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Review

Metallurgical Joining in the Modern Era: Techniques, Principles, and Applications in Welding

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Abstract

Welding represents a fundamental metallurgical process that has profoundly transformed modern industry, facilitating the fabrication of intricate structural components, transportation systems, and critical infrastructure. This comprehensive review traces the historical evolution of welding, from early metalworking techniques to contemporary advancements in high-precision, automated methodologies. An in-depth examination of diverse welding techniques including arc welding [Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW)], resistance welding, gas welding, and advanced energy beam processes [Laser Beam Welding (LBW), Electron Beam Welding (EBW)] is presented, with a focus on their underlying principles, industrial applications, and technological progressions. Furthermore, solid-state welding processes, such as friction and diffusion welding, are analyzed, underscoring their significance in aerospace, automotive, and high-performance engineering sectors. The study also evaluates prevalent welding defects, quality assessment methodologies (destructive and non-destructive testing), and recent innovations, such as artificial intelligence-driven welding optimization and hybrid welding approaches. With continuous advancements in automation, shielding gas technologies, and real-time monitoring systems, welding remains an indispensable pillar of industrial manufacturing. Future research should prioritize the enhancement of process efficiency, the refinement of weld integrity, and the development of sustainable, high-performance welding solutions to address the evolving demands of modern engineering and fabrication industries.

Keywords

Advanced metallurgical joining techniques, Automated welding technologies, Weld quality assessment, Hybrid and solid-state welding processes

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1. Introduction

Welding is a central metallurgical process that supports modern manufacturing by enabling the reliable joining of structural components, machinery, and critical infrastructure across diverse industrial sectors. It involves the application of heat, pressure, or both to create a metallurgical bond between metals, with or without filler material. Contemporary welding methods incorporate shielding systems that protect the molten pool from atmospheric contamination, ensuring durable and mechanically sound joints. Because of these advantages, welding has become indispensable in construction, transportation, aerospace, energy systems, and advanced manufacturing, increasingly replacing traditional mechanical fastening techniques such as riveting and bolting [1].

The development of welding spans thousands of years, beginning with early metalworking practices such as direct casting and forge welding during the Bronze and Iron Ages. These early techniques relied on heating or melting metals to create simple joints. A major technological transformation occurred during the Industrial Revolution, when forge welding became widespread in manufacturing and metal fabrication. Further progress followed in 1886 with Elihu Thomson's introduction of resistance welding, which laid the groundwork for large-scale industrial joining processes. Welding later played a pivotal role during and after World War I, particularly in military production, shipbuilding, and infrastructure development, reinforcing its significance in industrial growth [2].

Modern welding relies on four essential elements: base materials, heat source, shielding, and filler metals when required. Continued innovation has expanded the range of available processes, including arc, gas, and resistance welding, as well as high-energy beam methods. Advanced techniques such as laser beam welding, friction stir welding, and robotic welding systems now offer superior precision, improved metallurgical control, and higher productivity. Current trends incorporate artificial intelligence for process optimization, adaptive control for real-time feedback, and advanced non-destructive evaluation methods to ensure weld reliability and structural integrity [3,4]. Standardized terminology, as described in authoritative sources, provides a consistent framework for defining processes such as brazing, braze welding, welded joints, and welds, ensuring clarity and uniformity in engineering communication [5]. Figure 1 provides an overview of welding processes based on their heat source, illustrating the diverse range of available techniques and their industrial applications.

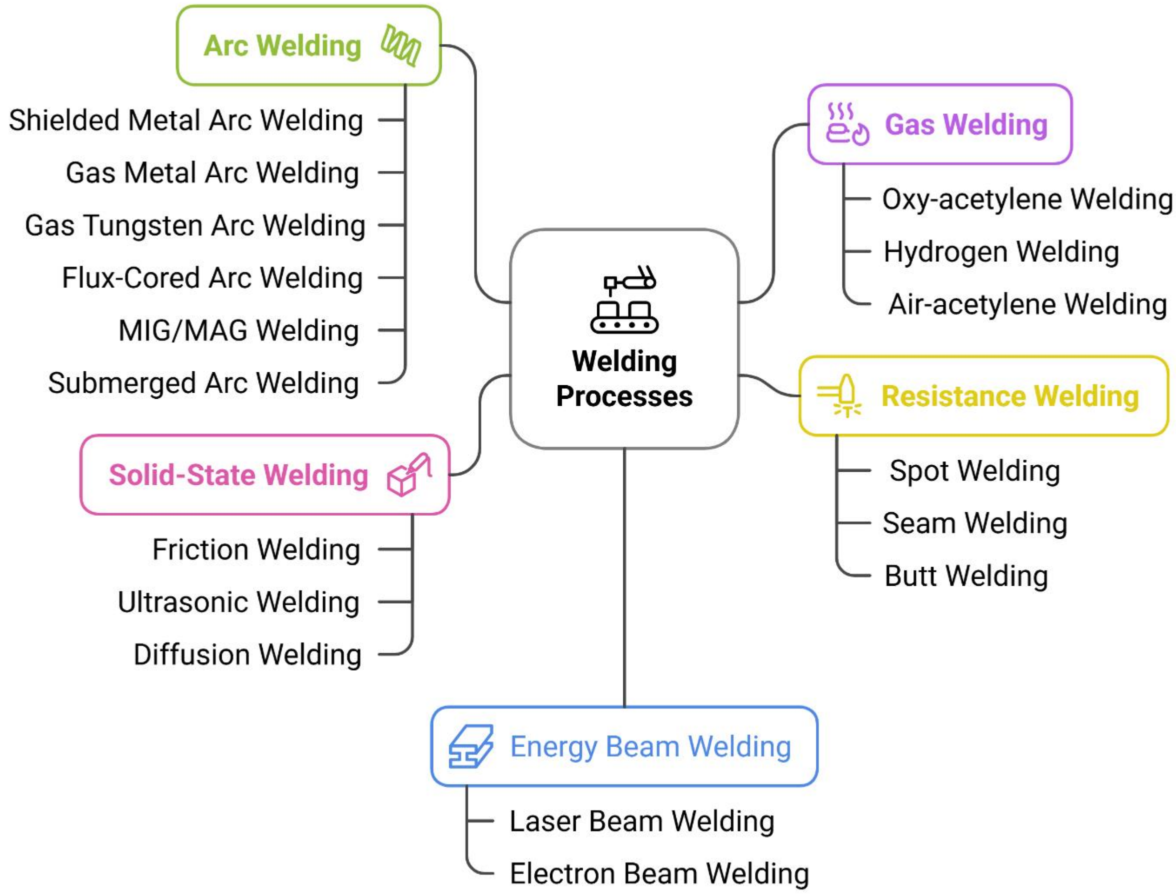

Figure 1. Classification of welding processes.

Welding enables a broad spectrum of engineering applications, ranging from heavy infrastructure and pipeline fabrication to aerospace components, high-temperature systems, and even extraterrestrial structures. Specialized processes allow joining operations in challenging environments such as underwater and space-based settings. As industrial demands shift toward lightweight structures, enhanced performance, and environmentally efficient fabrication, welding technologies are adapting to meet these expectations. Emerging developments such as hybrid welding systems, improved filler materials, intelligent monitoring tools, and automation-supported welding platforms are reshaping modern manufacturing [6].

A wide variety of weld types are used depending on geometric configuration and service requirements. Butt welds join components aligned in the same plane and are preferred for high-strength structural applications due to their ability to achieve full penetration. Fillet welds connect surfaces at an angle in T-, lap-, or corner-joint configurations, with profiles such as convex, concave, or flat. Autogenous welds rely solely on fusion of the base metal without filler, providing high precision in processes such as Gas Tungsten Arc Welding (GTAW) and laser welding. Slot and plug welds are used to join overlapping plates through elongated or circular openings, serving as efficient alternatives to mechanical fasteners in structural, automotive, and aerospace systems.

Welds may also be classified based on penetration depth. Full-penetration welds, or complete joint penetration welds, extend through the entire thickness of the joint and are required in critical load-bearing applications. Partial-penetration welds provide sufficient strength where full penetration is unnecessary or impractical. Welded joints themselves can be homogeneous, heterogeneous, or dissimilar, depending on the relationship between the weld metal and parent materials. Homogeneous joints exhibit similar metallurgical properties across the weld and base metal, while heterogeneous joints involve filler materials with distinct compositions. Dissimilar joints connect metals of significantly different chemical or mechanical properties, commonly used in pressure vessels, repair work, and specialty applications [7,8].

A completed weld contains several metallurgical zones and features that influence its performance. These include the base metal, the weld metal produced through melting and solidification, and the Heat-Affected Zone (HAZ), where microstructural changes occur due to thermal cycling as illustrated in Figure 2. Key geometric features such as the weld face, root, toe, and the fusion line govern stress distribution and susceptibility to cracking. The weld toe, in particular, is a known stress concentration region and a common site for fatigue crack initiation. Imperfections may arise from variations in heat input, solidification behavior, or technique. These deviations from ideal geometry are categorized in standard welding literature into groups based on morphology and origin, with certain imperfections considered acceptable depending on service requirements, while others qualify as defects requiring corrective action [9].

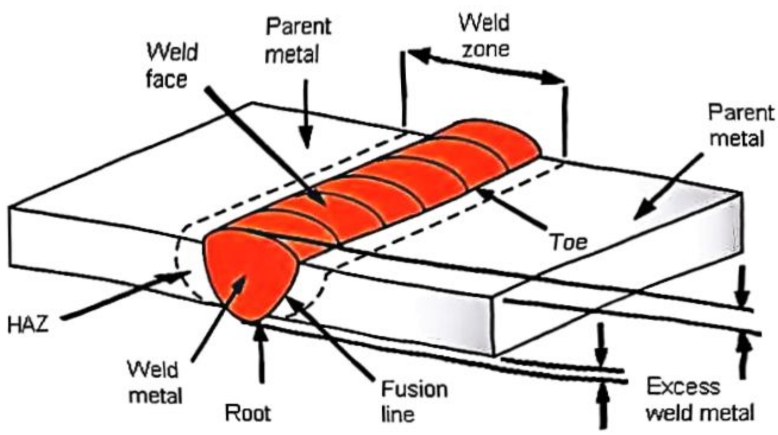

Figure 2. Butt weld.

This review offers a timely and substantive contribution by reframing metallurgical joining through an application-focused perspective. Rather than presenting welding processes as isolated techniques, it synthesizes a comprehensive suite of fusion, solid-state, and hybrid joining methods and directly connects their metallurgical characteristics to critical service-level performance metrics, including fatigue behaviour, fracture toughness, creep resistance, corrosion performance, and inspection or qualification requirements. This approach links process selection to engineering acceptability in real-world conditions. The review further distinguishes itself by integrating emerging technological enablers such as additive-manufacturing-compatible welding approaches, AI-driven process optimization, and real-time monitoring and non-destructive evaluation—and by examining their roles in enhancing weld reliability, repeatability, and industrial scalability. In addition, it identifies the most pressing knowledge gaps, including the need for standardized HAZ toughness methodologies, high-cycle fatigue datasets, and environment-specific qualification testing. Building on these insights, the review proposes a practical research and implementation roadmap that connects laboratory findings with certification pathways for aerospace, energy, and other high-performance manufacturing sectors. Collectively, these elements establish the article as both a comprehensive synthesis of current advances and a forward-looking guide that outlines actionable steps to accelerate the safe and effective adoption of next-generation joining technologies in demanding structural applications.

2. Welding Techniques: Process and parameters

2.1 Arc Welding

Arc welding encompasses a family of fusion-based joining processes that rely on an electric arc to generate the heat required to melt the base metal and, when applicable, the filler material. Upon solidification, a metallurgical bond is formed between the components. Arc welding remains central to industrial fabrication due to its adaptability, cost-effectiveness, and suitability for a broad range of materials and thicknesses. Common arc welding methods include Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Flux-Cored Arc Welding (FCAW), and Submerged Arc Welding (SAW). Each process involves distinct operational principles, consumables, and parameter sensitivities that govern weld quality, productivity, and mechanical performance.

2.1.1 Shielded Metal Arc Welding

SMAW, also known as Manual Metal Arc (MMA) welding, is among the earliest and most widely applied arc welding processes. Its origins date to the late 19th century, beginning with bare metal electrodes developed in Russia in 1888, later improved through coated electrodes introduced via the Kjellberg and quasi-arc methods in Sweden and the United Kingdom, respectively [10]. SMAW is valued for its versatility and applicability to ferrous and non-ferrous metals across all welding positions, although weld quality is strongly dependent on operator skill. The SMAW process establishes an electric arc between a flux-coated consumable electrode and the workpiece, reaching temperatures of approximately 6000°C sufficient to melt the electrode core, flux coating, and parent metal [11]. As the flux decomposes, it forms a protective gas shield and slag layer that prevents atmospheric contamination; the slag must be removed after solidification.

SMAW operates using Alternating Current (AC) or Direct Current (DC) power sources, with DC polarity influencing heat distribution: Direct Current Electrode Positive (DCEP) enhances penetration, whereas Direct Current Electrode Negative (DCEN) increases electrode melting rate. Transformers, rectifiers, generators, and inverter power sources are commonly used, each requiring constant-current characteristics for stable arc performance [12,13]. Weld quality is governed by several critical parameters. Amperage controls penetration and deposit rate, where insufficient current may cause porosity or lack of fusion, while excessive current can produce burn-through, spatter, and undercut. Voltage determines arc stability and weld pool fluidity, with Open Circuit Voltage (OCV) typically between 50–90 V and arc voltage between 20–40 V. Travel speed affects bead shape, fusion, and heat input, where excessively fast speeds create narrow, underfilled welds, and slow speeds lead to excessive reinforcement and cold laps [11].

Electrode coatings are categorized as rutile, basic, or cellulosic. Rutile electrodes allow smooth operation and good arc stability; basic electrodes provide low-hydrogen weld deposits suitable for high-strength applications; and cellulosic electrodes support deep penetration and high deposition rates, ideal for vertical-down welding [14]. Although SMAW is portable and equipment-simple, it has a low operating factor (~30%) compared with semi-automatic and automated processes. Common SMAW defects include slag inclusions, porosity, lack of fusion, undercut, arc strikes, and hydrogen cracking [14].

2.1.2 Gas Metal Arc Welding

GMAW, including Metal Inert Gas (MIG) and Metal Active Gas (MAG) welding, utilizes a continuously fed wire electrode and externally supplied shielding gas to maintain a stable arc and protect the weld pool. Its high deposition rates, automation compatibility, and all-position capability make it one of the most widely used industrial welding processes [15].

A motorized wire feed system delivers the electrode through a contact tip, where it melts into the weld pool. GMAW may be performed in semi-automatic, mechanized, or fully automated modes depending on application requirements [16].

Shielding gas selection significantly influences arc stability, penetration, spatter formation, and metal transfer behavior. For carbon and low-alloy steels, commonly used mixtures include Ar-O_2 and Ar-CO_2 blends [17]. GMAW supports multiple metal transfer modes–short-circuiting, globular, spray, and pulsed spray transfer–each suited to particular thicknesses, welding positions, and productivity targets [18]. Advantages of GMAW include high deposition efficiency, minimal post-weld cleaning, good weld pool visibility, and suitability for automation. Limitations include limited filler control, difficulty in spatter optimization, higher equipment complexity, and sensitivity to air drafts and base-metal cleanliness [18]. Recent innovations include synergic control algorithms, pulsed MIG technologies, and Industry 4.0-based systems featuring real-time monitoring, AI-assisted process optimization, and predictive maintenance, all contributing to improved repeatability and defect mitigation [30-32].

2.1.3 Gas Tungsten Arc Welding

GTAW, or Tungsten Inert Gas (TIG) welding, employs a non-consumable tungsten electrode under an inert shielding gas to produce high-quality, precision welds. GTAW is widely applied to thin-section materials and critical components where superior weld integrity is required [19]. An arc is struck between the tungsten electrode and the base metal while argon or helium shielding prevents oxidation. Filler metal may be added when required (Figure 3). Essential components include a stable AC/DC power source, tungsten electrode, precision-controlled torch, and shielding gas supply [20–21].

GTAW offers excellent control of heat input, bead morphology, and metallurgical outcomes. Its limitations include low deposition rates, high operator skill requirements, and slower welding speeds compared with consumable-electrode processes [21]. Advanced GTAW variants Pulse TIG, Activated TIG (A-TIG), Keyhole TIG (K-TIG), Multi-Electrode TIG (MT-TIG), and flux-assisted techniques such as Flux Zoned Tungsten Inert Gas (FZTIG), Strengthening Activated Tungsten Inert Gas (SA-TIG), and Nano-Strengthening Activated TIG (NSA-TIG) have enhanced penetration, productivity, and microstructural refinement [21–23]. These methods improve weld penetration, bead geometry, and heat-affected zone control, making GTAW increasingly competitive for thicker sections and high-performance applications [24].

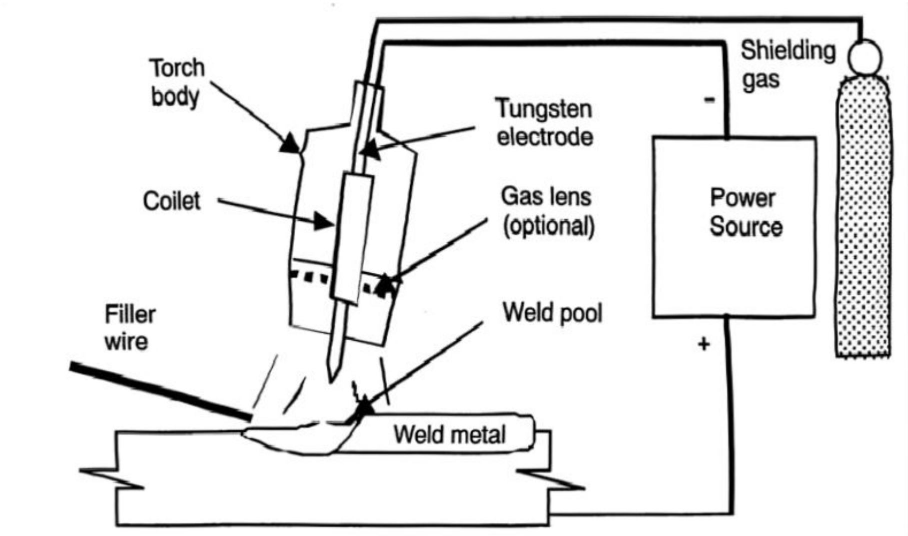

Figure 3. GTAW process [20].

2.1.4 Flux-Cored Arc Welding

FCAW evolved from GMAW to enhance productivity, adaptability, and weld quality in structural, shipbuilding, and heavy-fabrication applications. It employs a tubular electrode filled with flux, enabling self-shielding or gas-shielded operation depending on the wire type [25]. Self-shielded FCAW (FCAW-S) eliminates the need for external shielding gas, making it ideal for outdoor environments. Gas-shielded FCAW (FCAW-G) uses argon-CO_2 mixtures to stabilize the arc and improve mechanical properties [26].

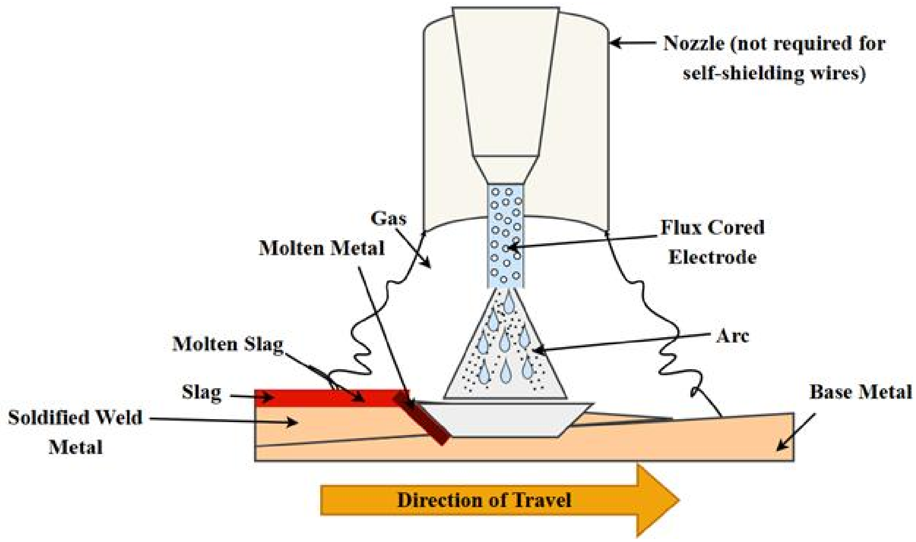

Figure 4. FCAW process.

FCAW operates by forming an arc between the flux-cored electrode and workpiece, with flux decomposition producing shielding gases and slag (Figure 4). Wire feed speed, voltage, current, electrode composition, and travel speed are key parameters influencing bead characteristics and penetration [26,27]. Common defects include porosity, slag inclusions, lack of fusion, and excessive spatter. Proper electrode storage, parameter optimization, and slag removal are essential for quality assurance [28]. Advantages of FCAW include high deposition rates, deep penetration, all-position capability, and suitability for thick materials. Limitations involve high fume emission, equipment complexity, slag removal requirements, and sensitivity to electrode contamination [28].

2.1.5 MIG/MAG Welding: Principles, Process, and Advancements

MIG/MAG welding is widely employed due to its versatility, high deposition efficiency, and compatibility with automation. The process initiates an arc between a consumable wire electrode and the workpiece, with shielding gases preventing oxidation [29]. Key variables current, voltage, wire feed speed, travel speed, Contact Tip to Work Distance (CTWD), and shielding gas composition control penetration, bead geometry, and metal transfer mode. MIG/MAG supports dip, globular, spray, and pulsed transfer modes, each offering trade-offs between heat input, spatter, and positional suitability [29]. Recent advancements include synergic control systems, pulsed MIG processes, and intelligent monitoring tools aligned with Industry 4.0 initiatives, significantly improving weld repeatability and efficiency [30–32].

2.1.6 Submerged Arc Welding

SAW is a highly efficient, fully mechanized process that produces deep penetration and high deposition rates. The arc is formed beneath a thick blanket of granular flux, preventing exposure to air and minimizing arc radiation (Figure 5). This unique configuration eliminates spatter and provides a clean, stable arc environment [33]. SAW operates using continuously fed wire electrodes and flux that both stabilizes the arc and influences the weld metal chemistry. Key parameters include current, voltage, travel speed, electrode size, electrode extension, flux composition, and polarity. DCEP offers deeper penetration, while DCEN is preferred for surfacing to reduce dilution [34,35]. SAW produces welds with excellent mechanical properties and low defect rates. However, it is generally limited to flat or horizontal positions due to molten flux flow behavior. Modern research focuses on multi-wire SAW, tandem systems, and parameter optimization using statistical approaches such as Response Surface Methodology (RSM) and Taguchi methods [36].

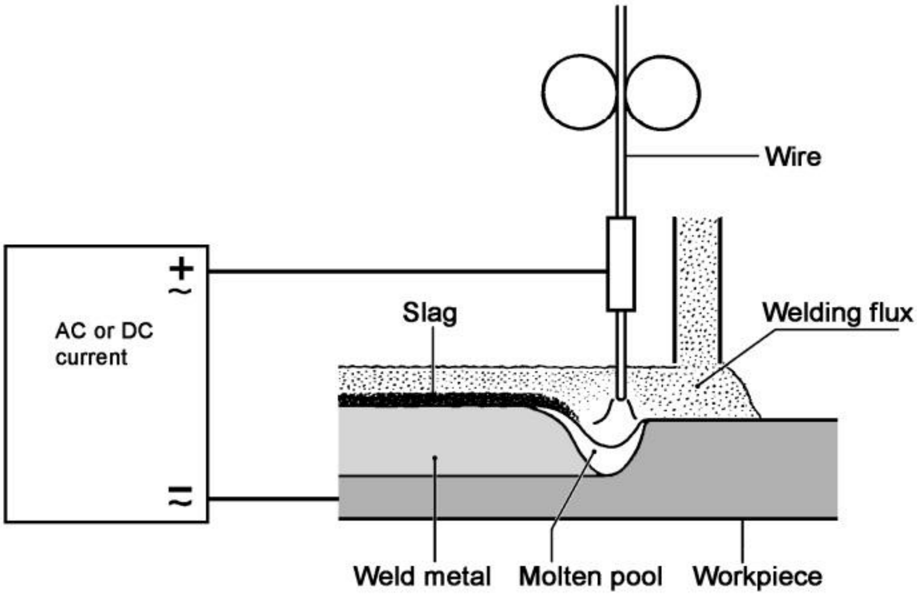

Figure 5. SAW process.

2.2 Gas Welding

Gas welding encompasses fusion processes in which a combustible gas–oxygen mixture provides the heat required to melt and join metals. Among these, Oxy-acetylene Welding (OAW) remains the most widely used because of its low equipment cost, portability, and ability to weld or braze a wide range of ferrous and non-ferrous alloys in both workshop and field conditions [37].

2.2.1 Oxy-Fuel Welding

OAW, commonly referred to as gas welding, uses the combustion of oxygen and acetylene to generate a high-temperature flame that melts the base metal and, where required, a filler rod. A typical OAW system comprises high-pressure oxygen and acetylene cylinders fitted with safety valves, pressure regulators, hoses, a mixing torch with interchangeable tips, flashback arrestors, and appropriate personal protective equipment (goggles, gloves, and flame-resistant clothing) [37]. The schematic arrangement of the torch, filler rod, and weld pool is shown in Figure 6.

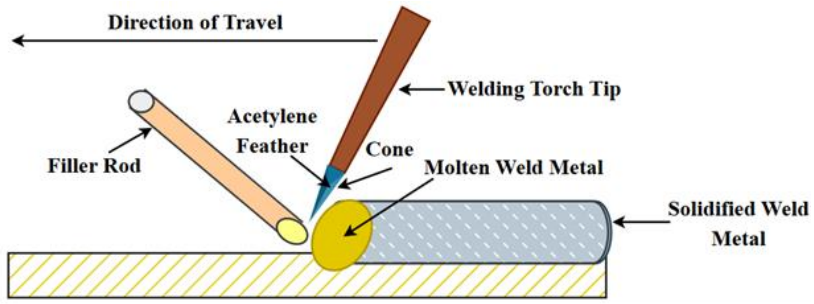

Figure 6. OAW process.

Within the torch, oxygen and acetylene are mixed in controlled proportions and ignited at the tip, producing a flame that can reach temperatures of about 3200 °C. Adjustment of the oxygen-to-acetylene ratio allows the welder to generate three principal flame types with distinct metallurgical effects. A neutral flame, obtained with approximately equal volumes of oxygen and acetylene, produces a clearly defined inner cone and is preferred for general welding of steels and most ferrous alloys. An oxidizing flame contains excess oxygen, has a shorter inner cone and higher temperature, and is used selectively for copper and some brasses, although excessive oxidation must be avoided. A carburizing (or reducing) flame, characterized by excess acetylene and an elongated inner cone with an acetylene feather, is used where oxidation must be minimized or a slightly carburizing atmosphere is beneficial, such as in some high-carbon steels [38].

OAW offers several advantages: the equipment is relatively inexpensive and highly portable, the process is adaptable to varying thicknesses and joint configurations, and the flame can be precisely controlled to deliver localized heating. However, its thermal efficiency is lower than that of electric arc processes, travel speeds are comparatively slow, and the method is less suitable for thick-section or high-productivity applications. Safety concerns related to handling and storing acetylene and high-pressure oxygen also require stringent procedural control [37–40]. Consequently, although OAW has been largely superseded by arc welding in mass-production environments, it remains important for repair work, brazing, cutting, and artisanal or field fabrication, where its flexibility and accessibility are decisive [39,40].

2.3 Resistance Welding

Resistance welding joins metals by passing a high electric current through components held under compressive force, causing localized heating at the faying surfaces due to electrical resistance. The molten or plasticized region solidifies under pressure to form the joint. The process is highly amenable to automation, does not require filler metal or shielding gas, and is therefore widely used for sheet-metal assemblies in the automotive, aerospace, and appliance industries [41].

2.3.1 Spot Welding

Resistance spot welding (RSW) is the most common resistance process and is used to join overlapping sheets at discrete locations, forming individual weld nuggets. In RSW, the sheets are clamped between water-cooled copper electrodes, a high current is applied for a controlled time to generate heat at the interface, and the molten zone solidifies under electrode force (Figure 7). Weld quality is primarily governed by four parameters: welding current, which controls heat input and nugget size; electrode force, which influences contact resistance and nugget formation; weld time, which determines the extent of melting and HAZ width; and cooling rate, which affects microstructure and residual stress [41,42].

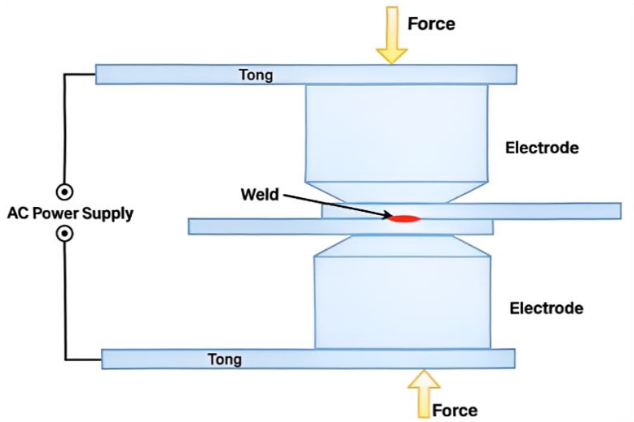

Figure 7. Resistance Spot Welding (RSW).

The microstructural evolution during RSW leads to a cast nugget surrounded by a heat-affected zone whose hardness and phase constitution differ from the base material. Typical welds show higher hardness within the nugget due to rapid solidification, with gradients across the HAZ that influence static and fatigue performance. Failure may occur via brittle interfacial fracture within the nugget or more ductile pull-out failure in which the nugget tears from the sheet. Optimizing process parameters and electrode design is therefore crucial to achieving robust fatigue performance and dimensional stability in multi-spot joints [42,43]. In industrial practice, RSW offers high production rates, good repeatability, and straightforward integration into robotic manufacturing lines, although joint accessibility and sheet stack-up geometry can impose design constraints [41–43].

2.4 Energy Beam Welding

Energy beam processes employ highly concentrated power sources to achieve deep penetration welds with very narrow heat-affected zones and low overall distortion. Laser Beam Welding (LBW) and Electron Beam Welding (EBW) are the two most established techniques and are increasingly used for high-value components where precision and metallurgical control are critical [44,50].

2.4.1 Laser Beam Welding

LBW uses a focused laser beam as the heat source to melt and join materials. Owing to its high power density, LBW can produce deep, narrow welds at high travel speeds, with minimal distortion and excellent dimensional accuracy. These attributes make it attractive for applications in aerospace, automotive body-in-white, shipbuilding, and high-strength steel fabrication [44].

Depending on beam intensity and interaction with the workpiece, LBW operates in two main modes. In conduction (melt-in) mode, the beam partially melts the surface and heat is conducted into the material, leading to shallow, wide welds suitable for thin sheets and precision work. In keyhole mode, the intense beam vaporizes metal, forming a deep, narrow cavity lined with molten metal; this mode enables single-pass welding of thick sections with high aspect ratio welds (Figure 8) [45,46]. Process performance is controlled by parameters such as laser power, power density, beam diameter and focus position, welding speed, shielding gas, and material reflectivity. Solid-state lasers (fiber, disk, and diode lasers) have largely replaced CO_2 lasers in many applications because of their higher electrical efficiency, flexible beam delivery, and superior coupling to reflective alloys like aluminum and copper [45,46].

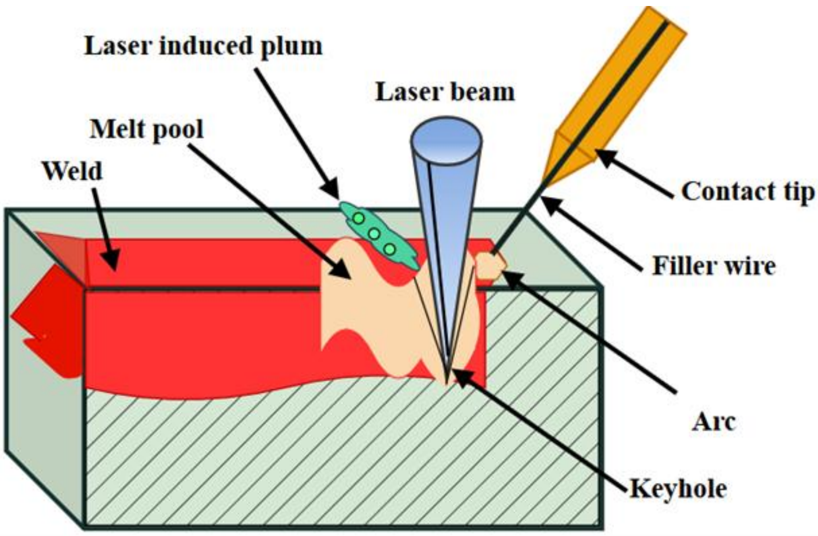

Figure 8. LBW process.

Hybrid Laser–arc Welding (LHW) combines LBW with gas metal arc welding, allowing simultaneous deep penetration and efficient gap-bridging with filler addition. This combination improves tolerance to joint fit-up, increases penetration depth, and enhances weld quality in thick or high-strength steels [47–49]. LBW and its hybrid variants offer excellent process speed, low heat input, and straightforward integration into automated manufacturing lines. Their main limitations are high capital and maintenance costs, stringent surface preparation and alignment requirements, and process sensitivity when welding highly reflective or highly conductive alloys. Ongoing research in real-time monitoring, adaptive control, and AI-assisted parameter optimization is expected to further expand the industrial deployment of LBW [48,49].

2.4.2 Electron Beam Welding

EBW is a high-precision fusion process in which a beam of high-velocity electrons is accelerated by a high-voltage power supply and focused onto the workpiece. The kinetic energy of the electrons is converted to heat upon impact, creating localized melting and, at sufficient power density, a keyhole that enables very deep, narrow welds with minimal distortion [50]. Because electrons are readily scattered by gas molecules, EBW is typically performed in a vacuum chamber, which also prevents oxidation and contamination of reactive alloys [51,52]. EBW systems commonly operate at accelerating voltages between 30 and 200 kV, achieving power densities up to ~10^7 W/cm². The process can be configured as high-vacuum EBW for maximum weld purity, reduced-pressure EBW to accommodate larger components, or non-vacuum EBW for even larger structures at the expense of increased beam-gas interactions. More advanced configurations employ multi-beam or hybrid electron beam techniques to preheat, weld, and post-treat the joint, tailoring residual stresses and microstructure in thick sections [51–53].

EBW is particularly suited to materials that are difficult to weld by conventional fusion processes, including refractory metals (tungsten, molybdenum), reactive metals (titanium, zirconium), high-strength steels, and nickel- and cobalt-based superalloys used in gas turbines and other high-temperature applications [50,53,54]. The vacuum environment minimizes contamination, while the very low overall heat input limits distortion and HAZ softening. EBW is also used in cladding, surface modification, and additive manufacturing, where it can produce near-net-shape components from titanium and superalloys for aerospace and medical devices [53,54]. The principal advantages of EBW include very deep penetration in a single pass, narrow welds with minimal distortion, high metallurgical cleanliness, and compatibility with precise Computerized Numerically Controlled (CNC) or robotic motion systems. Limitations arise from the high capital cost of equipment and vacuum systems, restrictions on component size imposed by the vacuum chamber (for high-vacuum EBW), and the sensitivity of the electron beam to stray magnetic fields, which can deflect the beam and impair weld accuracy. Despite these challenges, EBW remains a key enabling technology in high-value manufacturing, with its industrial scope widened by ongoing advances in hybrid welding and automated process control [51–54].

2.5 Solid-State Welding

Solid-state welding encompasses joining processes in which coalescence is achieved without melting the base materials. Instead, pressure, mechanical motion, and/or elevated temperature promote plastic deformation and diffusion across the interface. By avoiding the liquid phase, solid-state methods minimize solidification defects, limit HAZ softening, and are particularly effective for dissimilar or precipitation-strengthened alloys. Industrially important examples include friction welding, ultrasonic welding, and diffusion welding, each offering distinct capabilities in aerospace, automotive, power generation, and micro-engineering applications [55–57,68–71].

2.5.1 Friction Welding

Friction welding generates heat through mechanical friction between contacting surfaces under axial compression. The resulting plasticized interfacial layer consolidates into a solid-state joint once relative motion ceases and forging pressure is applied. Because the materials do not melt, friction welding can produce high-integrity joints with low distortion in both similar and dissimilar material combinations [55]. Variants include Rotary Friction Welding (RFW), Linear Friction Welding (LFW), orbital friction welding, friction extrusion, friction hydro-pillar processing, and Friction Stir Welding (FSW); among these, RFW and LFW are most widely used for bulk components (Figure 9) [56,57]. In RFW, one component is rotated relative to a stationary counterpart while an axial force is applied. Heat is generated at the interface during the friction phase, and once the required temperature is reached, rotation is stopped and the axial force is increased to forge the joint (Figure 10). Continuous-drive friction welding uses a motor to maintain rotation, whereas Inertia Friction Welding (IFW) employs a flywheel to store kinetic energy, which is then dissipated at the interface when the flywheel is disengaged (Figure 11). These processes are extensively applied to axisymmetric parts such as shafts, tubes, and rods, including many dissimilar combinations (for example, copper–stainless steel) that are difficult to join by fusion welding [55,56,58].

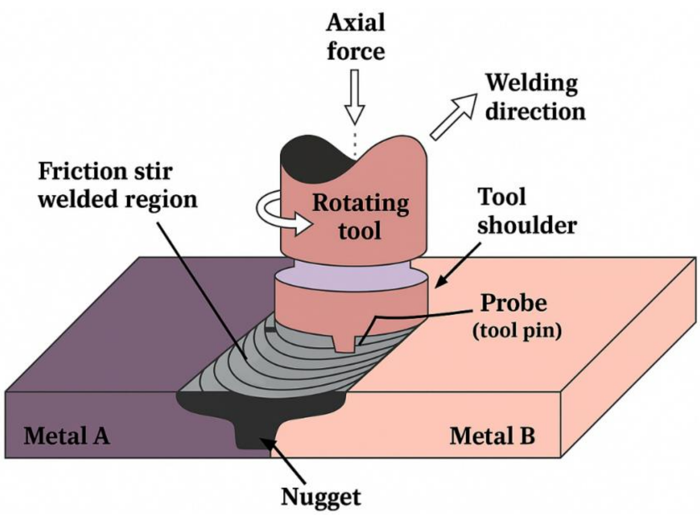

Figure 9. FSW process.

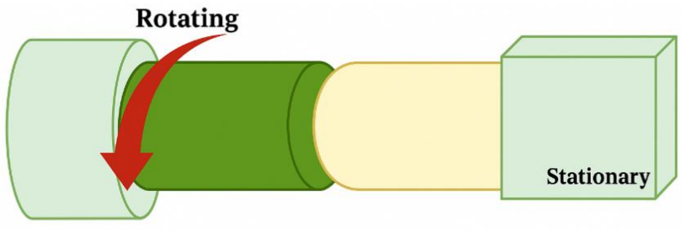

Figure 10. Fixed and rotating Parts of RFW machine.

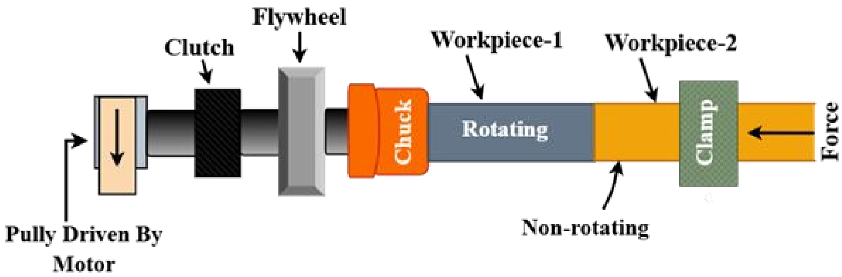

Figure 11. Process of IFW (Iracheta et al., 2015).

LFW replaces rotational motion with high-frequency linear oscillation of one component relative to the other under compressive load. The process proceeds through stages of initial rubbing, steady-state plasticization and flash extrusion, and final forging once oscillation ceases, producing a fully consolidated joint (Figure 12). LFW is particularly important for non-axisymmetric components in aero-engine and structural applications, where it offers excellent fatigue and creep performance with minimal distortion and without filler or shielding gas [57–59].

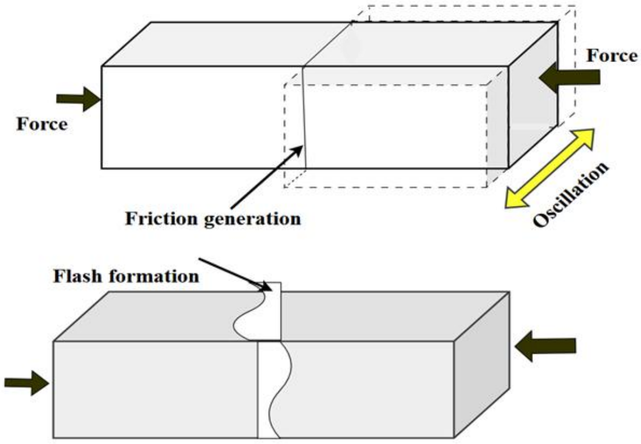

Figure 12. LFW process.

2.5.2 Ultrasonic Welding

Ultrasonic welding is a solid-state process in which high-frequency mechanical vibrations (typically 15–60 kHz) are superimposed on a static clamping force to join metals or polymers. The vibrations, transmitted through a sonotrode, cause interfacial friction, plastic deformation of surface asperities, and localized heating, leading to bonding without bulk melting. This process is widely used in automotive, aerospace, electronics, and medical device manufacturing, particularly for thin sheets, foils, and multi-layer stacks, including metal polymer and fiber-reinforced composite combinations [60]. An ultrasonic welding system consists of a power generator, transducer, booster, sonotrode (horn), and an anvil or fixture. Critical process parameters include vibration frequency and amplitude, clamping force, weld time, and energy input, all of which strongly affect weld strength and consistency [61,62]. The physics of bonding involves a complex interplay of frictional heating, severe plastic deformation, disruption of surface films, and short-range atomic diffusion, resulting in fine-grained, recrystallized structures at the interface with minimal HAZ [63].

Ultrasonic welding is particularly suitable for lightweight alloys (Al, Mg, Ti), thermoplastics (PE, PP), and certain dissimilar pairs such as Al–Cu or Ti–Al, although its effectiveness decreases for very hard, brittle, or highly conductive materials that either crack or dissipate heat too rapidly [60,64]. The process offers short cycle times, no need for filler or shielding gas, low distortion, and an environmentally benign operating environment. Its limitations include restrictions on joint thickness, relatively high equipment cost, and, in some high-load applications, weld strengths that may be lower than those achieved with fusion welding. Effective application therefore, requires careful optimization and monitoring of process parameters, aided increasingly by numerical modeling and in-process power or displacement measurements [65–67].

2.5.3 Diffusion Welding

Diffusion welding (or diffusion bonding) is an advanced solid-state joining technique in which components are held in intimate contact under moderate pressure at elevated temperature for sufficient time to allow significant atomic diffusion across the interface. Because the process occurs below the melting point of the materials, it preserves the bulk microstructure and avoids solidification defects, producing joints that can approach the strength and toughness of the parent materials [68,70,71]. The process can be divided into three stages. First, surface asperities deform under pressure, increasing the true contact area between the components. Second, at temperatures typically 50–80 % of the absolute melting point, atomic diffusion along grain boundaries and through the lattice promotes bonding across the interface, with pores and voids progressively shrinking. Finally, extended holding leads to pore elimination, grain growth across the original interface, and the formation of a near-monolithic microstructure (Figure 13) [68–71]. Successful diffusion welding requires meticulous surface preparation (removal of oxides and contaminants), accurate alignment and fixturing, well-controlled temperature and pressure cycles, and often post-weld heat treatment to refine microstructure and relieve residual stresses.

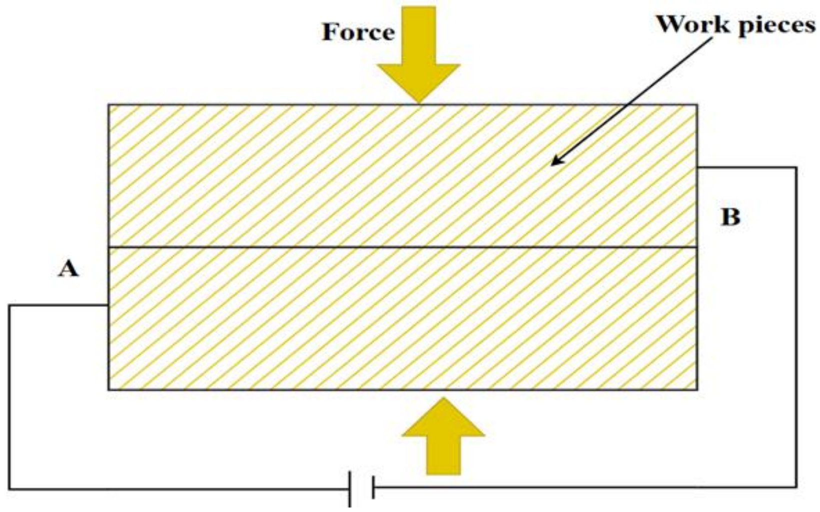

Figure 13. Diffusion welding using electrical resistance.

Diffusion welding is used in high-value sectors where joint integrity and dimensional accuracy are critical. Typical applications include joining titanium and nickel-base superalloy components in aero-engines and space hardware, fabricating nuclear reactor parts with demanding thermal and mechanical requirements, producing metal–ceramic joints and complex multi-layer structures in microelectronics, and manufacturing biocompatible implants and surgical instruments in the medical field [68–72]. Although the process is equipment-intensive and relatively slow, its ability to create defect-free, high-strength joints in difficult material combinations ensures its continuing importance in advanced manufacturing.

3. Testing Techniques of Weld Joints

Welded structures must withstand demanding service conditions in industries such as aerospace, automotive, energy, and construction. Ensuring weld integrity therefore requires systematic evaluation through Destructive Testing (DT) and Non-Destructive Testing (NDT) methods. These techniques allow engineers to assess mechanical strength, identify surface and subsurface flaws, and validate compliance with safety and performance standards. Recent advancements in welding research have expanded both DT and NDT methodologies, improving accuracy, automation, and reliability in weld assessment [73–75].

3.1 Destructive Testing Methods

Destructive testing involves intentional deformation or fracture of a weld specimen to determine its mechanical behavior under applied loads. Tensile testing is one of the most widely used techniques, providing essential information on yield strength, ultimate tensile strength, and elongation. These properties are important in assessing weld soundness in applications such as structural steels and aerospace components [75]. Bend testing evaluates ductility and discontinuities by bending the specimen to a prescribed angle and radius. It is commonly used to assess face, root, and side bends in qualification tests [73].

Charpy impact testing determines the toughness of weld metal and HAZ, offering insight into susceptibility to brittle fracture—especially relevant for high-strength steels and low-temperature service environments. Studies on Advanced High-Strength Steel (AHSS) and High Strength Low Alloy (HSLA) welds have shown that microstructural variations significantly influence impact resistance and crack initiation behavior [76,77]. Hardness testing methods such as Vickers, Rockwell, and Brinell help characterize hardness gradients across the weld and HAZ, facilitating prediction of localized brittleness or softening associated with multipass welding and thermally cycled regions [78]. Fracture toughness testing measures crack resistance under controlled loading, which is crucial for pressure vessels, pipelines, and offshore structures. Fatigue testing evaluates the performance of welded joints under cyclic loading; research confirms that mean stress, load ratio, and residual stress fields strongly influence fatigue life in welded assemblies subjected to variable amplitude loading [79].

3.2 Non-Destructive Testing Methods

NDT techniques allow weld inspection without damaging the component, making them integral to quality control during manufacturing and in-service monitoring. Visual Testing (VT) is the simplest and most accessible approach, used to identify surface discontinuities such as undercut, porosity, cracks, and misalignment. Radiographic Testing (RT) utilizes X-rays or gamma rays to reveal internal defects, including incomplete fusion, inclusions, and porosity, which are common in multipass welds. Ultrasonic Testing (UT) employs high-frequency sound waves for detecting subsurface flaws. Advanced phased-array UT has enabled improved detection accuracy in narrow-gap welds and complex geometries, making it valuable for modern fabrication tasks [80]. Magnetic particle Testing (MT) is used exclusively for ferromagnetic materials and highlights surface and near-surface discontinuities by attracting iron particles along flux leakage fields. Liquid Penetrant Testing (PT), suitable for both ferrous and non-ferrous materials, detects surface-breaking flaws through capillary action and dye visualization.

Eddy current Testing (ET) is effective for surface and near-surface inspection of conductive materials and is increasingly used in aerospace and automotive applications due to its speed and sensitivity. Acoustic Emission Testing (AET) identifies active crack growth or defect evolution under applied loads by monitoring transient stress waves. Recent work has shown that AET can detect imperfections generated during the MAG welding process, demonstrating its potential for real-time defect monitoring in industrial environments [81]. NDT methods continue to evolve, integrating digital signal processing, imaging systems, robotics, and data-driven monitoring frameworks. These advancements enhance detection capability and support predictive maintenance strategies for safety-critical welded structures [73, 80, 81].

4. Conclusion

Welding remains an indispensable pillar of contemporary industrial development, serving as a fundamental enabler of advancements in infrastructure, transportation, aerospace engineering, and high-precision manufacturing. Over the decades, welding methodologies have transitioned from rudimentary forge welding to highly sophisticated techniques, such as LBW, EBW and FSW. These technological innovations have facilitated unprecedented levels of precision, automation, and structural integrity, ensuring the reliability and efficiency of metal joining processes across diverse applications. The selection of an appropriate welding technique is inherently dependent on application-specific requirements, material characteristics, and environmental considerations, as each method presents distinct advantages and limitations. Conventional arc welding processes, including SMAW, GMAW and GTAW remain prevalent due to their versatility and adaptability. Concurrently, advanced welding technologies such as SAW, EBW and LBW are revolutionizing high-performance industries by offering enhanced control and superior metallurgical properties. Furthermore, solid-state welding techniques, such as friction welding and ultrasonic welding, provide viable solutions for applications requiring minimal heat input and exceptional joint strength, making them particularly valuable in specialized and precision-driven sectors.

Ensuring the structural integrity and reliability of welded joints necessitates stringent quality control measures, encompassing both destructive and non-destructive evaluation techniques. The integration of emerging technologies, including artificial intelligence-driven welding automation and real-time monitoring systems, is significantly augmenting process efficiency, precision, and defect detection, heralding a new era of intelligent and data-driven welding methodologies.

As industrial demands for stronger, lighter, and more resilient materials continue to escalate, the evolution of welding technologies must parallel these advancements. Future research should prioritize the development of hybrid welding techniques, environmentally sustainable welding processes, and the seamless incorporation of smart manufacturing paradigms. By capitalizing on these innovations, welding will persist as a transformative force in engineering and manufacturing, underpinning the development of safer, more efficient, and technologically advanced structures for future generations.

Conflicts of Interest

The authors have no conflicts of interest.

Generative AI Statement

The authors declare that no generative artificial intelligence (Gen AI) was used in the creation of this manuscript.

Abbreviations

AC: Alternating Current

AET: Acoustic Emission Testing

AHSS: Advanced High-Strength Steel

A-TIG: Activated TIG

CNC: Computerized Numerically Controlled

CTWD: Contact Tip to Work Distance

DC: Direct Current

DCEN: Direct Current Electrode Negative

DCEP: Direct Current Electrode Positive

DT: Destructive Testing

EBW: Electron Beam Welding

ET: Eddy current Testing

FCAW: Flux-Cored Arc Welding

FCAW-G: Gas-shielded FCAW

FCAW-S: Self-shielded FCAW

FSW: Friction Stir Welding

FZTIG: Flux Zoned Tungsten Inert Gas

GMAW: Gas Metal Arc Welding

GTAW: Gas Tungsten Arc Welding

HAZ: Heat-Affected Zone

HSLA: High Strength Low Alloy

IFW: Inertia Friction Welding

K-TIG: Keyhole TIG

LBW: Laser Beam Welding

LHW: Hybrid Laser-arc Welding

LFW: Linear Friction Welding

MAG: Metal Active Gas Welding

MIG: Metal Inert Gas Welding

MMA: Manual Metal Arc

MT: Magnetic particle Testing

MT-TIG: Multi-Electrode TIG

NDT: Non-Destructive Testing

NSA-TIG: Nano-Strengthening Activated TIG

OAW: Oxy-acetylene Welding

OCV: Open Circuit Voltage

PT: Penetrant Testing

RFW: Rotary Friction Welding

RSM: Response Surface Methodology

RSW: Resistance Spot Welding

RT: Radiographic Testing

SA-TIG: Strengthening Activated Tungsten Inert Gas

SAW: Submerged Arc Welding

SMAW: Shielded Metal Arc Welding

TIG: Tungsten Inert Gas

UT: Ultrasonic Testing

VT: Visual Testing

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