

Review

Hybrid Additive Manufacturing via Wire Arc Metal Deposition and Deformation for Microstructure Refinement and Performance Enhancement: A Review

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Abstract

Wire Arc Additive Manufacturing (WAAM) is a cost-effective and scalable technique for producing large metallic components; however, coarse columnar microstructures, strong crystallographic texture, and significant residual stresses limit its widespread adoption. Hybrid WAAM processes that integrate deformation-based techniques have been developed to address these limitations. This review provides an analysis of deformation-assisted WAAM, covering interlayer rolling, friction stir processing (FSP), machine hammer peening, laser shock peening, and ultrasonic-vibration-assisted techniques. These hybrid techniques introduce additional thermomechanical parameters (strain, strain rate, and applied stress) that significantly influence microstructure evolution. The governing physical metallurgy mechanisms are discussed in detail, including dislocation accumulation, recovery, static and dynamic recrystallization, and severe plastic deformation. Studies from 2022 to 2025 are critically reviewed, highlighting the effectiveness of hybrid WAAM in promoting columnar-to-equiaxed grain transformation, reducing anisotropy, mitigating defects, and improving mechanical properties across aluminum, titanium, steels, and nickel-based alloys. The integration of auxiliary processes such as in situ machining and heat treatment is also discussed. This review establishes a process–structure–property framework for hybrid WAAM and provides guidance for the development of advanced additive manufacturing systems for the production of near-net-shape components, with reported yield-strength gains of 20–40%, elongation gains of 10–30%, and fatigue-life improvements of up to 60% relative to as-built WAAM.

Keywords: Wire Arc Additive Manufacturing; hybrid manufacturing; friction stir processing; interlayer rolling; dynamic recrystallization; severe plastic deformation; microstructure–property relationships



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1. Introduction

Wire Arc Additive Manufacturing (WAAM), a Directed Energy Deposition (DED)-based process, has established itself as a practical technique for producing medium- to large-scale metallic components with high deposition rates and excellent material utilization. Compared with powder-based additive manufacturing, WAAM offers advantages in cost efficiency, scalability, and deposition speed, making it particularly attractive for aerospace, marine, energy, and tooling applications [1–4]. Despite these advantages, conventional WAAM is associated with several metallurgical and geometric limitations that restrict its broader industrial adoption.

A primary challenge in WAAM is the formation of coarse columnar grains aligned along the build direction, driven by steep thermal gradients and epitaxial solidification during layer-by-layer deposition. These columnar structures are typically accompanied by strong crystallographic textures, leading to pronounced mechanical anisotropy and reduced structural reliability [5–7]. Repeated thermal cycling and high heat input promote residual stress accumulation, which can result in distortion, cracking, and reduced fatigue performance [8–10]. Process-induced defects, including porosity, lack of fusion, and surface waviness, further degrade component quality and necessitate extensive post-processing [11–13]. Among the available mitigation strategies, deformation-based approaches are uniquely suited to address these limitations because they directly disrupt epitaxial solidification, fragment dislocation cells, and introduce stored strain energy that drives recrystallization, whereas purely thermal control (such as interpass cooling or pulsed-arc modulation) cannot eliminate columnar growth on its own.

To overcome these limitations, significant research has been directed toward hybrid WAAM processes that integrate mechanical deformation, and in some cases subtractive machining, into the additive manufacturing workflow. Deformation-assisted techniques (including interlayer rolling, hammer peening, friction stir processing (FSP), and ultrasonic vibration) introduce controlled plastic strain during or between deposition passes, promoting grain refinement, texture randomization, defect closure, and improved mechanical performance [14–18].

Hybrid WAAM approaches activate fundamental metallurgical mechanisms such as dynamic recrystallization (DRX) and severe plastic deformation (SPD). Interlayer rolling introduces sufficient stored strain energy to promote recrystallization during subsequent thermal cycles, leading to fine equiaxed grain structures and reduced anisotropy [19]. FSP applied to WAAM deposits eliminates porosity and produces ultrafine grains through intense shear deformation and DRX [20]. Ultrasonic vibration-assisted WAAM, where acoustic cavitation and streaming effects enhance melt pool convection and nucleation, has also shown promising grain refinement results [21,22].

This review systematically examines deformation-assisted WAAM, focusing on hybrid processing strategies incorporating deformation, fundamental microstructure evolution mechanisms under different thermomechanical conditions, and their implications for mechanical performance across major alloy systems. Relative to the most recent overlapping reviews [10,20–22], the specific contributions of the present work are: (i) a strain–temperature map that consolidates the operating regions of the five hybrid techniques onto a common normalized axis; (ii) cross-alloy comparative tables that allow direct comparison of microstructural and mechanical outcomes across aluminum, titanium, steels, and nickel-based systems; and (iii) an explicit linkage between the Zener–Hollomon parameter and the dominant microstructure-evolution mechanism for each technique. These elements are presented as a guidance tool for process selection and qualitative comparison, rather than as a quantitative predictive model for hybrid WAAM process design.

This review is organized as follows. Section 2 introduces the fundamentals of WAAM thermophysics. Section 3 describes hybrid deposition–deformation processes. Section 4 covers alloy-specific microstructure evolution. Section 5 presents the physical mechanisms of microstructure evolution. Section 6 discusses mechanical property improvements. Section 7 addresses the integration of auxiliary processes. Section 8 presents challenges and future outlook. Section 9 provides conclusions. Methodology and scope. The literature reviewed in this work was identified through Web of Science, Scopus, and Google Scholar searches combining the terms “Wire Arc Additive Manufacturing” or “WAAM” with each of the deformation techniques discussed (interlayer rolling, hammer peening, friction stir processing, laser shock peening, ultrasonic vibration). The primary date range was 2020–2025, with seminal pre-2020 references retained for foundational mechanisms (Hall–Petch, Kocks–Mecking, Kurz–Fisher, Olson–Cohen). Inclusion criteria were peer-reviewed primary research; review articles are included only when explicitly distinguished from primary studies. The alloy-family scope covers aluminum, titanium, steels, nickel-based superalloys, and (in this revision) magnesium and bimetallic systems.

Wire Arc Additive Manufacturing Within the Metal Additive Manufacturing Landscape

Metal additive manufacturing comprises a family of layer-wise processes broadly grouped into powder-bed fusion (PBF), Directed Energy Deposition (DED), and binder-jet/sheet-lamination variants. Within DED, WAAM uses an electric arc and a continuously fed wire feedstock, distinguishing it from powder-fed laser-DED and electron-beam variants by its higher deposition rate, lower capital cost, and preference for medium-to-large structural parts.

Compared with laser PBF, WAAM offers deposition rates one-to-two orders of magnitude higher (approximately 3–6 kg/h for WAAM vs. approximately 0.05–0.5 kg/h for PBF), at the expense of geometric resolution and surface finish. This trade-off positions WAAM as a near-net-shape technology for components in which the post-processing cost is justified by gains in deposition speed and feedstock economy.

Representative industrial application domains for WAAM include large aerospace structural members (wing ribs, bulkheads, and demonstrator landing-gear features [23]), marine and offshore structural panels, energy-sector heat-exchanger and pressure-vessel components, and tooling repair. The metallurgical limitations of conventional WAAM, namely coarse columnar microstructures, residual stresses, and strong texture, motivate the deformation-assisted hybrid strategies that are the subject of this review. Figure 1 summarizes the position of WAAM within the broader metal additive manufacturing landscape, the principal hybrid deformation-assisted variants covered in this work, and their associated microstructural and industrial outcomes.

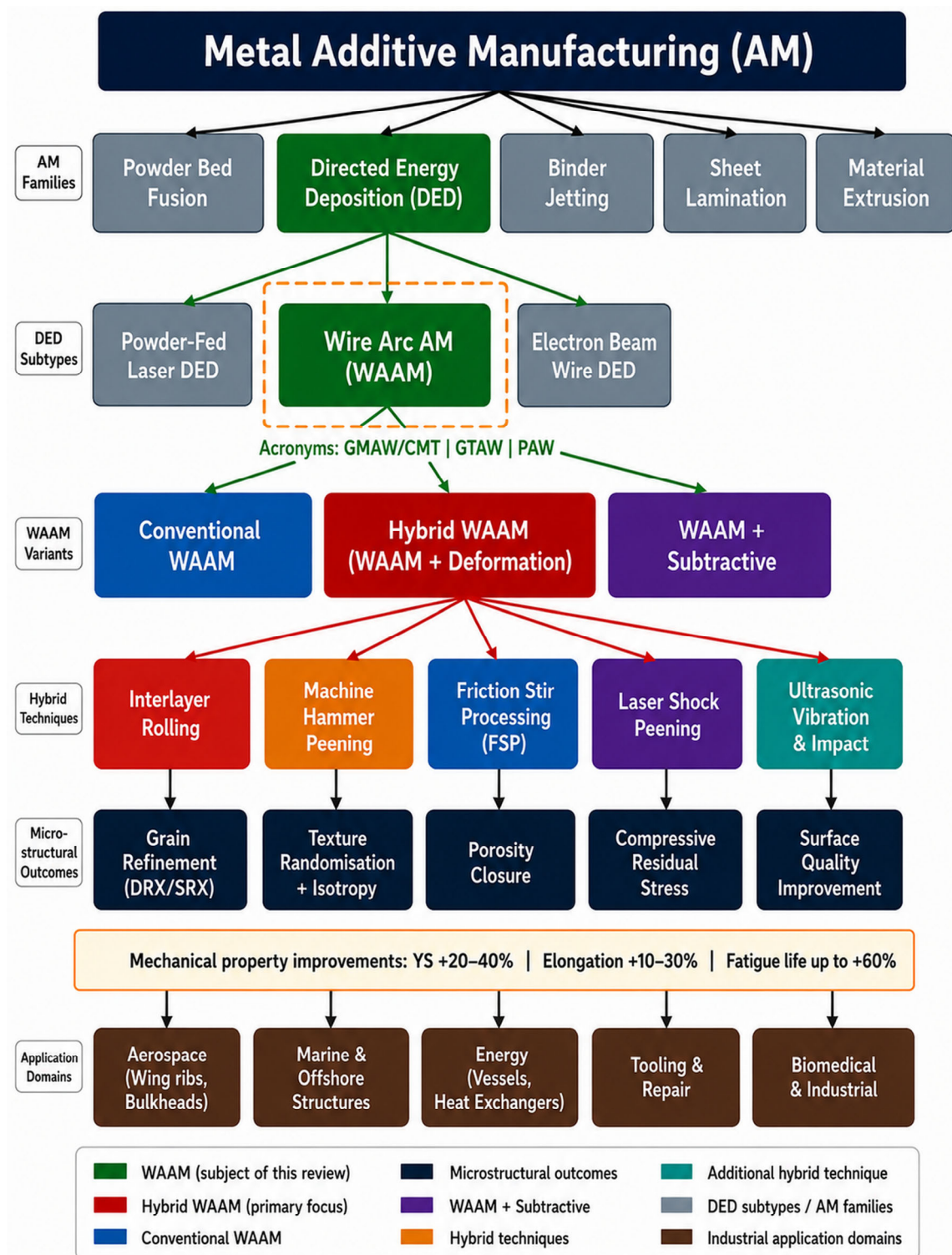


Figure 1. Classification of metal additive manufacturing (AM) processes, showing the position of Wire Arc Additive Manufacturing (WAAM) within the Directed Energy Deposition (DED) family, the principal hybrid deformation-assisted WAAM variants (primary focus of this review, highlighted in red), their microstructural outcomes, and representative industrial application domains.

2. Fundamentals of Wire Arc Additive Manufacturing and Thermophysical Characteristics

Wire Arc Additive Manufacturing is a Directed Energy Deposition process that uses an electric arc as a heat source and a continuously fed metallic wire as feedstock. It is typically

implemented using gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), or plasma arc welding (PAW) variants, including advanced modes such as cold metal transfer (CMT) and pulsed arc techniques. The thermophysical characteristics of WAAM are governed by high heat input, relatively low cooling rates, and steep directional thermal gradients, which collectively dictate solidification behavior and microstructure evolution.

During deposition, the melt pool experiences strong thermal gradients (G) and solidification rates (R), which determine the solidification mode according to the classical G/R criterion. High G/R ratios promote epitaxial columnar growth along the maximum thermal gradient direction, typically aligned with the build direction. Consequently, WAAM components frequently exhibit coarse columnar dendritic microstructures with pronounced crystallographic textures, particularly $\langle 100 \rangle$ or $\langle 110 \rangle$ orientations in cubic alloys [24–26].

Repeated thermal cycling inherent to WAAM further complicates microstructure evolution. Each newly deposited layer reheats previously solidified material, leading to complex thermal histories characterized by partial remelting, solid-state phase transformations, and cyclic recovery processes. These cycles can result in heterogeneous microstructures, including banded structures, heat-affected zones, and variations in grain size and morphology along the build height [27–29].

From a thermomechanical perspective, WAAM generates significant residual stresses due to non-uniform thermal expansion and contraction. Tensile residual stresses, particularly in the longitudinal direction, can lead to distortion, cracking, and reduced fatigue performance [30–32]. In addition, WAAM is susceptible to process-induced defects including porosity, surface waviness, and stair-stepping. These defects act as stress concentrators and can significantly degrade mechanical performance under cyclic loading [33–35]. Advanced process control strategies have been shown to reduce defect formation and improve microstructural uniformity; however, purely thermal control approaches are often insufficient to eliminate columnar grain growth and anisotropy, necessitating deformation-based hybrid processing strategies [36–38].

3. Hybrid WAAM Processes with Interlayer Deformation

Hybrid WAAM processes incorporate controlled plastic deformation into the layer-wise deposition sequence to modify both solidification behavior and subsequent solid-state microstructure evolution. Unlike conventional WAAM, where microstructure is primarily governed by thermal gradients and cooling rates, hybrid approaches introduce an additional degree of freedom through strain, strain rate, and stress, enabling thermomechanical control of grain structure, defect evolution, and residual stress state. The effectiveness of these processes arises from the interplay between strain-induced defect generation and thermally activated restoration mechanisms, including recovery and recrystallization.

Deformation mechanisms in hybrid WAAM can be broadly categorized by mode of strain application: compressive deformation (e.g., interlayer rolling), which introduces relatively uniform plastic strain across the deposited layer; localized impact deformation (e.g., hammer peening and ultrasonic impact), which generates high strain rates and near-surface plastic deformation; severe plastic deformation (e.g., FSP), characterized by intense shear deformation and large accumulated strains; and oscillatory or high-frequency deformation (e.g., ultrasonic vibration), which introduces cyclic stresses and modifies melt pool dynamics and solidification behavior. Each mode results in distinct strain distributions, strain rates, and thermal–mechanical interactions, leading to different microstructural outcomes.

3.1. Interlayer Rolling: Compressive Thermomechanical Processing

Interlayer rolling is one of the most extensively studied hybrid WAAM techniques, characterized by the application of compressive plastic deformation using rollers immediately after or between deposition passes. Hot interlayer rolling is applied at temperatures above the recrystallization temperature with limited intermediate cooling, while cold or warm rolling is applied after the deposited layer has cooled to a lower temperature; both modes are reported in the literature, and the choice influences the dominant restoration mechanism. The rolling process introduces relatively uniform plastic strain across the deposited bead, with strain magnitudes typically in the range of 5–30%, depending on roller geometry, applied load, and interpass temperature.

From a mechanistic standpoint, interlayer rolling increases dislocation density within the as-deposited microstructure, leading to significant strain hardening and accumulation of stored energy that serves as the driving force for subsequent recrystallization during thermal cycling. In alloys such as Ti-6Al-4V, steels, and aluminum alloys, rolling-induced deformation has been shown to disrupt epitaxial grain growth, promoting the transformation from columnar to equiaxed grain structures [35,36]. Gornyakov et al. [35] developed a coupled thermo-mechanical finite element model for in-process interlayer rolling during WAAM of a steel wall, showing that a slotted roller reduces tensile residual stress from approximately 500 MPa in the as-deposited condition to approximately 3 MPa in the rolled condition by the 9th layer (the prediction was validated against neutron-diffraction measurements as reported in the source) and limiting wall widening and reducing shape distortion. Rolling also contributes to defect mitigation by mechanically closing pores and enhancing interlayer bonding, reducing lack-of-fusion defects and improving structural integrity. The optimum rolling strain window is alloy- and feedstock-specific: reported optima for aluminum alloys [34] and Ti-6Al-4V [39] differ in magnitudes and in the temperature regime at which rolling is applied, reflecting differences in stacking-fault energy, recrystallization temperature, and dynamic-recovery rate rather than a fundamental disagreement about the rolling mechanism.

Process sensitivity. The optimum rolling strain magnitude is alloy-, feedstock-, and roller-geometry-specific. For Ti-6Al-4V and steels, rolling is typically applied at sub-recrystallization or $\alpha + \beta$ temperatures, where mixed discontinuous and continuous DRX are activated; for high-stacking-fault-energy aluminum alloys, the choice between hot and cold rolling shifts the dominant restoration mechanism between dynamic recovery and post-rolling static recrystallization (SRX) during interpass reheating. Comparison of optimum strain windows across studies must therefore control roller geometry, applied load, interpass temperature, and the alloy-specific recrystallization temperature, since the same nominal rolling reduction can yield different recrystallized fractions in different alloy systems. A representative hybrid interlayer hot-rolling WAAM configuration is shown in Figure 2.

3.2. Hammer Peening and Mechanical Impact: High Strain-Rate Deformation

Machine hammer peening (MHP) and related mechanical impact techniques introduce localized plastic deformation through repeated high-frequency impacts applied to the deposited surface. Unlike rolling, hammer peening generates high strain-rate deformation (typically 10^2 to 10^4 s⁻¹) concentrated in the near-surface region [38]. The high strain rates lead to rapid dislocation multiplication and formation of dense dislocation networks that can evolve into refined subgrain structures. A key advantage is the ability to introduce compressive residual stresses in the surface region, counteracting tensile stresses generated during WAAM deposition and significantly enhancing fatigue performance by delaying crack initiation and propagation [38,40]. Mechanical impact processes can also influence so-

lification behavior; impact-induced vibrations can disrupt dendritic growth and promote grain refinement, particularly in alloys with high susceptibility to hot cracking [40].

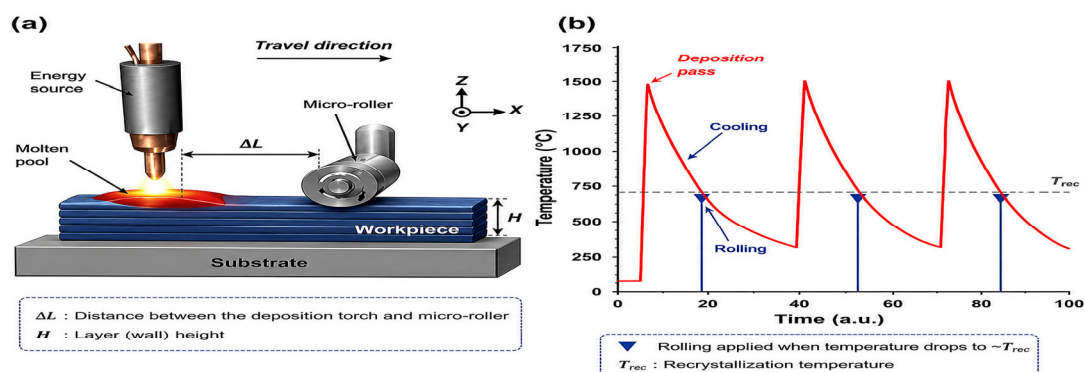


Figure 2. Schematic illustration of hybrid interlayer hot rolling and WAAM: (a) sequential deposition and roller engagement during in-process rolling; (b) representative interpass thermal profile, with rolling applied after the deposit temperature drops below the recrystallization threshold.

Process sensitivity. The depth and magnitude of the surface compressive residual-stress field induced by hammer peening scale with the impact energy, frequency, and overlap pattern. Reported outcomes are sensitive to substrate temperature: peening at near-ambient temperatures predominantly drives surface dislocation strengthening, whereas peening on a still-hot deposit can additionally activate near-surface recovery and partial recrystallization. The principal limitation is the depth of the affected zone, typically less than 0.5 mm; bulk grain refinement requires either FSP or repeated peening on partially completed layers. A representative robotic MHP-assisted WAAM system, the peening tooling, and characteristic surface modification produced on the deposited layers are shown in Figure 3.

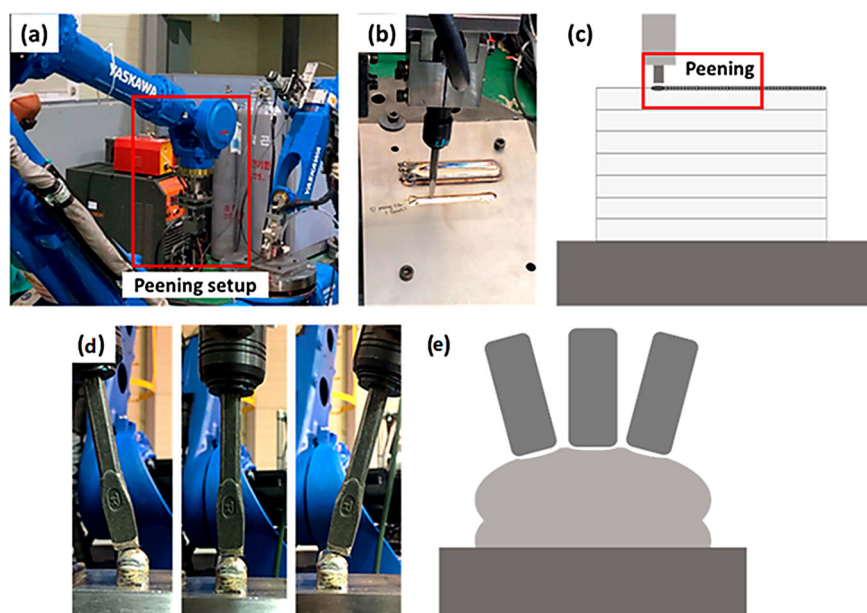


Figure 3. Machine hammer peening (MHP)-assisted WAAM system and representative peening characteristics: (a) robotic MHP setup integrated with the WAAM system, with the red box indicating the location of the peening tool; (b) close-up view of the hammer peening tool; (c) schematic of the interlayer peening operation, with the red rectangle marking the peened region on the deposited wall; (d) representative photographs of the robotic peening operation at sequential positions on the deposited layer; (e) schematic illustration of the peened bead morphology after interlayer peening. Adapted from Ref. [40].

3.3. Friction Stir Processing (FSP): Severe Plastic Deformation and Material Flow

Friction stir processing represents a severe plastic deformation technique successfully integrated into WAAM workflows. A rotating tool traversing the deposited layer generates intense shear deformation and frictional heating. The combined effects of high strain (typically greater than 100%) and elevated temperature result in extensive microstructural modification through continuous dynamic recrystallization (CDRX), leading to the formation of ultrafine equiaxed grains, often in the range of 1–10 μm [27,28]. FSP also promotes significant microstructural homogenization: the intense material flow redistributes second-phase particles, breaks up intermetallic networks, and eliminates porosity, resulting in improved strength, ductility, and fatigue resistance. The effectiveness of FSP is highly sensitive to tool rotational speed, traverse speed, and plunge depth, which control the strain rate and temperature field that in turn determine the extent of recrystallization and grain refinement [27,41].

FSP, despite the substantial benefits described above, also introduces process-specific risks that must be controlled. Insufficient tool plunge depth or excessive traverse speed can leave residual root defects (lack-of-bonding at the tool root), kissing bonds, or tunnel defects along the advancing side of the stir zone, which act as fatigue-crack initiation sites. Excessive shoulder engagement can thin the deposited bead and introduce subsurface flash. Tool wear and contamination can transfer iron-bearing intermetallics into aluminum alloys, locally embrittling the stirred zone. The optimum process window is therefore alloy- and feedstock-specific, and direct comparison of grain sizes or property gains across studies must control for tool geometry, plunge depth, traverse speed, rotational speed, and substrate temperature.

Process sensitivity. The dominant grain-refinement outcome of FSP scales with the imposed strain rate and stir-zone temperature, which are jointly set by tool rotational speed, traverse speed, and shoulder geometry. For high-stacking-fault-energy aluminum alloys, continuous dynamic recrystallization (CDRX) governs the bulk of the stir zone and produces the characteristic equiaxed micrometric grain structure; for low-to-medium stacking-fault-energy (SFE) systems, discontinuous dynamic recrystallization (DDRX) becomes more competitive. The reported tool-rotational-speed dependence of grain size in 205A aluminum [42] and Al-Cu-Sc [43] differs in trend; this difference is attributed to differences in tool geometry, base-alloy chemistry, and substrate temperature rather than to a fundamental disagreement about the FSP mechanism. Cross-laboratory comparison of FSP-WAAM outcomes must therefore control tool geometry, plunge depth, traverse speed, rotational speed, and substrate temperature. Figure 4 shows the schematic representation of friction stir additive manufacturing, illustrating tool rotation, axial force, material flow, and nugget formation during layer-by-layer processing. The experimental hybrid WAAM–FSP system developed by the authors on a HAAS VF-3 CNC platform is shown in Figure 5.

3.4. Laser Shock Peening (LSP): Deep Compressive Residual Stress Induction

High-energy pulse laser beams generate plasma shock waves that propagate into the deposited layer, inducing deep compressive plastic deformation (up to 1–2 mm depth) without solid tool contact. The strain rate can be extremely high (greater than 10^6 s^{-1}) while the temperature remains near ambient. Thangamani et al. [44] studied hybrid WAAM–LSP processing of NiTi shape memory alloys and reported that LSP progressively refined grains, reduced porosity from 13.08% to 4.10%, and significantly increased ultimate tensile strength (UTS) from 217 MPa to 426 MPa at the highest peening intensity. Sun et al. [45] demonstrated that LSP applied to WAAM-fabricated 2319 aluminum transformed tensile residual stresses into beneficial compressive stresses, resulting in greatly enhanced fatigue performance.

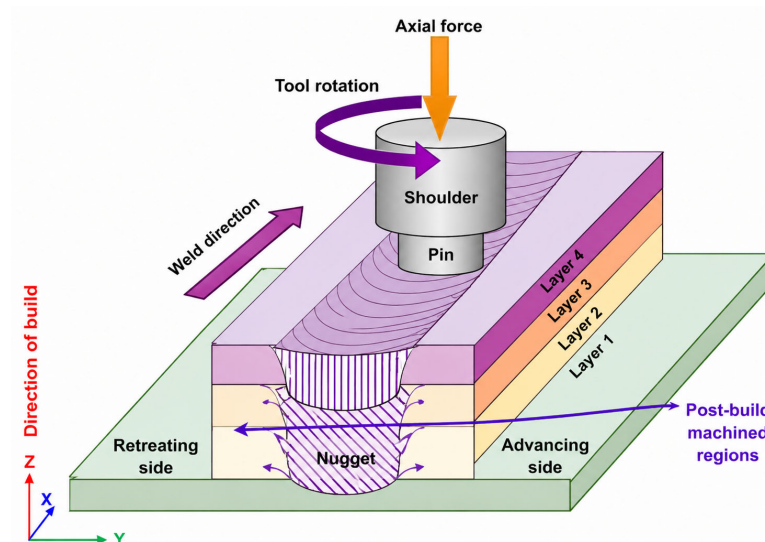


Figure 4. Schematic illustration of friction stir additive manufacturing (FSPAM), showing the rotating tool, axial force, material flow behavior, nugget formation, deposited layers, and advancing/retreating sides during layer-by-layer processing.

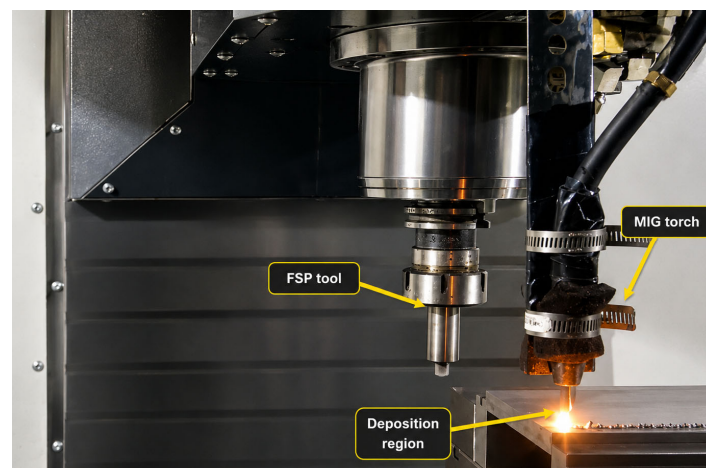


Figure 5. Experimental hybrid Wire Arc Additive Manufacturing–friction stir processing (WAAM–FSP) system developed using a HAAS VF-3 CNC platform (Haas Automation, Inc., Oxnard, CA, USA) retrofitted with a Power MTS 211Si MIG welding torch (Everlast Power Equipment Inc., South San Francisco, CA, USA) and friction stir processing tooling. The MIG torch was mounted adjacent to the spindle assembly, while the FSP tool was installed directly in the spindle to enable integrated additive deposition followed by interlayer friction stir processing (FSP) within the same manufacturing platform.

Mechanism. The LSP process operates on a confined-plasma principle. A short laser pulse (typically 5–30 ns) is focused onto an absorbing overlay (a sacrificial paint or metal foil) that vaporizes into a high-pressure plasma; a transparent confining layer (water curtain or glass) traps the plasma against the workpiece, generating a shock wave with peak pressures in the range of several GPa. The pressure pulse propagates through the substrate as a longitudinal stress wave, plastically deforming the surface layer when the local stress exceeds the dynamic yield strength. The combined absorbing-overlay/water-confinement geometry distinguishes LSP from direct-ablation laser peening and is the source of its capacity to introduce compressive residual stresses to depths of 1–2 mm without thermal damage to the substrate (Munther et al. [46]; Ermakova et al. [47]).

Process window and outcomes. LSP outcomes scale with laser fluence (typically $1\text{--}15\text{ GW cm}^{-2}$), pulse duration, spot overlap, and the absorbing-overlay/confinement-layer pair. In WAAM-fabricated structural alloys, reported outcomes include compressive residual-stress fields of $100\text{--}400\text{ MPa}$ in magnitude extending $0.5\text{--}1.5\text{ mm}$ below the surface, reduced surface porosity, and grain refinement in the near-surface region driven by shock-induced dislocation multiplication and dynamic recrystallization. The combined effects translate to fatigue-life improvements of $1.5\text{--}3\times$ over the as-built condition for aluminum and titanium WAAM systems [45–47]. The principal trade-off is process throughput, since LSP is currently slower than rolling or peening for large area coverage and requires line-of-sight access to the surface.

Process sensitivity. LSP outcomes are highly sensitive to the absorbing-overlay choice (paint vs. metal foil vs. ablation), the laser fluence, the spot overlap, and the confining-water-layer thickness. Cross-laboratory comparison of reported residual-stress depths must control for these parameters, since otherwise apparent differences in the response of nominally identical materials can be attributed entirely to process settings rather than to the alloy.

3.5. Ultrasonic Vibration-Assisted WAAM: Coupled Solidification-Deformation Control

Ultrasonic vibration-assisted WAAM simultaneously influences liquid-phase solidification and solid-state deformation. High-frequency vibrations (typically $20\text{--}40\text{ kHz}$) are introduced into the melt pool or substrate during deposition. The governing mechanisms are acoustic cavitation, acoustic streaming, and oscillatory stress fields, which collectively promote the columnar-to-equiaxed transition during solidification. Experimental studies have shown that ultrasonic vibration can significantly refine grain size in WAAM deposits, with reductions exceeding $50\text{--}80\%$ in certain alloy systems [48,49]. The cyclic nature of ultrasonic loading can also accelerate dislocation rearrangement and promote dynamic recovery and recrystallization under appropriate conditions.

Cavitation and streaming mechanisms. Acoustic cavitation refers to the nucleation, growth, and collapse of microbubbles in the melt pool driven by pressure oscillations at the imposed acoustic frequency. The collapse of these bubbles generates local shock waves and microjets that fragment growing dendrites and supply additional nucleation sites, promoting the columnar-to-equiaxed transition. Acoustic streaming refers to the steady fluid flow driven by acoustic energy gradients; it homogenizes the temperature and solute fields within the melt pool and reduces the steep thermal gradients that normally drive epitaxial columnar growth. The two mechanisms operate concurrently, and their relative contribution depends on the acoustic intensity, the melt-pool size, and the alloy solidification range.

Solid-state effects and reported outcomes. After solidification, the imposed cyclic stresses continue to influence the as-deposited microstructure through dislocation rearrangement and accelerated dynamic recovery. Liu et al. [48] applied interlayer ultrasonic-impact treatment to CMT-based WAAM AZ31 magnesium walls and reported substantial grain refinement and improved corrosion resistance through cavitation-assisted nucleation. Su et al. [49] applied multiple ultrasonic-impact modes to WAAM 18Ni-300 maraging-steel deposits and reported refined martensitic laths and improved tensile and fatigue properties. The principal limitations of ultrasonic-assisted WAAM are the difficulty of coupling acoustic energy efficiently into a moving melt pool, the wear of the sonotrode under repeated thermal cycling, and the limited penetration depth in thick deposits.

Process sensitivity. Reported grain-refinement and cavitation effects in ultrasonic-assisted WAAM are highly sensitive to the acoustic frequency, amplitude, and the coupling between the sonotrode and the workpiece. Direct comparison of reported refinement ratios across studies must therefore control for these factors, alongside the alloy-specific solidification range and melt-pool geometry.

3.6. Comparative Perspective on Hybrid Deformation Techniques

Each deformation-assisted WAAM technique offers distinct advantages: interlayer rolling delivers uniform bulk deformation and effective residual stress control; hammer peening offers high strain-rate surface modification and improved fatigue resistance; FSP produces severe plastic deformation and ultrafine grain structures; LSP achieves deep compressive residual stress fields without thermal damage; and ultrasonic vibration enables coupled melt pool and solid-state control. Despite their demonstrated benefits, each technique presents inherent limitations that must be carefully considered based on material system, component geometry, required performance, and production constraints. Table 1 summarizes the key characteristics of each approach.

Table 1. Comparison of hybrid WAAM deformation techniques. RS = residual stress; DRX = dynamic recrystallization; SRX = static recrystallization; CDRX = continuous DRX; CET = columnar-to-equiaxed transition.

Technique	Deformation Mode	Dominant Mechanism	Microstructure Effect	Key Benefit
Interlayer Rolling	Compressive strain	DRX/SRX	Equiaxed grains	Residual stress reduction
Hammer Peening	Impact deformation	Dislocation strengthening	Surface refinement	Fatigue improvement
FSP	Severe plastic deformation	CDRX	Ultrafine grains	Homogenization
LSP	Shock/non-contact	Subsurface DRX	Deep compressive RS	Fatigue and corrosion resistance
Ultrasonic Vibration	Oscillatory + cavitation	CET + cyclic plasticity	Grain refinement	Defect reduction

Per-alloy preferences. The choice among the five hybrid techniques is alloy-dependent and is governed by the dominant restoration mechanism active at the technique's operating conditions. For high-stacking-fault-energy aluminum alloys, FSP is the preferred route because continuous DRX dominates the stir-zone microstructure and produces the largest grain refinement at moderate processing temperatures. For titanium alloys (Ti-6Al-4V) and structural steels, interlayer rolling at sub-recrystallization or $\alpha + \beta$ temperatures is the most effective route; mixed discontinuous and continuous DRX is activated, and the rolling-induced compressive residual stresses additionally counteract the WAAM tensile-stress field. For nickel-based superalloys (Inconel 625, 718), interlayer rolling combined with a tailored post-deformation heat treatment is preferred; rolling fragments the as-deposited columnar dendrites and the subsequent solution-and-aging cycle redistributes the Laves phase and re-precipitates γ'/γ'' . Hammer peening and laser shock peening are best applied as surface-engineering supplements that improve fatigue performance, rather than as bulk grain-refinement strategies. The cross-alloy preferences are summarized in Section 6.1 and reflected in Tables 2 and 3.

Table 2. Summary of deformation influence on hybrid WAAM microstructure across alloy families.

Alloy Family	As-Deposited Microstructure	Deformation Response	Key Microstructural Evolution	Key References
Al alloys	Columnar grains (often mixed), porosity/hydrogen defects, coarse intermetallic networks	High	cDRX/DRX, ultrafine/equiaxed grains; porosity elimination; improved homogeneity	[25–27,33,41,50–53]
Ti alloys	Coarse epitaxial prior-beta columnar grains; α' martensite/lamellar alpha; anisotropy + residual stress	Very high	DRX/recrystallization; finer/more equiaxed microstructure; texture reduction; improved isotropy/ductility	[10,38,39,54,55]
Steels/stainless steels	Columnar ferrite/austenite/martensite; texture; residual stress; thermal-history sensitivity	Moderate	Moderate grain refinement; peening/LSP near-surface refinement + compressive residual stresses	[13,23,36,37,40,49,56]
Ni-based superalloys	Columnar gamma/dendritic solidification; segregation; Laves formation; sluggish recrystallization	Limited to moderate	Limited bulk grain refinement; rolling/FSP reduce segregation; peening/LSP deep compressive residual stress	[6,46,56–63]

Table 3. Representative hybrid WAAM-based studies and their key outcomes. FSP = friction stir processing; USI = ultrasonic impact treatment; HT = heat treatment; MHP = machine hammer peening; LSP = laser shock peening; RS = residual stress; HV = Vickers hardness.

Process	Material	Key Outcomes	Ref.
FSP	Al-Mg/SiC nanocomposite	Ceramic-reinforced nanocomposite wall with refined microstructure, reduced porosity, improved strength and hardness	[25]
FSP	AA2319 (Al-Cu)	Multi-pass stirring refined grains to 3.4 μm ; UTS ~193 MPa, hardness ~90 HV	[27]
FSP	Al-Cu-Sc	Sc microalloying + FSP: UTS > 300 MPa, improved plasticity and reduced anisotropy	[43]
FSP	AA4043 (Al-Si)	Refined uniform equiaxed grains by DRX, hardness increased by ~46%	[41]
FSP	Al-Zn-Mg-Cu + HEA	Grain refined to ~2.3 μm ; UTS ~374 MPa, elongation ~10.6%, HV ~152	[64]
Hot rolling	Al-Mg	Interlayer hot rolling homogenized strain distribution, improved work-hardening and ductility	[34]
Cold/hot rolling + HT	AA2219	Elongation increased by 35–54% after heat treatment; strength maintained	[65]

Table 3. Cont.

Process	Material	Key Outcomes	Ref.
Cold rolling + HT	Inconel 718	Low-cycle fatigue life increased after aging; grain refinement and fragmented Laves phase	[62]
In situ rolling	Al-Si	Refined primary Si and alpha-Al grains, reduced porosity, increased strength and ductility	[66]
Interlayer rolling	S355 steel	Slotted roller reduced tensile residual stress from 500 MPa to ~3 MPa in 9th layer	[35]
USI	AZ31 Mg alloy	Refined grain structure, compressive residual stresses; improved corrosion resistance, strength, fatigue life	[48]
MHP	Ti-6Al-4V	Grain refinement, transformed tensile RS to compressive; enhanced fatigue life without additional HT	[38]
Hot forging	Ti-6Al-4V	Forging at 920 °C: DRX, equiaxed alpha, weakened texture, increased strength and elongation	[23]
LSP	AA2319	Transformed tensile to compressive residual stresses; greatly enhanced fatigue life	[45]

4. Microstructure Evolution in Major Alloy Systems

4.1. Microstructure Evolution Mechanisms

In hybrid WAAM, the thermodynamics and physical metallurgy principles remain the same as in traditional manufacturing, but several distinctive characteristics apply. The processing zone is often spatially confined and produces steep gradients in both temperature and deformation. Materials experience multiple thermomechanical cycles spanning wide domains of strain, temperature, and time, and the final microstructure is the integrated result of all cycles. The stacking-fault energy (SFE) governs the dominant deformation mechanism and post-deformation microstructural changes.

The classical metallurgical phenomena active in hybrid WAAM, in order of increasing processing temperature, are: strain hardening at low deformation temperatures (characterized by increased dislocation density and stored energy described by $E_s = \frac{1}{2}Gb^2\rho$, where G is shear modulus, b is the Burgers vector, and ρ is dislocation density); annealing (recovery) at approximately 0.2 to 0.4 T_m ; static recrystallization (SRX) above approximately 0.5 T_m with sufficient prior strain, with kinetics following $X = 1 - \exp[-(kt)^n]$; and dynamic recrystallization (DRX) in hot deformation above 0.5 T_m , subdivided into discontinuous (dDRX) and continuous (cDRX) variants, the latter prevalent in high-SFE metals such as aluminum. Figure 6 presents the strain–temperature framework as a schematic map of the dominant microstructure-evolution mechanisms across the operating windows of the hybrid WAAM techniques. Figure 6 presents the strain–temperature framework as a schematic map of the dominant microstructure-evolution mechanisms across the operating windows of the hybrid WAAM techniques.

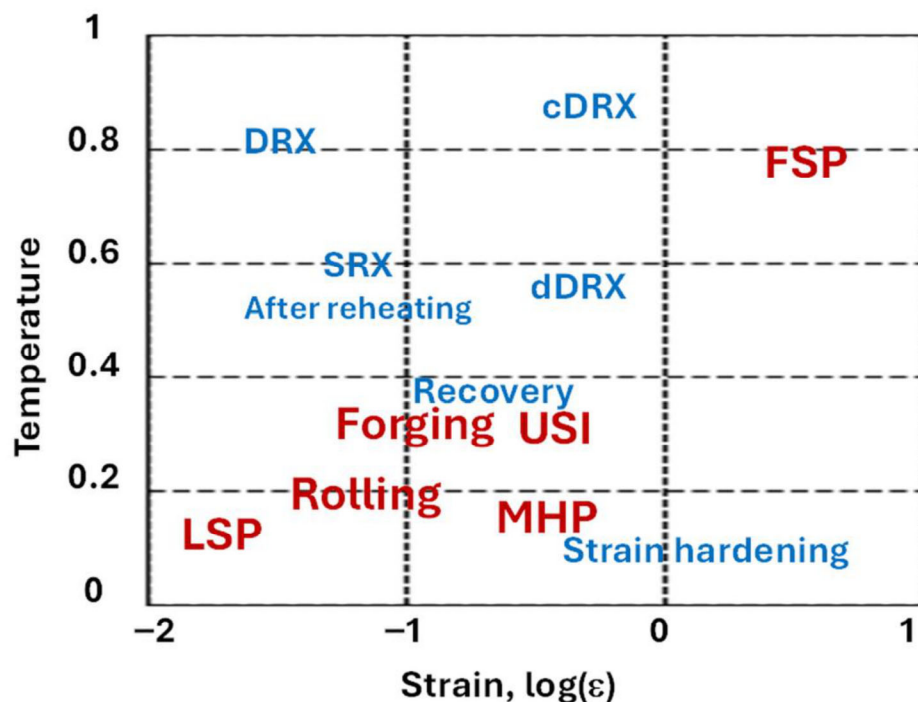


Figure 6. Schematic strain–temperature framework illustrating dominant microstructure evolution mechanisms in hybrid WAAM. Different deformation processes occupy distinct regions of the map, leading to varying contributions of strain hardening, recovery, static recrystallization (SRX), and dynamic recrystallization (DRX; d = discontinuous; c = continuous). Constructed by the authors as a synthesis of the deformation-mechanism boundaries reprinted from Refs. [19,22,67–69]; T/T_m homologous-temperature normalization applied for transferability across alloy systems.

4.2. Aluminum Alloys

Aluminum alloys in WAAM frequently develop coarse columnar grains and high porosity due to their high thermal conductivity, fluid melt pools, and sensitivity to hydrogen pickup [50]. CMT-based WAAM walls of 2319 aluminum alloy exhibit mixed columnar and equiaxed grains with θ/θ' precipitates, retaining approximately 72% of the tensile strength and about 65% of the fatigue strength of wrought AA2219 in the T62 (solution-treated and artificially aged) condition [51,70]. Combining WAAM with interlayer FSP on 2319 aluminum generates a vertical gradient microstructure with ultrafine grains near the processed surface, increasing the DRX fraction to approximately 62% and substantially refining grains by approximately 87% [52].

Elalem and Wu [41] compared metal inert gas (MIG)-based WAAM of 4043 aluminum alloy with a hybrid MIG-WAAM plus FSP route, in which FSP was applied immediately behind the advancing MIG deposition torch on the deposited layer. In the WAAM-only wall, interlayer heat accumulation promoted coarse, partially dendritic grains that coarsened with build height. In contrast, MIG-FSP imposed severe plastic deformation dominated by shear strain at a high strain rate; DRX produced consistently fine equiaxed grains (a few micrometers in diameter) across all layers with a more isotropic morphology, resulting in a 45.8% increase in microhardness (75.8 ± 7.7 HV for the unified additive–deformation manufacturing process (UAMFSP) vs. 52.0 ± 1.3 HV for MIG, $n = 27$ measurements per condition, transverse direction; $p = 0.0027$) compared with the WAAM-only wall. Figure 7 shows the experimental setup, the comparative grain-area distribution between MIG and MIG+FSP walls, and representative thermal contour maps recorded during fabrication.

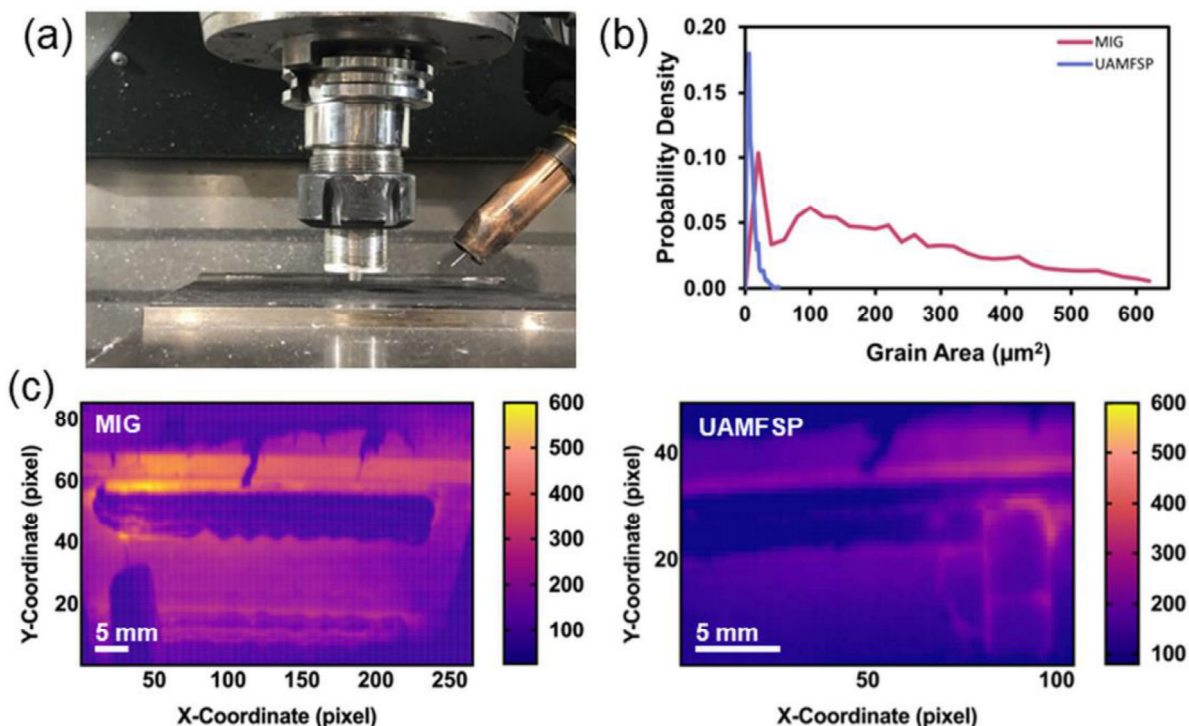


Figure 7. (a) Experimental setup consisting of MIG welder (Power MTS 211Si spool gun; Everlast Power Equipment Inc., South San Francisco, CA, USA) and FSP tool mounted on a CNC machining center (HAAS VF3, Haas Automation, Inc., Oxnard, CA, USA); (b) comparative probability density distributions of 2D grain area for MIG only and MIG + FSP (hybrid AM), showing a strong shift toward a narrow distribution of fine grains; (c) representative infrared thermographic temperature contour maps comparing thermal fields during fabrication. Reprinted from Ref. [41]. UAMFSP = unified additive–deformation manufacturing process.

Ma et al. [42] applied FSP to WAAM-fabricated 205A Al-Cu alloy, refining grains from approximately 22.8 μm to less than 5 μm , largely dissolving eutectic structures, and eliminating pore defects; FSP at 800 min^{-1} provided yield strength (YS) +32.7%, UTS +20.6%, and elongation +56.7%. Multi-pass FSP on 2319 Al walls refined grains in the stir zone to 3.4 μm [27]. For high-strength Al-Zn-Mg-Cu alloys, interlayer FSP combined with high-entropy alloy (HEA) particle reinforcement achieved grain refinement to approximately 2.3 μm and simultaneous improvements in hardness (~ 152 HV), UTS (~ 374 MPa), and elongation ($\sim 10.6\%$) [64]. Reported FSP grain-refinement outcomes vary across studies, with the optimum tool rotational speed and traverse speed depending on the base alloy, wire feedstock chemistry, and substrate temperature; apparent differences in the rotational-speed dependence reported by Ma et al. [42] for 205A aluminum and Zhou et al. [43] for Al-Cu-Sc reflect differences in alloy chemistry and tool geometry rather than a fundamental disagreement about the FSP mechanism. Figure 8 contrasts the as-deposited WAAM aluminum microstructure with the refined equiaxed grain structure obtained after interlayer FSP. The corresponding FSP post-treatment outcomes for 205A Al-Cu alloy, including the refined grain structure and the resulting tensile-property improvements, are shown in Figure 9.

4.3. Titanium Alloys

Titanium alloys, particularly Ti-6Al-4V, exhibit coarse, epitaxially grown prior- β columnar grains during conventional WAAM processing, followed by martensitic α' or basketweave α microstructures upon cooling [10]. This morphology contributes to pronounced anisotropy, elevated residual stress, and limited ductility. Maurya et al. [54] optimized a

WAAM-forging hybrid route for Ti-6Al-4V and reported improved microstructural homogeneity and mechanical performance after thermomechanical deformation. Hicks et al. [23] extended the hybrid WAAM concept to landing gear components by depositing WAAM Ti-6Al-4V features onto forged Ti-5Al-5Mo-5V-3Cr substrates, demonstrating acceptable microstructural continuity and mechanical performance. Residual stress development in WAAM Ti-6Al-4V has also been shown to depend strongly on deposition strategy and thermal history, with oscillation-path deposition producing lower residual stress levels compared to conventional single-bead and parallel-path strategies [23]. Overall, titanium alloys respond exceptionally well to deformation-assisted hybridization, with reported reductions in β -grain width, texture intensity, and residual stress [23]. Representative residual-stress distributions for hybrid WAAM walls processed under inter-layer peening (ILP) and unpeened conditions are shown in Figure 10.

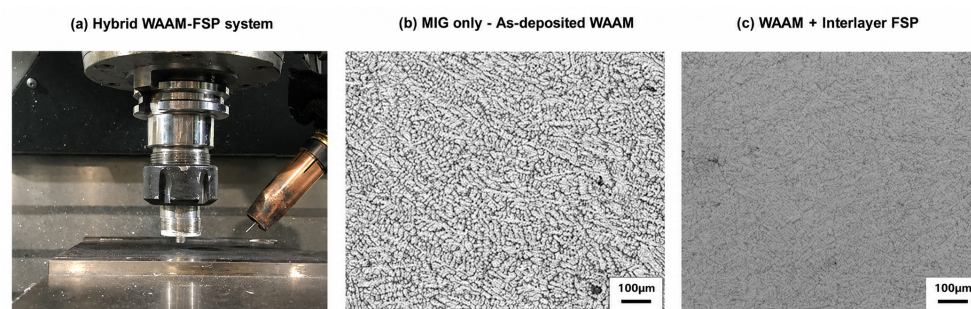


Figure 8. Hybrid WAAM–FSP applied to aluminum alloy walls: (a) experimental WAAM–FSP system developed using a HAAS VF-3 CNC platform; (b) representative as-deposited WAAM microstructure showing coarse columnar grains; and (c) refined equiaxed grain structure obtained after interlayer friction stir processing (FSP).

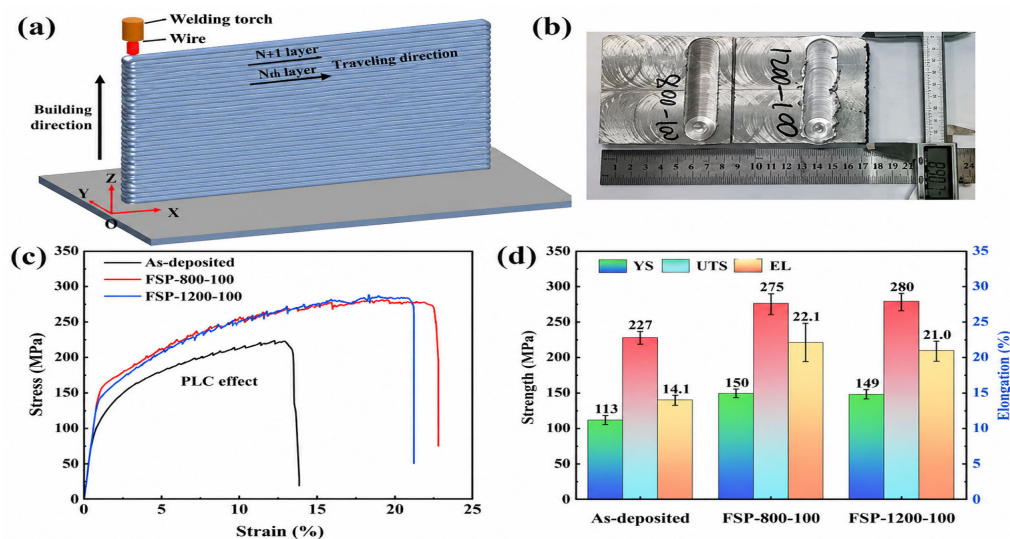


Figure 9. FSP post-treatment of WAAM-fabricated 205A Al-Cu alloy: (a) schematic of the WAAM deposition showing welding torch, wire feed, traveling direction, and the N+1 / Nth layer building geometry; (b) photographs of the as-deposited and FSP-processed samples; (c) stress–strain curves comparing the as-deposited, FSP-800-100, and FSP-1200-100 conditions, with the PLC effect marked on the as-deposited curve; (d) yield strength (YS), ultimate tensile strength (UTS), and elongation (EL) for the three conditions, showing substantial improvements after FSP. Adapted from Ref. [42].

4.4. Steels and Stainless Steels

In steels and stainless steels, microstructure evolution during WAAM is governed by solidification mode, phase transformations, and stacking-fault energy. Plain WAAM

often leads to columnar ferrite, austenite, or martensite depending on alloy content, with noticeable texture and high residual stress [13,23,54]. Panchenko et al. [57] showed that repeated reheating and slow cooling promote grain coarsening, texture sharpening, and heterogeneous hardness, confirming that poorly controlled thermal cycling can strongly degrade toughness and isotropy. Koley and Ganguly [40] demonstrated that interlayer MHP effectively suppressed hot cracking in Fe-based shape memory alloys by modifying the residual stress state and redistributing strain concentration in the solidifying weld pool. Overall, steels exhibit moderate but consistent microstructural refinement under hybrid processing, with degree of refinement generally lower than in titanium or aluminum due to higher recrystallization temperatures.

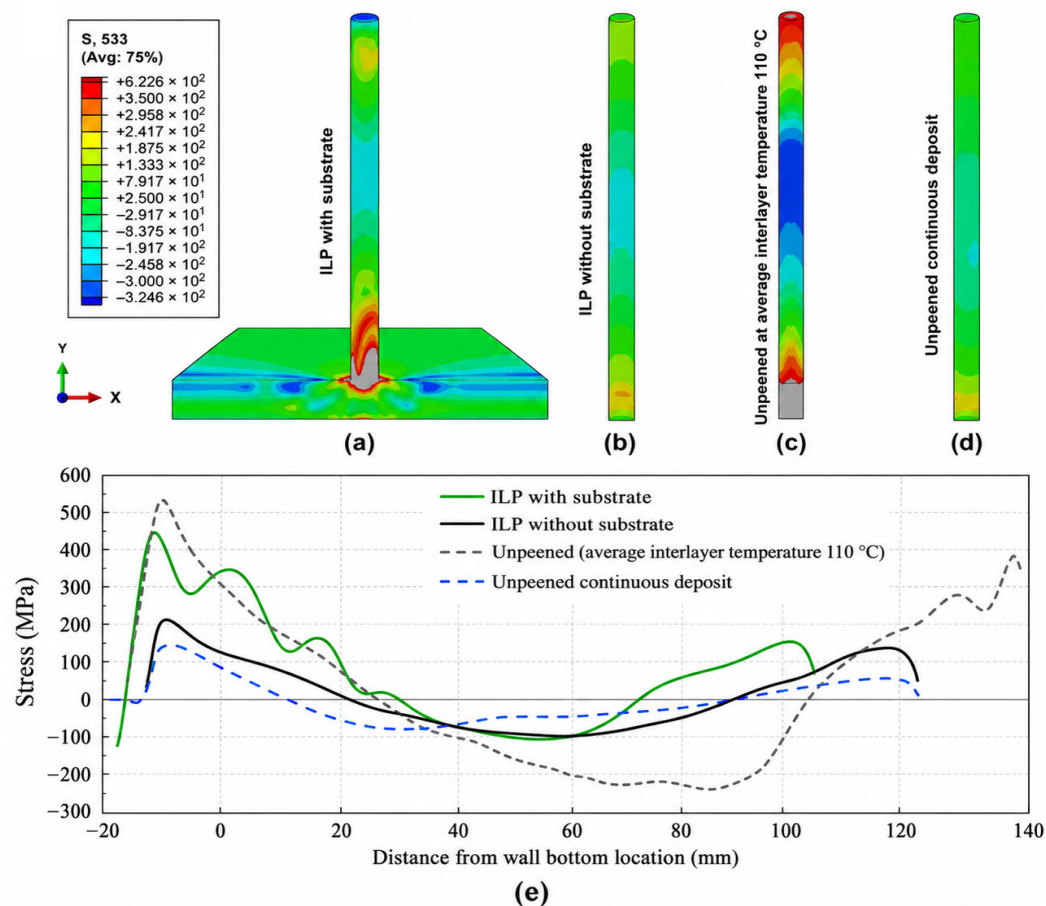


Figure 10. Residual stress distributions in hybrid WAAM walls under different processing conditions: (a) inter-layer peening (ILP) with substrate; (b) ILP without substrate; (c) unpeened deposit at an average interlayer temperature of 110 °C; (d) unpeened continuous deposit; (e) stress versus distance from the wall bottom location for the four conditions. Adapted from Ref. [23].

4.5. Nickel-Based Superalloys

Nickel-based superalloys such as Inconel 625 and Inconel 718 are prone to columnar solidification, segregation, Laves phase formation, and residual stress accumulation in WAAM. Their high γ'/γ'' strengthening precipitate content reduces recrystallization kinetics, limiting spontaneous grain refinement during cooling [58]. Interlayer rolling introduces plastic strain that fragments the as-deposited columnar dendritic structure and, aided by reheating from subsequent deposition, promotes recrystallization to produce finer equiaxed grains. Chen et al. [59] showed that raising the solution treatment temperature from 950 °C to 1150 °C dramatically reduced the Laves phase volume fraction and re-partitioned Nb into strengthening γ'' precipitates, improving tensile strength and elongation by approxi-

mately 35%. Grain refinement in superalloys is often less pronounced than in titanium and aluminum due to the slow recrystallization kinetics and the high hot-deformation strength characteristic of these alloys.

Effect of rolling and post-deformation heat treatment. Zhang et al. [60] applied interlayer rolling to WAAM Inconel 718, reporting that the fragmentation of columnar grains during rolling combined with subsequent solution treatment reduced the Laves volume fraction and produced a more homogeneous γ -matrix grain structure with refined γ'/γ'' precipitate populations. Zeng and Wu [61] reported that hybrid arc-and-micro-rolling additive manufacturing of GH4169D produced finer recrystallized grains and improved tensile properties relative to the as-deposited condition. Zhang et al. [62] showed that hybrid WAAM combined with cold rolling and a tailored heat-treatment cycle improved the high-cycle fatigue life of Inconel 718, attributable to refined Laves distribution and increased γ'' volume fraction.

Reproducibility considerations. Reported grain-refinement and property gains in the Inconel 718 family vary across studies, primarily because of the strong sensitivity to solution-treatment temperature, hold time, and the wire-feedstock chemistry (Nb, Mo, Ti levels) that controls Laves and γ'' kinetics. Comparable studies on Inconel 625, which lacks the γ'' precipitation mechanism, are less common in the deformation-assisted-WAAM literature; this is identified here as a target for follow-up investigation.

4.6. Magnesium and Emerging Alloy Systems

Magnesium alloys are an emerging system for hybrid WAAM. Liu et al. [48] applied interlayer ultrasonic-impact treatment to CMT-based WAAM AZ31 thin walls and reported significant grain refinement and improved mechanical and corrosion performance through cavitation-assisted nucleation and the redistribution of heat away from the melt-pool centerline. Yuan et al. [71] used a Sc-microalloyed dual-wire WAAM strategy to fabricate Mg-10.6Al-0.4Zn-0.2Mn-0.05Sc alloy walls, achieving yield strengths above 200 MPa after heat treatment through Sc-stabilized precipitates and refined grain structures.

Cu-Al bimetallic structures and steel-Cu functionally graded materials are also emerging hybrid-WAAM targets. Joshi et al. [72] used wire WAAM to process low-alloyed steels, copper-aluminum alloys, and their bimetals for heat-exchanger applications, demonstrating that interfacial integrity in dissimilar-metal hybrid WAAM remains a principal challenge for these systems. The literature on hybrid WAAM of magnesium and bimetallic systems is still emerging; conclusions in this subsection are presented as preliminary directions rather than as established performance correlations.

5. Microstructure Evolution Mechanisms Under Deformation-Assisted WAAM

Microstructural evolution in hybrid WAAM processes is governed by the coupled effects of temperature (T), strain (ϵ), strain rate ($\dot{\epsilon}$), and applied stress (σ). A useful framework is based on the Zener–Hollomon parameter: $Z = \dot{\epsilon} \exp(Q/RT)$, where high Z values favor work hardening and limited recovery, whereas low Z values promote dynamic restoration processes such as recrystallization.

The dominant restoration mechanism in hybrid WAAM is governed by the homologous temperature (T/T_m), the Zener–Hollomon parameter Z , and the alloy stacking-fault energy. Recovery dominates at homologous temperatures of 0.2–0.4 T_m through dislocation rearrangement without nucleation of new grains; static recrystallization is activated above approximately 0.4 T_m when sufficient prior strain has been stored and a thermal exposure follows; and dynamic recrystallization is the dominant pathway above approximately 0.5 T_m when deformation is concurrent with the elevated-temperature exposure. The transition between these regimes is alloy- and process-window-dependent: high-SFE

alloys (aluminum) consistently exhibit continuous DRX under FSP, while low-SFE alloys (austenitic steels and nickel-based superalloys) exhibit discontinuous DRX at higher rolling temperatures and recovery-dominated behavior at sub-recrystallization rolling. The mechanisms are therefore not uniformly effective across alloys; their relevance is set by the chosen technique's operating window relative to the alloy's homologous-temperature thresholds.

WAAM-specific modifications to classical recrystallization. The thermal cycling imposed by each successive deposition pass partially anneals the dislocation network introduced by the preceding interlayer deformation; the residual dislocation density in the final part therefore reflects the balance between strain-induced generation and thermally activated annihilation. The remelting zone immediately above the previous layer rests outside this balance, since it solidifies anew, and any deformation introduced after solidification is governed by the same kinetic framework but at a thermal-history offset relative to the bulk. Layer-to-layer thermal accumulation progressively raises the interpass temperature in tall builds, shifts the operating point toward lower Z , and accelerates both DRX and post-DRX grain growth, sometimes erasing the refinement benefit at upper layers. The implication for hybrid WAAM design is that the deformation step should be timed and located so that the recovery sink is overcome and recrystallization rather than recovery dominates; Sections 5.2 and 5.3 cite specific WAAM studies that document this behavior in aluminum, magnesium, and steel deposits.

5.1. Dislocation Accumulation, Work Hardening, and Substructure Formation

Plastic deformation introduced by hybrid WAAM generates a high density of dislocations within the crystal lattice. The evolution of dislocation density (ρ) during deformation can be described by $d\rho/d\varepsilon = k_1 - k_2\rho$, where k_1 represents dislocation generation and k_2 accounts for dynamic recovery. At high strain rates or low temperatures (high Z), dislocation generation dominates, leading to rapid work hardening and the formation of dislocation cells and subgrain structures characterized by low-angle grain boundaries, which serve as precursors to recrystallized grains. Rolling and hammer peening significantly accelerate dislocation accumulation, while FSP and ultrasonic vibration can produce extremely high dislocation densities due to severe plastic deformation and cyclic loading.

In the WAAM context, the cyclic thermal exposure imposed by each subsequent deposition pass partially anneals the dislocation network introduced by interlayer deformation, so that the residual dislocation density in the final part reflects the balance between strain-induced generation and thermally activated annihilation. This balance is most favorable for grain refinement when the deformation is applied at the start of an interpass cooling cycle, so that the recovered subgrain structure can serve as nuclei for subsequent recrystallization rather than being annealed away.

5.2. Recovery, Polygonization, and Annealing

At elevated temperatures, dislocation structures undergo recovery through thermally activated processes such as climb and cross-slip, reducing stored strain energy by rearranging dislocations into more stable configurations. The rate of recovery is strongly dependent on temperature and stacking-fault energy. High SFE materials (e.g., aluminum alloys) exhibit rapid recovery, while low SFE materials (e.g., austenitic steels and Ni-based alloys) retain higher dislocation densities, favoring subsequent recrystallization. In WAAM, recovery processes are frequently activated during interpass thermal cycling, resulting in partial stress relaxation and subgrain growth without fully eliminating deformation-induced heterogeneity.

WAAM-specific manifestation. The recovery contribution is most pronounced in HSLA and stainless-steel WAAM systems, where Panchenko et al. [57] reported partial

stress relaxation and subgrain growth across multiple deposition passes without full recrystallization. In aluminum WAAM, Singh et al. [13] showed that interpass-delay control modulates the residual dislocation density and the resulting hardness gradient through the build direction. The implication for hybrid WAAM is that the deformation step should be timed and located to introduce sufficient stored strain energy to overcome the recovery sink, so that recrystallization rather than recovery dominates the post-deformation evolution.

5.3. Static Recrystallization (SRX)

Static recrystallization occurs when plastically deformed material is exposed to elevated temperatures without additional deformation. Its kinetics can be described by the Johnson–Mehl–Avrami–Kolmogorov (JMAK) equation: $X = 1 - \exp(-kt^n)$, where X is the recrystallized fraction, k is a temperature-dependent rate constant, and n is the Avrami exponent. In hybrid WAAM, SRX is particularly relevant when deformation is applied at relatively low temperatures, followed by reheating during subsequent deposition passes, with new strain-free grains nucleating preferentially at high-energy sites such as grain boundaries and triple junctions.

WAAM-specific manifestation. Liao et al. [55] documented in situ tensile-deformation behavior of hybrid hot-rolled WAAM Al-Mg, demonstrating that SRX-driven grain refinement during interpass reheating accounts for a substantial fraction of the observed strength increase. The SRX mechanism is activated whenever the locally stored strain energy from the most recent deformation step exceeds the energy barrier for nucleation at the prevailing interpass temperature; for hybrid WAAM, this couples the rolling or peening parameters to the heat-input schedule of the subsequent passes.

5.4. Dynamic Recrystallization (DRX): Coupled Deformation-Recrystallization Processes

Dynamic recrystallization occurs when deformation is applied at elevated temperatures, allowing recrystallization to proceed concurrently with plastic deformation. The onset of DRX is conventionally defined by a critical strain ϵ_c , which is empirically related to the strain at peak flow stress ϵ_p by $\epsilon_c \approx 0.5\text{--}0.8 \epsilon_p$, where ϵ_c marks the onset of nucleation of new strain-free grains and ϵ_p the strain at which the flow curve reaches its peak before softening. In the hybrid-WAAM context, DRX is the dominant restoration mechanism for FSP-assisted aluminum deposits and for hot interlayer rolling of titanium and steel; the WAAM-specific manifestation is detailed in Sections 4.2 and 4.3. Two primary DRX mechanisms are relevant in hybrid WAAM.

Distinguishing SRX from CDRX in the WAAM context. SRX requires prior strain followed by a thermal exposure without further deformation; in WAAM-FSP, SRX is activated when a deformed layer is reheated by the next deposition pass without additional concurrent strain. CDRX, in contrast, proceeds concurrently with deformation through the progressive lattice rotation of subgrains; in the WAAM-FSP stir zone, CDRX dominates where shear strain accumulates at temperatures above approximately $0.5 T_m$. Distinguishing the two experimentally requires either crystallographic evidence (electron backscatter diffraction (EBSD) high-angle boundary fraction, low-angle boundary distribution, point-to-origin misorientation profiles within recrystallized grains) or kinetic evidence (the strain-vs-flow-stress curve shape, with cyclic softening for DDRX and monotonic flow for CDRX). Representative discriminations of SRX vs. CDRX in WAAM-FSP aluminum and rolled WAAM titanium are reported in [23,55].

Interlayer temperature control. Higher interlayer temperatures (longer thermal soaks) accelerate DRX by shifting the operating point toward lower Z , but they also accelerate post-DRX grain growth and may erase the refinement benefit. Lower interlayer temperatures (shorter thermal soaks) preserve the recrystallized grain size but may not fully

complete DRX, leaving a partially recrystallized structure with mixed coarse and fine grains. The optimum interlayer temperature is therefore alloy- and technique-specific and is set by balancing the DRX completion time against the grain-growth time at the operating temperature. Singh et al. [13] reported that interpass-delay control modulates the residual dislocation density and resulting hardness gradient in aluminum WAAM; Liao et al. [55] documented SRX-driven refinement during interpass reheating in hybrid hot-rolled WAAM Al-Mg.

CDRX is characterized by the gradual transformation of subgrain structures into recrystallized grains through progressive lattice rotation. This mechanism dominates in high SFE materials such as aluminum alloys and is the dominant mechanism in FSP-assisted WAAM, where large shear strains and moderate temperatures promote continuous grain refinement without distinct nucleation events.

DDRX involves the nucleation and growth of new grains during deformation, typically at pre-existing grain boundaries. This mechanism is common in low- to medium-SFE materials such as steels and nickel-based alloys, characterized by distinct nucleation of strain-free grains, grain boundary bulging and migration, and cyclic flow behavior in stress–strain curves. In hybrid WAAM, DDRX is often activated during high-temperature deformation processes such as interlayer rolling at elevated interpass temperatures.

5.5. Severe Plastic Deformation (SPD) and Ultrafine/Nanocrystalline Grain Formation

Severe plastic deformation occurs under conditions of very high strain ($\epsilon \gg 1$), leading to extensive grain subdivision and the formation of ultrafine-grained or nanocrystalline structures. The relationship between grain size (d) and strength follows the Hall–Petch relation: $\sigma_y = \sigma_0 + k \cdot d^{-1/2}$, where σ_y is the yield strength, σ_0 is the friction stress, and k is the Hall–Petch coefficient [67–69]. In hybrid WAAM, FSP produces ultrafine grains (1–10 μm or smaller), while hammer peening and ultrasonic impact produce nanostructured surface layers, and ultrasonic vibration can enhance grain refinement through cyclic plasticity and cavitation-assisted nucleation.

WAAM-specific implications. Among the hybrid techniques covered in this review, FSP is the principal SPD mode applied to WAAM deposits and the only one that consistently produces ultrafine equiaxed grains throughout the bulk of the stir zone rather than only in a near-surface layer. Hammer peening and laser shock peening produce SPD-class strain only in a shallow surface region, so their bulk grain-refinement contribution is limited; their principal role is residual-stress engineering and surface-fatigue improvement (Section 6.2).

5.6. Integrated Thermomechanical Pathways and Process–Structure–Property Implications

In practical hybrid WAAM processes, these mechanisms operate simultaneously and interact dynamically. The microstructure evolution pathway depends on the local thermomechanical history: high temperature with moderate strain leads to DRX; low temperature with high strain produces dislocation accumulation followed by delayed SRX; repeated thermal cycling activates recovery and SRX; and very high strain (SPD) results in ultrafine or nanocrystalline grains. The integration of deformation into WAAM fundamentally transforms the process–structure–property relationship: grain refinement enhances strength via Hall–Petch strengthening; texture randomization improves isotropy; defect closure improves fatigue resistance; and residual stress redistribution enhances dimensional stability.

Integrated chain from process variables to grain size. The local solidification mode at the deposition stage is set by the G/R ratio (Section 2). The post-solidification grain-refinement response to the interlayer deformation step depends on the Zener–Hollomon parameter $Z = \dot{\epsilon} \cdot \exp(Q/RT)$, which combines the imposed strain rate and the operating

temperature into a single kinetic descriptor. The recrystallized fraction follows the JMAK kinetics introduced in Section 5.3, $X = 1 - \exp[-(kt)^n]$, with the rate constant $k(T)$ and the Avrami exponent n set by the dominant DRX or SRX subtype. The final grain size is controlled by the balance between the nucleation density at the onset of DRX and the boundary-mobility budget through the post-peak cooling: high Z favors many nuclei and short post-peak boundary migration (fine grain), while low Z favors fewer nuclei and extended boundary migration (coarse grain).

Dominant factor for grain refinement. Among the candidate factors (strain magnitude, strain rate, thermal gradient, alloy stacking-fault energy), the dominant factor for hybrid-WAAM grain refinement is the strain rate at the operating temperature, parameterized via Z . Strain magnitude controls only whether the critical strain ϵ_c for DRX onset is exceeded (Section 5.4); thermal gradient governs the post-peak cooling rate and therefore the boundary-mobility budget; and the alloy stacking-fault energy governs whether continuous or discontinuous DRX dominates. The relative importance of each factor is alloy- and technique-specific: FSP of high-SFE aluminum is predominantly strain-rate-dominated (CDRX in the stir zone), while interlayer rolling of Ti-6Al-4V is predominantly thermal-history-dominated (mixed DRX in the $\alpha + \beta$ region).

5.7. Worked Examples of the Zener–Hollomon Framework

To illustrate the qualitative use of the Zener–Hollomon framework $Z = \dot{\epsilon} \exp(Q/RT)$ for assigning the dominant restoration mechanism in hybrid WAAM, two representative case studies are summarized below. These are not predictive calculations; they are diagnostic estimates intended to demonstrate how the framework anchors the experimental observations in physical-metallurgy mechanisms.

Case 1: FSP of WAAM-deposited 4043 aluminum [41]. Using a rotational speed of 1200 rpm with an 18 mm shoulder and 5.4 mm pin, the effective shear strain rate is approximately 30 s^{-1} . The peak processing temperature recorded by infrared (IR) thermography (FLIR T300, Teledyne FLIR / FLIR Systems, Inc., Wilsonville, OR, USA) was approximately 400°C ($T \approx 670 \text{ K}$). Taking $Q \approx 156 \text{ kJ/mol}$ as a representative activation energy for high-stacking-fault-energy aluminum alloys, $\ln Z \approx 31$. This places the process in the high- Z , dynamic-recrystallization regime; the operative mechanism is continuous dynamic recrystallization, consistent with the equiaxed micrometric grain structure observed in the stir zone.

Case 2: Interlayer hot rolling of Ti-6Al-4V [23]. At $T = 920^\circ\text{C}$ ($T \approx 1193 \text{ K}$, in the $\alpha + \beta$ region) with a strain rate of approximately 1 s^{-1} and a mid-range activation energy $Q \approx 240 \text{ kJ/mol}$ for the $\alpha + \beta$ region, $\ln Z \approx 24$. This places the process in the moderate- Z range that supports mixed discontinuous and continuous dynamic recrystallization, consistent with the experimentally observed reduction in texture intensity and the columnar-to-equiaxed transformation reported in the source. These two examples demonstrate the framework as a guidance tool for cross-system comparison rather than as a quantitative predictive model.

Toward a critical $\ln Z$ for the columnar-to-equiaxed transition. While no universal critical $\ln Z$ value for the columnar-to-equiaxed transition (CET) has yet been established for hybrid WAAM, the available data suggest that $\ln Z$ values in the range of approximately 28–32 (typical of FSP of high-SFE aluminum) consistently produce equiaxed structures, while $\ln Z$ values below approximately 22 (typical of slow hot rolling of titanium in the $\alpha + \beta$ region) preserve some columnar character without complete recrystallization. A definitive ZH–CET correlation requires controlled, single-variable experiments across alloy families with matched strain-rate and homologous-temperature ranges, and is identified here as a priority research direction.

Incorporating phase transformation kinetics. For alloys that undergo solid-state phase transformation during the WAAM thermal cycle (e.g., Ti-6Al-4V $\alpha \leftrightarrow \beta$ [23], steels $\gamma \rightarrow \alpha$ /martensite, Inconel 718 γ'/γ'' precipitation [59]), phase transformation kinetics enter the WAAM deformation model in two ways. First, the JMAK formalism introduced in Section 5.3 is used with transformation-specific kinetic constants $k(T)$ and Avrami exponents n . The transformation-temperature window relative to the deformation temperature determines whether the deformation drives (i) deformation-assisted phase transformation (e.g., dynamic strain-induced martensite in steels), (ii) phase transformation followed by deformation of the new phase, or (iii) deformation-only without transformation. Second, the Zener–Hollomon framework can be coupled to a phase-fraction term so that Z is computed for each phase separately when the phase fractions are non-negligible. This coupling is identified as a target for future quantitative WAAM-deformation modeling and is acknowledged as outside the scope of the present qualitative framework.

6. Mechanical Property Improvements and Performance Correlations

6.1. Strength-Ductility Synergy

Reproducibility and inter-study variability. Reported property gains in deformation-assisted WAAM vary across studies, even for nominally identical alloy and process combinations. The principal sources of variability are the wire-feedstock chemistry, the substrate temperature at the time of deformation, the inter-pass time, and the specific deformation-tool geometry. Multi-laboratory studies that hold these factors constant are limited; this is identified as an open research need that must be addressed before the property gains reported in this section can be cited as design-allowable values.

In conventional WAAM, coarse columnar grains and strong crystallographic textures result in anisotropic mechanical behavior and limited ductility. Hybrid deformation processes disrupt these structures and promote equiaxed grain formation, enabling simultaneous improvements in strength and ductility. Grain refinement enhances strength through the Hall–Petch relationship, while the reduction in defects such as porosity increases the effective load-bearing area. Texture randomization reduces directional dependence of slip systems, improving uniform plastic deformation. Increases of 20–40% in yield strength and 10–30% in elongation have been reported in hybrid WAAM materials compared with as-deposited counterparts [23,56,58]. Zhang et al. [65] showed that inter-pass rolling improved isotropic elongation by 35–54% after heat treatment while maintaining strength through θ'/θ'' precipitation. Zhou et al. [43] demonstrated that adding 0.15 wt.% Sc to WAAM Al-Cu walls combined with interlayer FSP increased UTS from 256 MPa to 303 MPa after FSP. Representative examples of hybrid WAAM + FSP, multilayer wall fabrication, grain refinement, and hardness improvement are shown in Figure 11.

Comparison with conventional counterparts. Where the underlying studies report it, hybrid-WAAM properties are quoted here relative to the conventional wrought or forged counterpart of the same alloy. For Ti-6Al-4V, Maurya et al. [54] reported that WAAM-forged Ti-6Al-4V at 920 °C and strain 0.6–0.9 reaches tensile strengths within approximately 5% of the forged baseline, with elongation recovery to within 10% of the wrought reference. For aluminum, Kannan et al. [51] reported that as-deposited WAAM 2319 retains approximately 72% of the tensile strength and approximately 65% of the fatigue strength of wrought AA2219 in the T62 condition, with the gap reduced after interlayer FSP [73,74]. For Inconel 718, hybrid WAAM with rolling and tailored heat treatment narrows the gap to wrought AMS 5663 strength to within approximately 10–15% [60,62]. Where the underlying study does not report the conventional-counterpart value, the gap is flagged as a research need rather than estimated from secondary sources.

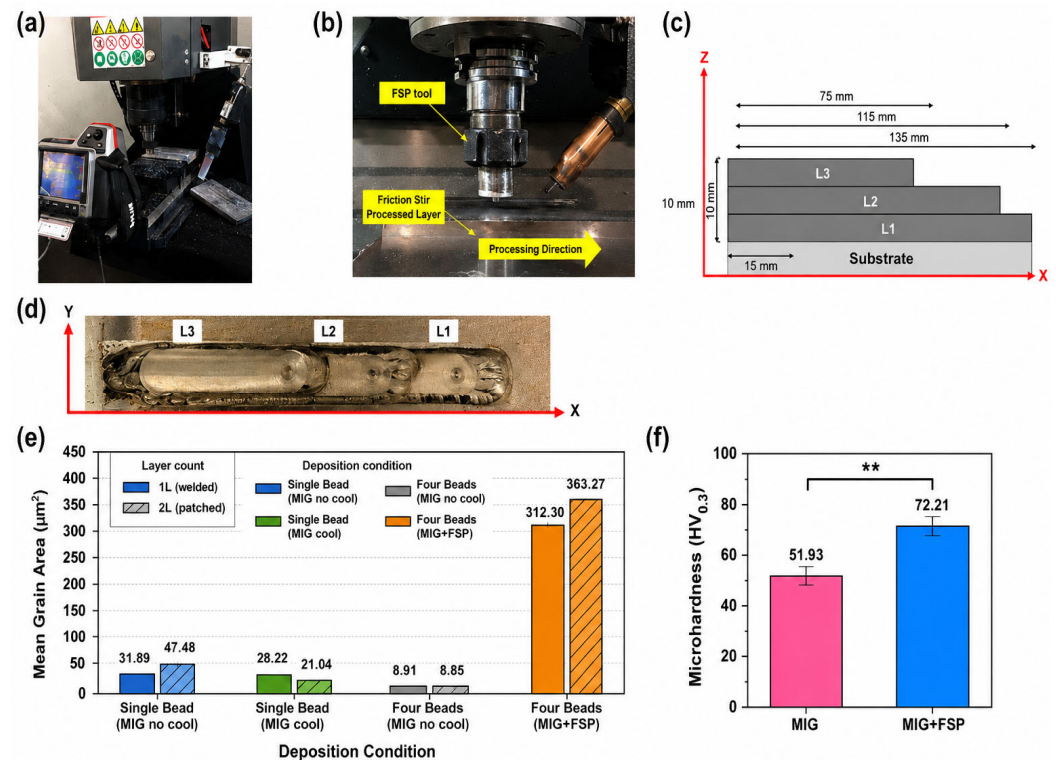


Figure 11. Hybrid WAAM combined with friction stir processing: (a) experimental WAAM + FSP setup with infrared thermal monitoring; (b) close-up view of the hybrid deposition and friction stir processing region showing processing direction; (c) schematic illustration of multilayer wall geometry and deposition dimensions; (d) top view of the deposited multilayer wall structure; (e) comparison of mean grain area under different deposition and cooling conditions; and (f) comparison of microhardness between MIG and UAMFSP fabricated walls. ** denotes $p < 0.01$.

6.2. Fatigue Performance

Fatigue performance in WAAM components is highly sensitive to surface condition, microstructural heterogeneity, and residual stress state. Hybrid deformation processes improve fatigue resistance through multiple mechanisms: grain refinement reduces slip localization; compressive residual stresses delay crack initiation; porosity closure removes critical stress concentrators; and surface integrity is enhanced through deformation-assisted smoothing. Interlayer rolling and hammer peening have been shown to significantly improve fatigue life in titanium and aluminum alloys by introducing beneficial compressive residual stresses and refining surface microstructure [38,39]. Zhang et al. [62] showed that cold rolling combined with heat treatment improves fatigue life in Inconel 718 due to γ'' precipitation and refined Laves distribution. Wang et al. [75] reported nearly isotropic fatigue crack growth behavior in hybrid additive manufactured Ti-6Al-4V ELI, with crack growth rates comparable to wrought material.

Process-specific risks. The fatigue gains documented above are conditional on selecting process windows that avoid the failure modes specific to each technique. Over-peening drives the surface to work-hardening saturation, where additional impacts induce surface micro-cracking and a detrimental tensile reflection layer immediately beneath the compressive surface region. Aggressive interlayer rolling introduces subsurface shear bands and, on thin-walled deposits, can trigger sheet-thinning instabilities that locally reduce the load-bearing section. FSP, when the rotational speed and traverse speed are mismatched to the substrate temperature, leaves tunnel defects, kissing bonds, or root-zone lack-of-bonding that act as fatigue-crack initiation sites. The fatigue benefit of each hybrid

technique is therefore window-bounded; reported gains should be interpreted alongside the corresponding process parameters.

6.3. Creep and High-Temperature Performance

Creep resistance in WAAM materials is strongly influenced by grain structure, phase stability, and defect distribution. Coarse columnar grains in conventional WAAM can accelerate creep deformation due to grain boundary sliding and anisotropic behavior. Hybrid deformation processes improve creep performance by refining grain structures, reducing segregation and second-phase instability, and eliminating defects that act as creep cavities. In nickel-based superalloys, deformation-assisted WAAM combined with heat treatment has been shown to improve high-temperature strength and reduce creep rate by stabilizing γ'/γ'' precipitates and reducing Laves phase content [59,63].

6.4. Reduction in Mechanical Anisotropy

Mechanical anisotropy is a critical limitation of conventional WAAM, arising from directional solidification and columnar grain growth. Hybrid deformation processes significantly reduce anisotropy by transforming columnar grains into equiaxed structures, randomizing crystallographic texture, and homogenizing phase distribution. In titanium alloys, hybrid WAAM processes have been shown to reduce anisotropy in elongation and strength to less than 5%, compared with 20–40% in conventional WAAM [10]. Table 3 summarizes representative hybrid WAAM-based studies and their key outcomes.

Process conditions reported in the cited studies (normalized cross-study comparison). Where the underlying study reports quantitative process parameters, these are summarized as follows to enable normalized comparison across techniques: FSP of 205A Al [42] employed 800 min^{-1} with traverse rate not reported; FSP of 2319 Al [27] used multi-pass stirring at $600\text{--}1200 \text{ min}^{-1}$; FSP of 4043 Al [41] employed 1200 min^{-1} , traverse 100 mm/min , plunge depth 0.2 mm ; FSP of Al-Zn-Mg-Cu reinforced with HEA particles [64] used 1000 min^{-1} with 50 mm/min traverse; FSP of Al-Cu-Sc [43] used 1200 min^{-1} at 50 mm/min ; interlayer rolling of S355 steel [35] used a slotted roller at 75 kN load; hot interlayer rolling of Al-Mg [34] used reduction ratios of 5–30%; cold rolling and aging of Inconel 718 [62] applied 30% rolling reduction followed by solution + aging; in situ rolling of Al-Si [66] used a 0.6 mm reduction per layer; cold/hot rolling of AA2219 [65] used reductions of 10–25% with subsequent T62 treatment; ultrasonic-impact treatment of AZ31 Mg [48] used 20 kHz at amplitude $30\text{--}50 \text{ }\mu\text{m}$; MHP of Ti-6Al-4V [38] employed peening at $25\text{--}100 \text{ Hz}$ with a hardened-steel hammer; LSP of AA2319 [45] used pulse energy $5\text{--}10 \text{ J}$ at 10 ns duration with water-confined geometry; hot forging of Ti-6Al-4V [23] used $T = 920 \text{ }^{\circ}\text{C}$ at strain rates $0.1\text{--}1 \text{ s}^{-1}$ to imposed strains $0.6\text{--}0.9$. Entries for which the source does not report quantitative process conditions are flagged in the running text as “not reported.”

7. Integration of Auxiliary Processes in Hybrid WAAM

7.1. Integration of Subtractive Machining

Due to the inherent characteristics of arc-based deposition, WAAM components typically exhibit limited dimensional accuracy and high surface roughness [46,53]. Wu et al. [76] developed a patented additive–deformation–machining (ADM) process and system that combines WAAM with FSP and milling in one platform cell, allowing both inner and outer edge surfaces to be machined at the layer level, resolving tool accessibility problems for complex geometries and preventing accumulation of geometric inaccuracies over multiple layers [77]. Bagherzadeh et al. [78] demonstrated quantitatively that as-built surface undulations reduce the fatigue endurance limit by approximately 35% and shorten fatigue life by approximately 60% relative to machined specimens. Table 4 summarizes the synergistic

effects of post-deformation machining in hybrid WAAM. Figure 12 illustrates the effect of post-deformation subtractive machining on WAAM ER70S-6 steel, including the coupon-extraction scheme, representative fracture surface, engineering stress–strain curves, and the S–N comparison between machined and as-built specimens.

Table 4. Synergistic effects of post-deformation machining in hybrid WAAM.

Objective	Deformation Only	Deformation + In Situ Machining
Grain refinement	Excellent and effective	Retained
Texture reduction	Excellent (driven by deformation)	Retained
Dimensional accuracy	Poor to moderate (bead waviness, stair-stepping)	Excellent
Surface integrity	Rough, uneven	Smooth, controlled finish
Fatigue life	Increased, but surface-dependent	Substantially increased
Residual stress state	Reduced; often more compressive near surface	Redistributed/tunable (depends on machining parameters and sequencing)

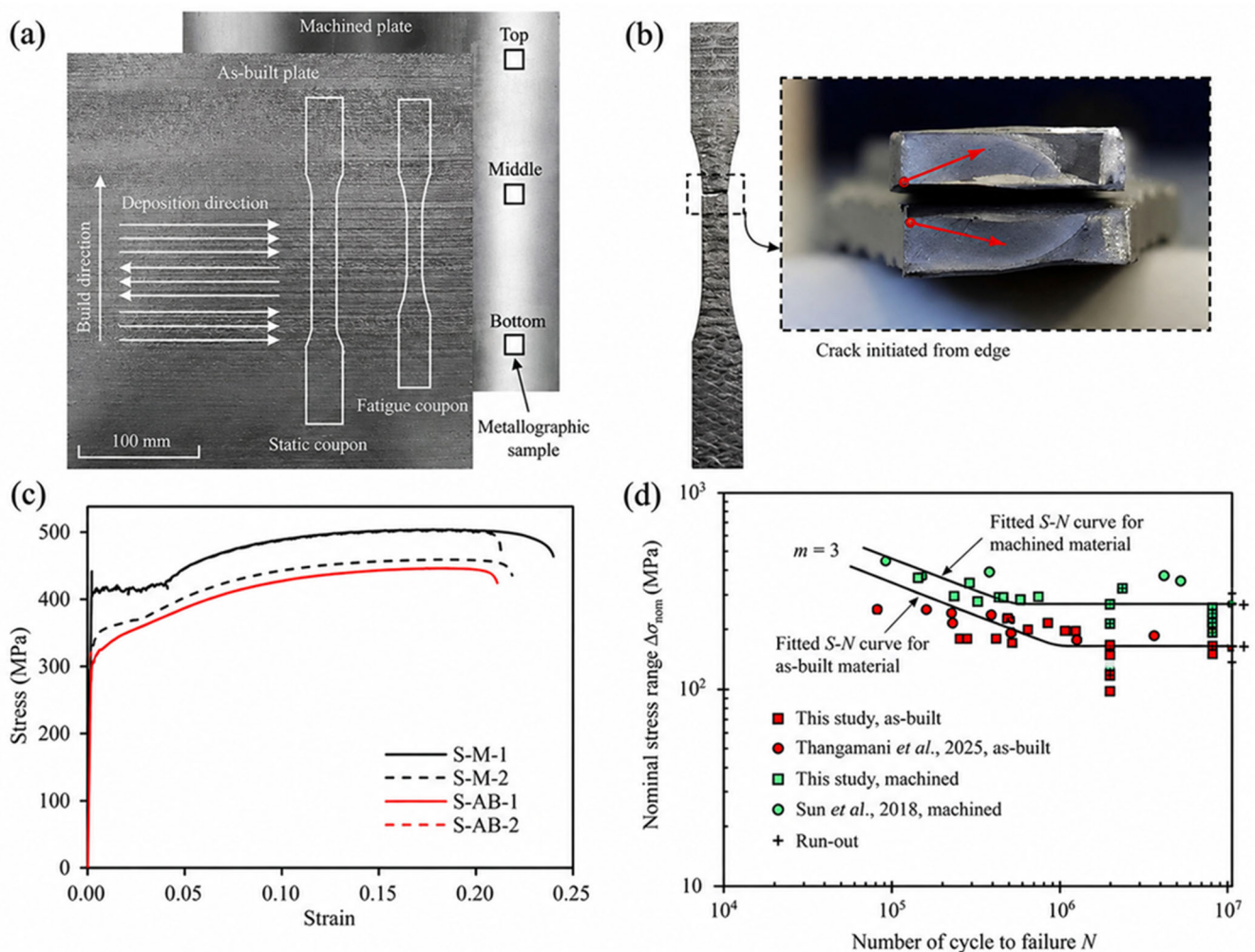


Figure 12. Effect of subtractive machining on the performance of WAAM ER70S-6 steel plates: (a) as-built and machined plate conditions and coupon extraction scheme; (b) representative fracture surface; (c) engineering stress–strain curves for machined and as-built coupons; (d) S–N comparison of as-built versus machined coupons. Adapted from Refs. [44,45,78].

7.2. In Situ Heat Treatment in Hybrid WAAM

Thermal management through in situ heat treatment provides a complementary pathway for controlling phase stability, residual stress evolution, and recrystallization kinetics alongside deformation-assisted processing. In contrast to conventional ex situ heat treatment applied after fabrication, in situ thermal control occurs during or between deposition passes and is inherently coupled with the transient thermal cycles of the WAAM process. Its primary role is to regulate the balance between strain hardening, recovery, and recrystallization.

For Ti-6Al-4V, mill annealing (sub-transus, 700–785 °C) produces a fine equiaxed microstructure with superior balance of tensile strength and ductility, while beta annealing (super-transus, 1015–1050 °C) forms a lamellar microstructure that improves fracture toughness and fatigue crack growth resistance. These regimes are described in detail by Lütjering and Williams [77], with WAAM-specific application context in Maurya et al. [54] and Hicks et al. [23]. For Inconel 718, solution treatment at approximately 980–1050 °C dissolves secondary phases, followed by two-stage aging (e.g., 720 °C then 620 °C) to precipitate γ' and γ'' phases. The corresponding WAAM-specific application is described by Chen et al. [59] and supported by the rolling-plus-heat-treatment data of Zhang et al. [60,62]. For heat-treatable aluminum alloys, T6 treatment (solutionizing, quenching, and artificial aging) maximizes strength by precipitating fine strengthening particles. The application of the T6 cycle to WAAM 2319 aluminum is detailed by Kannan et al. [51]. Ex situ and in situ heat treatments are best viewed as complementary strategies: in situ thermal control governs microstructure evolution during fabrication, while ex situ treatments are applied selectively to optimize final properties.

8. Challenges and Future Outlook

8.1. Process Integration and Scalability

Scaling from laboratory feasibility studies to industrial-scale production remains a primary obstacle. Maintaining consistent thermal histories and uniform microstructural evolution across large build volumes is still difficult, and integrating deformation processes such as rolling, FSP, or ultrasonic vibration into large-scale WAAM systems presents challenges in equipment design, tool accessibility, and process synchronization [21,79].

Cost efficiency and scalability. Quantitatively, conventional WAAM achieves deposition rates of approximately 3–6 kg h^{−1} for steel and aluminum alloys, one to two orders of magnitude higher than laser powder-bed fusion (~0.05–0.5 kg h^{−1}). The capital cost of a WAAM cell is correspondingly lower than that of an industrial laser PBF system, and the feedstock cost ratio is in the same direction (welding wire vs. atomized powder). Adding interlayer rolling, FSP, or peening to a WAAM cell increases cycle time by approximately 20–60% depending on the deformation parameters, layer thickness, and traverse speed, and adds tooling and motion-control overhead. The throughput penalty is non-trivial but is typically smaller than the rework or scrap penalty associated with the columnar-microstructure and porosity defects of as-deposited WAAM.

Energy efficiency. Campatelli et al. [80] compared the energy intensity of integrated WAAM-subtractive workflows with pure subtractive baselines for several aerospace component geometries and reported energy savings of the order of 30–65% in the WAAM-based route, primarily through reduced raw-material consumption and machining time. The energy overhead introduced by deformation steps (rolling and FSP, with their tool drives and forced cooling) is small relative to the savings from feedstock economy, so the integrated WAAM-deformation-machining cycle remains energetically attractive at the system level even when the hybrid step adds capital and per-cycle cost.

8.2. Process Control, Optimization, and Closed-Loop Monitoring

Hybrid WAAM introduces additional process variables including deformation timing, strain magnitude, and temperature control. Moving from open-loop fixed parameters to closed-loop control is a critical requirement for advanced hybrid WAAM systems.

8.3. In Situ Monitoring and Defect Detection

Real-time monitoring of microstructure evolution and defect formation remains a major challenge. Techniques such as thermal imaging, acoustic emission monitoring, and laser scanning are being explored, but integration into a unified control system is still limited. Future research should focus on integrated hybrid WAAM platforms combining multiple deformation techniques; real-time closed-loop control strategies supported by high-fidelity digital twins; expanding hybrid WAAM to emerging material systems including high-entropy alloys, advanced magnesium alloys, and functionally graded bimetallic structures; and developing standardized qualification frameworks incorporating deformation and machining steps to accelerate industrial adoption for fatigue-, creep-, and fracture-critical applications.

8.4. Extension of Materials and Hybrid WAAM Processes

High-entropy alloys (HEAs) containing five or more principal elements in near-equal composition represent a growing frontier for hybrid WAAM. Fe-Mn-Cr-Ni material systems have been processed by hybrid WAAM for in situ alloying using multiple elemental wires, creating complex solid solutions with exceptional ductility (80% elongation) [71]. Advanced magnesium alloys also offer significant opportunity, with WAAM of scandium-modified magnesium alloys achieving yield strength of at least 200 MPa [72]. Copper alloys and bimetals present particular fabrication challenges; Muzyk et al. [81] used wire WAAM to process low-alloyed steels, copper-aluminum alloys, and their bimetals, creating functionally graded materials for heat exchanger applications.

8.5. Toward Fully Integrated Additive-Deformation-Machining Systems

The future of hybrid WAAM lies in fully integrated manufacturing platforms that combine additive deposition, deformation processing, subtractive machining, and real-time monitoring. Such systems will enable adaptive process control, defect mitigation during fabrication, and near-net-shape manufacturing with tailored properties. Achieving this vision requires digital twins capable of predicting thermal, mechanical, and microstructural evolution in real time. The Wu et al. patented ADM process [76] represents one practical step toward such integration. As standards organizations begin to include deformation and machining steps within qualification frameworks for fatigue-, creep-, and fracture-critical parts, the path toward widespread industrial adoption will become clearer.

9. Conclusions

Hybrid WAAM processes incorporating deformation-assisted techniques advance the additive manufacturing of metallic materials. By introducing controlled thermomechanical conditions, these processes overcome the inherent limitations of conventional WAAM, including coarse columnar microstructures, anisotropy, and defect formation. The following conclusions can be drawn from this review:

(1) The principal contribution of this review is a strain–temperature guidance map that links the operating regions of the five hybrid deformation techniques (interlayer rolling, machine hammer peening, friction stir processing, laser shock peening, and ultrasonic vibration) to the dominant microstructure-evolution mechanisms (recovery, static and

dynamic recrystallization, severe plastic deformation) across aluminum, titanium, steel, and nickel-based alloy systems.

(2) Microstructure refinement under hybrid WAAM is consistently observed across alloy families: high-SFE aluminum responds preferentially to FSP via continuous dynamic recrystallization; titanium and steel respond to interlayer rolling at sub-recrystallization or $\alpha + \beta$ temperatures via mixed discontinuous and continuous DRX; and nickel-based superalloys benefit from rolling-assisted segregation control followed by post-deformation heat treatment to redistribute Laves phases. Quantitative outcomes are summarized in Section 6: yield-strength gains of 20–40%, elongation gains of 10–30%, and fatigue-life improvements of up to 60% relative to as-built WAAM.

(3) The Zener–Hollomon framework provides a guidance tool for assigning the dominant restoration mechanism under given thermomechanical conditions. Two worked examples (Section 5.7) demonstrate its qualitative use: $\ln Z \approx 31$ for FSP of 4043 aluminum (continuous dynamic recrystallization) and $\ln Z \approx 24$ for interlayer rolling of Ti-6Al-4V in the $\alpha + \beta$ region (mixed dDRX/CDRX). Each hybrid technique is window-bounded by process-specific risks (over-peening, FSP tunnel defects, aggressive-rolling subsurface damage) that condition the reported gains; reported improvements should therefore be interpreted alongside the corresponding process parameters.

(4) Industrial adoption of hybrid WAAM requires advances in closed-loop process control, digital-twin-supported real-time microstructure prediction, and standardized qualification frameworks that incorporate deformation and machining steps. Extension to magnesium alloys (Section 4.6), copper-aluminum bimetallic systems, and high-entropy alloys is an active frontier; reproducibility across laboratories remains limited and is identified here as a research gap that should be addressed in coordinated multi-laboratory studies.

Hybrid WAAM thus enables the transition from purely thermal additive manufacturing to thermomechanically engineered microstructures, with applications in aerospace, energy, defense, and transportation. Continued progress in process integration, monitoring, and qualification is required for broad industrial adoption.

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Nomenclature

Symbols

G	thermal gradient ($K\ m^{-1}$)
R	solidification rate ($m\ s^{-1}$)
Z	Zener–Hollomon parameter (s^{-1})
Q	activation energy for hot deformation ($J\ mol^{-1}$)
ρ	dislocation density (m^{-2})
k_1, k_2	rate coefficients in the dislocation evolution equation
σ_y	yield strength (MPa)

σ_0	friction stress in the Hall–Petch relation (MPa)
k	Hall–Petch coefficient (MPa m ^{1/2})
d	mean grain size (m)
ε_c	critical strain for the onset of dynamic recrystallization
ε_p	strain at peak flow stress
T	absolute temperature (K)
T_m	melting temperature of the alloy (K)
X	recrystallized fraction in the JMAK equation
t	time (s)
n	Avrami exponent
b	Burgers vector magnitude (m)
E_s	stored strain energy per unit volume (J m ^{−3})

Abbreviations

AM	additive manufacturing
CDRX	continuous dynamic recrystallization
CET	columnar-to-equiaxed transition
CMT	cold metal transfer
DDRX	discontinuous dynamic recrystallization
DED	Directed Energy Deposition
DRX	dynamic recrystallization
FSP	friction stir processing
GMAW	gas metal arc welding
GTAW	gas tungsten arc welding
HEA	high-entropy alloy
HV	Vickers hardness
LSP	laser shock peening
MHP	machine hammer peening
PAW	plasma arc welding
RS	residual stress
SFE	stacking-fault energy
SPD	severe plastic deformation
SRX	static recrystallization
USI	ultrasonic impact treatment
WAAM	Wire Arc Additive Manufacturing

References

- Li, Y.; Su, C.; Zhu, J. Comprehensive review of wire arc additive manufacturing: Hardware system, physical process, monitoring, property characterization, application and future prospects. *Results Eng.* **2022**, *13*, 100330. [[CrossRef](#)]
- Arana, M.; Ukar, E.; Rodriguez, I.; Iturrioz, A.; Alvarez, P. Strategies to reduce porosity in Al-Mg WAAM parts and their impact on mechanical properties. *Metals* **2021**, *11*, 524. [[CrossRef](#)]
- Chaturvedi, M.; Scutelnicu, E.; Rusu, C.C.; Mistodie, L.R.; Mihailescu, D.; Subbiah, A.V. Wire arc additive manufacturing: Review on recent findings and challenges in industrial applications and materials characterization. *Metals* **2021**, *11*, 939. [[CrossRef](#)]
- Gurmesa, F.D.; Lemu, H.G.; Adugna, Y.W.; Harsibo, M.D. Residual stresses in wire arc additive manufacturing products and their measurement techniques: A systematic review. *Appl. Mech.* **2024**, *5*, 420–449. [[CrossRef](#)]
- Jafari, D.; Vaneker, T.H.J.; Gibson, I. Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts. *Mater. Des.* **2021**, *202*, 109471. [[CrossRef](#)]
- Madesh, R.; Kumar, K.G. Development of metallurgical and mechanical properties of nickel-based superalloy employed by wire arc additive manufacturing. *J. Mater. Eng. Perform.* **2024**, *33*, 6718–6737. [[CrossRef](#)]
- Singh, S.R.; Khanna, P. Wire arc additive manufacturing (WAAM): A new process to shape engineering materials. *Mater. Today Proc.* **2021**, *44*, 118–128. [[CrossRef](#)]
- Zhang, H.; Li, R.; Liu, J.; Wang, K.; Weijian, Q.; Shi, L.; Lei, L.; He, W.; Wu, S. State-of-art review on the process-structure-properties-performance linkage in wire arc additive manufacturing. *Virtual Phys. Prototyp.* **2024**, *19*, e2390495. [[CrossRef](#)]
- Gao, Z.; Li, Y.; Shi, H.; Lyu, F. Microstructure characteristics under varying solidification parameters during CMT arc additive manufacturing of 2319 aluminum alloy. *Vacuum* **2023**, *214*, 112177. [[CrossRef](#)]

10. Kumar, D.; Vipin Wattal, R. Hybrid wire arc additive manufacturing techniques for Ti-6Al-4V functional components. *J. Mater. Sci.* **2025**, *60*, 22495–22530. [[CrossRef](#)]
11. Derekar, K.S.; Ahmad, B.; Zhang, X.; Joshi, S.S.; Lawrence, J.; Xu, L.; Melton, G.; Addison, A. Effects of process variants on residual stresses in wire arc additive manufacturing of aluminum alloy 5183. *J. Manuf. Sci. Eng.* **2021**, *144*, 071005. [[CrossRef](#)]
12. Han, Y. A finite element study of wire arc additive manufacturing of aluminum alloy. *Appl. Sci.* **2024**, *14*, 810. [[CrossRef](#)]
13. Singh, S.; Jinoop, A.N.; Paul, C.P.; Prashanth, K.G. Effect of interlayer delay on the microstructure and mechanical properties of wire arc additive manufactured wall structures. *Materials* **2021**, *14*, 4187. [[CrossRef](#)]
14. Vishwanath, N.; Suryakumar, S. Residual stress and distortion control in wire-arc additive manufacturing process through novel modular substrate. *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.* **2024**, *238*, 1570–1579. [[CrossRef](#)]
15. Dias, Y.E.P.; Lima, J.S.D.; Coêlho, G.D.C.; Maciel, T.M.; Neto, J.F.D.S.; Castro, W.B.D. Quality control, monitoring and techniques for surface quality optimization in wire arc additive manufacturing: A review. *Rapid Prototyp. J.* **2025**, *32*, 210–232. [[CrossRef](#)]
16. Fu, R.; Tang, S.; Lu, J.; Cui, Y.; Li, Z.; Zhang, H.; Xu, T.; Chen, Z.; Liu, C. Hot-wire arc additive manufacturing of aluminum alloy with reduced porosity and high deposition rate. *Mater. Des.* **2021**, *199*, 109370. [[CrossRef](#)]
17. Gudur, S.; Simhambhatla, S.; Venkata Reddy, N. Residual stress reduction in wire arc additively manufactured parts using in-situ electric pulses. *Sci. Technol. Weld. Join.* **2023**, *28*, 193–199. [[CrossRef](#)]
18. Li, B.; Nagaraja, K.M.; Zhang, R.; Malik, A.; Lu, H.; Li, W. Integrating robotic wire arc additive manufacturing and machining: Hybrid WAAM machining. *Int. J. Adv. Manuf. Technol.* **2023**, *129*, 3247–3259. [[CrossRef](#)]
19. Freitas, B.; Richhariya, V.; Silva, M.; Vaz, A.; Lopes, S.F.; Carvalho, O. A review of hybrid manufacturing: Integrating subtractive and additive manufacturing. *Materials* **2025**, *18*, 4249. [[CrossRef](#)]
20. Kapil, S.; Rajput, A.S.; Sarma, R. Hybridization in wire arc additive manufacturing. *Front. Mech. Eng.* **2022**, *8*, 981846. [[CrossRef](#)]
21. Meng, X.; Gardner, L. Hybrid construction featuring wire arc additive manufacturing: Review, concepts, challenges and opportunities. *Eng. Struct.* **2025**, *326*, 119337. [[CrossRef](#)]
22. Sitharaj, A.; Arulmurugan, B.; Karthi, N.; Dhanushh, M.S.; Deepak, S.R.; Ajay, M. Hybridization in metal additive manufacturing: Current status and future perspectives. In *Recent Advances in Additive Manufacturing, Volume 2*; Springer Nature: Singapore, 2025; pp. 467–482.
23. Hicks, C.; Tamimi, S.; Sivaswamy, G.; Pimentel, M.; McKegney, S.; Fitzpatrick, S. Hybrid manufacturing approach for landing gear applications: WAAM Ti-6Al-4V on forged Ti-5Al-5Mo-5V-3Cr. *J. Mater. Res. Technol.* **2024**, *30*, 6596–6608. [[CrossRef](#)]
24. Zhang, X.; He, Y.; Wei, Y. Adopting continuous multi-pass friction stir processing to enhance the wire-arc additive manufactured ER2319 thin-walled part. *CIRP J. Manuf. Sci. Technol.* **2023**, *46*, 230–241. [[CrossRef](#)]
25. Badri, E.; Shamsipur, A.; Abdollahzadeh, A. AlMg/SiC nanocomposite thin wall via hybrid wire arc additive manufacturing and friction stir processing. *J. Mater. Res. Technol.* **2025**, *38*, 2690–2706. [[CrossRef](#)]
26. Bagheri, M.; Mirsalehi, S.E. A novel hybrid WAAM-FSP approach for fabrication of ceramic-reinforced aluminum matrix nanocomposites. *J. Alloys Compd.* **2025**, *1042*, 183896. [[CrossRef](#)]
27. Guo, Y.; Jiang, X.; Min, J.; Dai, G.; Li, M.; Xia, Y.; Sun, Z. Microstructure evolution and grain refinement in 2319 aluminum alloy via WAAM coupled with multi-pass friction stir processing. *J. Alloys Compd.* **2024**, *1007*, 176338. [[CrossRef](#)]
28. Mishra, R.S.; Ma, Z.Y. Friction stir welding and processing. *Mater. Sci. Eng. R* **2005**, *50*, 1–78. [[CrossRef](#)]
29. Li, S.; Zhang, L.J.; Zhang, G.F.; Ning, J. In-situ induce reinforcement in WAAM of Al-matrix composite using active N₂ as shielding gas followed by friction stir processing. *J. Mater. Res. Technol.* **2024**, *30*, 1687–1695. [[CrossRef](#)]
30. Liu, L.; Xu, W.; Li, Y.; Liu, R.; Liu, R.; Huang, Y.; Dong, C. Effects of friction stir processing on microstructure and mechanical properties of Al-Cu alloy fabricated by WAAM. *J. Mater. Res. Technol.* **2025**, *34*, 539–551. [[CrossRef](#)]
31. Liu, L.; Xu, W.; Zhao, Y.; Lin, Z.; Liu, Z.; Dong, Y.; Dong, C. Tailoring the microstructure and mechanical properties of WAAM Al-Mg alloy via interlayer FSP. *J. Mater. Res. Technol.* **2023**, *25*, 1055–1068. [[CrossRef](#)]
32. Nguyen, D.S.; Song, J.; Fu, Y.; To, A.C. An integrated hybrid wire-arc DED, FSP, and milling system for multi-track, multi-layer part manufacturing. *Addit. Manuf. Lett.* **2024**, *11*, 100247. [[CrossRef](#)]
33. Zhou, S.; Xu, L.; Wang, S.; Xie, H.; Zhao, Y.; Sun, Z.; Dai, G.; Yang, G. Effect of friction stir processing and heat treatment sequences on the microstructural evolution and mechanical properties of wire arc additively manufactured aluminum alloys. *Mater. Sci. Eng. A* **2025**, *947*, 149133. [[CrossRef](#)]
34. Huang, J.; Fu, Y.; Zhai, W.; Li, R.; Zhao, X.; Lin, H.; Zhang, H.; Wang, G. Hybrid interlayer hot rolling and wire arc additive manufacturing of Al-Mg alloy. *J. Mater. Res. Technol.* **2024**, *30*, 7037–7050. [[CrossRef](#)]
35. Gornyakov, V.; Sun, Y.; Ding, J.; Williams, S. Modeling and optimizing hybrid process of wire arc additive manufacturing and high-pressure rolling. *Mater. Des.* **2022**, *223*, 111121. [[CrossRef](#)]
36. Lei, L.; Ke, L.; Xiong, Y.; Liu, S.; Du, L.; Chen, M.; Xiao, M.; Fu, Y.; Yao, F.; Yang, F.; et al. Microstructure, tensile properties, and fracture toughness of an in situ rolling hybrid with WAAM AerMet100 steel. *Micromachines* **2024**, *15*, 494. [[CrossRef](#)]
37. Xiong, X.; Qin, X.; Hua, L.; Wan, G.; Hu, Z.; Ni, M. Microstructure evolution and parameters optimization of follow-up hammering-assisted hybrid wire arc additive manufacturing. *J. Manuf. Process.* **2022**, *84*, 681–696. [[CrossRef](#)]

38. Hönnige, J.R.; Davis, A.E.; Ho, A.; Kennedy, J.R.; Neto, L.; Prangnell, P.; Williams, S. The effectiveness of grain refinement by machine hammer peening in high deposition rate wire-arc AM Ti-6Al-4V. *Metall. Mater. Trans. A* **2020**, *51*, 3692–3703. [\[CrossRef\]](#)
39. McAndrew, A.R.; Rosales, M.A.; Colegrove, P.A.; Hönnige, J.R.; Ho, A.; Fayolle, R.; Eytayo, K.; Stan, I.; Sukrongpang, P.; Crochemore, A.; et al. Interpass rolling of Ti-6Al-4V wire + arc additively manufactured features for microstructural refinement. *Addit. Manuf.* **2018**, *21*, 340–349. [\[CrossRef\]](#)
40. Xian, G.; Pan, J.; Lee, J.; Kang, N. Weakening the anisotropic property and refining prior-beta grains via hammer peening treatment during wire arc additively manufacturing of Ti-6Al-4V. *Metals* **2024**, *14*, 1261. [\[CrossRef\]](#)
41. Elalem, A.N.; Wu, X. Process-microstructure-property characteristics of aluminum walls fabricated by hybrid WAAM with FSP. *Materials* **2026**, *19*, 580. [\[CrossRef\]](#)
42. Ma, J.; Fan, S.; Gong, Y.; Jiang, Q.; Li, F. Influence of friction stir processing post-treatment on the microstructure and mechanical properties of 205A aluminum alloy produced by wire arc-DED. *Metals* **2025**, *15*, 331. [\[CrossRef\]](#)
43. Zhou, G.; Huang, T.; Su, L.; Huang, Q.; Wu, S.; Zhang, B. The microstructure and mechanical properties of deposited AlCuSc alloy wall structures fabricated by WAAM with FSP assistance. *Thin-Walled Struct.* **2025**, *209*, 112954. [\[CrossRef\]](#)
44. Thangamani, G.; Tamang, S.K.; Patel, M.S.; Narayanan, J.A.; Pallagani, J.; Rose, P.; Gianchandani, P.K.; Thirugnanasambandam, A.; Anand, P.I. Post-processing treatment of WAAM NiTi shape memory alloy using laser shock peening: A study on tensile behavior and fractography analysis. *Int. J. Adv. Manuf. Technol.* **2025**, *136*, 3315–3327. [\[CrossRef\]](#)
45. Sun, R.; Li, L.; Zhu, Y.; Guo, W.; Peng, P.; Cong, B.; Sun, J.; Che, Z.; Li, B.; Guo, C.; et al. Microstructure, residual stress and tensile properties control of wire-arc additive manufactured 2319 aluminum alloy with laser shock peening. *J. Alloys Compd.* **2018**, *747*, 255–265. [\[CrossRef\]](#)
46. Munther, M.; Martin, T.; Tajyar, A.; Hackel, L.; Beheshti, A.; Davami, K. Laser shock peening and its effects on microstructure and properties of additively manufactured metal alloys: A review. *Eng. Res. Express* **2020**, *2*, 022001. [\[CrossRef\]](#)
47. Ermakova, A.; Braithwaite, J.; Razavi, N.; Ganguly, S.; Berto, F.; Mehmanparast, A. The influence of laser shock peening on corrosion-fatigue behavior of wire arc additively manufactured components. *Surf. Coat. Technol.* **2023**, *456*, 129262. [\[CrossRef\]](#)
48. Liu, X.; Yin, S.; Zhang, G.; Li, Y.; Guan, R. Effect of interlayer ultrasonic impact on the microstructure, mechanical and corrosion properties of WAAM AZ31 Mg alloy thin wall. *J. Mater. Res. Technol.* **2024**, *33*, 180–192. [\[CrossRef\]](#)
49. Su, Z.; Yang, D.; Yang, C.; Fan, J.; Yan, D.; Peng, Y.; Wang, K. The influence of different ultrasonic impact treatment modes on microstructure and mechanical properties of 18Ni-300 steel fabricated by WAAM. *Virtual Phys. Prototyp.* **2024**, *19*, e2362424. [\[CrossRef\]](#)
50. Duan, X.; Cui, R.; Yang, H.; Yang, X. Hybrid additive and subtractive manufacturing method using pulsed arc plasma. *Materials* **2023**, *16*, 4561. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Kannan, A.R.; Pramod, R.; Prakash, K.S.; Shanmugam, N.S.; Yoon, J.; Oliveira, J.P. Understanding the microstructural evolution and fatigue behavior of aluminum 2319 fabricated by wire arc additive manufacturing. *Arch. Civ. Mech. Eng.* **2024**, *24*, 110. [\[CrossRef\]](#)
52. Dai, G.; Xue, M.; Guo, Y.; Sun, Z.; Chang, H.; Lu, J.; Li, W.; Panwisawas, C.; Alexandrov, I.V. Gradient microstructure and strength-ductility synergy improvement of 2319 aluminum alloys by hybrid additive manufacturing. *J. Alloys Compd.* **2023**, *968*, 171781. [\[CrossRef\]](#)
53. Qie, M.; Wei, J.; He, C. Microstructure evolution and mechanical properties of WAAM Al-Zn-Mg-Cu alloy assisted by interlayer FSP. *J. Mater. Res. Technol.* **2023**, *24*, 2891–2906. [\[CrossRef\]](#)
54. Maurya, A.K.; Yeom, J.T.; Kang, S.W.; Park, C.H.; Hong, J.K.; Reddy, N.S. Optimization of hybrid manufacturing process combining forging and WAAM Ti-6Al-4V through hot deformation characterization. *J. Alloys Compd.* **2022**, *894*, 162453. [\[CrossRef\]](#)
55. Liao, Z.; Yang, B.; Huang, M.; Wen, W.; Jiang, L.; Xiao, S. In-situ investigation on tensile deformation behavior of hybrid hot-rolled WAAM Al-Mg alloys. *J. Alloys Compd.* **2025**, *1010*, 177397. [\[CrossRef\]](#)
56. Nagarajan, S.; Carter, M.; Curtis, T.; Crawford, G. Cold spray-friction stir hybrid additive manufacturing of 316L SS. *Mater. Des.* **2025**, *255*, 114164. [\[CrossRef\]](#)
57. Panchenko, O.; Kladov, I.; Kurushkin, D.; Zhabrev, L.; Ryl'kov, E.; Zamozdra, M. Effect of thermal history on microstructure evolution and mechanical properties in WAAM of HSLA steel functionally graded components. *Mater. Sci. Eng. A* **2022**, *851*, 143569. [\[CrossRef\]](#)
58. Chen, Y.; Yang, C.; Fan, C.; Wang, M. Microstructure evolution and mechanical properties of a nickel-based superalloy repaired using wire and arc additive manufacturing. *Mater. Charact.* **2022**, *193*, 112315. [\[CrossRef\]](#)
59. Chen, S.; He, Z.; Xiao, J.; Gai, S.; Wang, Z.; Li, J. Modified heat treatment and related microstructure-mechanical property evolution of arc melting additively manufactured GH4169 Ni-based superalloy. *J. Alloys Compd.* **2023**, *947*, 169449. [\[CrossRef\]](#)
60. Zhang, T.; Li, H.; Gong, H.; Ding, J.; Wu, Y.; Diao, C.; Zhang, X.; Williams, S. Hybrid wire-arc additive manufacture and effect of rolling process on microstructure and tensile properties of Inconel 718. *J. Mater. Process. Technol.* **2022**, *299*, 117361. [\[CrossRef\]](#)
61. Zeng, L.; Wu, G. Microstructure and mechanical properties of GH4169D superalloy fabricated by hybrid arc and micro-rolling additive manufacturing. *Acta Metall. Sin.* **2023**, *60*, 681–690. [\[CrossRef\]](#)

62. Zhang, T.; Xu, W.; Gong, H.; Wu, Y.; Yuan, H.; Su, Y. Study on fatigue properties of hybrid wire arc additively manufactured and cold-rolled Inconel 718. *Rapid Prototyp. J.* **2025**, *31*, 1593–1605. [\[CrossRef\]](#)
63. Hasani, N.; Ghoncheh, M.H.; Kindermann, R.M.; Pirgazi, H.; Sanjari, M.; Tamimi, S.; Shakerin, S.; Kestens, L.A.I.; Roy, M.J.; Mohammadi, M. Dislocations mobility in superalloy-steel hybrid components produced using wire arc additive manufacturing. *Mater. Des.* **2022**, *220*, 110899. [\[CrossRef\]](#)
64. Shan, H.; Li, Y.; Wang, S.; Yuan, T.; Chen, S. Friction stir processing of wire arc additively manufactured Al-Zn-Mg-Cu alloy reinforced with high-entropy alloy particles. *J. Alloys Compd.* **2025**, *1020*, 179476. [\[CrossRef\]](#)
65. Zhang, T.; Li, X.; Gong, H.; Wu, Y.; Yuan, H.; Su, Y. Investigations on microstructure and tensile properties of hybrid WAAM deposition and cold/hot rolling for 2219 aluminum alloy. *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.* **2025**, 09544089251345011. [\[CrossRef\]](#)
66. Huang, J.; Zhang, H.; Li, R.; Zhao, X.; Lin, H.; Zhai, W.; Wang, G.; Fu, Y. Hybrid in-situ hot rolling and wire arc additive manufacturing of Al-Si alloy. *J. Manuf. Process.* **2024**, *127*, 328–339. [\[CrossRef\]](#)
67. Segal, V.M. Materials processing by simple shear. *Mater. Sci. Eng. A* **1995**, *197*, 157–164. [\[CrossRef\]](#)
68. Segal, V.M. Equal channel angular extrusion: From micromechanics to structure formation. *Mater. Sci. Eng. A* **1999**, *271*, 322–333. [\[CrossRef\]](#)
69. Segal, V.M. Severe plastic deformation: Simple shear versus pure shear. *Mater. Sci. Eng. A* **2002**, *338*, 331–344. [\[CrossRef\]](#)
70. Chen, Z.; Liang, Y.; Li, C.; Zhang, X.; Kong, J.; Fan, J.; Wang, K.; Peng, Y. Hybrid fabrication of cold metal transfer additive manufacturing and laser metal deposition for Ti6Al4V. *Materials* **2024**, *17*, 1862. [\[CrossRef\]](#) [\[PubMed\]](#)
71. Yuan, X.Y.; Han, S.J.; Han, L.; Li, S.; Wei, B.Q.; Guo, S.Y.; Zhang, K.; Wang, B.Y.; Hu, Z.T.; Wang, H.Y. Strength and ductility synergy in Mg-11Al alloys via Sc-microalloyed dual-wire arc additive manufacturing. *Mater. Res. Lett.* **2026**, *14*, 240–249. [\[CrossRef\]](#)
72. Joshi, R.S.; Singh, S.; Kumar, P. Wire arc additive manufacturing of low-alloyed steels, copper-aluminum alloys, and their bimetals. *J. Braz. Soc. Mech. Sci. Eng.* **2025**, *47*, 412. [\[CrossRef\]](#)
73. Wei, J.; He, C.; Zhao, Y.; Qie, M.; Qin, G.; Zuo, L. Evolution of microstructure and properties in 2219 aluminum alloy produced by WAAM assisted by interlayer FSP. *Mater. Sci. Eng. A* **2023**, *868*, 144794. [\[CrossRef\]](#)
74. Sun, Z.; Dai, G.; Ye, W.; Xing, Y.; Yao, J.; Jiang, T.; Guo, Y.H.; Lu, H.; Lu, J. Modified microstructure and enhanced mechanical performance of wire arc additive manufactured 2319 aluminum alloy via interlayer friction stir processing. *J. Cent. South Univ.* **2026**. [\[CrossRef\]](#)
75. Wang, G.; Zhang, M.; Fu, Y.; Zhang, H.; Zhai, W.; Lu, Y.; Li, R. Isotropy of fatigue crack growth in hybrid additive manufactured Ti6Al4V ELI titanium alloy. *Mater. Sci. Eng. A* **2024**, *909*, 146850. [\[CrossRef\]](#)
76. Wu, X.; Yang, Q.; Elalem, A.N. Additive Manufacturing System and Unified Additive-Deformation-Machining (ADM) Process of Manufacturing. US Patent 12311597B2, 27 May 2025.
77. Lütjering, G.; Williams, J.C. *Titanium*, 2nd ed.; Springer: Berlin, Germany, 2007.
78. Bagherzadeh, A.; Budak, E.; Ozlu, E.; Koc, B. Machining behavior of Inconel 718 in hybrid additive and subtractive manufacturing. *CIRP J. Manuf. Sci. Technol.* **2023**, *46*, 178–190. [\[CrossRef\]](#)
79. Rabalo, M.A.; Rubio, E.M.; Agustina, B.; Camacho, A.M. Hybrid additive and subtractive manufacturing: Evolution of the concept and last trends in research and industry. *Procedia CIRP* **2023**, *118*, 741–746. [\[CrossRef\]](#)
80. Campatelli, G.; Montevecchi, F.; Venturini, G.; Ingarao, G.; Priarone, P.C. Integrated WAAM-subtractive versus pure subtractive manufacturing approaches: An energy efficiency comparison. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2020**, *7*, 1–11. [\[CrossRef\]](#)
81. Muzyk, M.; Pakiela, Z.; Kurzydowski, K.J. Generalized stacking fault energies of aluminum alloys: Density functional theory calculations. *Metals* **2018**, *8*, 823. [\[CrossRef\]](#)

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