
Additive Friction Stir Deposition for Repair and Remanufacturing of Aluminium Alloys: Process Mechanics, Interface Integrity and Qualification Challenges — A Review

Dr. T. R. Chinnusamy

Professor, Department of Mechanical Engineering,

Sengunthar Engineering College,

Tiruchengode, Tamil Nadu, India.

chinnu_samy80@yahoo.co.in | ORCID: 0000-0002-3709-4237

Abstract

Repair of high-value aluminium components is difficult when the alloy is precipitation strengthened, fusion-weld sensitive or geometrically inaccessible. Additive friction stir deposition (AFSD) offers a solid-state alternative in which a rotating tool plastically deforms feedstock and consolidates it onto a prepared substrate without bulk melting. This review examines AFSD specifically as a repair and remanufacturing process rather than only as a freeform additive-manufacturing route. Peer-reviewed evidence on process mechanics, material flow, thermal history, alloy-specific microstructure, interface formation, defects, post-deposition treatment, mechanical performance, corrosion, monitoring and modelling is synthesized. The literature shows that defect filling alone is an inadequate measure of repair quality. Reliable repair requires intimate interfacial mixing, removal of oxide-contaminated damage, control of heat and axial force, and management of precipitate dissolution and re-ageing. The solid-state process can suppress solidification cracking and produce fine equiaxed grains, but excessive thermal exposure can soften 6xxx and 7xxx alloys, create through-thickness property gradients and enlarge the heat-affected region. Groove geometry, deposition path, overlap and local restraint strongly influence bonding at the deepest part of a repair. Post-deposition heat treatment can restore strength in heat-treatable alloys, although corrosion and fatigue must be qualified independently. The review concludes that AFSD repair should be approved through a process-qualification route linking damage removal, deposition records, interface inspection, property recovery and component-level validation. Priority research needs include defect-sensitive nondestructive evaluation, fatigue and corrosion allowables, closed-loop control, dissimilar-alloy compatibility and life-cycle evidence for remanufacturing.

Keywords: additive friction stir deposition; aluminium alloys; solid-state repair; remanufacturing; interface integrity; microstructure; process qualification

1. Introduction

Aluminium alloys are used in aircraft, rail vehicles, marine structures, tooling and transport systems because they combine low density with useful strength, corrosion resistance and manufacturability. Their economic value often resides not only in the material but also in the machining, inspection, certification and assembly already invested in a component. Wear, corrosion, impact, fretting or machining error can therefore create a repair problem in which replacing the entire part is technically unnecessary yet conventional restoration is unreliable. The challenge is particularly severe for precipitation-hardened 2xxx, 6xxx and 7xxx alloys. Fusion repair can introduce solidification porosity, hot cracking, segregation, distortion, a wide heat-affected zone and loss of the carefully developed temper. A practical repair technology must restore geometry while preserving or recoverably modifying the load path, microstructure and environmental resistance.

Metal additive manufacturing offers geometric flexibility, but many fusion-based routes reproduce the same melting and solidification problems that make high-strength aluminium difficult to weld. Powder-bed and directed-energy processes can generate steep thermal gradients, residual stress, oxide inclusions and composition changes, and they commonly require protected environments and extensive parameter development (DebRoy et al., 2018). Additive friction stir deposition is fundamentally different. A rotating, non-consumable deposition tool drives solid feedstock against a substrate; frictional and plastic-deformation heating lower the flow stress, while axial pressure and severe shear consolidate the material below the liquidus. Material is added layer by layer, but the deposit is thermomechanically worked rather than solidified from a melt (Mishra and Ma, 2005; Srivastava et al., 2021; Rathee et al., 2021; Shao et al., 2023; Dong et al., 2024).

The process is attractive for repair because it can add substantial volumes, operate in an open atmosphere, use rod or powder-containing feedstock and avoid solidification cracking. Griffiths et al. (2019) demonstrated the filling of holes and grooves in AA7075, establishing early feasibility for high-strength alloy repair. Subsequent

work has shown that deposition path, feedstock form, rotational speed, traverse speed, layer thickness and thermal management affect grain refinement, precipitate state, bonding and directional properties. More recent investigations have moved from simple filling toward engineered interfaces, stair-shaped repair geometries, dissimilar feedstock and post-deposition bonding treatments (Zhou et al., 2025; Kallien et al., 2025; Zhou et al., 2026).

However, the absence of melting does not guarantee a sound repair. A deposited region may appear dense while retaining a sharp, oxide-contaminated interface at the bottom of a cavity. High heat input can improve plastic flow and contact but over-age or dissolve strengthening precipitates. Low heat input can preserve the substrate temper yet cause incomplete transfer, weak interlayer bonding or discontinuities. Multiple reheating cycles generate vertical gradients, and the best hardness does not necessarily correspond to the best fatigue or corrosion performance. Repair success must therefore be defined by the component's service requirements rather than by deposition continuity alone.

Existing reviews have summarized AFSD equipment, parameters, materials, modelling and general applications (Li et al., 2024; Yasa et al., 2024; Korganci and Bozkurt, 2024). The repair problem warrants a more focused synthesis because it begins with damaged material, constrains tool access, produces a three-dimensional interface with a pre-existing substrate and ends with a component that may return to service. The central questions are: how should damage be prepared for deposition; what controls interfacial mixing and defect closure; how do different aluminium alloy families respond to the thermomechanical cycle; and what evidence is sufficient to qualify a repaired component? This review addresses those questions in a conventional process-structure-property-performance format and identifies the measurements needed to move AFSD from laboratory filling trials to repeatable remanufacturing practice.

2. Review Methodology

A structured narrative-review approach was adopted. Literature was identified using combinations of the terms additive friction stir deposition, friction stir additive manufacturing, solid-state additive manufacturing, aluminium repair, groove repair, through-hole repair, interfacial bonding, microstructure, precipitation, corrosion, fatigue, monitoring and modelling. Priority was given to peer-reviewed journal articles that reported process conditions, alloy condition, deposit geometry and at least one microstructural or mechanical outcome. Foundational friction-stir processing and metal-additive-manufacturing reviews were retained when they clarified material-flow, recrystallization or qualification principles. Conference-only reports, patents and unverified technical claims were not used as primary evidence for performance conclusions.

The evidence was organized into five connected domains: process mechanics and heat generation; repair preparation and deposition strategy; microstructure and precipitation; interface integrity and properties; and qualification for service. Numerical values were not pooled because machines, tool geometries, feedstock sizes, thermal metrics, specimen orientations and heat treatments differ substantially. Instead, the review compares directions of effect, recurring failure modes and conditions under which conclusions are transferable. Particular attention is given to 2xxx, 6xxx and 7xxx aluminium alloys because their response is controlled by both deformation-induced grain refinement and thermally sensitive precipitation.

Table 1. Scope and organization of the review evidence

Evidence domain	Included observations	Primary review question
Process mechanics	Rotation, translation, feed rate, layer height, axial force, torque and temperature	What creates stable transfer and consolidation?
Repair preparation	Damage removal, groove or hole geometry, access, substrate cleaning and restraint	How is the original damage converted into a depositable geometry?
Microstructure	Grain size, texture, dislocations, constituent particles and strengthening precipitates	How does the thermomechanical cycle change each alloy family?
Interface integrity	Mixing, oxide disruption, voids, kissing bonds, hardness gradients and fracture path	Does the repair carry load across the original boundary?
Service performance	Tension, fatigue, corrosion, wear, residual stress and component tests	Is the repaired region fit for the intended duty?
Process assurance	Monitoring, modelling, nondestructive evaluation, reproducibility and traceability	Can the repair be controlled and qualified repeatedly?

3. Fundamentals of Additive Friction Stir Deposition

3.1 Material transfer and consolidation

AFSD combines feedstock delivery, frictional heating, severe plastic deformation and forging pressure in a moving deposition zone. A solid rod is commonly fed through a hollow rotating tool, although process variants use twin rods, powder-filled feedstock or alternative delivery arrangements. Contact between the tool, feedstock and substrate produces heat by friction and plastic work. As the feedstock softens, it is upset beneath the shoulder and swept into a deposited layer. The tool translates while maintaining compressive contact, so consolidation depends on continuous renewal of deformable material and sufficient shear across the prior surface. Unlike fusion deposition, there is no melt pool, solidification front or solidification shrinkage; nevertheless, interfacial oxidation, inadequate flow and trapped contamination remain possible (Shao et al., 2023).

The local process is governed by coupled state variables rather than by rotational speed alone. Rotation controls shear rate and contributes to heat generation; traverse speed controls interaction time and material distribution per unit length; feed rate supplies volume and affects pressure; layer height changes confinement and reheating; axial force controls contact and forging; and tool features determine how material circulates. Two parameter sets with the same nominal heat-input index may generate different temperature, torque and interface-force histories because tool geometry, feedstock condition and substrate restraint differ. For repair, the cavity walls add another boundary: material must flow downward and laterally into the prepared feature while also mixing with the substrate.

Material transfer requires a compatible balance. Insufficient softening raises force and promotes discontinuous deposition, tearing or incomplete cavity filling. Excessive softening reduces shape control, enlarges flash and exposes a larger substrate volume to over-ageing. A high feed-to-travel ratio can overfill and create lateral extrusion; a low ratio can cause underfill or intermittent contact. The most useful process window is consequently defined by stable force and torque, continuous surface appearance, acceptable dimensional buildup and evidence of bonding at the deepest interface. Process settings should be reported together with tool-face design, feedstock cross-section, plunge or layer height, substrate thickness, restraint and preheating condition.

3.2 Thermal history and repeated deformation

Temperature in AFSD remains below bulk melting but can enter the solutionizing or over-ageing range of heat-treatable aluminium alloys. This distinction explains a central property trade-off. Severe deformation and dynamic recrystallization refine grains and can raise boundary strengthening, while thermal exposure dissolves, coarsens or redistributes strengthening precipitates. The resulting hardness is therefore the net outcome of grain refinement, dislocation storage, recovery and precipitation state. In AA6061 and AA7075, loss of the original T6 precipitate condition can dominate the as-deposited response even when the grain structure is much finer (Qiao et al., 2023; Elshaghoul et al., 2023).

Multilayer deposition creates a sequence of thermal cycles. Material near the substrate experiences the initial high-strain deposition event followed by reheating from every subsequent layer. The top layer experiences less reheating but may cool differently because of reduced restraint and heat sinking. This creates vertical gradients in grain size, precipitate distribution, hardness and residual stress. Comparable multilayer evidence in WE43 and AZ31B also demonstrates that repeated deformation and reheating cannot be inferred from a single section or orientation (Williams et al., 2021; Joshi et al., 2022a, 2022b; Sharma et al., 2022). Jiang et al. (2025) and later AA6061 studies show why a single hardness line or one tensile orientation cannot represent an entire build. Repair geometries intensify this problem because thick substrate regions extract heat differently from cavity corners and previously deposited material.

In-situ temperature, force and torque data are increasingly used to interpret process stability. Qiao et al. (2024a, 2024b) demonstrated that layer thickness and heat input alter dynamic recrystallization, texture, bonding and tensile response in AA6061. Paliwal et al. (2024) connected rotational speed to measured process signals and microstructure, while Qiao et al. (2025) showed that feedstock geometry and rotational-driving mode change force, torque and directional properties. These studies support a shift from recipe-based settings to state-based control using measured thermal and mechanical signatures.

Table 2. Principal AFSD variables and their repair-related effects

Variable	Primary physical effect	Too low	Too high
Rotational speed	Shear rate, frictional heating and mixing	High force, discontinuous transfer, weak bonding	Overheating, flash, precipitate dissolution, grain growth
Traverse speed	Interaction time and deposited material per length	Excessive heat accumulation and wide affected zone	Underfill, incomplete mixing and surface discontinuity
Feed rate	Supply volume, upsetting	Starvation and interrupted	Overfill, lateral extrusion and

Variable	Primary physical effect	Too low	Too high
	pressure and layer buildup	contact	dimensional error
Layer height	Confinement, strain and reheating of prior layers	Excessive compression and flash	Insufficient forging and interlayer discontinuity
Axial force	Real contact, oxide disruption and consolidation	Kissing bonds or void retention	Substrate distortion, tool overload and excess heat
Tool-face geometry	Material circulation and interfacial shear	Poor renewal or local stagnation	Uncontrolled flow, surface tearing or high torque
Cooling / preheating	Thermal gradient and precipitate kinetics	High flow stress and poor transfer	Softening, over-ageing and a larger heat-affected region

4. AFSD as a Repair and Remanufacturing Process

4.1 Damage assessment and repair preparation

A repair begins before deposition. The damaged component must be assessed to determine whether restoration is technically justified and whether remaining cracks, corrosion products or distorted material can be removed without compromising the load path. Surface cleaning alone is inadequate when corrosion penetrates along grain boundaries or fatigue cracks extend beneath visible damage. The repair preparation should remove structurally degraded material, produce a geometry accessible to the rotating tool and retain enough substrate thickness to withstand axial loading. Nondestructive examination before machining is therefore linked directly to cavity design.

Simple rectangular grooves are convenient for laboratory comparison but may create vertical walls and sharp bottom corners that are difficult to sweep with plasticized material. Griffiths et al. (2019) observed that upper regions of hole and groove repairs mixed more effectively than deeper regions, where sharp interfaces could remain. The limitation is mechanical: the tool acts mainly from above, while contact pressure and lateral strain decrease near the cavity bottom. Tapered, stepped or stair-like preparations can increase contact area, interrupt continuous oxide films and expose the interface to repeated shear. Zhou et al. (2025) reported improved grain refinement and tensile response for stair-shaped Al-Zn-Mg-Cu repair geometries, supporting geometry as an active process variable rather than a neutral specimen detail.

Preparation also controls contamination. Lubricants, penetrant residues, corrosion products and machining debris can become trapped at the bond line. Cleaning protocols should be compatible with aluminium surfaces and should specify the time between cleaning and deposition because a native oxide reforms rapidly. If lubricant is used on feedstock or tooling, its fate at the interface must be considered. Recent lubricant-free twin-rod approaches and post-deposition friction-diffusion treatments illustrate that contamination control and bond enhancement are closely connected (Kallien et al., 2025).

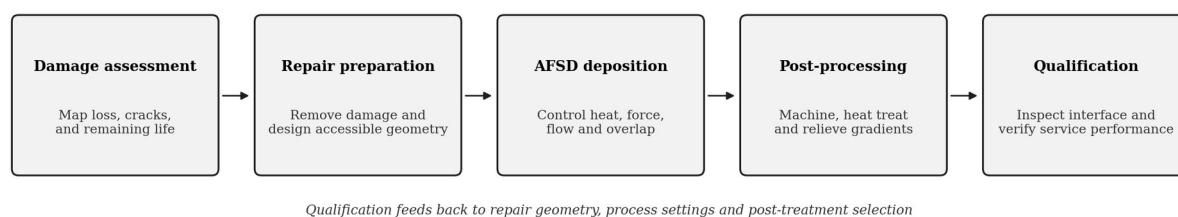
4.2 Deposition strategy for confined defects

Repair path planning differs from free-wall building. A through-hole may be filled by a stationary or orbiting strategy, whereas a long groove requires continuous translation and overlap. The first deposited material must wet and mechanically mix with the cavity floor; later passes must consolidate against both the substrate wall and earlier deposit. Starting and stopping locations can create local thermal excursions, feedstock accumulation or unbonded seams. Path planning should therefore define entry and exit positions, pass direction, overlap, dwell, edge coverage and the sequence used to raise the repair above the original surface for finish machining.

Dissimilar feedstock creates another design choice. Matching feedstock simplifies chemistry and post-treatment, but a stronger or more corrosion-resistant alloy may be selected to create a locally enhanced repair. Zhou et al. (2026) used AA7075 feedstock on an AA6061 substrate and reported strong interfacial mixing with a composition gradient and coupled precipitate strengthening. Such results are promising but cannot be generalized solely from static strength. Differences in thermal expansion, electrochemical potential, precipitation response and ageing treatment may create fatigue or corrosion penalties. Dissimilar repair must therefore be evaluated as a graded joint rather than as homogeneous filler.

The final deposited volume is normally oversized and machined to tolerance. This machining allowance must be planned because near-surface flash, oxide pickup and start-stop defects may be removed, while excessive stock removal can expose a weak interface or reduce the intended reinforcement depth. The deposition and finishing plans should be treated as one route. Dimensional metrology, datum control and distortion measurement are required before and after repair, particularly for thin aircraft skins or precision structures under high axial force.

Figure 1. Process chain for AFSD repair and remanufacturing



Source: Author's synthesis of the repair literature.

5. Alloy-Specific Microstructural Response

5.1 Al-Cu alloys

The strength of 2xxx aluminium alloys depends on copper-containing precipitates and dispersoids whose size, number density and distribution respond to the deposition thermal cycle. AFSD usually produces fine, equiaxed grains through dynamic recrystallization, but grain refinement does not uniquely determine performance. Repeated heating can dissolve metastable strengthening phases, redistribute Al_2Cu particles and change dislocation density. The as-deposited condition may therefore show local softening even when porosity is low and grain size is refined.

Corrosion evidence is especially important for Al-Cu alloys. Wang et al. (2024) reported that AFSD changed the number and distribution of Al_2Cu particles in AA2219, increasing galvanic microcells and susceptibility to localized and intergranular corrosion in the as-deposited condition. A subsequent T6 treatment improved corrosion resistance through precipitation and dislocation changes. This finding prevents a common overgeneralization: solid-state deposition avoids solidification defects, but it does not automatically preserve environmental resistance. Repair qualification for fuel tanks, marine structures or humid service must include corrosion testing representative of the alloy, temper and exposure.

For repair, the original substrate temper and the attainable post-deposition treatment must be considered together. A full solution treatment may restore precipitation potential but can distort a large component or be prohibited by existing assemblies. Local ageing may be more practical but may not homogenize the repair, heat-affected zone and substrate. The route must therefore define whether the objective is to recover original temper, achieve a lower but uniform qualified condition, or accept a local property gradient supported by structural analysis.

5.2 Al-Mg-Si alloys

AA6061 is widely used to study AFSD because it is readily available, weldable and sensitive to Mg-Si precipitation. Zeng et al. (2022) documented microstructural refinement during AFSD, and Qiao et al. (2023) quantitatively related grain, dislocation and precipitation contributions to mechanical behavior before and after heat treatment. The essential observation is that dynamic recrystallization creates fine grains, while deposition heat can dissolve or coarsen the beta-double-prime precipitates that provide the T6 condition. As-deposited strength can fall even as ductility increases.

Process monitoring studies show that no single direction of heat-input effect applies universally. Increasing heat can improve plastic flow, material-transfer efficiency and interlayer bonding when a low-energy condition is under-consolidated. Qiao et al. (2024b) found that heat input influenced both structural uniformity and precipitate formation in AA6061. Yet excessive or repeated exposure also increases recovery, precipitate coarsening and the width of the softened region. The relevant optimum is bounded below by bonding and above by unacceptable temper loss, distortion or grain growth.

Layer thickness, rotation and feedstock delivery change this balance. Qiao et al. (2024a) linked layer thickness to temperature, force, torque, recrystallization and texture. Paliwal et al. (2024) showed that rotational speed changed monitored signals and microstructure. Gao et al. (2025), Jiang et al. (2025), Qiao et al. (2025), Kumar et al. (2026) and Ding et al. (2026) further demonstrate that AA6061 deposits can exhibit directional and through-height differences in hardness, tensile strength, precipitation and recrystallization. For a repair, coupons should therefore be extracted relative to the original interface, deposition direction and build height, not only from the visually most uniform center.

5.3 Al-Zn-Mg-Cu alloys

The 7xxx series presents the strongest repair motivation and the most demanding metallurgy. These alloys combine high specific strength with poor fusion weldability and sensitivity to precipitate dissolution, over-ageing and stress-corrosion cracking. Griffiths et al. (2019) showed that AFSD could fill substantial AA7075 defects while reducing hardness by less than the catastrophic losses associated with an unsound fusion repair; however, lower-cavity mixing remained a limitation. Elshaghoul et al. (2023) later linked feed rate and rotational speed to heat generation, grain refinement, precipitate fragmentation and hardness in multilayer AA7075 deposited on AA2024.

The apparent benefits of fine grains must again be separated from temper recovery. The AFSD cycle can dissolve eta-prime strengthening precipitates and produce an as-deposited region that is soft relative to T6 or T7 feedstock. Post-deposition solution treatment and ageing can restore strength, but the response depends on retained solute, constituent particles, quench rate and component geometry. Local heat-affected regions outside the deposit may become the critical weak zone even when the deposited material responds well to ageing. Hardness maps should extend into unaffected substrate on both sides of the repair and through the full depth.

Geometry and interface design are particularly important because high-strength repairs will be judged by fracture location and fatigue behavior. Zhou et al. (2025) demonstrated that a stair-like interface increased contact and deformation during repair, although recovered tensile strength remained below the parent alloy. Kallien et al. (2025) compared AFSD and friction surfacing for groove repair and found characteristic differences in bonding and hardness gradients. Zhou et al. (2026) advanced the concept by using AA7075 feedstock to strengthen an AA6061 repair interface. These studies move the field from geometric filling toward designed material flow, but long-term fatigue, stress corrosion and damage tolerance remain under-reported.

Table 3. Representative AFSD evidence relevant to aluminium repair

Study	Material or repair case	Main contribution	Repair implication
Griffiths et al. (2019)	AA7075 holes and grooves	Demonstrated solid-state defect filling and identified weaker deep-interface mixing	Cavity geometry and bottom-interface inspection are essential
Zeng et al. (2022)	AA6061 build	Mapped grain refinement and microstructural evolution	Deposit quality must be interpreted with precipitation state
Qiao et al. (2023)	AA6061-T6	Quantified microstructure-property contributions and heat-treatment response	Post-treatment can recover strength but changes several mechanisms
Elshaghoul et al. (2023)	AA7075 on AA2024	Related feed rate and rotation to heat, grains, precipitates and properties	Feedstock delivery is a thermal and metallurgical control
Qiao et al. (2024a)	AA6061 layer thickness	Used in-situ signals to connect layer height with structure and properties	Layer plan should be included in the repair procedure specification
Wang et al. (2024)	AA2219 corrosion	Linked Al ₂ Cu redistribution to localized corrosion and T6 recovery	Corrosion qualification cannot be inferred from density or hardness
Zhou et al. (2025)	Al-Zn-Mg-Cu stair-like grooves	Showed interface geometry affects mixing, refinement and tensile response	Damage preparation is part of process optimization
Kallien et al. (2025)	High-strength Al groove repair	Compared AFSD with friction surfacing and bond-enhancement treatment	Repair selection should consider heat-affected width and bond quality
Qiao et al. (2025)	AA6061 feedstock modes	Monitored temperature, force and torque under different delivery modes	State variables can support closed-loop quality assurance
Zhou et al. (2026)	AA7075 feedstock on AA6061	Developed a dissimilar, interface-strengthening repair	Composition grading may enhance a repair but needs durability evidence

6. Interface Integrity and Defect Formation

6.1 Bond formation

A sound AFSD interface is produced by intimate contact, oxide disruption, plastic flow across the original boundary and metallurgical accommodation during the thermal cycle. In aluminium, the stable surface oxide does not dissolve readily; bonding depends on breaking, dispersing and transporting that film while clean metal surfaces are pressed together. Severe shear can fragment the interface and create a gradual transition in grain

morphology and composition. A sharp continuous boundary, by contrast, may indicate insufficient mixing even when no open void is visible.

The advancing and retreating sides need not be equivalent. Tool rotation and translation create asymmetric velocity and strain fields, and cavity walls constrain material differently. Zhou et al. (2025, 2026) reported side-dependent texture or strength in engineered repairs. Qualification should therefore sample both sides, the bottom, pass overlaps and start-stop zones. One centerline macrograph is not sufficient. Serial sectioning, high-resolution microscopy or volumetric inspection may be required to determine whether apparent bonding is continuous along the repair.

Dissimilar interfaces add diffusion and precipitation effects. A composition gradient can reduce an abrupt mechanical mismatch, but it may also create local electrochemical cells or brittle intermetallics depending on alloy selection and thermal exposure. The appropriate feedstock is therefore chosen from a compatibility assessment covering hot-deformation behavior, solution and ageing response, galvanic potential, service temperature and repair heat-treatment constraints. Static shear or tensile strength should be combined with fracture-path analysis to establish whether failure initiates at the original interface, within the deposit, in the heat-affected substrate or outside the repair.

6.2 Defect modes

AFSD avoids gas porosity and solidification cracking associated with a melt pool, but it has its own defect population. Macroscopic defects include underfill, flash, surface tearing, tunnel-like voids, delamination, unbonded pass overlaps and geometric distortion. Subsurface defects include oxide-rich seams, kissing bonds, entrapped debris and locally softened regions that are invisible in a polished section. Defects arise when material supply, heat, forging pressure, tool access and translation are not balanced.

The deepest region of a groove or hole is vulnerable because vertical pressure does not automatically create lateral wiping against every wall. Sharp corners can act as stagnant zones. A high-temperature dwell may improve filling but also widen the softened zone; additional passes may improve mixing while adding thermal exposure. Geometry changes such as bevels and steps can be more effective than simply increasing heat because they expose the interface to shear and increase available bonding area. Repair design should therefore use manufacturability criteria specific to solid-state flow.

Defect acceptance should be related to fracture mechanics and service loading. A small planar unbonded region normal to the principal stress may be more serious than a larger rounded pore. Kissing bonds are particularly challenging because their faces remain in contact and may be difficult to detect ultrasonically. Surface hardness cannot reveal them. The qualification programme must define defect type, location and maximum allowable size, then demonstrate that the chosen nondestructive method can detect that flaw in the relevant geometry and material condition.

7. Mechanical Properties and Post-Deposition Treatment

7.1 Strength, ductility and anisotropy

AFSD deposits often contain fine equiaxed grains and low porosity, which can support good ductility and reduce the strong columnar solidification texture found in many fusion additive processes. Nevertheless, directional properties can persist because shear texture, pass overlap, interlayer boundaries and vertical thermal gradients are directional. Tensile specimens taken along the deposition direction, transverse direction and build direction probe different combinations of these features. Qiao et al. (2025) and recent AA6061 investigations report meaningful differences between longitudinal and build-direction properties, while multilayer studies show height-dependent hardness and microstructure.

For repair, a specimen cut wholly from deposited material does not test the most critical path. Cross-interface tension, shear and bend tests are required to force load transfer through the bond. Notched tests can place the highest stress at the interface, and digital image correlation can reveal strain localization across hardness gradients. Full-field strain is especially useful when the nominal tensile strength appears acceptable but deformation concentrates in a narrow softened zone. Fractography should classify whether failure is ductile within deposit, interfacial, particle-assisted or initiated at a planar defect.

Static recovery is only the first level of performance. Aircraft and transport components are frequently fatigue limited. Fine grains may delay slip localization, but oxide seams, surface machining marks, residual stress and hardness mismatch can accelerate crack initiation. The repaired geometry may also relocate stress. Fatigue testing should therefore include the actual final surface condition, representative mean stress, environmental exposure and loading orientation. The scarcity of statistically supported S-N and fatigue-crack-growth data is one of the principal barriers to structural allowables.

7.2 Heat treatment and finishing

Post-deposition heat treatment is often necessary for heat-treatable aluminium alloys. Solution treatment followed by quenching and artificial ageing can rebuild precipitation strengthening in AA6061, AA7075 and AA2219, as shown by Qiao et al. (2023), Wang et al. (2024) and later studies. Yet a treatment developed for a small deposit may be impractical for a large repaired component. Quenching can distort thin sections, residual stresses may redistribute, and parent material outside the repair may respond differently because it began in another temper or experienced a different thermal cycle.

Local heat treatment reduces furnace and disassembly requirements but creates its own gradients. The temperature field and cooling rate must be measured or modelled, and the final condition should be mapped across deposit, interface, heat-affected zone and parent material. An apparently recovered peak hardness can conceal under-aged or over-aged bands. If the component cannot be restored to its original temper, the engineering drawing and structural assessment should identify the qualified post-repair condition rather than retaining the original material designation without qualification.

Finish machining removes excess deposit and restores dimensional tolerance, surface finish and mating geometry. Machining can also remove beneficial compressive layers or expose subsurface interface regions. Residual stress, tool marks and local heat from finishing may influence fatigue. Surface treatments such as shot peening, anodizing, conversion coating or sealing can be required, but their compatibility with the mixed or re-aged microstructure must be demonstrated. The complete process route, not the deposition step alone, determines service performance.

Table 4. Minimum qualification evidence for an AFSD aluminium repair

Qualification level	Minimum evidence	Acceptance purpose
Procedure definition	Alloy and temper, damage limits, preparation geometry, cleaning, tool, feedstock, path, monitored variables and post-treatment	Fix the process boundary and ensure repeatability
Geometric restoration	Three-dimensional metrology before deposition, after deposition and after machining	Confirm fill, machining allowance, distortion and final tolerance
Internal integrity	Qualified ultrasonic, radiographic or computed-tomography method plus destructive sectioning during procedure qualification	Detect voids, seams, lack of bonding and inclusions
Microstructural control	Grain, texture, precipitate and composition maps across deposit, interface, heat-affected zone and substrate	Establish the process-structure relationship
Static properties	Hardness map, cross-interface tension or shear, orientation-dependent tensile tests and fracture location	Verify load transfer and identify the weakest region
Durability	Fatigue, corrosion and stress-corrosion testing appropriate to service	Demonstrate that short-term strength is not misleading
Component validation	Proof, pressure, vibration or representative subcomponent test with an inspection plan	Confirm structural performance and inspection effectiveness

8. Monitoring, Modelling and Quality Assurance

8.1 In-situ monitoring

AFSD equipment can record commanded rotation, translation and feed, but command values do not fully describe the process state. Temperature, axial force, feedstock force, interface force and torque provide evidence of real contact and deformation. Stable signatures can define a normal operating window, while abrupt changes may indicate feed interruption, loss of contact, cavity transition or material accumulation. Qiao et al. (2024a, 2025) and Paliwal et al. (2024) demonstrate the value of synchronizing process signals with subsequent microstructure and properties.

Repair monitoring must be spatially registered to the tool path. A signal anomaly is useful only if it can be mapped to a location that is later inspected or sectioned. Data should include sampling rate, sensor position, calibration, filtering and synchronization. Temperature measurements require particular caution because embedded thermocouples, surface infrared systems and model-inferred interface temperatures observe different quantities. For qualification, the monitoring system should detect deliberately introduced deviations and should have limits tied to a measurable defect or property change.

Closed-loop control remains an important objective. Torque or force can be used to adjust feed rate, layer height or translation when geometry changes. However, controlling one signal may not control metallurgy: the

same force can occur at different temperatures, and a stable surface can coexist with precipitate over-ageing. Multivariable control combining force, torque and temperature is more defensible. Machine-learning models may assist prediction, as illustrated for AFSD Al2219 by Tam et al. (2026), but training data must preserve alloy, tool, geometry and sensor context, and uncertainty must be reported outside the calibration window.

8.2 Thermomechanical modelling

Models can reduce trial-and-error by estimating temperature, strain rate, material flow and accumulated thermal exposure. Friction-stir models commonly combine frictional and plastic-deformation heat sources with temperature-dependent flow stress and heat transfer. AFSD adds continuous feedstock, changing contact and multilayer activation. Sharma et al. (2022) developed a pseudo-thermomechanical approach that connected process settings to temperature-time response, Zener-Hollomon behavior and grain evolution in a magnesium deposit; the same modelling logic is relevant to aluminium repair, provided alloy-specific precipitation and boundary conditions are added.

Repair simulation must represent the cavity rather than assuming a flat substrate. Contact evolves as the cavity fills, and heat conduction varies with local remaining thickness. A useful model predicts not only peak temperature but also time above dissolution or ageing thresholds, accumulated strain, interfacial pressure and cooling rate. Model validation should compare measured temperatures and forces, macrographic fill, grain or hardness distributions and, where possible, material-flow markers. Agreement with one peak temperature is insufficient to establish predictive repair quality.

Integrated computational materials engineering can connect the process field to precipitation and strength. This is attractive for 6xxx and 7xxx alloys because a repair may satisfy geometric criteria while failing a temper-recovery requirement. The model should output uncertainty and identify sensitivity to friction, heat-transfer coefficient, contact and material properties. A validated model can then guide geometry-specific procedure qualification, but it does not replace destructive validation or nondestructive examination.

9. Sustainability and Industrial Implementation

Repair and remanufacturing can retain embodied material, machining and component value, but AFSD should not be labelled sustainable solely because it is solid state. A complete comparison includes damage-removal machining, feedstock production, tool manufacture, deposition electricity, fixturing, post-deposition heat treatment, finish machining, inspection, rejected repairs and the avoided manufacture of a replacement component. The absence of shielding gas and melting may reduce some burdens, while high axial loads, large machine tools and lengthy heat treatment add others. The relevant functional unit is a component returned to qualified service for a defined additional life.

Industrial adoption also depends on economics and logistics. AFSD is most attractive when replacement lead time, certification effort or component value is high and the damaged region is accessible to the tool. It is less attractive when the part is inexpensive, the defect cannot be fully removed, local geometry prevents tool contact or a global heat treatment is unacceptable. Repair cells require robust fixturing, traceable feedstock, validated machining allowances, calibrated monitoring and a clear route for disposition of out-of-window events.

Qualification should resemble a special-process framework. A written repair procedure specification should define essential variables and their allowable ranges. Procedure-qualification specimens should reproduce the alloy, temper, thickness, restraint, cavity geometry and post-treatment of the real component. Operators and equipment should be qualified, and production repairs should retain process records linked to inspection results. Changes in tool face, feedstock supplier, lubricant, layer plan or heat treatment should trigger documented evaluation rather than informal parameter substitution.

10. Research Gaps and Future Directions

The first priority is a repair-specific defect taxonomy and nondestructive-detection programme. Current studies rely heavily on sectioned coupons and optical macrographs. Industry needs reference specimens containing controlled planar lack of bond, oxide seams, underfill and overlap defects at known depths. Ultrasonic arrays, nonlinear ultrasonics, computed tomography and thermography should be compared against destructive truth so that probability-of-detection curves can be established for representative component geometries.

The second priority is durability. Cross-interface fatigue, fatigue-crack growth, corrosion fatigue and stress-corrosion cracking should be measured with statistically meaningful replication. Tests must include the final machined and protected surface, post-treatment condition, residual-stress state and relevant environment. Short transverse and build-direction specimens are particularly important because they place load across interfaces and thermal gradients that conventional longitudinal coupons may avoid.

The third priority is transferable process control. Studies should report measured force, torque and temperature together with tool geometry, feedstock condition, cavity shape and substrate restraint. Deliberate

perturbation experiments can determine which signal features precede weak bonding or excess softening. Physics-guided machine learning should be evaluated by holding out repair geometries, material batches or machines rather than randomly separating points from the same deposition campaign.

The fourth priority is alloy and treatment compatibility. Dissimilar feedstock may create locally strengthened or corrosion-resistant repairs, but composition gradients, galvanic interactions and ageing response require systematic design. Databases should connect alloy chemistry, temper, peak-temperature history, strain, cooling rate and post-treatment to precipitation, hardness, corrosion and fatigue. Repair-specific heat treatments that recover properties without distorting a whole component deserve particular attention.

The fifth priority is component-level evidence and standards. Most published work uses walls, blocks, grooves or holes under simplified loading. Subcomponents containing realistic curvature, variable thickness, fastener holes and multiaxial stress are needed. Demonstrations should compare repaired components with undamaged and conventionally repaired controls, quantify remaining-life recovery and include repeated repairs where relevant. Shared reporting requirements and round-robin studies would accelerate procedure qualification across laboratories and equipment platforms.

Table 5. Priority research questions for industrial AFSD repair

Research area	Unresolved question	Recommended evidence
Nondestructive evaluation	Can tight planar interfaces and oxide seams be detected reliably?	Seeded-defect reference blocks and probability-of-detection studies
Fatigue and damage tolerance	Where do cracks initiate and how fast do they cross the repair?	Orientation-specific S-N and crack-growth data with fracture mapping
Corrosion	How do precipitate and composition gradients affect localized attack?	Electrochemical mapping, immersion, intergranular and stress-corrosion tests
Closed-loop control	Which measured signals predict bond quality and temper loss?	Synchronized force, torque, temperature, geometry and destructive validation
Dissimilar repair	Can filler chemistry enhance performance without a galvanic penalty?	Diffusion, phase, hardness, corrosion and fatigue mapping
Qualification transfer	Which variables are essential across machines and component geometries?	Multi-machine round-robin procedures and uncertainty-based limits
Sustainability	When does repair deliver a genuine life-cycle advantage?	Component-life functional units including rework, heat treatment and avoided replacement

11. Limitations of the Review

The AFSD repair literature is expanding rapidly but remains heterogeneous. Machines, tool designs, parameter definitions, feedstock geometries, alloy tempers and specimen orientations differ, preventing defensible pooling of reported properties. Many studies investigate free-standing deposits rather than actual repaired defects, and results from deposits are used here only when they clarify mechanisms relevant to repair. Several recent investigations provide short-term tensile or hardness results but limited fatigue, corrosion or full-component validation. Accordingly, this review emphasizes recurring mechanisms, qualification needs and boundaries of transfer rather than a universal parameter window.

12. Conclusion

Additive friction stir deposition is a credible solid-state route for restoring aluminium components that are difficult to repair by fusion methods. Its principal advantages are continuous material addition without bulk melting, high deposition rate, refined equiaxed microstructures and reduced susceptibility to solidification cracking and gas porosity. These advantages are especially relevant to precipitation-hardened aluminium alloys used in high-value structures.

A successful AFSD repair is not defined by visible filling alone. Damage must be removed and converted into an accessible geometry; the deposit must mix with the cavity floor and walls; thermal exposure must remain compatible with the alloy and temper; and post-treatment must manage strength, corrosion and residual gradients. Rotation, translation, feed, layer height, axial force, tool geometry and thermal management act as a coupled system. Increasing heat can improve flow and bonding but also dissolve or coarsen strengthening precipitates and enlarge the softened zone.

The next stage of development is qualification rather than another isolated optimum. Repair procedures should connect measured process signatures to interface inspection, microstructural maps, cross-interface static

properties, fatigue, corrosion and component-level validation. With reliable nondestructive evaluation, closed-loop monitoring, alloy-compatible post-treatment and life-cycle evidence, AFSD can progress from laboratory defect filling to traceable repair and remanufacturing of safety-relevant aluminium structures.

References

- DebRoy, T., Wei, H.L., Zuback, J.S., Mukherjee, T., Elmer, J.W., Milewski, J.O., Beese, A.M., Wilson-Heid, A., De, A. and Zhang, W. (2018). Additive manufacturing of metallic components — Process, structure and properties. *Progress in Materials Science*, 92, 112–224. <https://doi.org/10.1016/j.pmatsci.2017.10.001>
- Ding, S. et al. (2026). Microstructural evolution and mechanical properties of deposit AA6061 aluminum alloy processed by additive friction stir deposition. *Materials Characterization*, 233, 116090. <https://doi.org/10.1016/j.matchar.2026.116090>
- Dong, X., Zhou, M., Geng, Y., Han, Y., Lei, Z., Chen, G. and Shi, Q. (2024). Recent advances in additive friction stir deposition: A critical review. *Materials*, 17(21), 5205. <https://doi.org/10.3390/ma17215205>
- Elshaghoul, Y.G.Y., El-Sayed Seleman, M.M., Bakkar, A., Elnekhaily, S.A., Albaijan, I., Ahmed, M.M.Z., Abdel-Samad, A. and Reda, R. (2023). Additive friction stir deposition of AA7075-T6 alloy: Impact of process parameters on the microstructures and properties of continuously deposited multilayered parts. *Applied Sciences*, 13(18), 10255. <https://doi.org/10.3390/app131810255>
- Gao, H., Dong, P. and Wei, Z. (2025). Microstructure and properties of 6061 aluminum alloy by additive friction stir deposition. *Metals*, 15(5), 539. <https://doi.org/10.3390/met15050539>
- Griffiths, R.J., Petersen, D.T., Garcia, D. and Yu, H.Z. (2019). Additive friction stir-enabled solid-state additive manufacturing for the repair of 7075 aluminum alloy. *Applied Sciences*, 9(17), 3486. <https://doi.org/10.3390/app9173486>
- Jiang, T., Zhang, M., Dai, G., Xie, Y., Zhang, Y., Guo, Y., Sun, Z. and Li, W. (2025). Microstructural evolution and mechanical properties of AA6061 aluminum alloy at various stages of additive friction stir deposition. *Journal of Alloys and Compounds*, 1039, 183015. <https://doi.org/10.1016/j.jallcom.2025.183015>
- Joshi, S.S., Patil, S.M., Mazumder, S., Sharma, S., Riley, D.A., Dowden, S., Banerjee, R. and Dahotre, N.B. (2022a). Additive friction stir deposition of AZ31B magnesium alloy. *Journal of Magnesium and Alloys*, 10(9), 2404–2420. <https://doi.org/10.1016/j.jma.2022.03.011>
- Joshi, S.S., Sharma, S., Radhakrishnan, M., Pantawane, M.V., Patil, S.M., Jin, Y., Yang, T., Riley, D.A., Banerjee, R. and Dahotre, N.B. (2022b). A multi modal approach to microstructure evolution and mechanical response of additive friction stir deposited AZ31B Mg alloy. *Scientific Reports*, 12, 13234. <https://doi.org/10.1038/s41598-022-17566-5>
- Kallien, Z., Rojas, V.A., Aspes, P., Swinney, A.N., Fleck, T.J., Jordon, J.B., Allison, P.G. and Klusemann, B. (2025). Additive friction stir deposition vs. friction surfacing: Comparison of friction stir-based approaches for groove repair of high strength aluminum alloys. *Materials & Design*, 258, 114511. <https://doi.org/10.1016/j.matdes.2025.114511>
- Korganci, M. and Bozkurt, Y. (2024). Recent developments in additive friction stir deposition (AFSD). *Journal of Materials Research and Technology*, 30, 4572–4583. <https://doi.org/10.1016/j.jmrt.2024.04.179>
- Kumar, J., Sharma, S., Mani Krishna, K.V., Joshi, S.S., Radhakrishnan, M., Patil, S.M. and Dahotre, N.B. (2026). Additive friction stir deposited AA-6061 alloy: Evolution of microstructure and mechanical properties. *Materials Science and Engineering A*, 956, 149917. <https://doi.org/10.1016/j.msea.2026.149917>
- Li, X., Li, X., Hu, S., Liu, Y. and Ma, D. (2024). Additive friction stir deposition: A review on processes, parameters, characteristics, and applications. *International Journal of Advanced Manufacturing Technology*, 133, 1111–1144. <https://doi.org/10.1007/s00170-024-13890-4>
- Mishra, R.S. and Ma, Z.Y. (2005). Friction stir welding and processing. *Materials Science and Engineering R: Reports*, 50(1–2), 1–78. <https://doi.org/10.1016/j.mser.2005.07.001>
- Paliwal, D. et al. (2024). In-situ monitoring of additive friction stir deposition of AA6061: Effect of rotation speed on the microstructure and mechanical properties. *Materials Science and Engineering A*, 902, 146620. <https://doi.org/10.1016/j.msea.2024.146620>
- Qiao, Q. et al. (2023). Quantitative study on the correlation between microstructure and mechanical properties of additive friction stir deposited 6061-T6 Al-Mg-Si alloy. *Journal of Materials Research and Technology*, 25, 6725–6736. <https://doi.org/10.1016/j.jmrt.2023.07.097>
- Qiao, Q. et al. (2024a). In-situ monitoring of additive friction stir deposition of AA6061: Effect of layer thickness on the microstructure and mechanical properties. *Additive Manufacturing*, 84, 104141. <https://doi.org/10.1016/j.addma.2024.104141>
- Qiao, Q., Tang, C.I., Lam, W.I., Pu, J., Shi, H., Qian, H., Li, Z., Guo, D., Zhang, D., Kwok, C.T. and Tam, L.M. (2024b). Effect of heat input on microstructure and mechanical properties of AA6061 alloys fabricated by additive friction stir deposition. *Journal of Materials Research and Technology*, 33, 6182–6195. <https://doi.org/10.1016/j.jmrt.2024.10.256>
- Qiao, Q. et al. (2025). In situ monitoring of temperature, force and torque in additive friction stir deposition of AA6061: Effect of rotational driving mode. *Materials Characterization*, 227, 115326. <https://doi.org/10.1016/j.matchar.2025.115326>
- Rathee, S., Srivastava, M., Maheshwari, S. and Siddiquee, A.N. (2021). Metal additive manufacturing using friction stir engineering: A review on microstructural evolution, tooling and design strategies. *CIRP Journal of Manufacturing Science and Technology*, 35, 560–588. <https://doi.org/10.1016/j.cirpj.2021.08.003>

- Shao, J., Samaei, A., Xue, T., Xie, X., Guo, S., Cao, J., MacDonald, E. and Gan, Z. (2023). Additive friction stir deposition of metallic materials: Process, structure and properties. *Materials & Design*, 234, 112356. <https://doi.org/10.1016/j.matdes.2023.112356>
- Sharma, S., Mani Krishna, K.V., Radhakrishnan, M., Pantawane, M.V., Patil, S.M., Joshi, S.S., Banerjee, R. and Dahotre, N.B. (2022). A pseudo thermo-mechanical model linking process parameters to microstructural evolution in multilayer additive friction stir deposition of magnesium alloy. *Materials & Design*, 224, 111412. <https://doi.org/10.1016/j.matdes.2022.111412>
- Srivastava, M., Rathee, S., Maheshwari, S., Noor Siddiquee, A. and Kundra, T.K. (2021). Friction stir additive manufacturing — An innovative tool to enhance mechanical and microstructural properties. *Materials Science and Engineering B*, 263, 114832. <https://doi.org/10.1016/j.mseb.2020.114832>
- Tam, C.W., Qiao, Q. and Chen, X. (2026). Prediction of the mechanical properties of additive friction stir-deposited Al2219 using machine learning. *Materials Genome Engineering Advances*, 4(1), e70046. <https://doi.org/10.1002/mgea.70046>
- Wang, Z. et al. (2024). Microstructure and localized corrosion properties of 2219 aluminum alloy manufactured by additive friction stir deposition. *Corrosion Science*, 240, 112508. <https://doi.org/10.1016/j.corsci.2024.112508>
- Williams, M.B., Robinson, T.W., Williamson, C.J., Kinser, R.P., Ashmore, N.A., Allison, P.G. and Jordon, J.B. (2021). Elucidating the effect of additive friction stir deposition on the resulting microstructure and mechanical properties of magnesium alloy WE43. *Metals*, 11(11), 1739. <https://doi.org/10.3390/met11111739>
- Yasa, E., Poyraz, O., Molyneux, A., Sharman, A., Bilgin, G.M. and Hughes, J. (2024). Systematic review on additive friction stir deposition: Materials, processes, monitoring and modelling. *Inventions*, 9(6), 116. <https://doi.org/10.3390/inventions9060116>
- Zeng, C., Ghadimi, H., Ding, H., Nematollahi, M. and Guo, S. (2022). Microstructure evolution of Al6061 alloy made by additive friction stir deposition. *Materials*, 15(10), 3676. <https://doi.org/10.3390/ma15103676>
- Zhou, Z., Shen, Y., Lyu, W., Xiong, W., He, Z., Lin, Y., Zhou, Z. and Guo, X. (2025). Interface stair-like design and repair performance of Al-Zn-Mg-Cu aluminum alloy based on additive friction stir deposition. *Journal of Materials Processing Technology*, 338, 118758. <https://doi.org/10.1016/j.jmatprotec.2025.118758>
- Zhou, Z., Shen, Y., Huang, J., Zhou, Z., Lyu, W. and Guo, X. (2026). Thermo-mechanical intermixing and interfacial metallurgical strengthening in 7075 feedstock repair of surface defects in 6061 aluminum via additive friction stir deposition. *Journal of Alloys and Compounds*, 1051, 185972. <https://doi.org/10.1016/j.jallcom.2026.185972>