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Editorial

Advanced Welding Technology and Its Applications

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1. Introduction

Welding technology is crucial to modern manufacturing, construction, and structural engineering. As industrial demands evolve toward higher performance, greater efficiency, and improved sustainability, the field continues to push the boundaries—embracing artificial intelligence, additive manufacturing, novel energy sources, and surface engineering strategies. Advanced welding technologies (AWTs) are driving fabrication efficiencies by reducing heat input, minimising distortion, and enabling the joining of dissimilar materials. Key advancements include friction stir welding (FSW) for aerospace light alloys, Hybrid Laser-Arc welding and AI-integrated robotic welding for real-time consistency.

Solid-state friction stir welding (SSFSW) is a solid-state joining method that is increasingly reviewed in AWT for its ability to join materials without melting them. This prevents defects commonly found in fusion welding and is ideal for aerospace and automotive parts. A comprehensive review of friction stir welding of metal matrix composites for automotive applications is presented in paper [1]. The review combines findings on mechanical properties and high-strain-rate behaviour to establish process–property–performance relationships relevant to crashworthy, lightweight vehicle applications. Solid-state friction stir techniques encompass both the joining operations of friction stir welding (FSW) and the layer-by-layer fabrication of Friction Stir Additive Manufacturing (FSAM). FSAM, derived from FSW, achieves layer-by-layer material deposition through solid-state bonding of the rotating tool. As an emerging solid-state additive manufacturing (AM) process, FSAM holds significant potential for large-scale AM of metals and composites [2].

Hybrid Laser-Arc welding bridges the gap between the deep penetration of lasers and the low cost of arc welding, enabling high-speed fusion of stainless and mild steel. Laser-arc hybrid welding (LAHW) offers the advantages of large penetration, high efficiency, and minimal deformation compared to laser welding. The study [3] demonstrates that synchronous wire-powder feeding combined with beam oscillation is a promising approach for achieving high-performance welded joints in high-strength aluminium alloys. The LAHW process is 50–100% faster than the autogenous laser welding. According to the review paper [4], a small joint gap is beneficial for hybrid welding, and the maximum welding speed is achieved for a gap of 0.6–1 mm. The 25 mm thick steel plates are successfully welded in a single pass using a LAHW at 1 m/min. The major applications of LAHW are found in the automobile and shipbuilding industries. Laser-arc hybrid welding has also found its application in the aerospace industry and other manufacturing industries. Recent studies have increasingly emphasised the role of advanced process control and hybrid welding techniques in improving the weldability of titanium alloys [5]. Compared with traditional arc welding methods, Laser–MIG hybrid welding provides better control of heat input, droplet transfer dynamics, and melt pool stability. Advanced welding techniques, such as Laser–MIG hybrid welding, play a significant role in improving compatibility.

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Their lower, more controlled heat input reduces the thickness of the intermetallic layer and residual stresses [6]. In recent years, the oscillating laser-arc hybrid welding (OLAHW) has attracted increasing attention due to its remarkable porosity-suppression capability. The study [7] provides a comprehensive understanding of the dynamic mechanisms of pore formation during OLAHW of aluminium alloy.

The rapid development of AWTs means that modern solutions for welding equipment are now appearing on the market, enabling the robotisation and automation of the welding process. Artificial intelligence and machine learning are systems that analyse data in real time to make micro-adjustments during the welding process. Using AI reduces the risk of human error and ensures highly repeatable welds in automated environments. Robots like COBOTs are gaining popularity in the welding industry, ensuring safe and effective collaboration with humans. An overview of collaborative robot applications in welding and additive manufacturing (AM) is described in the paper [8]. In the manufacturing sector, the use of COBOTs is significantly impacting welding and additive manufacturing. In welding, COBOTs can work alongside welders to perform repetitive or physically demanding tasks, while allowing skilled workers to focus on more complex aspects such as welding parameter selection, inspection, and quality control [9]. Furthermore, these robots have been found to improve welding precision, particularly in multi-pass welding on non-horizontal and curved surfaces, and to maintain process consistency, reducing distortion and defects and increasing productivity.

This Special Issue, titled "Advanced Welding Technology and Its Applications", presents nine original contributions, divided into five thematic sections: solid-state friction welding process, wire arc additive manufacturing, gas metal arc welding, hot-wire gas tungsten arc welding, and laser welding. The final thematic group brings together contributions addressing the surface performance of welded and overlaid components, with a shared emphasis on durability and sustainability. These papers collectively reflect the current state of the art across the most dynamic borders of welding science and engineering.

2. An Overview of Published Articles

2.1. Solid-State Friction Welding Process Optimisation

Cho et al. (Contribution 1) developed an artificial neural network (ANN) model to predict the tensile strength of friction stir welding (FSW) joints between dissimilar aluminium–copper combinations processed under cryogenic conditions. They incorporated heat transfer analysis outputs—specifically the maximum temperature and temperature gradient—as ANN inputs. Using the Hyperband tuner for model optimisation, the authors achieved tensile strength predictions with an average error of only 5.4%. This work underscores the potential of data-driven approaches to replace or substantially reduce the cost of experimental campaigns in FSW process development. Winiczenko et al. (Contribution 2) addressed the multi-objective optimisation of rotary friction welding (RFW) parameters for dissimilar AZ91D magnesium–AA6082 aluminium alloy joints, a material combination important for lightweight structural applications. They used a hybrid strategy combining ANNs with genetic algorithms. The authors simultaneously maximised tensile strength and minimised material loss (shortening) during welding, achieving a joint strength improvement from 24 to 81 MPa and a reduction in shortening from 8.25 to 0.23 mm. Together, these two studies highlight the power of AI-assisted methodologies in advancing friction welding of multi-material systems.

2.2. Wire Arc Additive Manufacturing

The second thematic group focuses on wire arc additive manufacturing (WAAM), an increasingly prominent technology for the near-net-shape fabrication of medium- and

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large-scale metal components. Garašić et al. (Contribution 3) investigated the influence of current type and AC polarity balance on the mechanical and microstructural properties of 6063 aluminium alloy walls produced by WAAM using an AC MIG process. Employing a TiB_2-refined Al–Mg–Si filler wire, the study demonstrated that polarity balance critically governs wall geometry, porosity, grain structure, and residual stress distribution, with the highest tensile strength of 172 MPa recorded in DC-MIG samples near the substrate—a region benefiting from accelerated cooling. These insights are fundamental for tailoring process parameters to achieve consistent part quality in aluminium WAAM.

Extending the application scope of WAAM to a more specialised domain, Bolot et al. (Contribution 4) examined the fabrication of complex-shaped sealed capsules from AISI 316L stainless steel for use in hot isostatic pressing (HIP) sintering of powder. The study demonstrated the feasibility of a hybrid WAAM–HIP manufacturing route by addressing robot trajectory generation from CAD models, characterising WAAM mechanical properties (UTS between 540 and 600 MPa), and confirming that HIP processing restores a fully austenitic structure. The proposed technology is identified as a promising candidate for medium-scale component manufacturing in the nuclear sector, illustrating how WAAM can serve as an enabling platform for advanced hybrid processes.

2.3. Gas Metal Arc Welding and Hot-Wire Gas Tungsten Arc Welding

The third thematic group addresses arc welding in two key industrial areas: all-position pipeline welding and protective cladding of structural steels. Liu et al. (Contribution 5) reviewed the status and technological advances in all-position narrow-gap gas metal arc welding (GMAW) for pipelines. This process is challenging due to frequent sidewall and interlayer lack-of-fusion defects, especially in non-flat positions. The review synthesises recent findings on droplet transfer, arc morphology, and molten pool behaviour in different welding positions. It also outlines optimisation strategies, including parameter adjustment, control of the external magnetic field, and laser-arc hybrid welding. The paper offers practical guidance for pipeline construction engineers and a structured research agenda for the welding community.

Regarding surface protection, da Cruz Jr. et al. (Contribution 6) explored the use of hot-wire gas tungsten arc welding (HW-GTAW) to clad low-carbon steel substrates with super-austenitic stainless steel. By comparing cold-wire (CW-GTAW) and hot-wire conditions, the authors demonstrated that the hot-wire configuration reduced dilution—a key advantage for preserving clad-layer integrity—while achieving competitive corrosion and wear resistance. This contribution underscores the relevance of HW-GTAW as an efficient and versatile cladding process for surface engineering applications.

2.4. Laser Welding

The fourth thematic area is devoted to laser welding, with a particular focus on the opportunities offered by dynamic beam control. Krishna Murthy et al. (Contribution 7) explored the influence of beam shape and modulation frequency on weld seam geometry, penetration depth, and capillary behaviour using a coherent beam combining (CBC) laser system. Three intensity distributions—single point, line–point–line, and boomerang—were applied at modulation frequencies of 1, 10, and 100 kHz during welding of duplex and austenitic stainless steels. High-speed imaging revealed significant effects of both beam shape and frequency on capillary stability and penetration characteristics. These findings position CBC laser technology as a versatile and highly controllable platform for precision welding, with important implications for the welding of advanced high-performance steels.

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2.5. The Surface Performance of Welded Components

The fifth and final thematic group brings together contributions addressing the surface performance of welded and overlaid components, with a shared emphasis on durability and sustainability. Zemlik et al. (Contribution 8) investigated the restoration of abrasive wear resistance in welded joints of boron-alloyed martensitic armour steel (500 HBW nominal hardness) through post-weld heat treatment (PWHT). Combining metallographic analysis with tribological testing on a T-07 tribotester, the study demonstrated that PWHT increased wear resistance by 55% compared to the as-welded condition—results of direct relevance not only to defence applications but also to the mining, construction, and transportation sectors where such steels operate under intense abrasive loading.

By broadening the scope, Czapiewski et al. (Contribution 9) conducted a systematic review of regenerative hardfacing methods applied to steel substrates. The review maps process–structure–property (PSP) relationships across arc-based hardfacing techniques and identifies measurable indicators—energy input, dilution, bead geometry, heat-affected zone characteristics—as the principal levers governing weld structure and functional properties, including hardness, wear resistance, and fatigue life. A dedicated PSP table is proposed as a practical framework for process optimisation, and research gaps are identified regarding standardisation of energy metrics and the definition of technology windows within welding procedure specifications (WPS/WPQR). By framing regenerative hardfacing explicitly within the circular economy paradigm, this review highlights welding's underappreciated role as a sustainability-enabling technology.

3. Future Perspectives

Advanced technologies will continue to improve welding quality through better process control, eliminating defects, and improving the final product. It is worth noting that these technologies also improve occupational safety by automating processes, thereby minimising employee exposure to hazardous substances. Technological transformation can bring numerous benefits to both welders and end consumers. Key changes may include optimising material consumption, improving quality control, and reducing occupational health and safety costs. AI will play an important role in these changes. Investing in modern welding technologies increases the efficiency and productivity of production processes. Also, AM technologies will play a key role. Currently, they are gaining popularity in many industries. AM welding technology primarily encompasses processes such as laser metal deposition and electric arc additive manufacturing. Their advantage is the ability to create complex parts directly from digital data, layer by layer. This enables the production of components with custom shapes and functionalities.

The nine contributions assembled in this Special Issue collectively reflect the breadth and vitality of current research in advanced welding technology. Across solid-state and fusion welding, additive manufacturing, laser processing, and surface engineering, common threads emerge: the pursuit of superior mechanical performance, the integration of intelligent computational tools, and an increasing awareness of sustainability imperatives.

The Guest Editor trusts that this welding collection will serve as a valuable reference for researchers and engineers working in welding science and will stimulate further inquiry into the many open questions that remain in this technologically rich and industrially critical field.

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