can be optimized independently through the stationary shoulder FSW (SSFSW) process. This process solves this problem by allowing the shoulder to slide over the workpiece while the internal pin rotates independently, transforming the shoulder from a heat source into a heat sink. Sundar et al. [109] used a static shoulder tool to join AA6061 aluminum, demonstrating that the reduced heat input

produces a narrower heat-affected zone (HAZ) and a finer crystallographic texture. EBSD analysis showed that the static shoulder creates a unique deformation path, dominated by simple shear texture components (B/B), significantly reducing the coarse-grained structure.

Sun et al. [110] applied SSFSW to 2A97 aluminum–lithium alloys, achieving a mirror-like, nearly burr-free surface finish. Microstructural characterization showed that the stationary shoulder prevents the coarsening of hardening precipitates near the surface, resulting in a more uniform distribution of hardness across the plate thickness. The surface layer develops a specific shear microstructure due to the sliding shoulder, while the center is dominated by pin-shear, creating a complex sandwich-type microstructure that improves damage tolerance and fatigue resistance. As schematically illustrated in Figure 15, the non-rotating shoulder slides smoothly over the joint line, applying forging pressure to keep the material plasticized, while the independently rotating pin generates heat through localized friction and mixing, creating a clear separation between mechanical forging and thermal agitation, which constitutes the fundamental principle behind the process's precision characteristics.



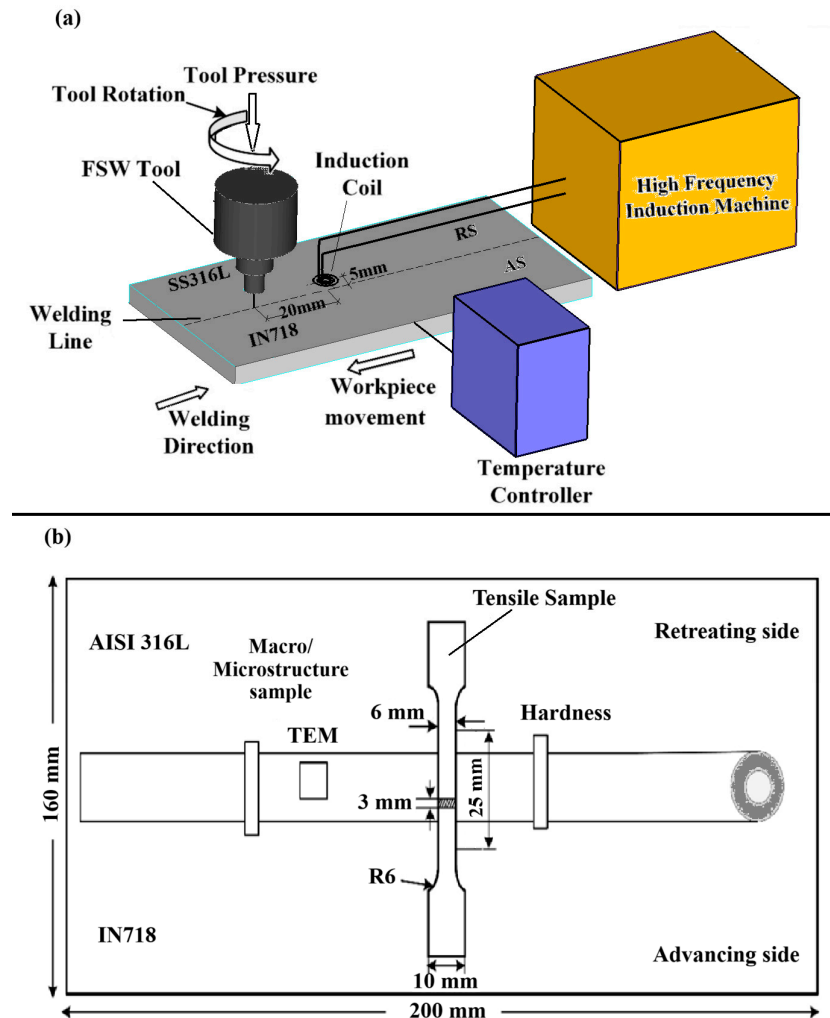
**Figure 15.** Schematic illustration of the (a) SSFSW process; (b) welding tool employed in the trials; (c) locations and dimensions of transverse specimen [110].

The SSFSW studies reviewed here confirm that separating the shoulder's thermal and forging functions, transforming it from a heat source into a heat sink while the pin continues to generate the necessary thermomechanical mixing, produces consistently superior surface quality and narrower HAZ widths compared to conventional FSW, particularly for heat-sensitive alloys such as Al–Li. The sandwich-type microstructure created by the combination of sliding-shoulder shear at the surface and pin-shear at the center also represents a genuinely novel structural feature whose implications for damage tolerance and fatigue crack propagation path have not yet been fully characterized. The primary limitation of the current SSFSW literature is the concentration on simple butt joint configurations.

### 3.3.2. Laser- and Induction-Assisted Hybrid Processes

For materials with high melting points, optical and electromagnetic energy sources are increasingly being integrated into the FSW process. Gong et al. [111] investigated a hybrid method that combines FSW with laser shock peening (LSP) on dissimilar joints made of titanium and aluminum alloys. Although the laser does not directly participate in the welding, post-weld laser peening introduces compressive residual stresses that effectively counteract stress corrosion cracking, the primary failure mode in dissimilar titanium–aluminum welds. High-energy laser pulses generate plasma shock waves that cause severe plastic deformation at the surface, neutralizing the harmful tensile stresses produced during the welding heat cycle, while simultaneously refining the surface grains into a nanostructured layer. This layer blocks the diffusion pathways required for the permeation of corrosive hydrogen, thereby inhibiting crack initiation.

Induction-assisted FSW is another important method for joining superalloys and steels. Raj et al. [112] evaluated the impact of induction preheating on dissimilar joints between Inconel 718 and SS316L, finding that the local increase in the base material's temperature prior to stirring allowed the material to flow properly, without the catastrophic tool degradation typically associated with cold joining of hard alloys. Electrochemical analysis showed that this thermal management strategy suppresses the precipitation of the harmful Laves phase in the nugget zone, providing corrosion resistance comparable to that of the base metal and a significant improvement over conventional processing. In a follow-up study, Raj et al. [113] analyzed the mechanical properties of these joints, noting that preheating encourages dynamic recrystallization, refining the grain structure and improving interfacial ductility. As illustrated schematically in Figure 16a, the induction coil is positioned just ahead of the rotating tool along the welding line, so that the Inconel and steel substrates are softened to a ductile state immediately before the tool engages, thereby reducing the yield stress and protecting the tool from severe abrasive wear.



**Figure 16.** Induction-assisted friction stir welding (I-FSW) of IN718/SS316L: (a) Schematic of the I-FSW process, showing the FSW tool, the induction coil positioned ahead of the tool, the high-frequency induction machine and the temperature controller; (b) layout for the extraction of the tensile, hardness, macro/microstructure and TEM specimens. Adapted from [113].

The laser- and induction-assisted hybrid processes reviewed in this section share a common operating principle—the external energy source raises the workpiece temperature before the FSW tool engages, effectively decoupling heat generation from material flow and enabling the processing of materials that would otherwise cause catastrophic tool degradation in cold-start conditions. Induction preheating has been most thoroughly validated for Inconel 718/SS316L joints, where it suppresses Laves phase formation and enables dynamic recrystallization that improves both corrosion resistance and ductility; laser shock peening has demonstrated particular value as a post-weld treatment for Ti-Al dissimilar joints, where it neutralizes surface tensile stresses that would otherwise promote hydrogen-assisted cracking. The key knowledge gap common to both approaches is the quantitative relationship between preheating temperature uniformity and the spatial distribution of IMC thickness and microstructural zone widths along the weld line, a relationship that is critical for establishing process tolerances in production environments but that has not yet been systematically characterized.

The hybrid process variants reviewed in Section 3 extend the achievable process envelope of FSW but simultaneously increase its complexity: each variant introduces

additional equipment, additional process variables, and additional optimization requirements that compound the already non-trivial parameter selection problem of conventional FSW. Managing this complexity in a systematic rather than empirical way requires the numerical modeling, machine learning, and statistical optimization tools reviewed in Section 4. The relationship between Sections 3 and 4 is therefore not merely sequential but functional: the process variants of Section 3 generate the experimental complexity that makes the digitalization approaches of Section 4 necessary, and the predictive models of Section 4 provide the parameter selection guidance that makes the hybrid variants of Section 3 practically deployable.

## 4. Digitalization and Industry 4.0 in FSW

Variations of the friction stir mixing process are also used in advanced surface engineering. Aliabadi et al. [114] demonstrated this by combining flame spraying with the friction stir mixing (FSP) process. After depositing a wear-resistant NiCrBSi layer, FSP was applied to consolidate the material, eliminating the porosity and lamellar defects that typically affect thermal spray-applied layers. The resulting coating was completely dense and metallurgically bonded to the substrate, which is clear evidence that friction-based mechanisms offer substantial industrial value, far exceeding that of conventional joining.

The integration of Industry 4.0 principles into the solid-state joining process represents a decisive shift from empirical, trial-and-error methodologies toward predictive digital frameworks. Within this paradigm, numerical modeling and simulation have become essential tools for deciphering the complex thermomechanical physics of the FSW process.

### 4.1. Numerical Modeling and Simulation (FEM/CFD)

The primary objective of numerical simulation in FSW is to predict temperature gradients, material flow trajectories, and potential defect formations without the associated costs of physical prototyping. Akbari et al. [115] observed that, while traditional Lagrangian methods work adequately for basic thermal analysis, arbitrary Lagrangian–Eulerian (ALE) and coupled Eulerian–Lagrangian (CEL) formulations are much better equipped to handle the extreme mesh distortion caused by severe plastic deformation.

#### 4.1.1. Heat Generation and Thermomechanical Behavior

Accurate prediction of heat generation is the foundation of any FSW simulation. Using a CEL-based finite element method, Salih et al. [116] analyzed heat generation and plastic flow in aluminum alloys, finding that maximum temperatures are localized directly under the shoulder of the tool. Their models also revealed that the residual stress profile is highly asymmetric and depends largely on clamping constraints and cooling rates. The maximum longitudinal residual stress peaks at the weld centerline and is approximately 40–50% of the material's yield strength.

Capturing the exact mechanisms of defect formation requires more sophisticated multiphysical approaches. Shi et al. [117] introduced a thermal–fluid–structural coupling model to study the generation of voids, treating the plasticized metal as a non-Newtonian fluid while simultaneously calculating the structural response of the tool. Their approach accurately predicted the occurrence of tunnel-type defects, directly correlating them with the inadequate vertical flow of material on the feed side. Their simulation reproduced the morphology and position of a “wormhole” defect: at high feed rates, the material flow is simply too slow to fill the cavity behind the pin, producing a volumetric void that aligns precisely with the metallographic results.

By implementing a spatially variable friction model, in which the friction coefficient dynamically adapts to local temperatures and slip rates, Yang et al. [118] demonstrated that static friction predominates in the hot center of the shoulder, while sliding friction occurs at the cooler outer edges. This is a distinction that standard Coulomb friction models systematically ignore, and its omission introduces significant errors in torque predictions.

Ji et al. [119] observed that specific geometric features of the tool contribute differently to the overall heat generation. They isolated the effects of the shoulder and the pin in their numerical models, finding that while the shoulder accounts for up to 80% of the total heat input, the characteristics of the pin—threads, flat surfaces, and similar surface features—determine the vertical mixing necessary to prevent root defects. Based on this, Akbari et al. [120] quantified the deformation generated by the individual components of the tool, finding that the strain rate reaches maximum values at the tip of the pin, a detail with direct implications for the design of tools intended for difficult-to-weld alloys.

The accuracy of FSW simulations also depends on the choice of friction law. Liu and Sun [121] argued that internal viscous dissipation plays a major role in heat generation, proposing a vortex-FSW simulation based on internal friction rather than solely on surface interactions. To further refine the boundary conditions, Liu et al. [122] developed an FEM model in which they accounted for the temperature-dependent friction coefficient. By dynamically adjusting friction in response to localized thermal changes, their method achieved significantly closer correspondence between simulated and experimental thermal cycles than models with constant friction.

The heat generation modeling studies reviewed in this subsection collectively identify the temperature-dependent friction coefficient as the single most important boundary condition improvement available to FSW simulation practitioners. Models that account for the transition from sticking to sliding friction across the shoulder contact zone, and that allow the friction coefficient to evolve with local temperature and slip rate, reproduce experimental torque and peak temperature measurements with substantially higher fidelity than constant-friction alternatives, without requiring significantly greater computational cost. The outstanding limitation is that all current friction models are calibrated on specific alloy-machine combinations and do not transfer reliably across platforms; developing physics-based friction constitutive laws that can be parameterized from material properties alone, rather than fitted to experimental data from a specific welding machine, would represent a major step toward truly predictive FSW simulation.

#### 4.1.2. Material Flow and Defect Prediction Using CEL

The coupled Eulerian-Lagrangian method has become the preferred approach for modeling extreme deformations in FSW, as highlighted by Laska et al. [123], who applied CEL to evaluate how tool geometry influences temperature and material flow in AA6082 aluminum, successfully visualizing the formation of “onion rings” and confirming that the periodicity of material deposition is directly controlled by the tool shape. Akbari et al. [124] mapped the strain and temperature distributions during FSW of AA5083 and AA7075, their CEL model correctly predicting that although higher rotational speeds expand the volume of the agitation zone, they also trigger excessive temperature if the plunge depth is not carefully calibrated. Defect prevention is ultimately the main goal of these simulations. Choudhary and Jain [125] used CEL to track undercut tunnel defects, confirming that they arise from a fundamental imbalance between the material pushed outward by the pin and the holding pressure exerted by the shoulder. Turkan and Karakas [126] reinforced this conclusion by showing that numerical models can identify the exact

combinations of feed and rotation speeds that produce voids, defining a safe process zone in a virtual environment.

The CEL-based defect prediction studies reviewed in this subsection represent the current frontier of FSW process simulation: by treating the workpiece material as a fully Eulerian continuum capable of arbitrary deformation, these models can faithfully reproduce the formation, morphology, and location of tunnel voids and wormhole defects that would be missed by Lagrangian or ALE formulations. The practical value of this capability is significant; the ability to define safe process zones in a virtual environment before committing to physical trials is precisely the kind of digital twin functionality that Industry 4.0 manufacturing requires. The primary constraint on the wider adoption of CEL models is computational cost: a high-fidelity defect-prediction simulation of a single welding pass currently requires hours to days of computing time on high-end hardware, making real-time process control infeasible. The development of surrogate models trained on CEL simulation libraries, essentially ML models that approximate the CEL solution at a fraction of the computational cost, is the most promising path toward bridging this gap.

#### 4.1.3. Crystal Plasticity Finite Element Modeling

Crystal plasticity finite element (CPFE) modeling represents a qualitatively different level of simulation fidelity from the continuum FEM and CFD approaches reviewed in Sections 4.1.1 and 4.1.2. Rather than treating the workpiece material as a homogeneous continuum with averaged constitutive properties, CPFE models resolve the deformation response at the level of individual grains, accounting for the orientation-dependent slip system activity that governs plastic flow in crystalline metals. In the FSW context, CPFE modeling is most valuable for predicting the crystallographic texture evolution in the stir zone—specifically, the development of the A, A-bar, A1\*, A2\*, B, and B-bar shear texture components that govern the anisotropic mechanical response of the weld discussed in Section 5.1.3—and for connecting process kinematics to the grain-scale deformation mechanisms that control both microstructural refinement and the fatigue crack propagation paths discussed in Section 5.1.5.

CPFE models of FSW are computationally intensive because the stir zone encompasses thousands of grains, each requiring the simultaneous solution of slip system shear rates on twelve or more slip systems at each integration point. The practical approach is therefore to apply CPFE on representative volume elements extracted from positions within the weld cross-section where the strain, strain rate, and temperature history have been established by a prior continuum FEM or CEL simulation: the continuum model provides the thermomechanical loading path, and the CPFE model predicts the resulting texture and grain-scale stress-strain distribution. Applied in this two-step manner, CPFE has been used to predict the specific shear texture components observed in AA7075-T6 stir zones and to connect them to the fracture path anisotropy documented by Kesharwani et al. [127], providing a mechanistic explanation for the crystallographic weakness planes that determine macroscopic failure location. For dissimilar joints, CPFE models of the aluminum stir zone can also quantify the heterogeneous strain partitioning between differently oriented grains at the IMC-metal interface, providing a grain-scale interpretation of the fracture toughness threshold behavior described in Section 2.6.4.

The primary limitation of CPFE in the FSW context is the requirement for experimentally validated single-crystal constitutive parameters—slip system hardening rates, latent hardening ratios, and initial critical resolved shear stresses—which must be determined for each alloy and temper condition and are not universally available in the literature. For commercially important alloy systems such as AA7075 and AA2024, these parameters have been established and CPFE texture predictions are reliable; for the high-

entropy and specialty alloys reviewed in Section 2.5, CPFE parameter sets are still being developed, limiting the applicability of the approach to the material systems where it would be most novel.

#### 4.1.4. Phase-Field Modeling and AI-Assisted Simulation

Phase-field modeling offers a continuum-scale alternative to the purely empirical IMC thickness measurements that currently dominate the characterization of dissimilar FSW interfaces. The phase-field method represents the spatial distribution of phases, aluminum matrix, intermetallic layer, and steel or magnesium substrate, through a continuous order parameter field that evolves according to a free energy functional incorporating both bulk thermodynamic driving forces and interfacial energy contributions. Unlike sharp-interface models that must explicitly track the IMC–metal boundary, phase-field models resolve the diffuse transition zone between phases naturally, making them well-suited to the complex multi-phase morphologies that develop at FSW interfaces where several IMC species co-exist across layer thicknesses of the order of micrometers. In the Al-Fe system, phase-field models parameterized with the CALPHAD thermodynamic database can predict the preferential nucleation of  $\text{Fe}_2\text{Al}_5$  over  $\text{FeAl}_3$  under FSW thermal conditions, consistent with the thermodynamic argument of Section 2.6.1, and simulate the morphological evolution of the IMC layer during non-isothermal thermal cycling, capturing the acceleration of growth near the temperature peak that the analytical integral of Section 2.6.3 approximates but cannot fully resolve for complex multi-phase systems. Phase-field modeling is therefore most valuable as a predictive tool for new material combinations where experimental IMC characterization data are limited, and as a means of validating the simplifying assumptions embedded in the analytical parabolic growth model.

The integration of artificial intelligence with FSW simulation, AI-assisted simulation, addresses the primary practical limitation of high-fidelity models: computational cost. A full CEL simulation of a single FSW pass requires hours to days on high-end hardware; a CPFE texture evolution calculation on a representative volume element requires similar resources. Neither is compatible with the real-time or near-real-time process optimization that Industry 4.0 manufacturing requires. Two AI architectures are particularly relevant to this challenge. Physics-informed neural networks (PINNs) embed the governing partial differential equations of heat conduction and plastic flow as constraints in the network training process, producing models that satisfy physical conservation laws by construction rather than by data fitting alone. Because they are constrained by physics rather than relying entirely on data, PINNs can generalize more reliably to process conditions outside the training distribution than purely data-driven neural networks, a critical advantage in FSW where experimental datasets are small. Surrogate models trained on libraries of high-fidelity CEL or CPFE simulations represent the second approach: a neural network or Gaussian process regression model is trained to map process inputs (rotation speed, traverse speed, axial force, tool geometry) directly to outputs of interest (peak temperature, IMC thickness, stir zone texture index) at a fraction of the computational cost of the underlying simulation. Once trained, these surrogate models can be queried thousands of times per second, enabling their integration into real-time adaptive control loops or multi-objective optimization algorithms of the type reviewed in Section 4.3. The development and experimental validation of PINN and surrogate model frameworks for the principal FSW material systems, particularly dissimilar Al–steel, Al–Mg, and Al–Cu joints where high-fidelity simulation data are most scarce, is identified as one of the highest-priority computational research directions in the field.

## 4.2. Machine Learning and Artificial Intelligence

Machine learning and artificial intelligence handle nonlinear process complexity in ways that traditional analytical models simply cannot match.

### 4.2.1. Overview and Real-Time Defect Detection

In a critical review of machine learning applications in FSW, Elsheikh [128] organized current efforts into three main areas: joint property prediction, real-time process control, and tool failure diagnosis. The review makes an important observation: while conventional finite element models are computationally expensive, trained machine learning algorithms can provide near-instantaneous predictions. One of the most significant practical demonstrations of this capability comes from Guan et al. [129], who developed a machine learning framework driven by force data to identify internal flaws such as tunnels and voids. By training their algorithms on dynamic fluctuations in axial and transverse forces, they achieved high classification accuracy, showing that force signals carry a characteristic fingerprint corresponding to specific defect states.

The machine learning defect detection studies reviewed in this subsection demonstrate an important principle: force signals contain richer information about the internal state of the FSW process than simple visual inspection or post-weld metallography, and that information can be decoded by appropriately trained classifiers with high accuracy. The work by Guan et al. [129] is particularly significant because it demonstrates that the transition from a defect-free to a defect-generating condition produces a detectable signature in the force data before the defect is fully formed, suggesting that closed-loop defect prevention, rather than just defect detection, may be achievable. The key unresolved question is model generalizability: force signatures for tunnel void formation in AA2024 may not be the same as those in AA6082 or in a steel–aluminum dissimilar joint, and the extent to which defect classifiers trained on one alloy system can be transferred to another without retraining has not been systematically investigated.

### 4.2.2. Predictive Modeling of Mechanical Properties

The largest body of ML work in the FSW field focuses on predicting ultimate tensile strength and related mechanical properties. Anandan and Manikandan [130] applied various regression models to predict ultimate tensile strength (UTS) in AA2050-T8 joints, using K-Fold cross-validation to ensure robustness. Their approach demonstrated that data-driven methods can reliably relate rotation and traverse speeds to ultimate joint strength, effectively acting as a virtual testing laboratory. In a subsequent study, Anandan and Manikandan [131] adapted this methodology to predict peak temperatures in joints between AA7050 and AA2014A. Their methodology is valuable from a practical point of view because temperature directly governs the dissolution of hardening precipitates, and their model eliminated the need for embedded thermocouples. Verma et al. [132] extended machine learning modeling to aircraft-grade alloys, mapping the complex relationships between tool rake angle and the resulting microhardness profile in high-strength aluminum systems.

The mechanical property prediction studies reviewed in this subsection collectively establish that data-driven regression models can reliably map rotation speed, traverse speed, and selected tool parameters to UTS and peak temperature in aluminum FSW joints, provided that the training dataset is sufficiently representative of the target parameter space and that appropriate cross-validation strategies are applied to guard against overfitting. The practical utility of these models, eliminating the need for extensive physical trial matrices to characterize a new alloy–parameter combination, is directly proportional to the diversity of the training data. The most important limitation currently

constraining this field is the small size of typical FSW experimental datasets (30–200 runs), which is a natural consequence of the cost and time associated with each physical weld trial. Strategies for data augmentation, including transfer learning from related alloy systems and the use of high-fidelity simulation data to supplement experimental observations, deserve greater attention as a path toward more generalizable models.

#### 4.2.3. Comparison of Algorithms and Advanced Architectures

Research has progressively moved beyond simple regression and toward more systematic comparisons of algorithm architectures. Mysliwiec et al. [133] evaluated Random Forest, XGBoost, and Multilayer Perceptron neural networks for optimizing welding of AA2024-T3 aluminum, finding that ensemble methods such as XGBoost frequently outperform individual neural networks when processing noisy experimental data typical of real welding trials. Neural networks are particularly effective when optimizing for multiple simultaneous objectives. Nejad et al. [134] designed an artificial neural network to evaluate fatigue life in AA2024-T351 joints, combining it with multi-objective optimization algorithms to identify process parameters that maximize fatigue life while minimizing residual stresses.

The algorithm comparison studies reviewed in this subsection consistently find that ensemble methods, particularly XGBoost and Random Forest, outperform individual neural networks when applied to the small, noisy experimental datasets typical of FSW research. This finding is consistent with the broader ML literature and reflects the fact that ensemble methods are more robust to overfitting in low-sample-size regimes. The more important trend identified in this subsection, however, is the shift from single-output optimization toward multi-objective optimization frameworks that simultaneously maximize strength while minimizing residual stress, grain size, or tool wear, an approach that much more closely mirrors the actual engineering design problem. The outstanding challenge is the development of standardized multi-objective benchmark problems for FSW optimization that would allow rigorous comparison of different algorithmic approaches across the same experimental basis.

#### 4.2.4. Deep Learning and Ensemble Methods

Rabe et al. [135] applied deep learning to force feedback signals to detect void defects. Unlike conventional machine learning approaches, which require manual feature extraction, their model automatically learned the hierarchical features embedded in the force signal, which is a more robust solution for quality assurance. To improve the prediction accuracy in asymmetric welding configurations, Matitopanum et al. [136] used ensemble methods, superimposing multiple weak predictive models into a single strong learning model and substantially improving UTS predictions for complex joint geometries. The result emphasizes the principle that managing the inherent stochasticity of FSW requires algorithmic architectures that are sophisticated enough to capture it.

The deep learning and ensemble studies reviewed in this subsection mark an important transition in FSW machine learning research: from models that require expert feature extraction from raw signals to architectures that learn their own feature representations directly from force, torque, and acoustic emission time-series data. This transition has practical consequences, because manual feature engineering requires domain expertise that may not always be available in production environments, while end-to-end deep learning models can in principle be trained and deployed by engineers without specialized signal processing knowledge. The primary limitation of the deep learning approach in the FSW context is the requirement for large labeled training datasets, which are expensive to generate. Hybrid approaches that combine physics-based feature extraction with deep learning classifiers, using Section 1.4's thermomechanical

framework to guide feature selection, represent a promising direction for maximizing model performance at minimal experimental cost.

#### 4.2.5. Algorithm Architectures, Dataset Characteristics, and Performance Metrics

Across the ML studies reviewed in Sections 4.2.1–4.2.4, five distinct algorithmic categories are employed: feedforward artificial neural networks (ANNs), ensemble methods (Random Forest and XGBoost), convolutional neural networks (CNNs) applied to force and torque time-series, Gaussian process regression (GPR), and deep learning architectures with automatic feature extraction. Each category has a characteristic strength and limitation in the FSW context that is not always made explicit in individual studies but becomes apparent when the literature is surveyed as a whole.

Feedforward ANNs remain the most common architecture in the FSW ML literature, reflecting their historical precedence and the availability of accessible implementations. Their primary limitation is sensitivity to overfitting in the small-dataset regime that characterizes most FSW experimental programs. The typical FSW ML study draws on between 30 and 120 experimental weld trials, a number constrained by the cost and time of physical welding experiments. At this sample size, a fully connected ANN with more than two hidden layers is at serious risk of learning noise rather than generalizable process physics, and only a subset of the reviewed studies applies rigorous cross-validation strategies—such as K-Fold or leave-one-out—to verify that reported accuracy metrics generalize beyond the training data. Ensemble methods, particularly XGBoost, consistently outperform individual ANNs on FSW datasets of this size, a result consistent with the general machine learning literature showing that ensemble methods are more robust in the low-sample-size regime because they combine the predictions of multiple weak learners in a way that averages out individual model biases.

CNNs and deep learning architectures occupy a different niche: rather than predicting joint properties from tabulated process parameters, they operate directly on raw time-series data, spindle force, torque, and acoustic emission, and learn their own feature representations without manual signal processing. Guan et al. [129] and Rabe et al. [135] both demonstrate that force signal classifiers can achieve defect detection accuracies above 90%, but their models are trained and validated on single-alloy, single-machine datasets. The transferability of force-signal fingerprints across alloy systems and welding platforms has not been systematically investigated, and this is a significant practical limitation: a classifier trained to recognize tunnel void signatures in AA2024 may not correctly identify the same defect in AA7075 or in a steel–aluminum dissimilar joint, because the force response to material flow deficit depends on the material's flow stress, which varies substantially between alloy systems.

Table 4 summarizes the key ML studies reviewed in Section 4.2, including the algorithm type, target output, dataset size, reported accuracy metric, and the primary limitation identified. The table reveals two structural patterns that are not visible from any single study. First, prediction accuracy ( $R^2$  or classification rate) is consistently high, typically above 0.93 for regression tasks and above 90% for classification, but is almost always reported on training or cross-validation splits from the same alloy system used for training, not on independent alloy combinations. Second, dataset sizes are uniformly small (30–120 runs), meaning that the reported accuracy values represent performance within the experimental space, not generalization beyond it. Gaussian process regression, which explicitly models prediction uncertainty and is therefore better suited to small datasets than deep neural networks, has received comparatively little attention in FSW and represents an underexplored alternative with potentially higher practical value in low-data regimes.

An important practical distinction that the literature does not always make explicit is the difference between offline-trained models, applied post-process to predict or

diagnose joint quality from historical data, and online or real-time models embedded in a closed-loop control system that adjusts process parameters during welding. The vast majority of published FSW ML models are offline: they are trained on historical experimental datasets and used to predict properties or classify defect states after the fact. Real-time adaptive control requires models with inference times compatible with control cycle frequencies (typically 10–100 Hz for FSW force control), which rules out computationally expensive deep architectures in their standard form. Lightweight surrogate models, polynomial response surfaces, Gaussian processes, or compressed neural networks, trained on high-fidelity simulation or experimental data, represent the most promising path toward real-time deployment, and this distinction should be explicit in any future assessment of ML applicability in FSW process control.

**Table 4.** Summary of machine learning studies in FSW reviewed in Section 4.2: Algorithm type, target output, dataset size, reported accuracy, and primary limitation.

| Reference                  | ML Algorithm(s)             | Predicted Output                   | Dataset Size | Model Performance                                        | Limitations/Notes                                          |
|----------------------------|-----------------------------|------------------------------------|--------------|----------------------------------------------------------|------------------------------------------------------------|
| Anandan & Manikandan [131] | Random Forest, SVR, ANN     | UTS (AA2050-T8)                    | ~60 runs     | R <sup>2</sup> up to 0.97 (RF)                           | Single alloy; no cross-alloy validation                    |
| Anandan & Manikandan [131] | Multiple regression models  | Peak temperature (AA7050/AA2014A)  | ~50 runs     | R <sup>2</sup> > 0.95                                    | Temperature only; no microstructure output                 |
| Verma et al. [132]         | ANN                         | Microhardness profile              | ~45 runs     | RMSE < 5 HV                                              | Rake angle range narrow; limited to 2xxx/7xxx              |
| Mysliwiec et al. [133]     | RF, XGBoost, MLP            | UTS (AA2024-T3)                    | ~80 runs     | XGBoost R <sup>2</sup> = 0.96; MLP R <sup>2</sup> = 0.91 | Noisy data; RF/XGBoost superior for small N                |
| Nejad et al. [134]         | ANN + NSGA-II               | Fatigue life, residual stress      | ~70 runs     | MAPE < 6%                                                | Multi-objective; Pareto front not validated experimentally |
| Guan et al. [129]          | SVM/force-signal classifier | Defect state (tunnel, void, sound) | ~200 samples | Classification accuracy > 90%                            | Single alloy; offline trained; transfer not tested         |
| Rabe et al. [135]          | CNN (deep learning)         | Void defect detection              | ~150 samples | >92% detection rate                                      | End-to-end; no manual features; dataset small              |
| Matitopanum et al. [136]   | Ensemble (stacking)         | UTS (asymmetric joints)            | ~90 runs     | R <sup>2</sup> = 0.94 (stacked)                          | Asymmetric geometry; limited to one alloy pair             |

#### 4.3. Statistical Optimization Techniques

Statistical optimization methods remain fundamental to experimental design in FSW. They provide the framework that links input parameters, such as rotation speed, traverse speed, and tool tilt, to measurable outputs, such as tensile strength, microhardness, and grain size, allowing researchers to determine optimal process parameters without exhaustive physical testing.

##### 4.3.1. Overview of Optimization Strategies

Prabhakar et al. [137] reviewed measurement and optimization strategies in FSW, arguing that the stochastic nature of material flow requires robust statistical frameworks to contain experimental variance. The traditional trial-and-error approach is too inefficient for industrial-scale reliability, making structured design of experiments essential. Asadi et al. [138] reinforced this with a multivariate study that simultaneously optimized mechanical and microstructural properties, demonstrating that targeting a single

objective, such as tensile strength, for example, often comes at the expense of corrosion resistance or ductility, making multi-objective formulations a practical necessity.

The statistical optimization overview studies reviewed in this subsection establish a foundational principle that is frequently underappreciated in individual experimental FSW papers: single-response optimization—maximizing tensile strength alone, for example—routinely produces process conditions that are suboptimal or actively detrimental for other performance dimensions such as ductility, corrosion resistance, or tool wear. This observation motivates the multi-objective and multi-response optimization approaches discussed in subsequent subsections and underscores the importance of defining the full vector of performance requirements before selecting a process window. The key limitation of the statistical optimization literature is its almost exclusive focus on laboratory-scale FSW with purpose-built fixtures and well-controlled thermal boundary conditions; the extent to which optimized parameter sets remain robust when transferred to industrial-scale welding systems, where machine compliance, fixturing variability, and thermal history of the workpiece all introduce sources of variability that the statistical models do not account for, is a critical gap.

#### 4.3.2. Response Surface Methodology

Akbari and Asiabaraki [139] combined RSM with the Nondominated Sorting Genetic Algorithm (NSGA-II) to optimize tool parameters for aluminum lap joints, navigating the objectives of maximizing joint strength while minimizing sheet thinning and burr formation. For dissimilar joints, where process interactions are more complex, RSM proved equally valuable. Jain et al. [140] developed a second-order regression model for AA6061/AA7075 composite joints that accurately captured the interaction between rotation speed and tool rake angle. Haribalaji et al. [141] applied RSM to dissimilar AA2014 and AA7075 joints, identifying rotation speed as the dominant factor governing metal mixing. Extending this to microstructural management, Ramamurthy et al. [142] used RSM to directly link process parameters to grain size and microhardness in AA2014/AA6063 welds, while Akbari et al. [143] applied the methodology to optimize friction stir machining of piston alloys for maximum wear resistance.

The RSM studies reviewed in this subsection demonstrate that second-order response surface models can capture the interaction effects between rotation speed, traverse speed, and tool geometry parameters with sufficient fidelity for practical process optimization across a wide range of aluminum alloy combinations. The consistent finding, that rotation speed is the dominant factor in most FSW RSM studies, but that its optimal value is strictly material dependent and cannot be transferred from one alloy to another without reoptimization, is both a practically important caution and an indication of the current limitation of empirical modeling: the models accurately describe what happens in a specific experimental space but do not reveal the physical mechanisms responsible for the observed trends. The integration of RSM with physics-based surrogate models, using the thermomechanical framework of Section 1.4 to constrain the response surface rather than fitting it purely empirically, is an underexplored direction that could produce more transferable optimization results.

#### 4.3.3. Taguchi Method and Gray Relational Analysis (GRA)

The Taguchi approach remains highly regarded for its effectiveness in reducing experimental volume through signal-to-noise analysis. Boukraa et al. [144] extended this method by coupling Taguchi models with gray relational analysis, translating competing performance indicators, such as elongation and tensile strength, into a unified gray relational degree that simplifies the optimization of complex joint characteristics. Researchers have increasingly coupled these statistical foundations with meta-heuristic

algorithms. Kahhal et al. [145] combined RSM with Particle Swarm Optimization (PSO) to identify parameter combinations that maximize the strain rate while keeping peak temperatures low, with PSO converging to the global optimum noticeably faster than conventional gradient descent. Karumuri et al. [146] confirmed the value of Taguchi-based GRA for different aluminum welds, demonstrating its ability to handle highly nonlinear relationships between tool geometry and traverse speed.

The Taguchi-GRA studies reviewed in this subsection demonstrate a pragmatic approach to multi-objective FSW optimization that has proven particularly productive for dissimilar aluminum joints, where the number of process variables and their interaction complexity would make full factorial experimentation prohibitively expensive. The translation of competing performance indicators into a unified Gray relational degree, while inevitably introducing some information loss through the aggregation step, provides a tractable single-metric optimization framework that industrial practitioners can implement without advanced statistical training. The primary limitation is the sensitivity of the Gray relational degree to the weighting scheme applied to individual performance indicators, which is typically specified by the experimenter rather than derived from the data; this introduces a subjective element that can lead to different optimal process windows depending on how the performance objectives are weighted, making it difficult to compare results across studies that use different weighting strategies.

#### 4.3.4. Validation of High-Strength and Marine Alloys

Kumar et al. [147] applied RSM to maximize the strength of FSW welded joints for AA6082 and AA7050, while Mehdi et al. [148] adopted a multiple-response RSM strategy for welding different AA2014/AA6061 materials. A consistent conclusion of both studies is that the optimal processing parameters are strictly material-dependent. Thus, the 7xxx series alloys require distinctly lower heat inputs than their 6xxx counterparts to avoid dissolution of critical strengthening precipitates. The design of the statistical matrix itself also matters. Abd Elnabi et al. [149] tested various Taguchi orthogonal matrices during welding of different Al alloys, finding that the chosen matrix strongly influences the statistical reliability of the result. Ahmed et al. [150] took this work towards direct industrial applications, adapting FSW parameters for marine-grade AA5451 and establishing a precise operational envelope that satisfies stringent marine certification requirements.

The high-strength and marine alloy optimization studies reviewed in this subsection are notable for demonstrating that statistical optimization frameworks can be extended beyond laboratory-grade alloys to materials with direct industrial certification requirements, including marine-grade AA5451. The consistent finding that 7xxx series alloys require lower heat inputs than 6xxx counterparts to preserve critical strengthening precipitates is a practically important design rule, but it also highlights the current limitation of purely empirical optimization: the RSM models identify the optimal parameter window for a given alloy without revealing why a lower heat input is superior, which means that the model cannot be used to predict whether the same parameter window would remain optimal if the alloy temper, sheet thickness, or joint geometry were changed. Closing this gap, connecting the statistical process window to the underlying precipitate dissolution kinetics described in Section 1.4.3, would produce optimization strategies that are genuinely transferable across alloy variants rather than valid only for the specific combinations used to build the model.

The numerical models, machine learning frameworks, and statistical optimization techniques reviewed in Section 4 share a common objective: predicting the outcome of an FSW process before it is executed, or diagnosing a deviation in real time as it occurs. What they predict, however, are macroscopic process outputs. The ultimate measure of joint

quality is microstructural: whether the grain structure, precipitate distribution, IMC layer morphology, and defect population produced by a given process history are compatible with the mechanical and durability requirements of the application. Section 5 examines these microstructural outcomes directly, providing the experimental and analytical framework that connects the process variables of Sections 1 through 4 to the structural performance that determines whether a joint is fit for service.

## 5. Microstructural Challenges and Defect Characterization

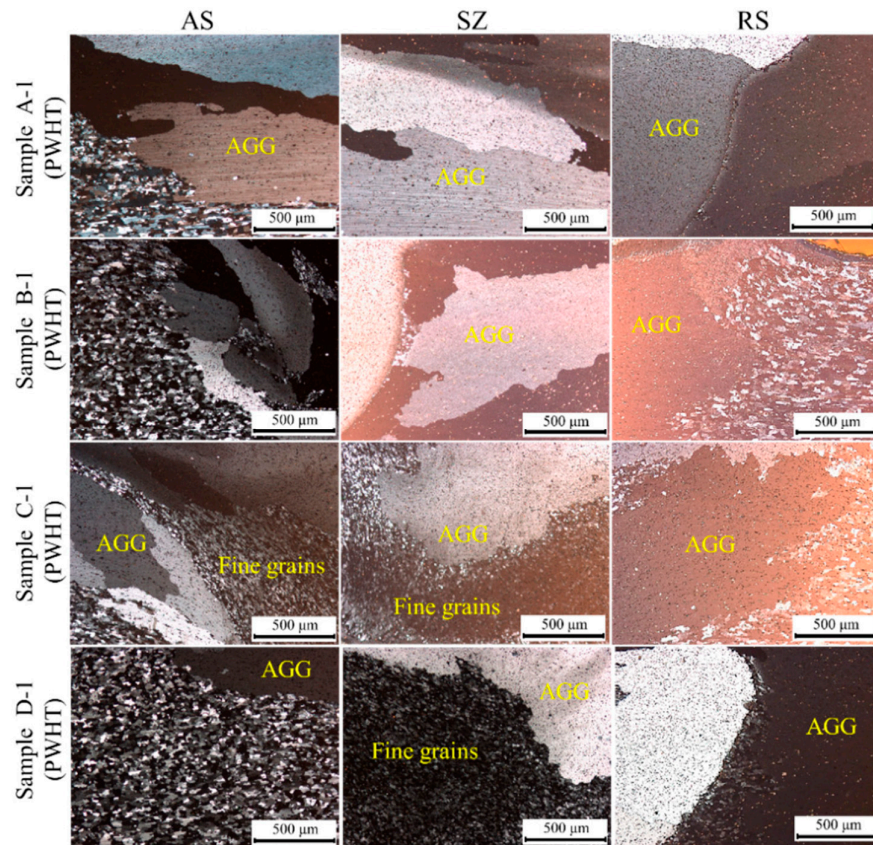
The mechanical reliability of an FSW joint ultimately depends on the microstructural changes induced by severe thermomechanical cycling. Since FSW operates entirely in the solid state, the integrity of the joint is not governed by solidification mechanics, but by dynamic recrystallization and the dissolution and reprecipitation of the strengthening phases, processes that are sensitive to small variations in thermal history and much less permissive than it might initially appear.

### 5.1. Microstructural Evolution

#### 5.1.1. Dynamic Recrystallization and Grain Growth

Intense plastic deformation in the stir zone typically produces a refined, equiaxial granular structure through continuous dynamic recrystallization. This refined state is, however, thermodynamically unstable. Kalinenko et al. [151] found in AA6061-T6 that abnormal grain growth frequently occurs during post-weld cooling or subsequent heat treatments. As the precipitates that normally fix the grain boundaries dissolve, these boundaries migrate rapidly, leaving behind a heterogeneous microstructure that can severely compromise ductility.

Figure 17 from Baghdadi et al. [152] illustrates the extent of this transformation in post-weld heat-treated joints, along the advancing side, the agitation zone, and the retreating side. The micrographs show a significant change after heat treatment, with the initially fine grains in the agitation zone undergoing massive abnormal expansion, swelling to hundreds of micrometers or even millimeters and effectively swallowing the adjacent thermomechanically affected areas. The result is an illustration of the fragile thermodynamic equilibrium between the driving forces of migration at grain boundaries and the retarding effect of second-phase particle dissolution.



**Figure 17.** AGG occurs in the microstructure of PWHTed Al5083-l6061 (T6) at a constant travel speed of 100 mm/min [152].

Rajendran et al. [153] addressed the fatigue implications of this microstructural discontinuity in AA2024-T6, finding that an optimized post-weld heat treatment can homogenize the precipitate distribution and delay crack initiation even when coarse grains are present.

The studies on dynamic recrystallization and grain growth reviewed in this subsection establish a practically important but often overlooked principle: the refined, equiaxed grain structure produced in the stir zone by continuous dynamic recrystallization is thermodynamically metastable, and this metastability can be triggered by any subsequent thermal event, including post-weld heat treatment, elevated-temperature service, or even the residual heat from adjacent weld passes in multi-pass configurations. The driving force for abnormal grain growth is the dissolution of the precipitate population that normally pins grain boundaries, and the kinetics of this process are highly sensitive to the specific thermal history of each zone within the weld cross-section. The most important unresolved question is whether the optimized post-weld heat treatment strategies demonstrated for specific alloy combinations, such as the precipitate homogenization treatment for AA2024-T6, can be systematically predicted from the precipitate dissolution and re-precipitation kinetics of Section 1.4.3, or whether each alloy and process combination requires independent empirical determination of the post-weld heat treatment window.

### 5.1.2. Precipitation Behavior and Corrosion Susceptibility

The thermal cycling imposed during FSW fundamentally alters the precipitation state of heat-treatable aluminum alloys, causing dissolution in the stir zone and coarsening of precipitate grains in the stir zone. Non-heat-treatable alloys face a different

problem, called thermal sensitization. Ning et al. [154] characterized the precipitation of the anodic  $\beta$  phase ( $\text{Al}_3\text{Mg}_2$ ) along grain boundaries in AA5083, noting that FSW parameters directly control the phase continuity. A network connected at grain boundaries leaves the alloy extremely vulnerable to intergranular corrosion.

In the case of high-strength 7xxx alloys, Guo et al. [155] showed that retrogression and re-aging treatments can disrupt the connectivity of grain-bound precipitates in Al-Zn-Mg-Cu joints, improving the stress corrosion cracking resistance without compromising the tensile strength. In dissimilar joints, galvanic coupling becomes the dominant corrosion mechanism; thus, Lu et al. [156] studied the corrosion behavior in dissimilar aluminum joints, finding that the sharp microstructural gradient at the interface establishes a localized galvanic cell that promotes preferential corrosion in the affected surface area of the more anodic material.

Wang et al. [157] illustrate how FSW addresses these vulnerabilities through three simultaneous modifications: physical flattening of the surface to reduce exposure to corrosive media; replacement of the tensile residual stresses with a compressive layer, going from +58.3 MPa to −25.7 MPa at the weld periphery; and forcing a discontinuous distribution of fine precipitates across the grain size while narrowing the precipitate-free zones. Together, these modifications interrupt the active micro-galvanic pathways responsible for localized attack.

In a similar approach, Meng et al. [158] demonstrated that multi-pass friction stir remanufacturing can refine coarse precipitates and eliminate pre-existing micro-defects, restoring the fatigue strength of the material.

The electrochemical consequences of FSW-induced microstructural gradients become most pronounced in dissimilar metal joints, where the potential difference between the two base materials superimposes on the weld-induced electrochemical heterogeneity to establish multi-scale galvanic cells. In Al-Mg systems, the equilibrium potential difference between aluminum and magnesium is approximately 0.7 V versus the saturated calomel electrode (SCE), which is among the largest galvanic couples encountered in structural lightweight alloys. When a continuous IMC network bridges the two materials in the stir zone, it provides a low-resistance electronic pathway for the galvanic current, and the more anodic magnesium dissolves preferentially. Jayaraj et al. demonstrated that intense mechanical mixing of Al and Mg, combined with IMC precipitation, generates localized galvanic microcells that degrade corrosion resistance even in regions remote from the main joint interface, because dispersed Mg-rich particles embedded in the aluminum matrix act as discrete anodes. In Al-Cu systems, the polarity is reversed: the Cu-rich intermetallic phases ( $\text{Al}_2\text{Cu}$  and  $\text{Al}_4\text{Cu}_9$ ) are cathodic relative to the aluminum matrix by approximately 0.5–0.8 V versus SCE, and their presence at the joint interface accelerates pitting of the surrounding aluminum through oxygen reduction at the IMC surface. The practical consequence is that thin but continuous IMC layers are more corrosively aggressive than thick but discontinuous ones, because continuity determines the effective cathode area available to drive anodic dissolution of the aluminum matrix. Submerged FSW of Al-Cu joints addresses this by producing a thinner, more uniform  $\text{CuAl}_2$ -dominated IMC layer in which the cathodic phase is minimally connected, reducing the effective galvanic driving force. Table 5 summarizes the dominant corrosion mechanisms, their electrochemical drivers, and the most effective mitigation strategies for the principal dissimilar material systems reviewed in Section 2.

**Table 5.** Dominant corrosion mechanisms, electrochemical drivers, and mitigation strategies for principal FSW material systems.

| System                   | Dominant Corrosion Mechanism                                             | Electrochemical Driver                                               | Most Effective Mitigation                                                          | Key Reference                       | System                   |
|--------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------|------------------------------------------------------------------------------------|-------------------------------------|--------------------------|
| Al-Mg (AA6061/AZ31B)     | Galvanic corrosion via IMC network                                       | $\Delta E \approx 0.7$ V (vs. SCE) between Al and Mg                 | Strict IMC volume fraction control; tool offset to Mg side; FSP compressive layer  | Jayaraj et al. [62]; Fu et al. [44] | Al-Mg (AA6061/AZ31B)     |
| Al-Mg (AA5083)           | Intergranular corrosion via $\beta$ -phase ( $Al_3Mg_2$ ) sensitization  | Anodic $\beta$ -phase at grain boundaries                            | FSW parameter control to limit $\beta$ -phase continuity; retrogression + re-aging | Ning et al. [154]                   | Al-Mg (AA5083)           |
| Al-Cu (AA2024/Cu)        | Pitting accelerated by cathodic Cu-rich phases ( $Al_2Cu$ , $Al_4Cu_9$ ) | $\Delta E \approx 0.5$ – $0.8$ V (vs. SCE) between Al matrix and IMC | Thin, discontinuous IMC via stationary shoulder or UFSW; Ni-P duplex coating       | Mao et al. [49]; Chen et al. [159]  | Al-Cu (AA2024/Cu)        |
| Al-Zn-Mg-Cu (7xxx)       | Stress corrosion cracking via grain-boundary precipitate connectivity    | Zn/Mg-rich GP zone dissolution under stress                          | Retrogression + re-aging (RRA) to disrupt precipitate connectivity                 | Guo et al. [155]                    | Al-Zn-Mg-Cu (7xxx)       |
| Similar Al (FSW general) | Preferential attack at precipitate-free zones (PFZ) and TMAZ/HAZ         | PFZ lower corrosion potential than matrix                            | IRFSW: compressive residual stress + discontinuous fine precipitates               | Wang et al. [157]                   | Similar Al (FSW general) |

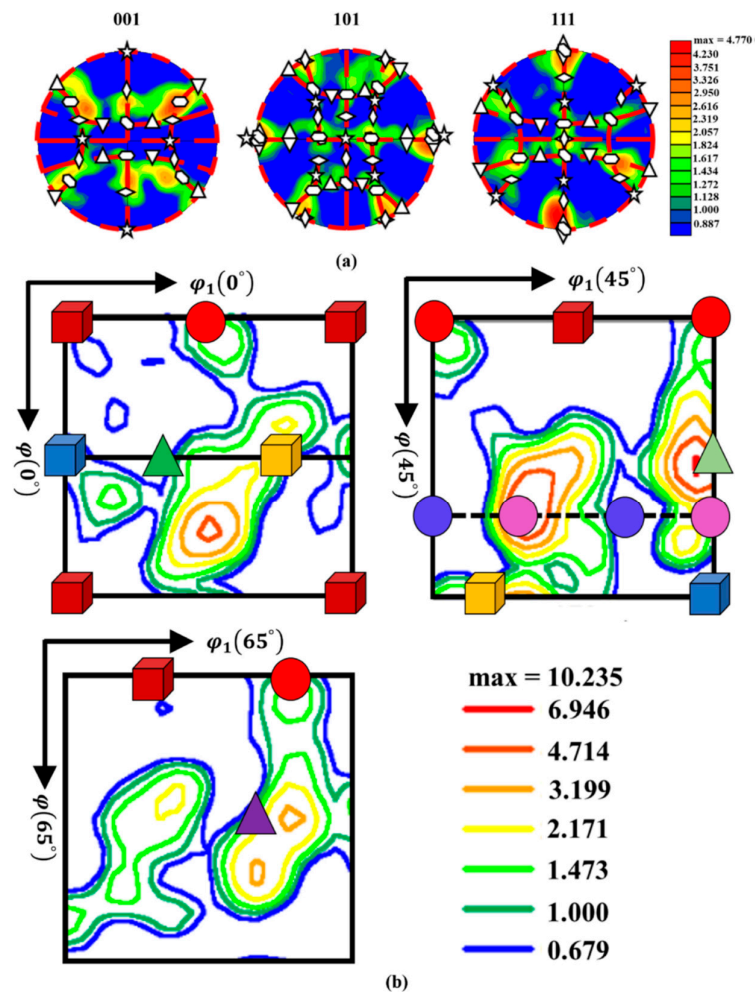
The studies on precipitation behavior and corrosion susceptibility reviewed in this subsection identify the precipitate-free zone (PFZ) width and the grain boundary precipitate connectivity as the two microstructural parameters most directly controlling corrosion performance in FSW joints. In heat-treatable alloys, the thermal cycle of Section 1.4.3 dissolves strengthening precipitates in the stir zone and coarsens them in the HAZ, creating a gradient in both electrochemical potential and mechanical properties that establishes the conditions for galvanic attack. In non-heat-treatable 5xxx alloys, the sensitization mechanism, continuous  $\beta$ -phase ( $Al_3Mg_2$ ) precipitation along grain boundaries, is driven by the same thermal history, but its mitigation requires parameter control rather than post-weld treatment. Despite significant progress in understanding these mechanisms, the long-term corrosion performance of FSW joints under realistic marine and automotive service conditions, including cyclic stress, fluctuating electrolyte chemistry, and elevated temperature, remains a significant knowledge gap, particularly for the dissimilar material pairs where galvanic coupling between the two alloys superimposes on the weld-induced electrochemical gradients.

### 5.1.3. Influence of Welding Speed and Texture

The traverse speed largely controls the heat input during friction stir welding and, thereby, the degree of precipitate dissolution. Kim et al. [160] found a direct relationship between welding speed and the strengthening mechanisms in the case of 7075 aluminum alloy. High traverse speeds reduce the net heat input and restrict the coarse growth of  $\eta$  precipitates in the heat-affected zone (HAZ), which is the area with the lowest mechanical strength of the joint. Mohammadi-pour et al. [161] have highlighted this in aerospace-

grade 7075-T6 welds, emphasizing that a narrow thermal cycle is essential to maintain high joint efficiency.

Figure 18 from Kesharwani et al. [127] captures the crystallographic consequences of severe thermomechanical deformation in AA7075-T6, observing strong concentrations of the  $A_1^*/A_2^*$  and  $A/\bar{A}$  shear texture components in the polar figures and orientation distribution functions. These intense localized textures, driven by dynamic recrystallization and rotating tool kinematics, create planes of crystallographic weakness that ultimately dictate the macroscopic fracture path under tensile loading.



**Figure 18.** Superimposed ideal shear texture component on AA7075-T6 plate weld using square-shaped pin: (a) PF and (b) orientation distribution function sections at  $\phi_2 = 0^\circ$ ,  $45^\circ$ , and  $65^\circ$ , respectively [127].

Mehri et al. [162] translated these structural changes into sheet-forming behavior, showing that the altered structure of the stir zone generally decreases local formability relative to the unaffected base metal.

The welding speed and texture studies reviewed in this subsection establish a direct causal chain from process parameters to crystallographic texture to macroscopic fracture path that is both scientifically rigorous and practically consequential: the  $A_1^*/A_2^*$  and  $A/\bar{A}$  shear texture components concentrated in the stir zone of high-strength aluminum welds are not merely microstructural curiosities but active determinants of the fracture path under tensile loading. The findings that traverse speed controls precipitate dissolution kinetics, and therefore the balance between grain boundary strengthening and precipitate

strengthening in the HAZ, while tool rotation direction governs the spatial symmetry of the texture distribution in double-sided configurations, together define a two-parameter space for texture engineering in FSW joints. What remains to be established is a quantitative relationship between texture index, fracture anisotropy, and fatigue crack growth rate for the specific texture components generated in FSW, which would allow designers to specify texture targets alongside conventional mechanical property requirements in joint design standards.

#### 5.1.4. Advanced Alloys and Thermal Cycling

In the case of ultrathin sheets, Ni et al. [163] showed that high-speed friction stir welding (FSW) on AA7075-T6 sheet produces very short thermal cycles that prevent complete dissolution of the precipitate, resulting in a specialized microstructure that retains much of the original hardness of the base alloy. Tang et al. [164] noted that process kinematics also shape microstructural symmetry and found that alternating tool rotation direction during friction stir welding (FSW) on both sides of 6061 aluminum produces an interlaced grain architecture that eliminates the weak interface line characteristic of standard lapped welds. Liang et al. [165], noting that post-weld treatments continue to extend the operational limits of FSW, subjected 6N01 alloy joints to electropulsing combined with artificial aging, finding that the applied electrical pulses accelerated the nucleation of nanoprecipitates and led to a rapid recovery of tensile strength. For lithium-alloyed systems, the thermal sensitivity of the T1 hardening phase requires strict cooling protocols. Tao et al. [166] showed that immediate water quenching followed by artificial aging is mandatory for 2198-T8 Al-Li joints to preserve this phase, a finding confirmed by the more extensive analysis of Al-Li thermal degradation by Yang et al. [167].

At the tool level, Hou et al. [168] proposed a geometry that incorporates pin eccentricity. By offsetting the central axis of the pin with respect to the axis of rotation of the shoulder, the tool generates a pulsating stirring motion with an extended swept volume. This forces chaotic and asymmetric mixing of the plasticized metal, fragments persistent oxide layers, and leads to superior metallurgical consolidation compared to conventional concentric designs.

The advanced alloy and thermal cycling studies reviewed in this subsection collectively highlight the two thermal management strategies most critical for preserving the properties of precipitation-sensitive alloys in FSW: high traverse speed for AA7075-T6 ultrathin sheets, which limits the thermal cycle duration and prevents complete precipitate dissolution, and immediate water quenching combined with artificial aging for Al-Li 2198-T8 joints, which preserves the T1 hardening phase that is essential to this alloy's strength. Both strategies are consistent with the thermal cycle framework of Section 1.4.3 but require alloy-specific implementation, confirming that the general framework can guide parameter selection but cannot replace alloy-specific characterization. The emerging application of electropulsing and innovative tool geometry modifications, such as eccentric pin designs, suggests that the field is moving toward increasingly precise microstructural control strategies; the outstanding challenge is demonstrating that the microstructural improvements achieved with these approaches in laboratory settings translate to reliable performance advantages in the complex thermal environments of multi-pass, large-scale manufacturing operations.

#### 5.1.5. Fatigue Behavior, Fracture Mechanics, and Residual Stress in FSW Joints

The mechanical reliability of FSW joints in cyclic service depends on three interrelated factors whose individual effects are well-documented but whose combined influence is less completely understood: the residual stress state inherited from the welding thermal cycle, the microstructural zone architecture that creates mechanical

property gradients across the weld cross-section, and the presence of geometric or microstructural stress concentrators—including IMC layer morphology in dissimilar joints, abnormal grain growth zones, and precipitate-free zones at grain boundaries—that act as fatigue crack initiation sites. A unified treatment of these factors is necessary because interventions that improve one dimension frequently compromise another: post-weld heat treatment that homogenizes the precipitate distribution and reduces HAZ hardness gradients may simultaneously relieve the beneficial compressive residual stresses that retard crack initiation at the weld surface.

### Residual Stress Distribution

The residual stress profile in a completed FSW joint is characteristically asymmetric, reflecting the asymmetric thermal cycle established by the AS/RS temperature difference described in Section 1.4.2. Salih et al. demonstrated through CEL-based finite element modeling that the maximum longitudinal residual stress peaks at the weld centerline and reaches approximately 40–50% of the material's yield strength in tension, while the outer regions of the HAZ are in compression. This M-shaped longitudinal stress profile is qualitatively consistent across aluminum alloy systems but varies in magnitude with rotation speed, traverse speed, and clamping configuration. The compressive regions outside the HAZ are generally beneficial for fatigue performance because they retard crack initiation at the weld toe; the tensile region at the weld centerline is the primary concern because it superimposes on applied service stresses and can accelerate fatigue crack propagation if a microstructural stress concentrator is present. Wang et al. [157] showed that in-process rolling FSW transforms this profile, converting the centerline tensile stress of +58.3 MPa to a compressive value of −25.7 MPa, which substantially improves corrosion fatigue resistance by simultaneously closing micro-surface cracks and reducing the driving force for stress corrosion cracking. Post-weld shot peening and laser shock peening achieve a similar stress reversal by introducing a surface compressive layer through mechanical or plasma shock loading, and both have been shown to be effective for dissimilar titanium–aluminum joints where the residual tensile stress at the weld surface is the primary driver of stress corrosion cracking failure.

### Fatigue Crack Initiation and Propagation

Fatigue crack initiation in FSW joints is not uniformly distributed across the weld cross-section. In similar-material aluminum joints, Rajendran et al. [153] found that crack initiation consistently occurs at the advancing-side TMAZ/HAZ boundary, the location that combines the highest longitudinal tensile residual stress with the steepest hardness gradient and the narrowest precipitate-free zone. This location is predictable from the thermomechanical framework of Section 1.4 and represents the intersection of three unfavorable conditions: thermal softening without compensating grain refinement (HAZ), mechanical deformation without full recrystallization (TMAZ), and high tensile residual stress (advancing side thermal peak). In dissimilar material joints, the dominant crack initiation site shifts: in Al–steel joints, fractures predominantly propagate through the continuous Fe<sub>2</sub>Al<sub>5</sub> IMC layer at the interface, because the cleavage planes of this phase provide a lower-energy fracture path than any microstructural feature in the aluminum or steel substrates. In Al–Mg joints, as established by the material flow analysis of Section 2.2.1, brittle IMC clusters concentrate at the weld root due to the maelstrom flow mechanism, making the root the preferential fatigue initiation site, a location that is largely inaccessible to conventional post-weld surface treatments.

The propagation rate of fatigue cracks in the stir zone is governed by the crystallographic texture established by dynamic recrystallization. As discussed in Section 5.1.3, the  $A_1^*/A_2^*$  and  $A/\bar{A}$  shear texture components concentrated in the SZ of AA7075-

T6 joints create planes of crystallographic weakness that determine the macroscopic fracture path. Crack propagation rates in textured SZ material can differ from the base metal by a factor of two to three depending on the loading direction relative to the texture, with crack propagation perpendicular to the welding direction (across the SZ) being significantly faster than propagation parallel to it. This directional sensitivity is particularly important for components that experience multiaxial fatigue loading, and it is not adequately captured by S-N data generated under uniaxial conditions alone.

### Corrosion–Fatigue Interactions

The interaction between corrosive environments and cyclic loading is an area where FSW joints are particularly vulnerable. The galvanic microcells established at the stir zone boundaries in dissimilar joints generate anodic dissolution pits that act as stress concentrators under cyclic loading, accelerating crack initiation by orders of magnitude relative to the dry fatigue condition. In marine-grade AA5083 joints, the sensitized  $\beta$ -phase ( $\text{Al}_3\text{Mg}_2$ ) network at grain boundaries provides both a preferential corrosion pathway and a reduced-toughness crack propagation path, creating a compounding effect in which corrosion and fatigue damage are mutually reinforcing rather than independent. Qian et al. [106] demonstrated that ultrasonic impact treatment of AA2219 FSW joints produces a surface nano-crystallized layer with compressive residual stress that simultaneously seals the grain boundary corrosion channels responsible for pitting initiation and increases the threshold stress intensity factor for fatigue crack propagation. This dual functionality, addressing both the corrosion and the mechanical drivers of corrosion–fatigue failure in a single post-weld operation, represents one of the most promising directions in FSW durability engineering, and the development of analogous treatments for dissimilar Al–Mg and Al–steel joints, where both galvanic driving force and IMC brittleness contribute to fatigue vulnerability, merits dedicated research attention.

### Long-Term Structural Reliability

Despite the volume of published FSW fatigue data, the long-term structural reliability of FSW joints under realistic service conditions, combined mechanical loading, thermal cycling, and corrosive exposure over periods of years, remains poorly characterized. Most published fatigue datasets are generated under constant-amplitude uniaxial loading in laboratory air, which does not replicate the variable-amplitude multiaxial loading that structural components experience in aerospace or marine service. The limited available data on variable-amplitude fatigue suggests that the Miner's rule damage accumulation predictions commonly used in structural design are conservative for FSW joints by a factor of approximately 1.5–2.5 relative to constant-amplitude predictions, reflecting the beneficial retardation effect of occasional overload cycles that increase compressive residual stress near crack tips. However, this retardation benefit is sensitive to the magnitude and sequence of overload events and may be eliminated or reversed in the presence of aggressive electrolytes that accelerate crack tip dissolution during the retardation period. Establishing validated fatigue S-N curves and crack propagation rate data for the principal dissimilar FSW material systems under combined loading and corrosive conditions, data that does not yet exist in the published literature for most combinations, is therefore identified as the highest-priority gap for structural certification of FSW joints in safety-critical applications.

## 5.2. Intermetallic Compound Formation

### 5.2.1. Defect Classification, Formation Mechanisms, and Mitigation Strategies

The microstructural integrity of an FSW joint depends not only on the phase transformations and IMC formation discussed in Section 5.1 and the remainder of Section

5.2, but also on the absence of discrete structural defects that arise when process parameters fall outside the viable thermomechanical window defined in Section 1.4. These defects can be classified into four categories according to their spatial origin and formation mechanism: volumetric defects within the stir zone bulk, planar defects at the joint interface, surface defects at the top weld surface, and microstructural defects distributed throughout the thermomechanically affected zones. Understanding the formation mechanism of each category is essential for diagnosis and mitigation, because superficially similar defect appearances can arise from fundamentally different causes that require opposing corrective actions.

#### Volumetric Defects: Tunnel Voids and Wormholes

Tunnel voids, also termed wormhole defects, are the most structurally critical volumetric defects in FSW and form when the material velocity on the advancing side of the tool is insufficient to fill the cavity that the retreating pin leaves behind. As established in Section 1.4.2, this deficiency arises from an imbalance between the material transport capacity of the tool, governed by rotation speed and pin geometry, and the rate at which material must be supplied to fill the advancing cavity, governed by traverse speed. The void is therefore most likely to form at high traverse speeds, low rotation speeds, or with tool geometries that produce insufficient vertical mixing. The numerical models of Shi et al. [117] and Wu et al. [105] confirm this mechanism, showing that the material flow velocity at the back of the pin falls below a critical threshold when the traverse-to-rotation speed ratio exceeds the material-specific limit. The practical mitigation strategies are consistent across material systems: reduction in traverse speed, increase in rotation speed, or adoption of ultrasonic assistance to increase material flow velocity, as demonstrated in Section 3.2. Tunnel voids that do not break the surface are particularly hazardous because they are difficult to detect by visual inspection, and their presence reduces fatigue life by an order of magnitude relative to sound joints through the stress concentration they introduce.

#### Planar Defects: Kissing Bonds and Hook Defects

Kissing bonds and hook defects are planar defects that develop at the original joint interface in butt and lap configurations, respectively, and are united by a common formation mechanism: insufficient plastic flow across the faying surface to disrupt the native oxide film and achieve metallurgical bonding, despite the appearance of a consolidated joint in macrographic cross-section. In butt joints, kissing bonds form when the tool plunge depth is insufficient to plasticize material across the full joint thickness, leaving a thin unbonded interface at the root whose oxide film is intact. Because kissing bonds are essentially closed interfaces under compressive loading and do not scatter ultrasound significantly differently from bonded material, they are notoriously difficult to detect non-destructively and represent one of the most serious quality assurance challenges in FSW of thick-section butt joints. Hook defects in lap joints arise from a different geometric mechanism: the plasticized material from the upper sheet is deflected upward at the advancing side rather than being forged into the interface, creating a hook-shaped unbonded region that concentrates stress under peel or tensile-shear loading. Basak et al. [169] demonstrated that pre-existing interfacial oxide layers in rolled aluminum sheets exacerbate this problem, agglomerating into zigzag defects along the bond line. The primary mitigation for both defect types is increased tool penetration depth combined with pin geometry modifications that direct material flow toward the joint interface, with the circumferential groove pin studied by Liu et al. [23] being a documented example of the latter approach for Al-steel lap joints.

### Surface Defects: Flash, Surface Roughness, and Thinning

Surface defects in FSW are generally less structurally critical than volumetric or planar defects but are important for fatigue performance and dimensional accuracy. Flash formation, the extrusion of plasticized material beyond the shoulder periphery, occurs when the heat input is excessive relative to the shoulder diameter and axial force, producing a fin of material along the weld edge that acts as a stress concentrator in fatigue loading if not removed. Surface roughness, characterized by the periodic transverse undulations known as tool marks, is an inherent feature of FSW produced by the cyclic material deposition behind the rotating pin; its amplitude increases with traverse speed and decreases with rotation speed, and it can be minimized through the use of a stationary shoulder that smooths the surface without contributing heat. Sheet thinning, produced by excessive shoulder plunge depth or insufficient axial force control, reduces the local section thickness below the design minimum and introduces geometric stress concentration at the weld edges. All three surface defect types are detectable by visual inspection or profilometry and are straightforwardly mitigated by parameter adjustment, making them the least challenging defect category from a quality assurance perspective.

### Microstructural Defects: Oxide Entrapment, Abnormal Grain Growth Zones, and Precipitate-Free Zones

Microstructural defects are distributed throughout the weld cross-section rather than concentrated at discrete locations, and their structural consequences emerge under long-term or cyclic loading rather than under static tensile testing. Oxide entrapment occurs when the native aluminum oxide film from the faying surface is not fully disrupted and dispersed by the plastic flow around the tool pin, instead agglomerating into discrete oxide-rich bands or particles that provide preferential crack initiation sites. Basak et al. [170] identified this mechanism in rolled aluminum sheet joints where the as-rolled oxide is thicker and more coherent than in machined surfaces, and demonstrated that it produces zigzag defect morphologies that are distinct from both kissing bonds and tunnel voids in their fracture surface appearance. Abnormal grain growth zones, arising from the dissolution of grain-boundary pinning precipitates during post-weld thermal treatment as described in Section 5.1.1, create local regions of dramatically coarser grain structure that reduce ductility and fatigue crack resistance disproportionate to their volume fraction. Precipitate-free zones at the HAZ-TMAZ boundary, arising from the thermal cycle described in Section 1.4.3, represent the lowest-hardness region of the weld cross-section and are the consistent crack initiation site in fatigue testing of precipitation-hardened aluminum FSW joints, as established in the Fatigue Crack Initiation and Propagation Subsection. These microstructural defects are not individually severe, but their cumulative effect on fatigue performance, particularly when oxide entrapment coincides with a precipitate-free zone at the advancing-side boundary, can be significantly worse than either defect alone, and their interactions remain insufficiently studied in the published literature.

Across all four defect categories, the process–structure–property chain established in Section 1.4 provides the diagnostic framework: the defect type identifies whether the process parameter excursion was thermal (too much or too little heat input) or kinematic (insufficient material flow velocity), and the formation mechanism points directly to the corrective action. Uday and Rajamurugan [171] summarized this principle for flow-related defects, emphasizing that the viable process window is defined by the balance between rotation speed governing heat generation and traverse speed governing cooling rate, with cold-weld defects forming below the window and hot-weld defects above it. The four-category framework presented here extends this principle to the full defect spectrum and connects each category to its detection method, mitigation strategy, and

service consequence, providing a more systematic basis for FSW quality assurance than the case-by-case treatment that currently dominates the literature.

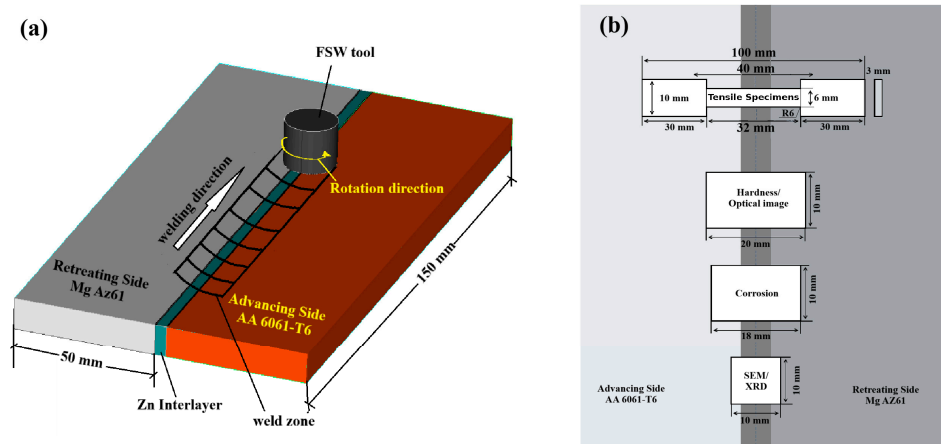
Jain et al. [172] examined multi-pass welding in different AA6082 and AA5083 joints, finding that while successive passes improve the macroscopic homogeneity, repeated thermal cycling accelerates the diffusion of alloying elements and SiC microparticles at the interface. Without careful thermal management, this prolonged exposure significantly thickens the brittle reaction layer.

Hashmi et al. [173] highlighted that structural defects in welded joints originate from inadequate heat input or disturbed material flow and, in a wear analysis of AA6082/SiC composites, showed that progressive tool wear changes the pin profile during operation, compromising the stirring action and ultimately generating subcutaneous voids. Salah et al. [174] applied EBSD to multi-pass friction stir processing of Si-rich TIG welded dissimilar joints, confirming that the flow pattern, fundamentally governed by whether the harder or softer alloy occupies the advancing side, controls both the degree of mechanical mixing and the local stoichiometry of the resulting IMCs. Mabuwa et al. [175] confirmed this in AA6082/AA8011 configurations, showing that strategic material positioning alters the heat input distribution and suppresses continuous and brittle intermetallic networks. Habba et al. [176] demonstrated that when joining AA5083-H111 by the FSW process, it provides superior joint integrity and measurable economic advantages over the MIG and TIG alternatives. The fundamental mechanics of the process, however, remain very sensitive to parameter selection. Basak et al. [170] found that pre-existing interfacial oxide layers in rolled aluminum sheets can be entrained in the agitation zone, agglomerating into zigzag defects that readily initiate fractures. Uday and Rajamurugan [171] have summarized the broader implications of flow-related defects, emphasizing that a viable process window depends entirely on the balance between the rotational speed, which governs heat generation, and the traverse speed, which governs the cooling rate. Operation outside this envelope produces either cold weld defects, such as tunnel voids, or hot-weld defects, such as excessive burr. Tool kinematics add an additional degree of control, as emphasized by Meyghani and Awang [177], who identified the tool tilt angle as a key variable governing thermomechanical behavior and heat generation in the stir zone. To address complex geometries and dimensional inaccuracies, Dong et al. [169] introduced wire-based FSW, which actively feeds and shears the filler material downward to bridge the assembly gaps and maintain joint strength despite structural discontinuities. The performance of the joints can be further improved by specific compositional adjustments and post-weld surface treatments. Qiu et al. [178] showed that Al-Mg microalloying systems with scandium and zirconium produce fine and coherent  $\text{Al}_3(\text{Sc,Zr})$  dispersoids, which counteract the loss of yield strength and increased susceptibility to corrosion normally induced by FSW thermal cycling. From a surface engineering perspective, Chen et al. [159] applied Ni-P duplex coatings over an anodic aluminum oxide interlayer, significantly improving the wear and corrosion resistance of 6061-T6 FSW joints in aggressive environments.

Systems characterized by extreme metallurgical incompatibility, such as steel-magnesium joints, require specialized tooling strategies, as noted by Khalaf et al. [179], who investigated the effect of the number of tool shoulders, ranging from one to four, finding that frictional heat generation increases with the number of shoulders up to a critical threshold. A two-shoulder configuration was found to be optimal, providing sufficient thermal energy for solid-state bonding without causing massive elemental degradation or leading to excessive growth of Fe-Mg intermetallic.

Figure 19 illustrates a friction stir butt welding configuration in which a zinc foil interlayer is pre-placed between the aluminum and magnesium plates. As the rotating tool advances along the joint line, it thermomechanically plasticizes the zinc barrier and

sweeps it into the stir zone, preventing direct atomic contact between the two base metals and replacing the brittle Al-Mg intermetallic compounds with more mechanically favorable Zn-rich binary and ternary compounds, a substitution that directly translates into higher overall joint strength.



**Figure 19.** (a) Friction stir butt welding (FSBW) of AA6061-T6/AZ61 with a Zn interlayer: (a) Schematic of the FSBW configuration, showing the tool, the welding and rotation directions, the Zn interlayer between the advancing-side aluminum and the retreating-side magnesium, and the plate dimensions; (b) dimensional layout for the extraction of the tensile, hardness/optical, corrosion and SEM/XRD specimens. Adapted from [180].

Qian et al. [106] applied ultrasonic impact treatment to AA2219 joints and found that the resulting surface nano-crystallization, combined with a compressive residual stress layer, substantially improved the resistance to stress corrosion cracking, a result that points to surface engineering as a viable complement to parameter optimization when corrosion performance is a priority. The inherently solid nature of friction-based techniques gives them a great advantage in additive manufacturing, especially in terms of component density. Shen et al. [181] demonstrated that friction-based additive manufacturing produces fully dense Al-Li structures, avoiding the gas porosity that persistently compromises fusion-based alternatives such as wire-arc additive manufacturing, a problem that Yi et al. [182] noted requires complex mitigation strategies that add cost and complexity to the process. Friction-assisted additive manufacturing represents a truly competitive path to producing defect-free, corrosion-resistant structural parts, rather than a mere academic curiosity. Hybrid processing strategies add an additional degree of control over thermal cycling and phase evolution, as highlighted by Zhao et al. [102], who found that ultrasonic vibration-enhanced FSW (UVEFSW) profoundly influences both intermetallic compound development and dynamic recrystallization in Al/Mg joints. Acoustic energy physically breaks down continuous, brittle IMC layers into isolated particles, stopping macroscopic crack propagation pathways that would otherwise form, while simultaneously refining the grain structure of the weld nugget and improving the overall ductility of the joint. The two effects are complementary, with fragmented IMCs eliminating the primary fracture pathway and granular refinement increasing the energy required to propagate any crack that does initiate.

The IMC formation studies reviewed in Section 5.2, taken together with the material-system-specific evidence of Section 2, permit a synthesis that would not be possible from either set of studies alone. The unifying conclusion is that IMC growth kinetics in FSW are

governed by the same parabolic diffusion law in all dissimilar metal systems, but the activation energy, the critical thickness for embrittlement, and the dominant brittle phase differ systematically between systems:  $\text{Fe}_2\text{Al}_5$  is the most problematic phase in Al–steel joints above approximately 5  $\mu\text{m}$ ,  $\text{Al}_{12}\text{Mg}_{17}$  in Al–Mg joints above approximately 3  $\mu\text{m}$ , and  $\text{Al}_2\text{Cu}$  in Al–Cu joints above approximately 2  $\mu\text{m}$ . These thresholds, combined with the quantitative process–temperature relationships of Section 1.4.3, define a thermomechanical design space for each material pair that can, in principle, be navigated without extensive empirical trial-and-error. The outstanding challenge is that the thermal boundary conditions in multi-pass, large-scale, or geometrically complex joints deviate significantly from the idealized configurations in which these thresholds have been measured, and this variability makes the consistent application of these design rules in production environments an unsolved problem that merits focused research attention.

### 5.3. Friction Stir Additive Manufacturing

Friction stir additive manufacturing (FSAM) extends the thermomechanical principles of FSW from a joining operation into a layer-by-layer material deposition process, producing fully dense solid-state builds without the gas porosity, solidification cracking, and oxide inclusions that persistently limit the structural reliability of fusion-based additive manufacturing routes such as wire-arc additive manufacturing (WAAM) and laser powder bed fusion. The process operates by sequentially depositing and consolidating strips or plates of feedstock material using the same frictional heating and severe plastic deformation that generate the stir zone in conventional FSW. Shen et al. [181] demonstrated that FSAM of 2195 Al–Li alloy produces fully dense structures with a refined equiaxed grain microstructure and mechanical properties comparable to conventionally forged material, confirming that the process eliminates the density deficit that constrains fusion-based AM of aluminum alloys. This section provides an expanded treatment of the process physics, microstructural development, mechanical performance, and scalability challenges of FSAM, which is identified as one of the most strategically significant directions in FSW research given its growing relevance to aerospace and marine structural fabrication.

#### 5.3.1. Process Mechanics and Thermal Accumulation Across Build Height

The fundamental distinction between FSAM and conventional FSW lies in the thermal boundary condition experienced by the deposited material: in single-pass FSW, the heat generated by the tool dissipates primarily into the backing plate and the surrounding base material; in FSAM, each successive layer is deposited onto previously consolidated material whose thermal conductivity and heat capacity are lower than those of the base plate, leading to progressive thermal accumulation as the build height increases. This effect is analogous to the interlayer temperature rise observed in WAAM but occurs more gradually in FSAM because the heat input per pass is lower and the deposition rate is limited by the traverse speed of the FSW tool. Numerical studies of thermal accumulation in FSAM suggest that peak temperatures in the stir zone increase by 15–30 °C per deposited layer until a quasi-steady state is established after approximately 4–6 layers, at which point the balance between heat input and conduction through the lower layers stabilizes the thermal cycle. The practical consequence is that the first few layers experience a thermal cycle similar to conventional FSW, while upper layers experience higher peak temperatures and slower cooling rates, a gradient that produces a heterogeneous microstructure through the build height that must be characterized and managed to achieve uniform mechanical properties across a component.

The inter-pass temperature, the temperature of the previously deposited layer at the moment the next FSW tool pass begins, is the primary process variable controlling thermal

accumulation and can be managed through active cooling, dwell time between passes, or active preheating. Active cooling between passes (forced air, water mist, or cryogenic spray) reduces inter-pass temperature and limits grain coarsening in the upper layers, but at the cost of increased process cycle time. Conversely, allowing inter-pass temperature to stabilize naturally produces a more uniform thermal gradient through the build height at the expense of increased grain size in the lower layers. The optimal strategy depends on the alloy system: for precipitation-hardened 7xxx and 2xxx alloys, where grain coarsening and precipitate dissolution in the HAZ are the primary concerns, active cooling is generally preferred; for work-hardened 5xxx alloys, where corrosion sensitization through  $\beta$ -phase precipitation is the main risk, maintaining moderate inter-pass temperatures that allow partial recovery without excessive dwell time above 150 °C is more appropriate.

### 5.3.2. Layer Bonding Mechanisms and Interface Quality

The bond quality between adjacent layers in an FSAM build is governed by the same mechanisms that determine joint quality in conventional FSW: the plasticized material in the stir zone of the current pass must flow sufficiently to disrupt and disperse the oxide film present on the top surface of the previously deposited layer, achieving intimate metal-to-metal contact and diffusion bonding across the entire layer interface. The critical process variables for layer bonding are the plunge depth (which determines the depth of tool penetration into the previous layer and hence the degree of oxide disruption), the rotation speed (which controls the intensity of mechanical stirring and oxide film fragmentation), and the traverse speed (which controls the dwell time available for atomic diffusion across the interface). Insufficient plunge depth produces unbonded regions at the layer interface—equivalent to the kissing bond defect in conventional FSW lap joints—that are particularly difficult to detect non-destructively because they close under compressive stress and do not produce a measurable acoustic signature. Excessive plunge depth causes thinning and potential fracture of the previously deposited layer, which is irreversible and terminates the build. The viable process window for plunge depth is therefore narrow, typically  $\pm 0.1$  mm from the optimum, and maintaining this tolerance across a build that may span hundreds of millimeters in the through-thickness direction requires real-time feedback on the tool axial force.

### 5.3.3. Residual Stress Evolution in Multilayer Builds

Residual stress in FSAM builds accumulates progressively through the deposition sequence and reflects the complex superposition of thermal contraction stresses from each cooling pass on the stress state inherited from all previous passes. Unlike single-pass FSW, where the residual stress profile is established in a single thermal cycle and can be characterized by the M-shaped longitudinal distribution described in the Residual Stress Distribution Subsection, FSAM builds develop a three-dimensional residual stress field whose magnitude and spatial distribution depend on the number of layers, the build geometry, the fixturing strategy, and the thermal management approach. In general, the lowest layers of an FSAM build experience the highest cumulative residual tension in the build direction, because they are heated and cooled most frequently as successive layers are deposited above them; the uppermost layers experience the lowest residual stress because they undergo only a single thermal cycle. This gradient in build-direction residual stress creates a risk of delamination between lower layers under fatigue loading, a failure mode that has no direct analog in single-pass FSW and that requires characterization using synchrotron X-ray or neutron diffraction techniques that can penetrate the full thickness of a multilayer build—methods that remain less accessible than the conventional

surface-sensitive X-ray diffraction techniques used for single-pass residual stress measurement.

#### 5.3.4. Anisotropic Mechanical Behavior

The crystallographic texture and grain morphology produced by FSAM are inherently anisotropic, and the mechanical properties of a completed build vary significantly depending on the orientation of the applied load relative to the deposition direction and the welding direction of individual passes. In the plane of each deposited layer, the  $A_1^*/A_2^*$  and  $A/\bar{A}$  shear texture components established by dynamic recrystallization in the stir zone provide reasonable strength and ductility in directions parallel to the tool traverse. In the build direction (through-thickness), mechanical properties are controlled by the layer interface quality rather than by the bulk texture: a well-consolidated interface with complete oxide disruption and adequate diffusion bonding exhibits mechanical properties approaching those of the wrought material, while an interface with residual oxide films or kissing bond defects fails at stresses well below the nominal material strength. The ratio of build-direction UTS to in-plane UTS—effectively the anisotropy index of the FSAM build—is a sensitive indicator of process quality and can serve as a manufacturing acceptance criterion analogous to the joint efficiency used for conventional FSW butt joints. Published data for Al-Li and Al-Mg-Si FSAM builds indicate anisotropy indices between 0.85 and 0.97, with the higher values achieved when active cooling maintains consistent inter-pass temperatures and precise plunge depth control ensures complete layer bonding.

#### 5.3.5. Defect Typology Specific to FSAM

FSAM introduces several defect types not encountered in single-pass FSW, whose formation mechanisms and detection strategies require specific attention. Lack-of-fusion (LOF) defects at layer interfaces, described above, are the most structurally critical because they create planar crack-like discontinuities that cannot be closed by post-process treatment. LOF probability increases with decreasing plunge depth, increasing traverse speed, and increasing inter-pass temperature, because all three conditions reduce the energy available for oxide film disruption. Surface waviness, a periodic undulation in the top surface of each deposited layer produced by the shoulder's forging action, can cause geometric misfit between adjacent layers if not machined flat between passes, creating thickness variations that act as notch stress concentrators in fatigue loading. Flow-induced porosity, caused by insufficient material velocity to fill the cavity behind the pin during deposition at high traverse speeds, produces tunnel-type voids within the bulk of the deposited material; this is mechanistically equivalent to the wormhole defect in conventional FSW and responds to the same process adjustments, reduced traverse speed or increased rotation speed, documented in Section 1.4 and the Section 3.2 UaFSW discussion. Layer-to-layer thermal cycling also drives progressive grain coarsening at the HAZ of lower layers, creating a gradient microstructure through the build height that can be mistaken for a defect in ultrasonic inspection but represents a thermal processing artifact rather than a void or crack.

#### 5.3.6. Process Scalability and Manufacturing Implementation

The scalability of FSAM to large structural components, the application most prominently identified for this process in aerospace and marine fabrication, introduces engineering challenges that are qualitatively different from those encountered in laboratory-scale builds and that have received limited systematic attention in the published literature. Tool wear is the most immediate constraint: unlike single-pass FSW, where a single tool may process hundreds of meters of weld before replacement, an FSAM

build of a large structural panel requires the tool to traverse the full area of the panel multiple times, accumulating tool–workpiece contact distances that can exceed those of conventional FSW by one to two orders of magnitude. For aluminum alloys, this is manageable with standard H13 tool steel; for harder alloys such as Al–Li 2195 or titanium, tool replacement mid-build introduces an interface where tool geometry change may produce a step change in microstructural quality that becomes the weakest point of the build. Machine stiffness is a second practical constraint: the axial forces required to maintain adequate plunge depth in FSAM (typically 10–30 kN for aluminum) must be sustained with sub-millimeter precision over the full lateral extent of a large build, which demands a stiffer and more precisely force-controlled machine platform than standard FSW gantry systems provide. Fixturing also presents challenges at scale: the cumulative distortion of a large multilayer builds due to residual stress and thermal contraction can cause the upper surface of later layers to deviate significantly from the nominal plane defined by the fixturing system, requiring adaptive control of plunge depth or in-process re-surfacing to maintain layer flatness. These scalability constraints are solvable but require engineering investment that has not yet been extensively documented in the open-source literature, and the development of industry-relevant design rules for large-scale FSAM implementation represents a priority research direction that the field has yet to address in a systematic way.

The microstructural analysis of Section 5 completes the three-part structure of this review. Section 2 characterized the material-system challenges that make dissimilar FSW difficult; Section 3 described the process variants and Section 4 the digital tools developed in response to those challenges; and Section 5 has examined the microstructural outcomes that ultimately determine whether the engineering objectives have been achieved. The conclusions and future perspectives of Section 6 synthesize the most significant findings across all five content sections, identify the scientific and engineering questions that remain unresolved, and propose a research roadmap oriented toward the AI-integrated and Industry 4.0-enabled solid-state joining systems that represent the field's most consequential near-term development direction.

## 6. Industrial Scalability and Implementation Challenges

The preceding sections have reviewed FSW from a predominantly scientific perspective, examining material systems, process physics, microstructural evolution, and digitalization tools. The translation of these advances from laboratory demonstration to industrial production involves a distinct set of challenges, engineering, economic, regulatory, and organizational, that are not adequately captured by process-performance metrics alone. This section addresses these challenges directly, covering the transition to robotic and automated platforms, inline monitoring and adaptive control, tool durability, sustainability, and the specific barriers that currently prevent wider industrial adoption of dissimilar FSW technologies.

### 6.1. From Laboratory Machines to Industrial Platforms: Robotic Fsw and Automation

Laboratory FSW research is almost universally conducted on purpose-built, high-stiffness CNC milling machine-type platforms that provide precise axial force control, rigid workpiece fixturing, and controlled thermal boundary conditions. Industrial FSW, particularly for large structural components in aerospace and marine applications, is increasingly implemented on industrial robot arms or large-format gantry systems, both of which differ from laboratory platforms in ways that directly affect process quality. Industrial robot arms offer the geometric flexibility needed to weld complex three-dimensional joints but have inherently lower stiffness than CNC gantry systems: the compliance of multi-joint robot kinematics means that the axial force applied by the FSW

tool varies as the robot traverses a weld path, particularly at corners and direction changes, producing variability in plunge depth and heat input that is not present in single-axis laboratory traverses. Studies on robotic FSW consistently report that force control algorithms, which adjust robot joint torques in real time to maintain a target axial force rather than a target position, are essential for producing joints of consistent quality, and that positional control alone, which is adequate on rigid laboratory machines, produces unacceptable variability on robot platforms.

The automation of FSW joining sequences is technically mature for simple butt and lap joint geometries in the automotive sector, where high-speed FSW of aluminum battery enclosures has been demonstrated at industrial throughput rates. The automation challenge becomes substantially more difficult for the complex joint geometries and dissimilar material combinations reviewed in this manuscript, where the process window is narrower and the consequence of parameter excursion is more severe. The development of offline programming tools that can generate robot trajectories for complex FSW joints while incorporating the thermomechanical constraints of Section 1.4, ensuring that the programmed traverse speed, rotation speed, and axial force at each point on the path maintain interfacial temperatures within the material-specific process window, represents an active area of industrial software development that has received limited academic attention.

### *6.2. Inline Monitoring, Adaptive Control, and Closed-Loop FSW*

The shift from empirical process development to digitally controlled FSW depends critically on reliable inline monitoring signals that can characterize joint quality in real time without interrupting the weld. Several monitoring modalities have been investigated: spindle torque and axial force, which carry information about material flow resistance and plasticization quality; thermographic imaging of the weld surface; acoustic emission monitoring, demonstrated by Ambrosio et al. [107] to characterize tool–workpiece interaction; and vision-based surface inspection. Of these, spindle torque and axial force are the most practically accessible, and the ML defect classifiers reviewed in Section 4.2 demonstrate that these signals carry sufficient information to distinguish sound joints from those containing tunnel voids or kissing bonds with classification accuracies above 90%.

The transition from monitoring to closed-loop adaptive control has not yet been demonstrated reliably outside laboratory conditions for the complex dissimilar material systems reviewed in this manuscript. For the subtle deviations that precede IMC layer breakthrough in dissimilar joints, a gradual increase in interfacial temperature that accelerates phase growth without immediately manifesting as a detectable force signal anomaly, a model-based predictive controller using the parabolic IMC growth integral of Section 2.6 as its internal process model is conceptually the most promising architecture, and represents a high-value target combining the thermomechanical framework with real-time sensor fusion.

### *6.3. Tool Durability and Cost in Production Environments*

Tool cost and tool life are among the most significant practical barriers to wider industrial adoption of FSW, particularly for non-aluminum material systems. For aluminum alloys, H13 tool steel provides an adequate combination of hot hardness, toughness, and cost, and tool lives of several hundred meters per tool are achievable in production. For harder materials, WC-Co cemented carbide tools cost significantly more per unit and suffer from cobalt binder dissolution at elevated temperatures. PCBN tools offer the best performance for high-melting-point materials but are brittle and expensive, preventing widespread production adoption. For the high-entropy and specialty alloys

reviewed in Section 2.5, no currently available commercial tool material provides an adequate combination of hot hardness, toughness, chemical inertness, and cost, a fundamental barrier to industrial scaling for these materials. Tool wear prediction and condition monitoring are important complements to tool material development: spindle torque monitoring provides a lagging indicator of severe degradation, while the ML signal classification approaches reviewed in Section 4.2 offer a more sensitive route to early-stage wear detection.

#### *6.4. Sustainability: Energy and Environmental Considerations*

FSW carries inherent sustainability advantages relative to conventional fusion welding. FSW of aluminum alloys typically requires 0.1–0.5 kJ/mm of weld length, compared to 1–3 kJ/mm for MIG or TIG welding of equivalent section thickness. Standard FSW configurations require neither shielding gas nor filler wire, eliminating associated CO<sub>2</sub> emissions; comparative analyses suggest this reduces the carbon footprint of the joining operation by approximately 40–60% relative to MIG welding for typical aluminum structural applications. Post-weld heat treatment, often required after fusion welding to restore mechanical properties, is reduced or eliminated in well-optimized FSW joints. At the system level, FSW enables dissimilar material joining strategies that reduce structural weight; a 10% reduction in vehicle structural weight reduces fuel consumption by approximately 6–8% over the vehicle operational life, a benefit that substantially exceeds the process energy savings alone. Quantifying this full lifecycle benefit through standardized lifecycle assessment frameworks, which has not yet been done comprehensively for dissimilar FSW joints, would significantly strengthen the industrial adoption argument.

#### *6.5. Laboratory-to-Industry Transferability and Adoption Barriers*

The transferability of laboratory FSW findings to industrial production is constrained by several systematic factors: laboratory studies use simplified joint configurations that do not represent structural component complexity; laboratory machines are stiffer and more precisely controllable than industrial robots or large-format gantry systems; and the absence of standardized testing protocols makes quantitative comparison between studies unreliable and prevents construction of the design databases that structural certification requires.

The major barriers currently preventing large-scale industrial adoption of dissimilar FSW technologies fall into five categories: (i) tool cost and life, particularly the absence of an economically viable tool material for steel and titanium; (ii) capital investment in the high-stiffness, high-force machines required for non-aluminum systems; (iii) the absence of widely adopted process certification standards for dissimilar FSW joints in safety-critical structures, where FSW of similar aluminum alloys has established qualification frameworks but dissimilar combinations do not; (iv) the limited availability of validated structural performance data, fatigue S-N curves, fracture toughness values, and corrosion-fatigue interactions, for dissimilar FSW joints under realistic service loading conditions, as discussed in Section 5.1.5; and (v) the workforce training gap associated with transitioning from established fusion welding practices. Addressing these five barriers through materials research, machine development, standardization activity, structural testing programs, and workforce development is the program of work required to realize the industrial potential that the scientific evidence reviewed in this manuscript demonstrates is achievable.

The industrial implementation of FSW is not primarily a scientific problem—the process physics are well understood and the performance advantages over fusion welding are well-documented—but an engineering and organizational problem involving tool

materials, machine stiffness, certification standards, structural performance databases, and workforce capability. The most important near-term contributions the research community can make to accelerating industrial adoption are: standardized multiaxial fatigue and corrosion-fatigue test data for the principal dissimilar material systems; validated tool wear models and condition monitoring systems for non-aluminum applications; and lifecycle sustainability assessments that quantify the full system-level carbon benefit of weight reduction through dissimilar joining. These represent a research agenda that is as consequential as the material science advances reviewed in the preceding sections.

## 7. Conclusions and Future Perspectives

### 7.1. Synthesis of Main Findings

This review has examined FSW as a unified manufacturing platform rather than a collection of isolated process variants, tracing the connections between dissimilar material challenges, process engineering solutions, digital process tools, and microstructural outcomes. Several conclusions emerge from this integrated analysis that would not be apparent from any individual section alone.

On dissimilar material joining, the collective evidence across Al-steel, Al-Mg, and Al-Cu systems establishes two cross-cutting principles. First, the fracture mode transition from brittle IMC cleavage to ductile base-metal failure is a more reliable indicator of joint quality than absolute UTS values, because it signals a change in the controlling failure mechanism rather than merely a shift in measured load. Second, hybrid process strategies consistently outperform parameter-optimized conventional FSW in IMC control across all three systems, at the cost of increased process complexity. The thermodynamic and kinetic framework of Section 2.6 provides the physical basis: the parabolic IMC growth law, operating through the non-isothermal FSW thermal cycle, means that peak temperature reduction is intrinsically more effective than accelerated post-peak cooling, and that the exponential temperature dependence of the growth rate constant makes even modest interfacial temperature reductions disproportionately effective. This principle unifies the mechanistic explanation for every IMC mitigation strategy reviewed in Section 2 within a single physical framework.

On process variants, UFSW and UaFSW address distinct limitations through fundamentally different mechanisms, rapid convective quenching in the former and acoustoplastic dislocation mobility enhancement in the latter, making their benefits complementary. Stationary shoulder and induction-assisted variants extend the processable material range at opposite ends of the hardness spectrum, collectively defining a process engineering toolkit that spans from the most thermally sensitive Al-Li alloys to the hardest currently processable nickel superalloys.

On digitalization, CEL-based defect prediction, CPFE texture modeling, phase-field IMC simulation, and ML-based process control together represent a transition from empirical to predictive FSW process design that is partially complete at the research level. The most significant gap is not the capability of individual tools but the absence of integrated frameworks connecting high-fidelity simulation to real-time adaptive control through surrogate models capable of inference at control-loop frequencies.

On microstructure, the HAZ remains the weakest structural link in FSW joints of precipitation-hardened alloys under both static and fatigue loading regardless of parameter optimization, confirming that post-weld treatments and hybrid variants are required to meet the most demanding structural performance requirements. The FSAM defect taxonomy of Section 5.3.5 and the four-category defect classification of Section 5.2.1 together provide a systematic diagnostic framework connecting defect type to process excursion type that was absent from the prior literature.

### 7.2. Unresolved Scientific Challenges

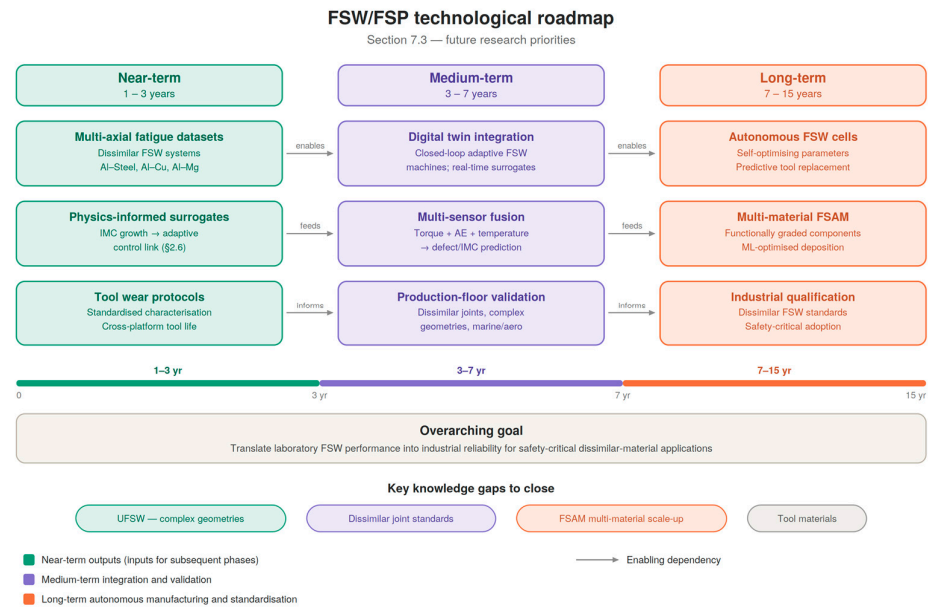
Five challenges stand out as the most consequential unresolved problems. First, IMC layer control under variable thermal boundary conditions: The critical thickness thresholds of Section 2.6.4 have been established in idealized laboratory configurations, and no validated method yet exists for predicting whether these thresholds will be respected across the full extent of a complex structural weld. Second, cross-platform model transferability: All current FEM, CPFE, and ML models are calibrated on specific machine–material combinations and do not transfer reliably without re-calibration, severely limiting their utility for production process development. Third, the absence of validated multiaxial corrosion–fatigue data for dissimilar FSW joints: The S–N and fracture toughness database required for structural certification in aerospace and marine applications does not yet exist, and its generation represents the highest-priority experimental program for enabling industrial adoption. Fourth, the tool material gap for high-entropy alloys, titanium, and hard specialty alloys: No commercial material currently provides acceptable hot hardness, toughness, chemical inertness, and cost simultaneously for these systems. Fifth, long-term durability of metal–polymer FSW joints under hygrothermal aging and cyclic loading is the primary knowledge gap preventing production adoption of solid-state metal–polymer joining.

### 7.3. Future Research Priorities and Technological Roadmap

Near-term priorities (1–3 years) are those whose outputs are required as inputs for subsequent developments: validated multiaxial fatigue and corrosion–fatigue datasets for the principal dissimilar FSW material systems; physics-informed surrogate models connecting the IMC growth framework of Section 2.6 to real-time adaptive control; and standardized tool wear characterization protocols enabling reliable tool-life prediction across machine platforms (Figure 20).

Medium-term priorities (3–7 years) center on integrating validated digital twins with closed-loop adaptive control: FSW machines that monitor spindle torque, acoustic emission, and surface temperature simultaneously, feed these signals to surrogate models of IMC growth and defect formation processes in real time, and adjust process parameters autonomously to maintain conditions within the thermomechanically defined safe window. The technical foundation for this already exists in research form; the gap is integration and production-floor validation.

The long-term trajectory (7–15 years) points toward fully autonomous FSW manufacturing cells with self-optimizing parameters, predictive tool replacement scheduling, and digital quality records linked to component service life management. FSAM will evolve from single-material deposition toward multi-material functionally graded components whose composition profile is optimized by the same ML frameworks that currently optimize single-material process windows. The expansion of the processable material range through purpose-designed tool materials and the standardization of dissimilar FSW qualification procedures for safety-critical applications will collectively determine how quickly the scientific performance demonstrated in the laboratory translates into the industrial reliability that mainstream adoption requires.



**Figure 20.** Graphical technological roadmap for FSW/FSP research and development.

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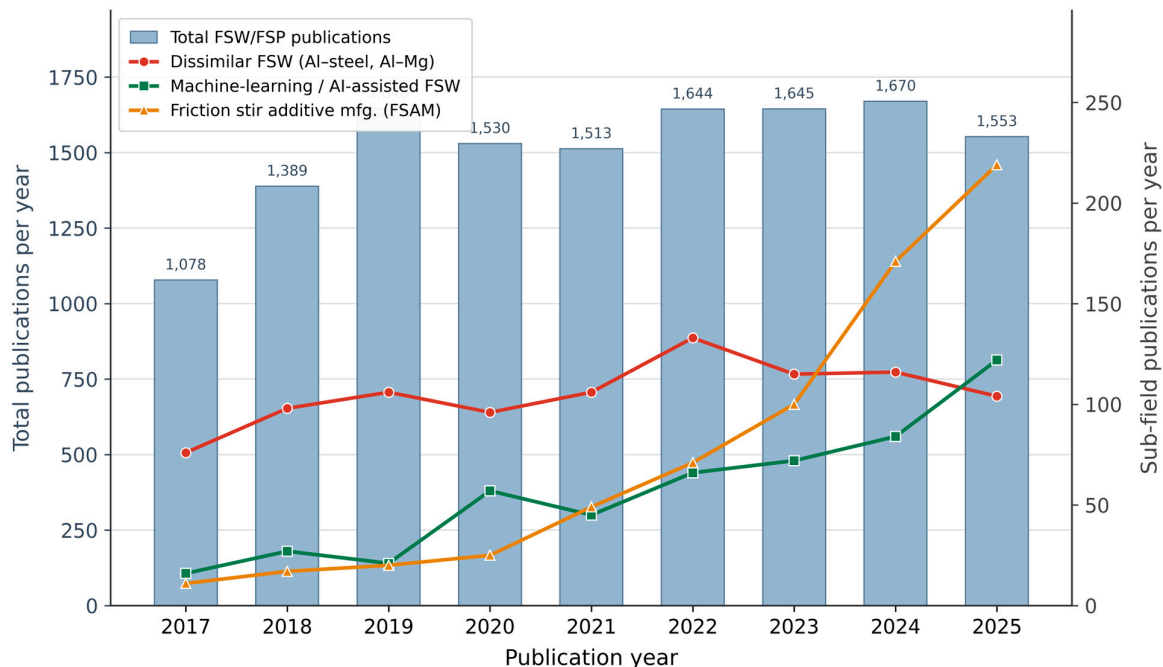
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## Appendix A



**Figure A1.** Annual publication output for FSW/FSP-related research indexed in Scopus, 2017–2025. Bars (left axis) denote total peer-reviewed publications per year; overlaid trend lines (right axis) track three sub-fields: dissimilar FSW (Al-steel and Al-Mg systems), machine-learning/AI-assisted FSW, and friction stir additive manufacturing (FSAM). After a sharp rise to 2019, total output plateaued at roughly 1500–1670 publications per year, while FSAM and, to a lesser extent, ML/AI-assisted FSW showed pronounced relative growth.

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