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The New Era of Fusion and Solid-State Joining: A Review of Latest Welding Techniques and Applications

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Abstract

This review examines the rapidly changing field of solid-state joining and welding technologies, emphasizing new developments, practical uses, and future research avenues. Strategies that lower heat input, enhance joint integrity, and allow the connecting of sophisticated and dissimilar materials have gained importance within the last decade. Solid-state techniques are particularly appealing for lightweight alloys used in the automotive and aerospace industries because they reduce melt-related defects and the formation of brittle intermetallic. These techniques include friction stir welding (FSW) and its variations, friction stir spot welding (FSSW), linear friction welding (LFW), magnetic/electromagnetic pulse welding (MPW/EPW), and diffusion bonding. Fusion-based technologies have also evolved: high-power laser beam welding, laser–arc hybrid welding (LAHW), and hybrid processes integrate energy sources to achieve deep, high-quality welds at high speeds while controlling heat-affected zones. Ultrasonic welding has expanded beyond electronics into thermoplastic and composite joining, aided by process control and tooling innovations. Key enabling trends include process hybridization (combining complementary heat/force inputs), process monitoring and closed-loop control (increasing repeatability and enabling automation), and tailored tool and fixture designs for dissimilar-material joining. Emerging applications range from battery pack assemblies and electric-vehicle structures to additive-manufactured component joining and in-space construction. Predictive multiphysics models for microstructure evolution, standardized testing for dissimilar joints, scale-up strategies for novel solid-state methods, and environmentally friendly, energy-efficient industrial implementations are among the urgent research gaps identified by this review, which synthesizes literature from 2018–2025 to summarize mechanisms, benefits, limitations, and typical process windows. In order to provide reliable, high-throughput joining solutions for next-generation materials and structures, the review concludes by outlining a future research agenda that focuses on digitalization, sustainability metrics, and interdisciplinary work that integrates materials science, mechanical engineering, and controls engineering.

Keywords: Dissimilar material joining, friction stir welding, hybrid welding processes, laser–Arc hybrid welding, solid-state welding, ultrasonic welding

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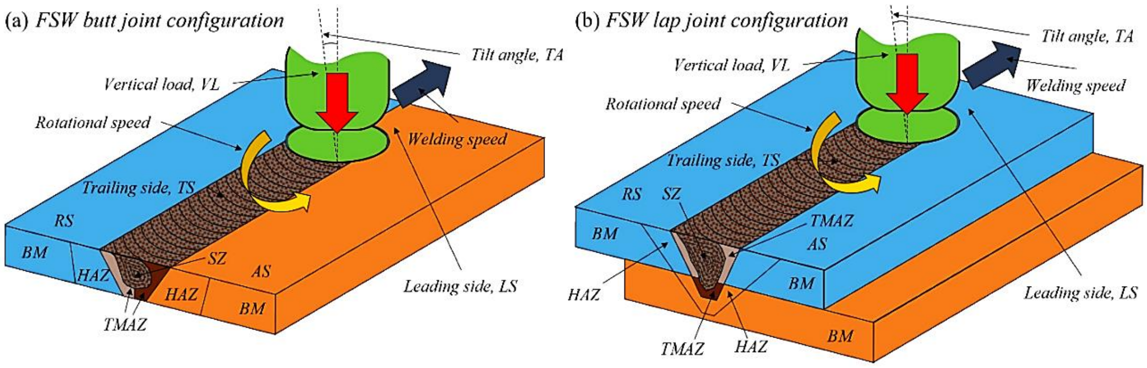
INTRODUCTION

Modern production relies heavily on joining and welding processes. Although conventional fusion welding techniques like gas metal arc welding (GMAW) and shielded metal arc welding (SMAW) are still widely used, fast innovation has been spurred by industrial needs for lighter structures, higher throughput, less distortion, and the joining of incompatible or advanced alloys. Solid-state joining techniques, which fuse metals below their melting points, have developed into commercially feasible methods at the same time [1–4].

Friction Stir Welding (FSW) has emerged as a cornerstone of modern solid-state joining technologies, exemplifying the shift toward processes that prioritize joint integrity, reduced thermal damage, and applicability to advanced and dissimilar materials – central themes in The New Era of Fusion and Solid-State Joining: A Review of Latest Welding Techniques and Applications. Developed in 1991, FSW joins materials below their melting point through severe plastic deformation induced by a rotating, nonconsumable tool traversing along the joint interface [5–9]. This solid-state mechanism bypasses typical fusion-related defects such as porosity, hot cracking, and solidification anomalies, making FSW particularly suitable for lightweight alloys used in aerospace, automotive, and shipbuilding industries. As highlighted in the review, recent advances focus on optimizing tool geometry, adapting innovative process kinematics (including bobbin and orbital tools), and expanding FSW's applicability to high-temperature and reactive alloys such as titanium and nickel-based superalloys [10–12]. Variants like friction stir spot welding (FSSW) and linear friction welding (LFW) further extend its versatility, enabling high-throughput fabrication and complex joint configurations. FSW's ability to produce high-quality, defect-free welds at industrial scale aligns with the review's narrative on welding innovations that meet the demands of modern manufacturing – enhancing productivity while maintaining performance in next-generation material systems (Figure 1).


(a) *FSW butt joint configuration*

(b) *FSW lap joint configuration*

Figure 1. Scheme of FSW in the (a) butt and, (b) lap-joint configurations [2].

Magnetic pulse welding (MPW) represents one of the most promising high-velocity solid-state joining techniques in the modern era of welding technology, as outlined in The New Era of Fusion and Solid-State Joining: A Review of Latest Welding Techniques and Applications. Unlike conventional fusion methods that rely on heat and filler material to create joints, MPW uses intense electromagnetic forces to accelerate one workpiece toward another at high velocity, producing a metallurgical bond through impact and plastic deformation without melting the base materials [13–15]. This extreme but controlled deformation facilitates solid-state bonding with minimal heat-affected zones, reducing residual stresses, distortion, and undesirable microstructural changes – attributes that align with the review's emphasis on joining strategies that lower heat input and enhance joint integrity. MPW is particularly advantageous for joining dissimilar metals, such as aluminum to copper or aluminum to steel, where thermal fusion welding often leads to brittle intermetallic and performance degradation. By leveraging electromagnetic energy rather than direct heating, MPW achieves nearly distortion-free joints, making it suitable for lightweight structural applications, automotive electrical connectors, and battery pack assemblies – key application domains highlighted in the review [16, 17]. The process exemplifies the shift toward solid-state methodologies that address contemporary industrial challenges, including joining advanced alloys and multimaterial systems while preserving their intrinsic properties and enabling high throughput (Figure 2).

The last decade has seen an acceleration of hybrid approaches that combine the advantages of multiple energy sources or merge fusion and solid-state principles, supported by advances in control systems and additive manufacturing integration. This review frames the recent developments in both fusion and solid-state joining, emphasizing techniques that have demonstrated clear application potential in transportation, aerospace, electronics, and energy sectors.

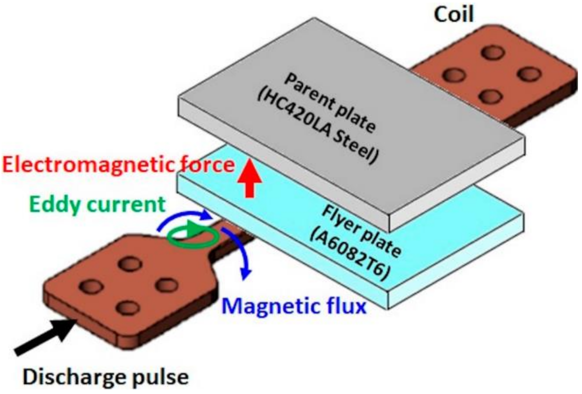


Figure 2. Electromagnetic pulse welding (MPW) [8].

LITERATURE REVIEW

Solid-State Joining: Friction-Based Methods: Friction stir welding (FSW), introduced in 1991, has remained among the most impactful solid-state joining processes [15, 16]. Recent reviews and systematic studies [2022–2025] emphasize FSW's ability to produce high-integrity joints without melting, thereby avoiding typical fusion defects such as porosity and solidification cracking [1–3, 15]. Modern FSW research focuses on tool geometry optimization, process kinematics (including orbital and bobbin tools), and the extension of FSW to high melting point and reactive alloys (Ti, Ni-based superalloys) through controlled heat input and advanced tool designs [1–3, 16]. Variants such as linear friction welding (LFW) (Figure 3) and friction stir spot welding (FSSW) have been adapted for high-throughput automotive and aerospace joining applications [1, 13]. Reviews report that FSW-based techniques now support industrial-scale manufacturing for aluminum alloys, and advances in tool materials and cooling strategies expand applicability to steels and dissimilar joints, though challenges persist with intermetallic compound formation in aluminum–titanium systems and thermal management for steels [2, 3, 15].

Electromagnetic and High-Velocity Solid-State Methods: Electromagnetic pulse welding (MPW/EPW) and magnetic pulse welding exploit high-speed impact and controlled plastic deformation to form metallurgical bonds with minimal thermal input [8, 9]. Recent literature highlights MPW's effectiveness in joining dissimilar metals such as Al–Cu and Al–steel, producing joints with extremely small heat-affected zones and negligible distortion [8, 9]. MPW has been successfully demonstrated for tubular and cylindrical geometries and is increasingly adopted for battery and electrical conductor assemblies where preservation of base-material properties is critical [8, 9].

Diffusion Bonding and Transient Liquid Phase Joining: Diffusion bonding (DB) and transient liquid phase (TLP) bonding are widely used for high-performance applications requiring creep resistance, hermetic sealing, and thermal stability [3, 12, 15]. Reviews indicate that DB and TLP are indispensable in aerospace and electronics for joining nickel-based superalloys, ceramic-to-metal interfaces, and thin metallic foils [12, 15]. Advances in interlayer composition, surface activation techniques, and controlled processing atmospheres have significantly improved joint quality while reducing bonding temperature and dwell time requirements [12].

Laser, Laser–Arc Hybrid and Advanced Fusion Methods: Fusion welding processes have evolved through the adoption of high-brightness energy sources and hybrid configurations. Laser beam welding (LBW) offers high power density, precise energy delivery, and deep penetration with narrow heat-affected zones, enabling automated production and high-precision applications [4, 14]. Hybrid laser–arc welding (HLAW/LAHW) combines the precision of lasers with the gap-bridging capability of arc welding, enabling higher welding speeds and thicker single-pass welds suitable for shipbuilding and heavy engineering sectors [6, 7]. Contemporary literature analyzes keyhole stability, process window optimization, and dissimilar material joining strategies such as steel–copper and steel–aluminum systems [4–7] (Figure 4).

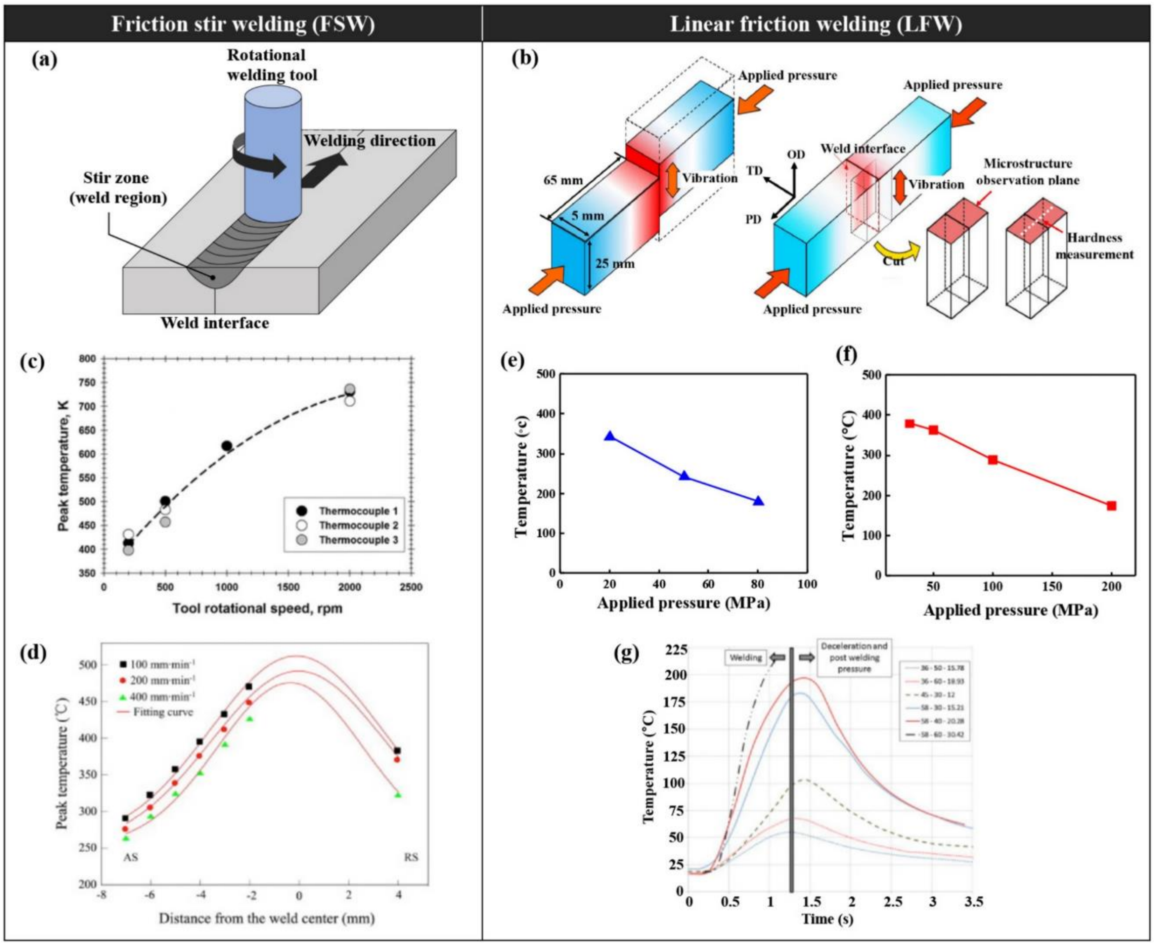


Figure 3. Schematic illustrations of a FSW, b LFW and the relationship between peak welding temperatures and welding parameters of FSWed c AA1050 joints [1].

Ultrasonic and Vibration-Assisted Joining: Ultrasonic welding (USW) has progressed from microelectronic interconnections to joining thermoplastics, fiber-reinforced thermoplastics (FRTP), and metallic foils [10, 11, 17]. Recent bibliometric studies highlight growing interest in large-area ultrasonic welding and hybrid ultrasonic-assisted processes that improve material flow and reduce energy consumption [10, 11]. Current research focuses on sonotrode design, energy-dose control, and process modeling to enhance joint consistency and scalability [10, 17].

Hybrid and Digitalized Welding: Sensors, Control, and Additive Integration: Across both fusion and solid-state joining domains, the integration of sensors, closed-loop control systems, and digital twin frameworks is shaping modern welding practice [4, 6, 15]. In-process monitoring using optical, acoustic, and thermal sensors enables real-time defect detection and adaptive parameter control, improving joint reliability for complex geometries [4, 14]. Hybrid manufacturing approaches, including joining additively manufactured components, require careful management of residual stresses and microstructural gradients; recent reviews emphasize the need for multiscale modeling that links process physics with mechanical performance [15].

METHODOLOGY

This review was prepared by a systematic literature synthesis of peer-reviewed journal articles, conference proceedings, and authoritative reviews published from 2018–2025. Databases searched included Science Direct, MDPI, PubMed Central, and Google Scholar using keyword combinations such as 'friction stir welding review', 'magnetic pulse welding', 'laser welding review', 'ultrasonic welding review', and 'solid-state welding review'. Priority was given to review articles and experimental studies that reported mechanisms, process-parameter windows, microstructural evolution, and industrial applications. The selected literature was analyzed to identify recurring themes, strengths, limitations, and gaps. Comparative tables and schematic process summaries were created to synthesize findings across techniques.

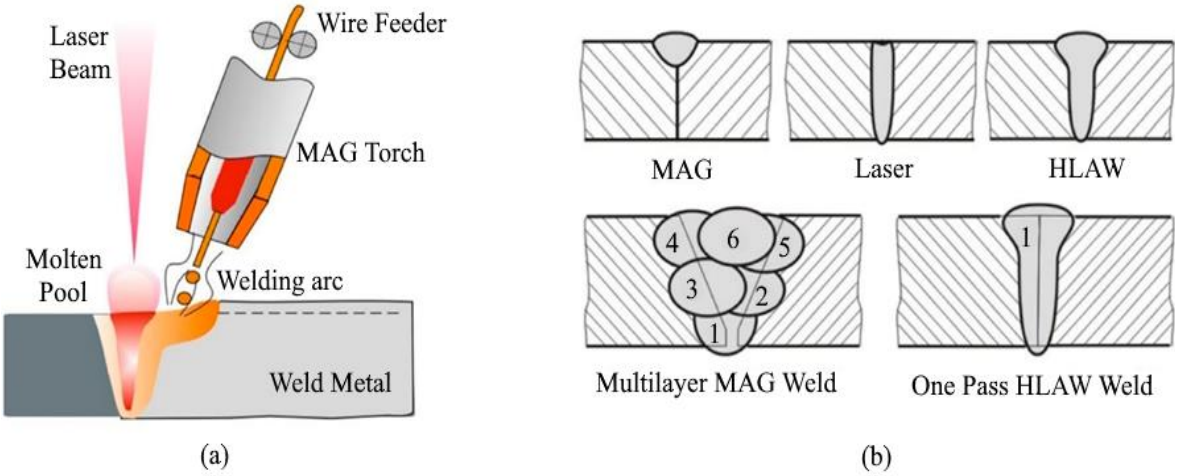


Figure 4. Hybrid laser–metal active gas (MAG) system: (a) setup; (b) comparison of weld shapes and geometric features obtained through different processes [6].

FUTURE SCOPE

Multiphysics and multiscale modeling that couples thermal, mechanical, and metallurgical evolution to predict joint properties. Standardized protocols and performance metrics for evaluating dissimilar and multimaterial joints to accelerate industrial adoption. Scale-up studies that translate laboratory demonstrations (especially for MPW, diffusion bonding, and advanced FSW variants) into high-throughput manufacturing lines. Green manufacturing metrics: lifecycle, energy efficiency, and resource-use analyses for welding processes to support sustainability goals. Digital twins and AI-assisted closed-loop control to enable adaptive welding in variable production settings and for in-situ repair. Interdisciplinary work linking materials science, tooling engineering, and control systems to design weld schedules for next-generation alloys and additive assemblies.

CONCLUSION

The past decade has witnessed dynamic advancement in both fusion and solid-state joining technologies. Solid-state approaches have proven especially powerful for joining lightweight and dissimilar materials with reduced defects, while fusion methods have become more precise and faster through laser and hybridization strategies. The integration of sensors, sophisticated tooling, and process control is crucial to unlocking the full industrial potential of novel welding techniques.

While challenges remain – including the joining of highly dissimilar material pairs, standardization, and scale-up – a coordinated agenda that prioritizes modeling, sustainability, and digitalization will accelerate the translation of laboratory innovations into robust manufacturing solutions.

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