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Technical Review on the Role of Soldering and Brazing in Conventional Mechanical Joining Processes

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Abstract

Soldering and brazing are essential conventional non-fusion mechanical joining processes that rely on capillary action to introduce a lower-melting-point filler metal between solid base materials, forming strong metallurgical bonds without melting the parent metals. Defined by the American Welding Society (AWS), soldering operates below 450°C, while brazing occurs above this threshold but below the solidus of the base metals. This technical review comprehensively examines their fundamental principles, including wetting, spreading, and capillary flow, alongside key metallurgical aspects such as filler metal selection, phase interactions, Intermetallic Compound (IMC) formation, and microstructural evolution. The study highlights critical process parameters (temperature, flux, atmosphere, heating methods), mechanical properties (shear strength, fatigue, creep, and thermal cycling resistance), and comparative performance against welding, adhesive bonding, and mechanical fastening. Soldering excels in electronics for low-heat, high-conductivity PCB assembly using lead-free SAC alloys, while brazing delivers superior high-strength, hermetic joints for aerospace, automotive, HVAC, and medical applications. Advantages include minimal distortion, excellent dissimilar material compatibility, and automation potential, though challenges involve joint clearance sensitivity, intermetallic growth, and temperature limitations. Recent advances in lead-free solders, high-temperature alloys, automation with Industry 4.0, and hybrid techniques further enhance their relevance. This review underscores the enduring importance of soldering and brazing in modern manufacturing for precision, reliability, and multi-material engineering solutions.

Keywords: Soldering, Brazing, Mechanical joining processes, Mechanical fastening, Flux.

1 | Introduction

Mechanical joining processes encompass a wide range of techniques used to assemble components into functional structures or systems without relying solely on fusion of the base materials. These processes are broadly classified into mechanical fastening, adhesive bonding, and metallurgical joining methods such as welding, soldering, and brazing [1]. Unlike welding, which involves localized melting and coalescence of the

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base metals, soldering and brazing are classified as conventional non-fusion joining processes. They achieve bonding through the introduction of a lower-melting-point filler metal that wets and adheres to the solid base materials, primarily via capillary action. Historically, these processes date back to ancient civilizations, with evidence of brazing and soldering techniques used in jewelry, tools, and artifacts by the Egyptians and other early metallurgists. In modern engineering, mechanical joining plays a critical role in enabling the assembly of complex, multi-material structures while preserving the integrity of the parent materials. Soldering and brazing occupy a unique position in this spectrum, offering reliable, permanent joints with minimal thermal distortion compared to fusion welding [2].

1.1 | Overview of Soldering and Brazing

Soldering and brazing are capillary-action-driven joining processes that utilize a filler metal with a melting point lower than that of the base metals. According to the American Welding Society (AWS), soldering is defined as a process where the filler metal (solder) has a liquidus below 450°C (840°F), while brazing employs a filler metal with a liquidus above 450°C (840°F) but still below the solidus temperature of the base materials [3], [4]. In both cases, the base metals remain unmelted, and the molten filler is drawn into the joint clearance by capillary forces, forming a metallurgical bond upon solidification. The fundamental mechanisms common to both processes include surface wetting, spreading, and diffusion at the filler-base metal interface. Key differences arise from the operating temperature: soldering typically produces joints suited for electrical conductivity and low-to-moderate mechanical loads, whereas brazing yields stronger, more thermally resistant joints capable of handling higher structural demands and dissimilar material combinations. Common filler metals for soldering include tin-based alloys (often lead-free in modern applications), while brazing fillers frequently involve silver, copper, nickel, or aluminum-based alloys [5]. Flux or protective atmospheres are often employed to remove oxides and promote wetting.

1.2 | Importance in Modern Manufacturing and Engineering Applications

Soldering and brazing remain indispensable in contemporary manufacturing due to several unique advantages over alternative joining methods. These processes introduce minimal heat input, reducing residual stresses, distortion, and metallurgical changes in heat-sensitive or thin-section components [6–8]. They excel at joining dissimilar metals (steel to copper, aluminium to stainless steel) and complex geometries that would be challenging or impossible with welding. Additionally, they enable high-precision, leak-tight, and electrically conductive joints while supporting batch processing and automation. In modern engineering, soldering dominates the electronics industry for assembling Printed Circuit Boards (PCBs), semiconductors, and electrical connections, where low process temperatures protect delicate components [9]. Brazing is widely applied in high-performance sectors such as aerospace (turbine components, heat exchangers), automotive (radiators, fuel systems), HVAC and refrigeration (pipework and coils), medical devices, and power generation. Their ability to produce strong, corrosion-resistant, and fatigue-tolerant joints under demanding service conditions underscores their continued relevance amid advances in materials science and Industry 4.0 automation.

1.2.2 | Fundamental principles and basic concepts of both soldering and brazing

Soldering is a joining process in which two or more metal components are bonded by melting and flowing a filler metal (solder) into the joint, without melting the base materials. The molten solder wets the surfaces of the base metals, spreads across them, and is drawn into the narrow joint gap primarily by capillary action [10]. Upon cooling and solidification, it forms a metallurgical bond at the interface. The basic concepts of soldering revolve around three key phenomena: wetting, spreading, and capillary flow. Wetting occurs when the molten solder forms a low contact angle with the base metal surface, indicating good metallurgical compatibility. This is facilitated by flux, which removes surface oxides and prevents re-oxidation during heating. Common solder alloys include tin-based systems (such as Sn-Ag-Cu lead-free solders), which offer suitable melting ranges and electrical conductivity. Soldering is particularly valued for producing joints with good electrical and thermal conductivity while imposing minimal thermal stress on heat-sensitive components. Brazing is a metal-joining process that produces coalescence of materials by heating them to the brazing temperature in the presence of a filler metal having a liquidus above 450°C (840°F) but below the solidus temperature of the base metals. The filler metal is distributed between closely fitted faying surfaces by capillary action, without melting the base materials. Like soldering, brazing relies on capillary action, wetting, and diffusion at the filler-base metal interface. However, the higher process temperatures enable the use of more robust filler alloys (silver-based, copper-based, nickel-based, or aluminum-based) that often result in stronger metallurgical bonds and improved high-temperature performance [11]. Flux or controlled atmospheres (reducing, inert, or vacuum) are typically used to promote wetting by removing oxides. The six fundamentals of brazing generally include proper joint clearance, cleanliness, fluxing or atmosphere control, uniform heating, filler metal selection, and post-braze cooling to achieve consistent joint quality, strength, and hermeticity.

1.2.3 | Key differences between soldering and brazing

Although soldering and brazing share the same core mechanisms (capillary filling with a non-melting base metal), they differ primarily in operating temperature and resulting joint characteristics. The table below summarizes the key temperature-related differences:

Table 1. Temperature comparison between soldering and brazing.

Parameter	Soldering	Brazing
Liquidus temperature	Below 450°C (840°F)	Above 450°C (840°F)
Typical process temperature	180-400°C (350-750°F)	540-1,620°C (1,000-2,950°F)
Common filler examples	Sn-Pb (183°C), SAC305 (217-220°C)	Ag-Cu-Zn (650-850°C), Cu-P (700-800°C), Ni-based (1,000°C)
Effect on base metal	Very low heat input, minimal distortion	Moderate heat input, higher diffusion
Typical joint strength	Lower (shear strength often 20-60 MPa)	Higher (can match or exceed base metal)

These differences arise directly from the temperature-dependent behaviour of the filler metals and the extent of metallurgical interaction at the joint interface.

2.2 | Comparison with Other Joining Methods

Soldering and brazing occupy a unique position among mechanical joining processes. The following table provides a clear comparison across key engineering criteria.

Table 2. Comparison of soldering, brazing, welding, adhesive bonding and mechanical fastening.

Criterion	Soldering	Brazing	Welding	Adhesive Bonding	Mechanical Fastening
Process temperature	450°C	450°C	Very high (base metal melts)	Room temperature or low	No heat
Base metal melting	No	No	Yes	No	No
Joint strength	Low to moderate	Moderate to high	Highest	Low to moderate	Moderate (depends on fasteners)
Distortion/residual stress	Very low	Low	High	Very low	None
Dissimilar materials	Good	Excellent	Limited	Excellent	Good
Electrical/thermal conductivity	Excellent	Very good	Good	Poor	Poor (contact only)

Table 2. Continued.

Criterion	Soldering	Brazing	Welding	Adhesive Bonding	Mechanical Fastening
Hermeticity/leak tightness	Good	Excellent	Excellent	Moderate	Poor
Disassembly	Difficult	Difficult	Very difficult	Difficult	Easy
Typical applications	Electronics, PCBs	Aerospace, HVAC, automotive	Structural fabrication	Composites, panels	Assemblies requiring maintenance
Main limitation	Lower strength at elevated temp.	Higher heat input than soldering	Distortion, HAZ changes	Environmental degradation	Weight addition, stress concentration

Soldering and brazing provide an excellent balance of moderate strength, minimal distortion, good conductivity, and the ability to join dissimilar metals advantages that make them complementary rather than competitive with the other methods in many engineering contexts.

3 | Metallurgical and Physical Aspects

3.1 | Filler Metals and Alloys Used in Soldering and Brazing

Filler metals are central to both soldering and brazing, as they provide the medium for metallurgical bonding while the base metals remain unmelted. Selection depends on the base materials, service conditions, melting range, and regulatory requirements such as lead-free mandates in electronics. In soldering, filler metals (solders) have a liquidus temperature below 450°C (840°F). Traditional tin-lead alloys (Sn63/Pb37 eutectic at 183°C) were widely used for their excellent wetting and low cost, but environmental concerns have driven the adoption of lead-free alternatives [12]. Common modern solders include tin-silver-copper (SAC) alloys such as Sn96.5/Ag3.0/Cu0.5 (SAC305, melting range 217-220°C), Sn95.5/Ag3.8/Cu0.7, and Sn96.5/Ag3.5 (near-eutectic). Other variants incorporate antimony, bismuth, or indium to adjust melting behavior or improve mechanical properties.

In brazing, filler metals have a liquidus above 450°C but below the solidus of the base metals. AWS A5.8/A5.8M classifies these into groups including silver-based (BAg), copper-phosphorus (BCuP), copper (BCu), nickel-based (BNi), aluminum-based (BAI), and gold-based alloys [13]. Popular examples are:

I. Silver-based (BAg series): BAg-1 (Ag-Cu-Zn-Cd, ~620–650°C), BAg-7 (Ag-Cu-Zn-Sn).

II. Copper-phosphorus (BCuP): BCuP-2 (Cu-P, self-fluxing on copper, 700-800°C), widely used in HVAC and plumbing.

III. Nickel-based: For high-temperature and corrosion-resistant applications (e.g., turbine components).

IV. These fillers often include additives (Zn, Sn, Ni, Mn) to lower melting point, improve fluidity, or enhance wettability on specific substrates.

3.2 | Wetting, Spreading, and Capillary Action Mechanisms

Figure in shows the success of soldering and brazing which hinges on the filler metal's ability to wet, spread, and flow into the joint via capillary action. Wetting refers to the molten filler forming a low contact angle (90°) on the base metal surface, driven by favorable surface energies between the liquid filler, solid substrate, and surrounding atmosphere (or flux) [14]. Poor wetting results in beading and weak joints. Spreading follows wetting as the molten filler expands across the surface, influenced by surface tension, viscosity, temperature, and oxide removal. Fluxes (chemical or atmospheric) play a critical role by dissolving or reducing surface oxides, preventing re-oxidation, and lowering the interfacial energy.

Capillary action then draws the molten filler into the narrow joint clearance (typically 0.025-0.125 mm for optimal flow). This phenomenon arises from the combined effects of adhesion (between filler and base metal) and surface tension, overcoming gravity and viscosity [15]. The driving force increases with smaller gaps and better wetting, but excessive narrowing can impede flow due to friction. Joint clearance, surface roughness, and uniform heating are critical parameters; capillary forces are strong enough to enable flow in any orientation (horizontal, vertical, or overhead). These mechanisms are temperature-dependent: higher brazing temperatures generally enhance fluidity and diffusion but risk excessive intermetallic growth or base metal erosion.

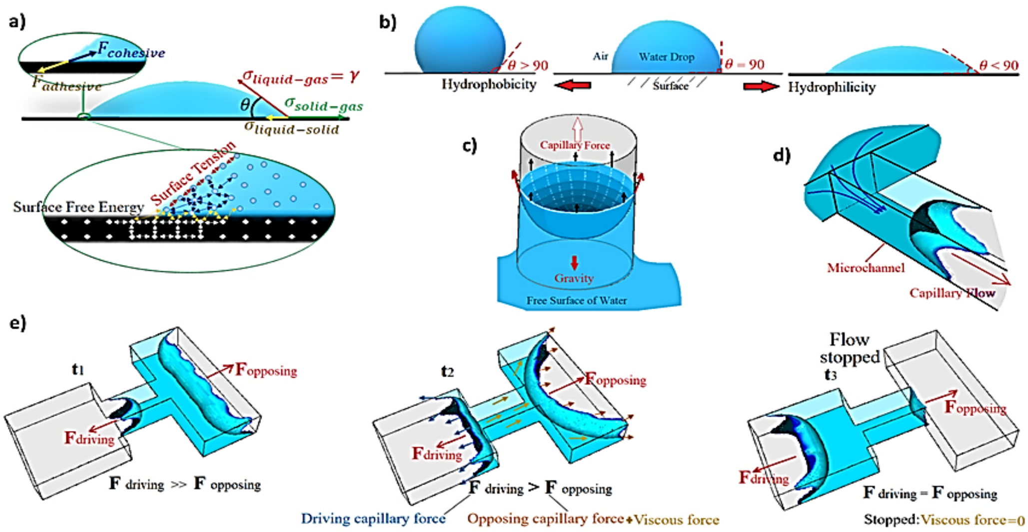

Fig. 1. Mechanism of wetting and capillary flow of water in microchannels based on surface and capillary forces.

Fig. 1 shows a schematic illustration of capillary action driven by the hydrophilicity of surrounding surfaces. In *Fig. 1.a*, the interaction between adhesive and cohesive forces is illustrated, leading to droplet movement and changes in curvature and contact angle until equilibrium is reached through force balance. In *Fig. 1.b*, the change in the contact angle of an aqueous droplet caused by the hydrophilicity of the surface is shown. In *Fig. 1.c*, capillary action within a narrow tube is demonstrated, where the liquid rises against gravity and stops when the capillary force becomes equal to the weight of the water column. In *Fig. 1.d*, capillary flow through a microchannel is presented. Finally, in *Fig. 1.e*, capillary flow into the narrow cross-section of the channel is shown, causing the liquid in the larger channel to drain. The process continues until the opposing retention pressure at the channel neck prevents further downstream drainage [16].

3.3 | Phase Diagrams and Metallurgical Interactions

Phase diagrams are essential tools for understanding melting behaviour, phase stability, and potential reactions during soldering and brazing as shown in *Fig. 2*. Binary and ternary diagrams (Sn-Pb, Sn-Ag-Cu for solders; Ag-Cu, Cu-P for brazing fillers) reveal solidus/liquidus temperatures, eutectic points, and solubility limits [17].

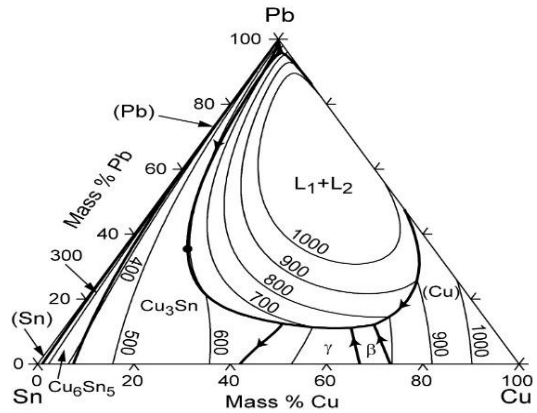

Fig. 2. Liquidus projections in phase diagrams[17].

Eutectic or near-eutectic compositions (Sn63/Pb37 or SAC305) are preferred because they melt and solidify at a single temperature or narrow range, minimizing liquation (partial melting) and ensuring rapid joint filling. Non-eutectic alloys exhibit a melting range where solid and liquid phases coexist, which can lead to sluggish flow or segregation.

Metallurgical interactions involve diffusion across the filler-base metal interface. In soldering, limited solid-state diffusion occurs due to lower temperatures. In brazing, higher temperatures promote greater atomic diffusion, solid-solution formation, or Intermetallic Compound (IMC) layers [18]. For example, in copper brazing with BCuP fillers, phosphorus aids self-fluxing and forms stable phases. Excessive diffusion can lead to brittle IMCs or erosion of thin base metals. Phase diagrams help predict these interactions and guide filler selection to avoid undesirable phases.

3.4 | Joint Microstructure and Interface Formation

The microstructure of soldered and brazed joints consists of the solidified filler metal, interfacial reaction layers, and unaffected base metal. A typical interface features a thin diffusion or reaction zone where metallurgical bonding occurs through solid-solution formation or IMC growth.

In soldered joints (especially lead-free SAC alloys on copper), scallop-shaped Cu_6Sn_5 and Cu_3Sn IMCs form at the interface. These layers provide bonding but can become brittle if overly thick, affecting reliability under thermal cycling or mechanical stress [19].

Brazed joints often exhibit more pronounced diffusion zones due to higher temperatures. For instance, silver-based fillers on steel or copper may form solid-solution layers or discrete IMCs, while nickel-based fillers on stainless steel produce complex boride or silicide phases. The joint microstructure may include primary dendrites, eutectic phases, or precipitates within the filler matrix, depending on cooling rate and composition.

Optimal microstructures exhibit good wetting (continuous interface) without voids, excessive IMC growth, or porosity. Factors influencing microstructure include holding time, cooling rate, joint gap, and base metal composition. Rapid cooling can refine the structure and limit brittle phase formation [20].

3.5 | Thermal Effects and Heat-Affected Zones

Unlike fusion welding, soldering and brazing do not melt the base metals, resulting in significantly smaller Heat-Affected Zones (HAZ) and lower residual stresses. However, thermal effects are still present and vary with process temperature. Soldering introduces minimal heat input, producing a very narrow or negligible HAZ. This makes it ideal for heat-sensitive electronics and thin sections, with little risk of distortion, grain growth, or loss of mechanical properties in the base metal [21].

Brazing, with higher temperatures (often 600-1100°C+), creates a moderate HAZ where diffusion, recovery, recrystallization, or softening can occur. In work-hardened or precipitation-hardened alloys (copper-beryllium or certain steels), prolonged exposure may cause annealing and strength reduction. Controlled atmospheres or short cycle times help mitigate these effects [22].

Residual stresses are generally low compared to welding due to uniform heating and the absence of solidification shrinkage in the base metal. However, differential thermal expansion between dissimilar metals or rapid cooling can induce stresses. Post-process heat treatment is rarely needed but may be applied for stress relief in critical applications [23]. Overall, the lower thermal impact of soldering and brazing preserves base metal properties better than welding, contributing to their suitability for precision assemblies and multi-material components.

4 | Process Parameters and Techniques

4.1 | Soldering Process Parameters

Successful soldering depends on careful control of key process parameters to ensure proper wetting, capillary flow, and joint integrity while protecting sensitive components.

I. Temperature: The soldering temperature is typically maintained 30-50°C above the liquidus temperature of the solder alloy. For common lead-free SAC305 solder, this corresponds to a process temperature range of 240-260°C. Excessive temperature can cause excessive IMC growth, component damage, or solder oxidation, while insufficient temperature leads to poor wetting and cold joints [24].

II. Flux: Flux is essential for removing surface oxides, preventing re-oxidation, and promoting wetting. Flux activity ranges from "no-clean" (mild) to "water-soluble" or "rosin-activated" (more aggressive). The choice depends on the base metals, required cleanliness, and post-process residue requirements [25]. Flux must be activated within the soldering temperature range and remain effective throughout the heating cycle.

III. Heating methods: Soldering heating must be rapid and localized to minimize thermal exposure. Common methods include hand soldering with electric irons, wave soldering for mass production of PCBs, reflow soldering in ovens (using solder paste), and selective soldering [26]. Precise temperature control and uniform heating across the joint are critical to avoid defects such as bridging, tombstoning, or insufficient fillet formation.

Process time is usually short (seconds to a few minutes), making soldering highly suitable for automated high-volume electronics assembly.

4.2 | Brazing Process Parameters

Brazing parameters are more demanding due to higher temperatures and the need for stronger structural joints.

I. Temperature: Brazing is performed at temperatures ranging from 540°C to over 1,200°C, depending on the filler metal. The process temperature is typically held 20-50°C above the filler's liquidus to ensure good fluidity while remaining safely below the solidus of the base metals [13]. Precise temperature control prevents base metal melting, excessive erosion, or undesirable metallurgical changes.

II. Atmosphere: Atmosphere control is often more critical in brazing than in soldering. Inert (argon, nitrogen) or reducing atmospheres (hydrogen, dissociated ammonia, or vacuum) minimize oxidation and eliminate or reduce the need for flux. Vacuum brazing is widely used for aerospace and high-purity applications because it provides excellent oxide removal and produces clean, high-quality joints without flux residues [27].

III. Fixturing: Proper fixturing maintains joint clearance and alignment during heating and cooling. Fixtures must withstand brazing temperatures, allow for thermal expansion, and avoid introducing contamination. Self-fixturing designs (press-fit or tack-welded assemblies) or ceramic/metal fixtures are commonly employed.

Uniform heating and controlled cooling rates are necessary to minimize residual stresses, especially when joining dissimilar materials.

Brazing cycles can range from a few minutes (torch or induction) to several hours in furnace processes.

4.3 | Common Heating Methods

Both soldering and brazing utilize a variety of heating sources, each offering specific advantages depending on production volume, joint complexity, and material sensitivity:

I. Torch brazing/soldering: Manual or mechanized oxy-fuel torches provide localized heating and are highly versatile for repair work and small-batch production. It offers good operator control but depends heavily on skill and can lead to inconsistent results.

II. Furnace brazing: Ideal for batch or continuous production. Components are heated uniformly in controlled-atmosphere or vacuum furnaces. This method ensures excellent temperature uniformity, minimal distortion, and high repeatability, making it preferred for aerospace and automotive heat exchangers [28].

III. Induction heating: Uses electromagnetic fields to generate rapid, localized heating. It is fast, energy-efficient, and suitable for automated lines. Induction is commonly used for brazing carbide tools and tubular assemblies.

IV. Resistance heating: Current is passed through the workpiece or electrodes to generate heat directly at the joint. It provides very rapid heating and is useful for high-volume production of small parts.

V. Laser soldering/brazing: Offers precise, non-contact heating with minimal heat input to surrounding areas. Laser processes are increasingly used in electronics (soldering) and precision medical or micro-brazing applications due to their excellent control and ability to join heat-sensitive components [29].

Other methods Include Infrared (IR) reflow for soldering and dip brazing for aluminum assemblies. The choice of heating method significantly influences joint quality, production rate, and cost.

4.4 | Flux Selection and Role in Joint Quality

Flux plays a pivotal role in both soldering and brazing by chemically cleaning surfaces, preventing oxidation, and improving wettability. Without effective fluxing, even the best filler metals will produce defective joints.

I. Flux types are soldering and brazing fluxes. The soldering include rosin-based (R, RMA, RA), organic acid, and no-clean formulations. Brazing fluxes are typically more aggressive (borax-based, fluoride-based, or chloride-based) and classified by AWS A5.31 according to their temperature range and base metal compatibility.

II. Role in joint quality: Flux removes oxides, lowers surface tension, and protects the joint during heating. It directly influences wetting speed, flow characteristics, and final joint soundness. Excessive or overly aggressive flux can cause corrosion or leave harmful residues, while insufficient flux leads to voids and poor bonding [30].

III. Post-process considerations: Residue removal is important for electronics (soldering) and food/medical applications (brazing). No-clean and low-residue fluxes are increasingly favored for environmental and reliability reasons.

Proper flux selection and application are therefore critical for achieving defect-free, reliable joints with consistent mechanical and functional performance.

5 | Mechanical Properties and Performance

5.1 | Strength and load-bearing capacity of soldered and brazed joints

The mechanical strength of soldered and brazed joints is generally lower than that of the base metals or fusion welds, but remains sufficient for many engineering applications when properly designed. Joint strength is primarily governed by the shear strength of the filler metal and the interfacial bond rather than tensile strength, because lap-type joints (which impose shear loading) are most common [31].

Soldered joints typically exhibit shear strengths in the range of 20-60 MPa, depending on the alloy. Lead-free SAC solders (SAC305) usually provide shear strengths of 30-50 MPa at room temperature, with good ductility but rapid strength reduction above 100-150°C. Traditional Sn-Pb solders offer slightly lower strength but better creep resistance in some cases [32].

Brazed joints are significantly stronger, often achieving shear strengths of 100-350 MPa or more. Silver-based fillers can produce joints with tensile strengths approaching or exceeding those of many base metals (200-400 MPa in copper or steel assemblies). Nickel-based and high-temperature brazing alloys maintain useful strength even at elevated temperatures (up to 800-1000°C), making them suitable for structural applications in aerospace and power generation [33], [34].

Overall, brazed joints generally offer higher load-bearing capacity than soldered joints, while both benefit from large bonding areas that distribute loads effectively and reduce stress concentrations compared to mechanical fasteners.

5.2 | Fatigue, Creep and Thermal Cycling Resistance

Fatigue performance is critical in dynamic service environments. Brazed joints generally exhibit superior fatigue resistance due to their higher strength and better metallurgical bonding. Well-executed brazed joints can withstand high-cycle fatigue comparable to the base metal when fillet geometry is optimized and defects are minimized [35]. Soldered joints, particularly in electronics, are more susceptible to fatigue cracking under vibration or thermal mismatch, although modern lead-free solders have improved cyclic performance.

Creep resistance is temperature-dependent. Soft solders exhibit noticeable creep even at room temperature under sustained load, limiting their use in high-stress, long-term applications. Brazed joints using nickel or cobalt-based fillers demonstrate excellent creep resistance at elevated temperatures, making them suitable for turbine blades, heat exchangers, and exhaust systems [36], [37].

Thermal cycling resistance is especially important for joints involving dissimilar materials. Differential thermal expansion can induce cyclic stresses. Brazed joints usually perform better due to stronger interfaces and higher ductility in some filler systems [38]. Soldered joints in electronics often fail via solder joint fatigue during repeated thermal excursions between -40°C and 125°C, a common reliability concern addressed through optimized joint design and underfill materials.

5.3 | Corrosion Resistance and Environmental Durability

Corrosion resistance depends heavily on the filler metal composition, base materials, and service environment. Soldered joints are prone to galvanic corrosion when dissimilar metals are joined, particularly in the presence of flux residues. Lead-free solders can be more susceptible to tin whisker growth or electrochemical migration in humid environments. Proper flux removal and conformal coatings significantly improve durability in electronics.

Brazed joints generally offer better environmental durability. Silver-based and copper-phosphorus fillers provide good corrosion resistance in many atmospheres, while nickel-based alloys excel in aggressive environments (high temperature, oxidation, or chemical exposure). Vacuum or controlled-atmosphere brazing produces cleaner joints with fewer corrosion initiation sites [39]. However, improper flux selection or incomplete residue removal can lead to localized pitting or crevice corrosion, especially in chloride-rich environments.

Both processes benefit from post-joint protective coatings or passivation treatments when exposed to harsh conditions such as marine, automotive under-hood, or chemical processing environments.

5.4 | Factors Affecting Joint Integrity and Failure Modes

Several factors influence the integrity of soldered and brazed joints:

I. Joint Clearance and Geometry: Incorrect clearance reduces capillary flow or creates stress risers.

II. IMC Thickness: Thin, uniform IMCs enhance bonding; excessive growth (especially in soldering) leads to brittleness.

III. Defects: Voids, porosity, incomplete filling, or flux entrapment act as crack initiation sites.

IV. Thermal History: Overheating causes base metal erosion or excessive diffusion; rapid cooling can induce residual stresses [40].

V. Surface Preparation: Poor cleaning results in weak interfacial bonds.

VI. Common failure modes include:

VII. Cohesive failure within the filler metal (typical in soft solders).

VIII. Adhesive failure at the interface (due to poor wetting or thick brittle IMCs).

IX. Fatigue cracking propagating from fillets or voids.

X. Creep rupture under sustained high-temperature loads.

XI. Corrosion-induced failure (pitting or galvanic attack).

Brazed joints more frequently fail in the base metal or heat-affected zone when the joint itself is sound, indicating that the braze can be stronger than the substrate.

5.5 | Testing and Evaluation Methods

Mechanical evaluation of soldered and brazed joints is performed using standardized test methods to quantify strength, ductility, and reliability:

I. Shear testing: The most common method (ASTM B749 for soldered joints, AWS C3.2 for brazed joints). Single-lap or double-lap shear specimens are widely used because they replicate typical service loading.

II. Tensile testing: Used to evaluate butt or scarf joints, providing data on ultimate tensile strength and elongation.

III. Peel testing: Assesses joint toughness and adhesion, particularly useful for thin-sheet assemblies or electronics [41].

IV. Fatigue testing: Cyclic loading (tension-tension or shear) per ASTM E466 or similar standards to determine endurance limits.

V. Creep and stress-rupture testing: Conducted at elevated temperatures to evaluate long-term performance.

VI. Thermal cycling tests: Accelerated reliability testing (IPC-9701 for electronics) to simulate service conditions.

Non-destructive methods such as visual inspection, X-ray radiography, ultrasonic testing, and dye penetrant inspection complement mechanical tests. Microstructural analysis (optical and scanning electron microscopy) is routinely performed to correlate joint quality with observed mechanical behaviour.

5.6 | Comparative Overview of Curves

Stress-strain and load-displacement curves for soldered and brazed joints highlight fundamental differences in their mechanical performance, primarily driven by the bonding temperature, the composition of the filler metal, and the nature of the metallurgical interface [42]. The primary distinction between the two lies in the magnitude of the load and the stiffness (slope) of the initial elastic region (see *Table 3* and *Fig. 3*). Brazing, which occurs above 450°C, typically produces joints with mechanical properties approaching or sometimes exceeding those of the bulk filler metal due to high mechanical constraint. Soldering, occurring below 450°C, results in lower-strength joints that are highly susceptible to time-dependent deformation (creep).

Table 3. Stress-strain curves comparing soldered against brazed joints.

Feature	Soldered Joint Curve	Brazed Joint Curve
Elastic slope	Shallower (lower modulus of tin-based fillers)	Steeper (Higher modulus of silver/copper fillers)
Peak load (UTS)	Significantly lower (11–50 MPa)	Significantly higher (150–260+ MPa)
Deformation	Large plastic region; high creep sensitivity	Limited plastic region; often fails abruptly
Failure point	Usually within the solder or at the IMC layer	Often at the joint interface or "heat-affected zone"

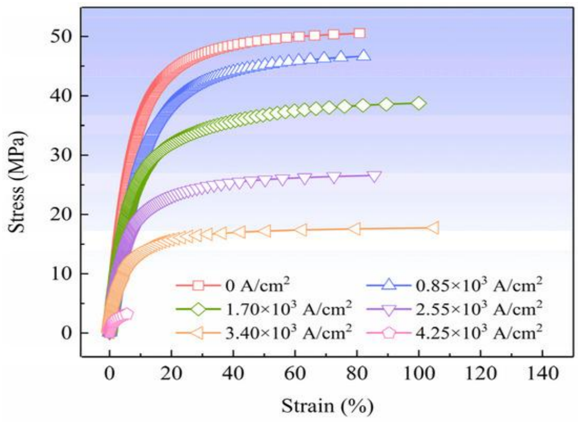

Fig. 3. The stress-strain curves of Cu/Sn-58Bi/Cu solder joints at different current densities [43].

6 | Applications in Industry

Soldering and brazing serve critical roles across diverse industrial sectors by enabling reliable, low-distortion, and often dissimilar-material joints. *Table 4* summarizes the primary applications, typical processes/fillers, and key performance requirements.

Table 4. Summary of industrial applications of soldering and brazing.

Industry Sector	Primary Process	Typical Fillers	Key Performance Requirements	Common Joint Types
Electronics & electrical	Soldering	SAC305, Sn-Ag-Cu, Sn-Bi (lead-free)	Electrical conductivity, thermal cycling reliability, miniaturization	SMT, through-hole, reflow
Aerospace, automotive & heavy engineering	Brazing	BAg (silver), BNi (nickel), BCuP	High-temperature strength, creep & fatigue resistance, hermeticity	Lap, tubular, honeycomb
Plumbing, HVAC & refrigeration	Brazing (mainly)/soldering	BCuP-2, BAg-7, lead-free Sn alloys	Leak-tightness, pressure resistance, corrosion resistance	Tubular, sleeve
Medical devices & precision instruments	Brazing/soldering	Precious metal, nickel-based, biocompatible alloys	Biocompatibility, hermetic sealing, precision & minimal distortion	Ceramic-to-metal, micro-joints
Emerging & specialized	Both (incl. laser/vacuum)	Advanced lead-free, active solders, high-temp alloys	Thermal management, lightweighting, sustainability	Hybrid, 3D packaging, battery cooling

6.1 | Electronics and Electrical Industries (Soldering)

Soldering is the cornerstone joining method in electronics due to its low temperature, excellent electrical and thermal conductivity, and suitability for high-density assemblies [44]. It is widely applied in PCB assembly, semiconductor packaging, power electronics, and consumer devices. Lead-free SAC alloys dominate to meet RoHS requirements, supporting automated processes like reflow and wave soldering (see *Fig. 4*).

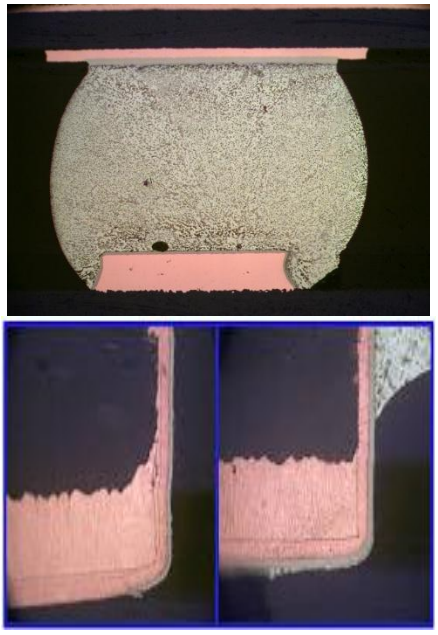

Fig. 4. Cross-sectional views of soldered PCB joints showing solder fillet formation and interfacial structure [45].

6.2 | Aerospace, Automotive and Heavy Engineering (Brazing)

Brazing delivers the high-strength, high-temperature, and vibration-resistant joints required in demanding environments [46]. Aerospace applications include turbine components, heat exchangers, and structural honeycomb seals. Automotive uses focus on EV battery cooling systems, radiators, and exhaust components as shown in *Fig. 5*. Heavy engineering employs it for power generation equipment and industrial heat exchangers.

Fig. 5. Brazed aerospace turbine engine components and assemblies, highlighting complex high-performance joints [47].

6.3 | Plumbing, HVAC and Refrigeration Systems

These sectors rely heavily on brazing for leak-proof, pressure-resistant copper tubing joints in refrigerant lines, condensers, and evaporators. Copper-phosphorus (BCuP) self-fluxing alloys are popular for HVAC/refrigeration, while soldering serves lower-pressure plumbing applications (see *Fig. 6*). Nitrogen-purged torch brazing ensures clean, oxide-free internal surfaces [48].

Fig. 6. Typical HVAC and refrigeration copper tube brazed joints during installation and assembly [49].

6.4 | Medical Devices and Precision Instruments

Brazing and soldering enable hermetic, biocompatible joints in surgical tools, implants, catheters, and sensor feedthroughs. Vacuum or controlled-atmosphere brazing joins dissimilar materials (ceramic-to-metal or titanium-to-stainless steel) with minimal distortion and no harmful residues (see *Fig. 7*)[50].

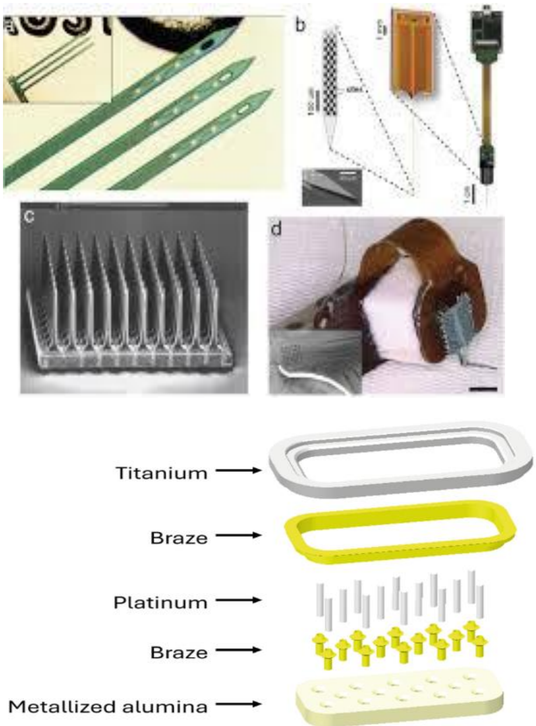

Fig. 7. Precision medical and implantable devices featuring brazed ceramic-to-metal or micro-scale joints [51].

7 | Advantages and Limitations

7.1 | Advantages of Soldering as a Joining Process

Soldering offers several distinct advantages that make it the preferred joining method in many applications, particularly in electronics and precision assemblies:

I. Low process temperature: Operating below 450°C (typically 180-400°C), soldering introduces minimal heat input. This significantly reduces thermal distortion, residual stresses, and metallurgical changes in the base metals [52]. For example, reflow soldering of SAC305 occurs at 240-260°C, protecting delicate components.

II. Excellent electrical and thermal conductivity: The metallic joint provides superior conductivity far better than adhesives.

III. Ability to join dissimilar materials: Effective for combinations such as copper-gold or tin-coated surfaces without melting base metals.

IV. High precision and miniaturization support: Enables assembly of micro-scale components in high-density interconnects, supporting modern electronics trends.

V. Ease of automation and high-volume production: Reflow, wave, and selective soldering achieve high throughput with excellent repeatability.

VI. Reworkability: Joints can be desoldered and repaired relatively easily, aiding prototyping and maintenance.

These features make soldering ideal where low thermal impact and electrical performance are critical.

7.2 | Advantages of Brazing as a Joining Process

Brazing provides higher-performance characteristics suited to structural and demanding environments:

I. Superior joint strength and load-bearing capacity: Shear strengths typically range from 100-350 MPa (or higher in optimized joints), often matching or exceeding base metal strength. Silver-based alloys (BAg series) can achieve 200-400 MPa tensile strength in copper or steel assemblies [53].

II. Excellent high-temperature performance: Maintains integrity up to 800-1100°C depending on the alloy (nickel-based fillers for 1000°C service), with good creep and oxidation resistance.

III. Outstanding capability for dissimilar metals and complex geometries: Joins steel-to-copper, aluminum-to-stainless steel, or ceramic-to-metal effectively.

IV. Hermetic and leak-tight joints: Produces continuous, void-free seals ideal for pressure systems and heat exchangers.

V. Minimal distortion compared to welding: Lower heat input than fusion welding results in better dimensional control.

VI. Versatility in batch processing: Furnace and vacuum methods allow simultaneous joining of multiple joints with high repeatability.

Brazing is highly valued in aerospace, automotive, and power generation where durability under extreme conditions is essential.

7.3 | Limitations and Challenges of both Processes

Despite their strengths, soldering and brazing have inherent limitations:

I. Lower strength than fusion welding: Joints are generally weaker under tensile or peel loads. Soldered joints are particularly limited in high-structural applications.

II. Temperature limitations: Soldered joints (SAC305) lose significant strength above 100-150°C. Brazed joints have higher limits but are still constrained by filler alloy diffusion and base metal softening.

III. Dependence on joint clearance and surface condition: Optimal gaps are narrow (0.025-0.13 mm); deviations cause incomplete filling or voids.

IV. IMC formation: Excessive brittle IMCs (Cu_6Sn_5 in SAC solders) can reduce ductility and fatigue life.

V. Flux-related issues: Residues may cause corrosion or electrical shorts; aggressive fluxes require thorough cleaning.

VI. Inspection difficulties: Hidden defects often need advanced NDT methods.

VII. Dissimilar metal risks: Galvanic corrosion and thermal expansion mismatch can degrade performance.

VIII. Brazing adds challenges such as higher energy use, risk of base metal erosion, and more complex fixturing [54].

7.4 | Economic Considerations

Economic factors strongly influence process selection:

I. Material costs: Lead-free solders (SAC305) are moderately priced but more expensive than legacy Sn-Pb. High-silver brazing alloys (BAg) and nickel-based fillers can be significantly costlier; copper-phosphorus (BCuP) offers a more economical alternative for copper tubing [39].

II. Equipment and setup costs: Soldering systems (reflow ovens, wave machines) generally require lower capital investment than large vacuum or atmosphere-controlled brazing furnaces.

III. Productivity: Soldering excels in high-volume electronics (thousands of joints per minute via automation). Brazing productivity varies torch methods are slower, while furnace brazing joins multiple components simultaneously, improving efficiency for batch work.

IV. Skill requirements: Manual torch soldering/brazing demands trained operators. Automated processes reduce manual skill dependency but require experienced process engineers for validation.

V. Lifecycle costs: Soldering offers easier rework, lowering repair expenses. Brazing provides longer service life in harsh environments, potentially reducing maintenance [55]. However, defects in critical applications (aerospace/medical) can incur high failure costs.

The economic edge of both processes often comes from reduced post-joint machining, lower scrap due to minimal distortion, and enabling multi-material lightweight designs (see *Table 5*).

Table 5. Detailed comparison of soldering and brazing.

Aspect	Soldering	Brazing
Process temperature	450°C (typical 180-400°C)	450°C (typical 540-1200°C+)
Typical shear strength	20-60 MPa (SAC305: 30-55 MPa; Sn63Pb37: 37-55 MPa on Cu)	100-350+ MPa (BAg: 200-400 MPa; BNi: higher at elevated temp.)
Service temperature limit	Up to 100-150°C (strength drops sharply)	Up to 800-1100°C (alloy-dependent)
Distortion/heat input	Very low	Low to moderate
Electrical conductivity	Excellent	Very good
Hermeticity	Good	Excellent
Key advantage	Precision, automation, reworkability	High strength, high-temp performance, dissimilar metals
Main limitation	Lower strength & temp resistance	Higher energy use, potential base metal effects
Relative material cost	Moderate (lead-free higher than Sn-Pb)	Higher for Ag/Ni alloys; lower for BCuP
Productivity	Very high in automated electronics	High in furnace batch; lower in manual torch
Skill requirement	Moderate (high in manual; low in automated)	Moderate to high (especially manual)

8 | Quality Control, Inspection, and Reliability

8.1 | Common Defects in Soldered and Brazed Joints

Defects in soldered and brazed joints can compromise mechanical strength, electrical performance, hermeticity, and long-term reliability. Early identification is essential to prevent field failures. *Table 6* summarizes the common defects in soldered and brazed joints.

Table 6. Common defects in soldered and brazed joints.

Defect	Process (Soldering/Brazing)	Root Causes	Recommended Detection Methods	Prevention Methods
Cold joints	Soldering (mainly)	Insufficient heat, poor wetting, movement during solidification, contaminated surfaces	Visual inspection (dull, grainy appearance), X-ray, AOI	Proper temperature control (30-50°C above liquidus), adequate flux, clean surfaces, stable fixturing
Solder bridging/shorts	Soldering	Excess solder/flux, improper paste volume, close component spacing, misalignment	Visual/AOI, X-ray radiography	Optimized stencil design, controlled solder paste volume, IPC-compliant pad spacing, proper reflow profile
Insufficient solder/opens	Soldering/brazing	Insufficient filler volume, poor wetting, blocked flow, contamination	Visual, X-ray, electrical testing, ultrasonic	Accurate solder paste dispensing, proper joint clearance (0.025-0.13 mm), thorough surface cleaning
Voids/porosity	Both	Gas entrapment (flux outgassing, moisture), inadequate atmosphere control, rapid cooling	X-ray radiography, ultrasonic testing, CT scan	Use of low-voiding solder paste/flux, controlled heating/cooling rates, vacuum or inert atmosphere in brazing
Tombstoning /component shift	Soldering	Uneven heating, unbalanced surface tension, poor pad design	Visual / AOI, 3D AOI	Symmetrical pad/thermal relief design, uniform reflow profile, proper component placement
Incomplete penetration/lack of fill	Brazing (mainly)	Improper joint clearance, uneven heating, poor wetting, insufficient capillary action	X-ray, ultrasonic, visual fillet inspection	Optimized joint gap, uniform heating (torch/furnace control), proper flux/atmosphere, good fixturing
Base metal erosion	Brazing	Excessive temperature or dwell time, aggressive filler diffusion	Microstructural analysis (cross-section), visual	Controlled brazing temperature and time, selection of compatible filler alloys
Flux entrapment/residue	Both	Excessive or aggressive flux, inadequate cleaning, poor atmosphere control	Visual, dye penetrant, corrosion testing	Minimal effective flux quantity, proper post-cleaning (especially for electronics/medical), no-clean or low-residue flux
Cracking	Both	Rapid cooling, residual stresses, brittle IMCs, thermal expansion mismatch	Visual, dye penetrant, ultrasonic, X-ray	Controlled cooling rates, compatible materials, stress-relief design, proper fillet formation
Poor wetting/discontinuous fillets	Both	Surface oxides/contamination, incorrect temperature, unsuitable flux	Visual inspection, wetting balance test	Thorough cleaning/passivation, correct flux selection, proper process temperature

9 | Recent Advances and Future Trends

9.1 | Development of Lead-Free Solders and Eco-Friendly Materials

The drive toward lead-free soldering has progressed beyond first-generation SAC305 alloys to third-generation formulations incorporating bismuth, antimony, nickel, and other micro-additives [56]. These alloys address limitations in reliability, wettability, and processing while reducing environmental impact.

9.2 | Advanced Brazing Alloys and High-Temperature Applications

Brazing alloy development focuses on nickel-based, cobalt-based, and diffusion-braze systems for service temperatures exceeding 1,000-1,200°C. Modern nickel-cobalt fillers provide superior oxidation resistance (improvements of 18-22%), creep strength, and joint integrity in turbine blades, heat exchangers, and hydrogen systems [57]. Flux-free and cadmium-free formulations eliminate residues, reduce emissions, and improve internal cleanliness.

Reactive air brazing and ultra-high-temperature variants (Ni-C eutectic systems reaching remelt temperatures above 1,300°C) enable joining of ceramics to metals for hypersonic and fuel-cell applications [58]. These alloys support thinner sections and lightweight designs in aerospace and energy sectors while maintaining high joint strength.

9.3 | Automation, Robotics and Industry 4.0 Integration

Automation has shifted soldering and brazing toward intelligent, flexible systems. Robotic cells with laser, induction, or selective heating, combined with collaborative robots (cobots), handle high-mix production with minimal manual intervention [59].

Industry 4.0 features include real-time thermal profiling, AI-driven defect detection via AOI/SPI, digital twins, and closed-loop parameter adjustment. These technologies improve yield, traceability, and energy efficiency while addressing labor shortages (see *Fig. 8*).

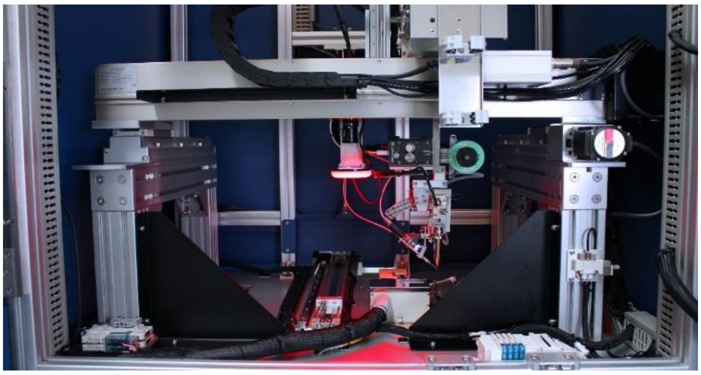

Fig. 8. Examples of automated robotic soldering/brazing workstations and gantry-style robotic cells used in high-precision manufacturing [60].

9.4 | Hybrid Joining Techniques (Soldering/Brazing Combined with Others)

Hybrid methods combine soldering or brazing with complementary processes to overcome individual limitations, such as low peel strength or poor fatigue resistance in dissimilar-material joints [61]. Common approaches include brazing and adhesive bonding for enhanced toughness and corrosion protection, laser-assisted brazing with mechanical elements, and magnetic/microwave hybrid soldering for rapid processing and energy savings. These techniques are particularly effective for aluminum-to-steel, metal-to-composite, and ceramic-to-metal assemblies in automotive, aerospace, and medical devices (see *Fig. 9*).

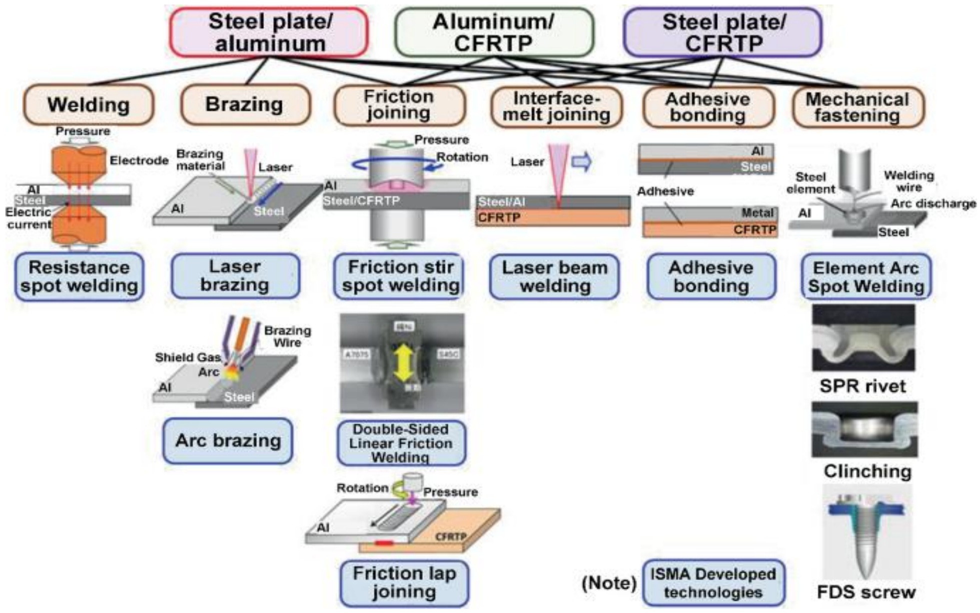

Fig. 9. Schematic of hybrid joining techniques, including combinations of brazing with adhesive bonding, laser processes, and mechanical fastening for multi-material assemblies [62].

10 | Conclusion

Soldering and brazing remain indispensable joining technologies that bridge the gap between low-distortion precision assembly and high-performance structural bonding. By preserving base metal integrity through non-fusion capillary mechanisms, they offer unique advantages in minimizing thermal distortion, enabling dissimilar material combinations, and producing electrically conductive, leak-tight joints qualities unmatched by many alternative methods. Their applications span critical sectors from electronics miniaturization to aerospace turbine components and medical devices, demonstrating versatility and reliability under diverse service conditions.

Despite limitations such as moderate strength compared to welding and sensitivity to process parameters, ongoing developments in eco-friendly lead-free solders, advanced high-temperature fillers, vacuum/atmosphere-controlled processes, and robotic automation continue to expand their capabilities. Hybrid joining approaches further address weaknesses, enhancing toughness and multifunctionality in lightweight multi-material structures. In an era of Industry 4.0, sustainable manufacturing, and complex material systems, soldering and brazing provide cost-effective, high-quality solutions that support innovation while reducing energy consumption and post-processing needs. Their continued evolution will play a vital role in meeting future demands for precision, durability, and environmental responsibility across engineering disciplines. Mastering these processes through proper design, parameter control, and quality assurance remains essential for achieving reliable, long-lasting assemblies.

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Data Availability

Sufficient data is available upon request.

Conflict of Interest

No potential conflict of interest was reported by the authors.

Consent for Publication

All authors have provided their consent for the publication of this manuscript.

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