Chapter 5
Advanced Joining and Welding Techniques: An Overview

Kush Mehta

Abstract Joining and welding is an essential component of manufacturing technology. New developments in joining and welding are evolved in order to acquire extraordinary benefits such as unique joint properties, synergistic mix of materials, cost reduction of component, increase productivity and quality, complex geometrical configurations, suitability and selection of material to manufacture new products. This chapter provides an update on recent developments of welding and joining to showcase above benefits. Theoretical background, process parameters, novel aspects, process capabilities, and process variants along with its application are presented in this chapter. Advanced welding and joining techniques are addressed under different headings of fastening and bonding processes, developments of arc welding processes, advanced beam welding techniques, sustainable welding processes, micro-nano joining and hybrid welding.

Keywords Arc · Bonding · Fastening · Heat · Joining · Productivity · Quality · Welding

5.1 Introduction

Joining and welding technologies play a crucial role in the area of manufacturing. There are many conventional joining and welding technologies available and that can be, and are applied successfully, the scope of their modification and development always exists and is tremendously increasing day by day with the accelerated commercial requirements. Modifications and development in conventional welding and joining techniques and innovations in this field are being made to attain the tangible benefits such as favorable joint properties, synergistic mix of materials, significant reduction in the component cost, tremendous enhancement in produc-

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tivity, excellent quality, attaining complex geometrical configuration, and ability to deal with variety of materials to manufacture new products. Innovative approaches of joining and welding technology have provided a new window through which the variety of materials such as reactive metals, composites, plastics, non-metallic materials and dissimilar materials can be joined. These advancements of welding and joining techniques are discussed in the present chapter.

The main objective of this chapter is to provide an introductory knowledge of recent developments in the area of welding and joining processes along with its basic concepts and special features of different techniques, assuming the basic understanding of the readers with regard to conventional welding and joining.

Over the past few years, sustainable welding processes, hybrid mechanical fastening, micro-nano joining, adhesive joining, activated arc welding processes, pulsed arc welding processes, narrow groove arc welding and hybrid welding and joining processes have been the prime topics of research in this field. Figure 5.1 presents the classification (based on recent advancements) of advanced welding and joining processes that can be classified in five subsections such as advanced fastening and bonding, advanced fusion welding, micro and nano-joining, advanced non fusion welding and hybrid welding processes.

5.2 Advanced Fastening and Bonding Processes

There are so many conventional fastening and bonding processes available which are capable to join variety of materials. The main objective behind the developments in conventional fastening and bonding processes is to successfully join special materials with excellent joint properties. Recently developed advanced fastening and bonding processes such as hybrid bonded fastened joining, clinching and electrostatic bonding are discussed here.

5.2.1 Hybrid Bonded Fastened Joints

Hybrid bonded fastened joints are produced by simultaneous actions of adhesive bonding and mechanical fastening. There are two types of hybrid bonded fastened joints, such as, the joints that use bolts/rivets are known as hybrid bonded–bolted joints (see Fig. 5.2a), and the joints that use of pins with adhesive are known as hybrid bonded pinned joints (see Fig. 5.2b). Individual approaches of mechanical fastening and adhesive bonding are successfully applied to metallic materials and plastics. However, an individual approach of mechanical fastening and adhesive joining is difficult for joining of dissimilar materials, composite materials and brittle metallic materials [1, 2]. Considering the aforementioned limitations, hybrid approach of bonded fastened joint is developed in order to avoid individual limitations of fastening and adhesive joining.

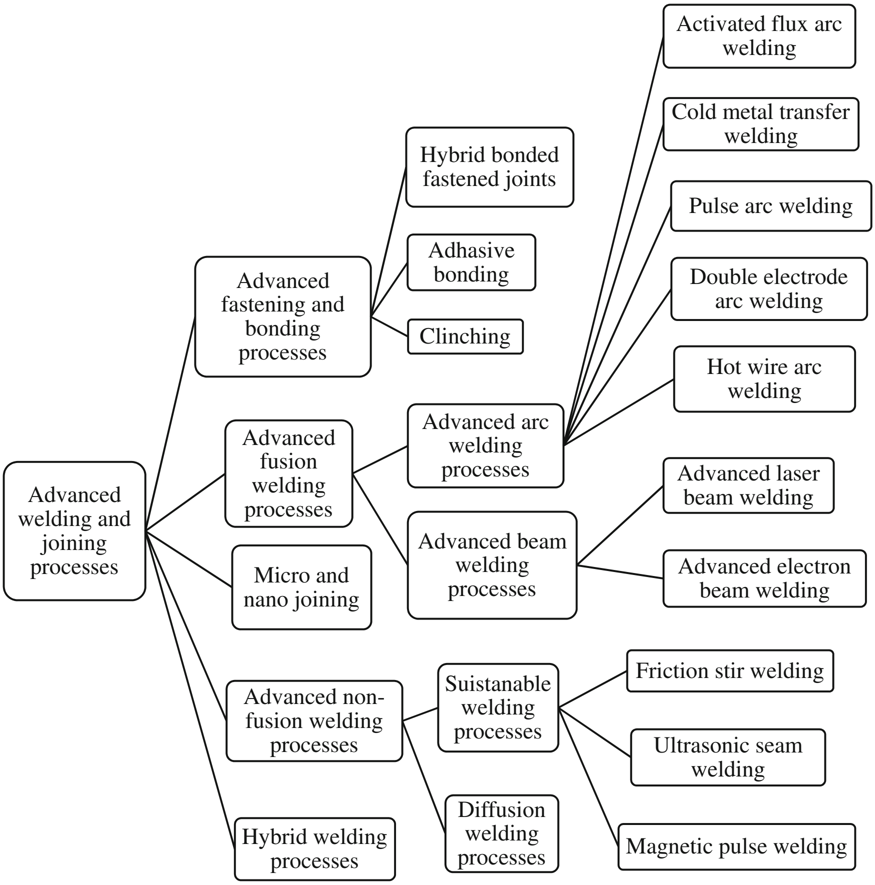


Fig. 5.1 Classification of advanced welding and joining processes

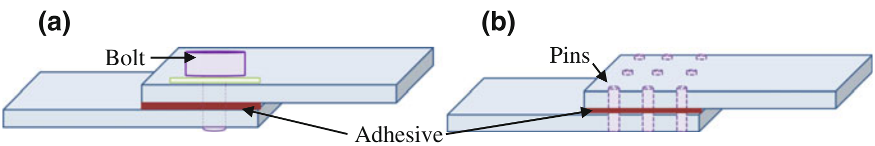


Fig. 5.2 Hybrid bonded fastened joints **a** hybrid bonded bolted joint and **b** hybrid bonded pinned joint

Selection of adhesives, strength of adhesive in service, ability to sustain fatigue load are common difficulties that exist, when joining of composite–composite, composite-metal and dissimilar materials systems. In case of mechanical fastening, load distribution capacity and mechanical strength are issues associated with joining of composite-composite, composite-metal, and brittle metallic materials. In order to

Table 5.1 Process parameters of hybrid bonded fastened joints [1, 2]

Parameters of workpiece materials	Geometrical parameters	Different types of joint configuration	Different types of adhesives	Different types of fasteners[a]
Type of workpiece material	Adhered thickness	Single-lap and double lap joints	Hysol Shell 951 Epoxy	Sphere type pin fastener
Thickness	Overlap length	Scarf joint	Pliogrip 7400/7410 Polyurethane	Wedge type pin fastener
Strength of material	Width	Stepped lap joint	3 M 2216 epoxy	Protruding type fastener head
Young's modulus of material	Bond-line thickness	T-joint	Montagefix-PU Polyurethane	Countersunk type fastener head
Similar or Dissimilar system of materials	Fastener-hole clearance	Flush and triangular fillet joints		Rounded shaped head type fastener
		Butt joint		Polygonal shaped head type fastener

[a]Fasteners: pin mean diameter less than 1 mm without top head, bolt and rivet are denoted as fasteners

address these issues, hybrid approach of bonded fastened joining is developed. Fastening system can help to sustain axial loads while its distribution can be handled by adhesives. Most important parameters such as type of joint configuration, type of fastener, adhesive material and its thickness, loading condition, type of material being used and fastener-hole clearance of hybrid bonded fastened joints are required to take into the considerations [1]. Table 5.1 shows process parameters reported under the literature of hybrid bonded fastened joints. Combinations of these parameters lead to the formation of metallurgically sound joints.

Applications

- Joining of materials such as polymers, aluminum composites, steel-composite, aluminum–aluminum, titanium-composite, and magnesium-composite materials, in order to obtain light weight structure for aerospace applications [1, 2].
- Joining of automobile components, especially body work assembly made out of aluminum and its alloys and composites [1].
- Joining of fiberglass in the nautical industries [1].
- Joining of non-metallic materials such as plastics, ceramics, polymers and glass, etc. [1].

5.2.2 *Adhesive Injection Fastening*

Adhesive injection fastening is advanced hybrid bonded fastened joining technique, invented at the welding institute (TWI) for joining of plastics [3]. Later, this technique is applied to materials such as aluminum, composites, and aerospace

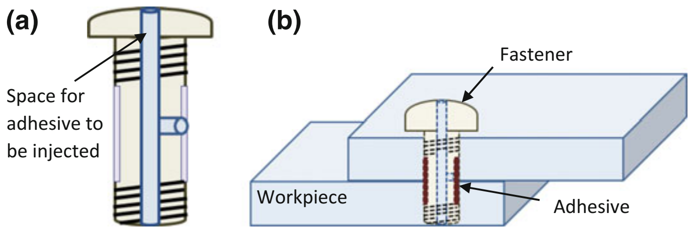


Fig. 5.3 Adhesive injection fastening, **a** internal mechanism of fastener and **b** Adhesive injection fastening joint

metals. Process principle of adhesive injection fastening is illustrated in Fig. 5.3. A novel mechanism of adhesive injection through fastener is introduced at the interface between fastener and workpiece in this technique (Fig. 5.3a). Use of this technique provides rapidity of process, excellent sealing ability, and fatigue resistance of adhesive. The use of adhesive can be saved with this simplified hybrid bonded fastened joint technique [3]. Stiffening and strengthening can be further improved by this technique as the adhesive is exactly located at the interface between fastener and workpiece as shown in Fig. 5.3b.

5.2.3 Clinching

Clinching is known as press-joining technique, aimed to join thin sheets using specially designed tools or without application of the tool, through interlock formed by plastic deformation of base materials (refer Fig. 5.4 for process description). Clinching is alternative joining method of riveting, screwing, adhesive joining, and spot welding. The clinching process is found advantageous compared to other joining methods in terms of flexibility, repeatability, cleanness, processing time, cost, energy consumption, eco-friendliness, temperature, mechanical and thermal stresses generated, and fatigue characteristics of joints [4].

The most common types of clinch are cylindrical, beam, star, flat and self-piercing elements. The round, flat, square and star type of clinching joints do not require tooling as a filler material while self-piercing needs an external consumable tool as shown in Fig. 5.4. Clinching can be applied to most of the metals, plastics, polymers, wood, composites, and dissimilar materials. Super hard and brittle materials are difficult to join by clinching process [4]. Process parameters of clinching are presented in Table 5.2.

Recent developments of clinching
In order to improve clinching process, further developments such as heat assisted clinching [5] and clinching with adhesives [6] have been reported. Heat assisted clinching helps to increase the material ductility of workpiece that subsequently extend the clinching joint ability. Heat assisted clinching also leads benefits in terms

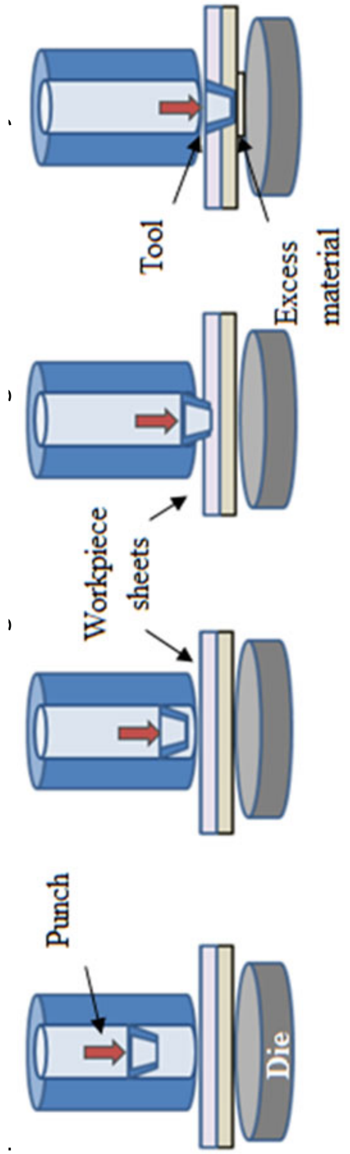


Fig. 5.4 Basic process description of clinching, **a**, **b** offsetting, **c** upsetting, and **d** flow pressing

Table 5.2 Process parameters of clinching [4, 6]

Parameters related to workpiece materials	Parameters related to die and punch	Working process parameters
Material of workpiece	Shape and dimensions of the punch and die	Punch force
Thickness	Tool material and its geometry	Length of interlock
Similar or dissimilar system of materials	Die groove dimensions	Loading direction
Thinning of workpiece sheet	Punch corner radius	
Mechanical properties of workpiece material	Draft radius	

of required punch force as the yield stress of the material is reduced when heat is applied externally. However, the amount of heat needed for preheating is a critical process parameter of this technique. Clinch with adhesives is called "clinchbonding" wherein, suitable adhesive is applied between workpiece sheets. Clinchbonding can improve fatigue and tensile properties of joints [6].

Applications of clinching

- Joining of metal to metal for the application of automobile chassis (automotive, trucks, buses, railways) [6].
- Joining of aerospace materials such as composites, aluminum, titanium, composite-metal dissimilar joints [4, 6].
- Manufacturing applications of ropeways and different nautical equipments [4, 6].
- Joining of railways and automobile bodies [6].
- Joining of dissimilar materials [6].

5.3 Advanced Arc Welding Processes

Arc welding falls under the classification of fusion joining techniques used to join a variety of materials through melting and solidification of the base material by an arc with or without application of filler material. Developments of arc welding processes such as activated flux arc welding, cold metal transfer arc welding, narrow gap arc welding, pulse arc welding, tabular wire arc welding and double electrode arc welding are discussed in the following subsections.

5.3.1 Activated Flux Arc Welding Processes

Activated flux arc welding processes are advanced methods of joining in which the activating layer of flux containing of metallic oxides, fluorides and chlorides are applied on the weld surface of a workpiece as shown in Fig. 5.5a through liquid paste or spray. Liquid paste of activated flux is prepared with the help of solvent like acetone/ethanol. Activated arc welding increases the weld bead penetration and reduces bead width of weld as shown in Fig. 5.5c, while conventional arc welding provides weld bead with low penetration and broad width as shown in Fig. 5.5b. Concept of activated flux arc welding process is observed for processes such as activated tungsten inert gas welding (A-TIG), activated flux gas metal arc welding (A-GMAW), activated flux plasma arc welding (A-Plasma welding) and activated flux laser welding [7–10].

5.3.1.1 Activated Flux Tungsten Inert Arc Welding

The first study on activated flux arc welding is applied on A-TIG of titanium and its alloys by Paton Electric welding institute. A-TIG is also known as flux assisted-TIG welding process. The maximum literatures for activated flux arc welding are found for A-TIG process hitherto [7]. A-TIG can significantly improve the penetration level of weld up to 8–12 mm which is impossible to obtain through conventional TIG technique. Improvement of penetration is achieved by the effect of *"reverse*

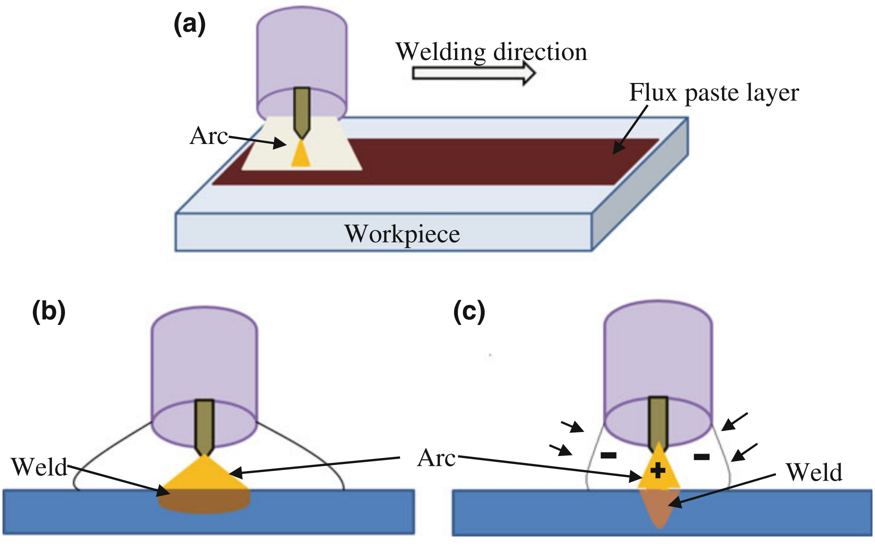


Fig. 5.5 **a** Process principle of activating flux arc welding, **b** weld characteristics of conventional welding, and **c** weld characteristics of activated flux welding

Marangoni convection" and *"arc constriction mechanisms."* Marangoni convection is known as surface-tension driven convection or thermo-capillary convection, which is having a considerable effect on the penetration level of the weld. The reverse Marangoni effect comes into the effect when activating flux is pasted on the workpiece, in which the direction of surface tension becomes inward towards the center, which consequently affects the fluid flow of the weld pool. This phenomenon ultimately increases the penetration level and reduces the width of the weld. In case of arc constriction mechanism, the arc generated on the surface of the flux pasted workpiece is reduced its width as shown in Fig. 5.5c. This arc constriction provides focused heat source by an arc with its higher power and density that subsequently results in higher penetration. Phenomenon of electronegativity of flux is found responsible for arc constriction in the literatures [7].

A-TIG for repair application

A-TIG can also be applied for the repair work of any mechanical component. A-TIG is suitable for repair work due to its advantages such as no need to prepare V-groove, filler wire is not required, weld shrinkage and distortion is reduced, and single pass of welding up to 10–12 mm is achievable by its autogenous mode. Development of A-TIG for nuclear power plant is reported in the article published by TWI team [11].

Process Parameters affecting A-TIG performance

The process parameters that affect A-TIG performance are summarized in Table 5.3. Type of flux, forces acting on process, input parameters and workpiece material are the major factors which affects A-TIG performances. Selection of fluxes depends on the type of workpiece to be welded. Compatibility of different fluxes with chemical compositions of workpiece is most important parameter.

Table 5.3 Summary of process parameters of A-TIG [7]

Major parameters	Sub-parameters	Types
Flux	Mixtures of acetone or ethanol with metal oxides, fluorides or chlorides	CuO, HgO, ZnO, MgO_2, TiO_2, Cr_2O_3, SiO_2, ZrO_2, TiO_2, MoO3, Al_2O_3, Fe_2O_3, Co_3O_4, MoS_2, NiF_2, CaF_2, AlF_3
Forces acting in A-TIG	Marangoni force, electromagnetic or Lorenz force, bouncy force, aerodynamic drag force	Surface tension, density caused forces, magnetic effect caused forces, current caused forces
Process input parameters of welding	Welding current, welding speed, arc length, electrode geometry, shielding gas composition	Conical shaped electrode tip, frustum and wedge shaped electrode
		Argon, Helium, mixture of argon and helium, mixture of argon and nitrogen
Properties of workpiece material to be welded	Thickness of the workpiece, chemical composition of workpiece material	Ferrous and non-ferrous workpiece materials, surface active and reactive elements of workpiece such as sulfur, oxygen, tellurium, selenium, manganese, aluminum, silicon

Fluxes reported in literatures for different workpiece materials are presented in Table 5.3. In addition to this, Marangoni forces, electromagnetic force, buoyancy force and aerodynamic drag force are acting on A-TIG process. These forces are affected by the properties of workpiece, type of flux used, welding current, and magnetic effect. Welding current and welding speed affects heat input mainly while arc length, electrode geometry, shielding gas composition governs operational performances, which ultimately affects weld bead shape of the joint [7].

It is reported that, the A-TIG technique has been successfully applied on different metallic materials such as carbon steel, stainless steel, aluminum, magnesium, copper, zirconium, nickel-based alloys and low activation ferritic/martensitic (LAFM) steels [7].

5.3.1.2 Other Activated Arc Welding Processes

A-GMAW technique is carried out for AISI 1020 carbon steel with three oxide fluxes such as Fe_2O_3, SiO_2, and $MgCO_3$. The flux of $MgCO_3$ has performed excellent in terms of obtaining optimum weld bead profile, improved tensile strength, and hardness [10]. A-plasma arc welding is analyzed with flux elements of Ti, Cr, and Fe. Concentrated arc with narrow temperature field can improve weld properties if A-plasma arc welding is applied [8]. A-laser welding can improve penetration level significantly at low power. A unique mixture of flux such as 50% ZrO_2, 12.09% $CaCO_3$, 10.43% CaO, and 27.48% MgO has provided 2.23% higher penetration for ferritic stainless steel than the normal laser welding [12]. The conduction mode of laser welding is required to achieve improved penetration [9]. However, A-GMAW, A-plasma arc welding and A-laser welding are not much applied for research and practical applications so far.

5.3.2 Cold Metal Transfer Arc Welding

Cold metal transfer (CMT) arc welding is developed for metal inert gas welding (MIG)/metal active gas welding (MAG) by Fronius company. CMT is fully mechanized automatic welding process in which arcing and wire feeding are well controlled during operation. In this advance process, the metal transfer occurs in cold condition. Since this process is a cold arc process, it leads with advantages such as low heat input, spatter free metal transfer and extremely stable arc [13].

The process principle of CMT is illustrated in Fig. 5.6. CMT is a cold welding process in which the controlled short circuit type arc is generated between workpiece and filler type electrode of MIG/MAG welding. Initially, the filler wire is melted and then after it is transferred to the workpiece through controlled short circuit mode. The filler wire moves forward during the welding (see Fig. 5.6a, b) and that is pulled back again as soon as the short circuit occurs (see Fig. 5.6c, d). This way the metal transfer to the workpiece happens in cold condition. In this

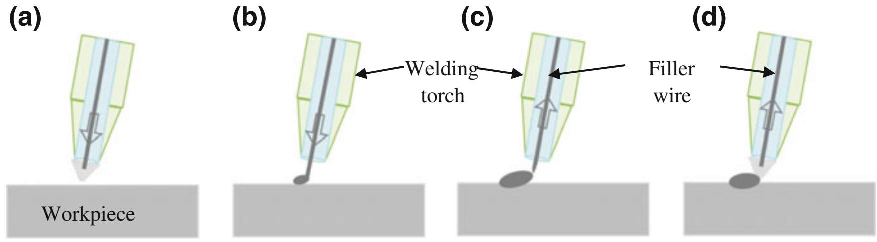


Fig. 5.6 Process principle of CMT, **a** arc generation with forward wire motion, **b** metal transfer with short circuit mode and forward wire motion, **c** metal transferred and reverse wire motion, and **d** wire is back to its position

process, metal transfer occurs drop by drop as presented in Fig. 5.6b–d. Re-ignition of arc again happens and this cycle is repeated [13, 14]. Process parameters such as forward and reverse motion of electrode and electrical characteristics are major factors that affect performance of CMT technique. Low voltage and low current are recommended parameters in order to obtain drop by drop metal transfer phenomena of CMT [14].

CMT pulse
The CMT pulse technique combines a CMT cycle and pulsed cycle that leads to the more heat input. The performance and flexibility of process can be significantly improved by combining pulse cycle with CMT cycle [14, 15].

Advanced CMT
Advanced CMT is even cooler relative to CMT. In this case, process control is carried out through polarity of the welding current. At the phase of short circuit, the polarity reversal is done that in turn provides results of extremely controlled heat input and intensely gap bridge-ability that allows up to 60% higher deposition rate [14, 15].

Applications of CMT

- CMT can weld ultra- thin sheets (0.3 mm) of metallic materials [15].
- Welding of dissimilar materials such as aluminum–steel, aluminum–magnesium, and aluminum–titanium, etc. [14–17].
- A well-controlled and precise cladding can be done by CMT [14, 16, 18].
- Repair of mechanical components (for example: cracks generated in the steam turbine case are efficiently repaired by CMT process [18]).

5.3.3 *Pulse Arc Welding*

Pulse gas tungsten arc welding and pulse gas metal arc welding (P-GMAW) process are the most commonly used important types of pulse arc welding techniques reported in literatures for different metallic materials under the classification of pulse arc welding.

P-GMAW operates on the pulsed current power source which is developed to improve process stability, weld penetration, deposition rate of filler wire and weld deposition properties [19]. Weld deposition can be improved by two steps of advanced solidification: one at the time of pulse off period and second at the time of weld spot developed during next pulse [20]. Important process parameters of P-GMAW are pulse duration, pulse frequency and three different currents such as mean current, peak current and base current that subsequently affects the velocity of molten droplet [21]. Additionally, process parameters such as welding speed, filler wire size, rate of filler wire feed and shielding gas affects performance of P-GMAW [20]. Weld defects of bad weld surface, lack of fusion, undercut, burn-backs, and stubbing-in may have caused due to improper selection of these process parameters [21].

P-GMAW provides spray transfer with overall reduced heat input. This process is able to result in excellent weld bead appearance due to tiny molten droplet caused through spray transfer mode. Formation of spatter is eliminated by P-GMAW. Heat affected zone is reduced to a great extent through this process [20, 21].

P-GMAW is applied to join different materials such as aluminum and steels and alloy steels, etc. [19, 20].

5.3.4 Double Electrode Arc Welding

Double electrode arc welding process is a novel welding technique in which consumable or non-consumable type electrodes are brought into the action in order to bypass the wire current. This bypass current of the second electrode reduces the heat input on main set-up while increases the deposition rate of first consumable electrode [22].

The process principle of double electrode arc welding concept is demonstrated in Fig. 5.7. It shows two different electrodes such as consumable type electrode of gas metal arc welding (GMAW) and non-consumable type electrode of plasma torch. The non-consumable electrode of plasma torch is added as bypass torch while GMAW electrode is main electrode. Both of these bypass torch and GMAW torch are operated with same power source as presented in Fig. 5.7. Because of bypass arc, the heat input by current of base material is reduced with an increase in deposition rate of consumable wire. Additionally, deposition efficiency is also increased for the reduced heat input at the same or increased or controllable deposition rate [22]. There are different technologies reported in the literatures for double electrode arc welding, such as gas tungsten arc welding (GTAW)-GMAW process, plasma welding-GMAW process and submerged arc welding-GMAW

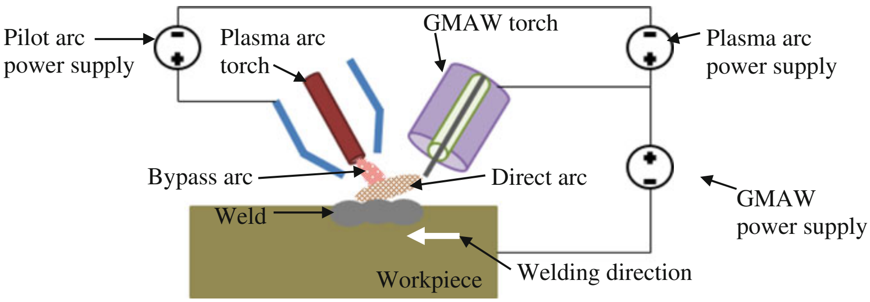


Fig. 5.7 Concept of bypass current of plasma arc welding and gas metal arc welding [22], with kind permission from Elsevier

process [22]. The aforementioned double electrode arc welding techniques are discussed in the subsequent sections.

5.3.4.1 Gas Tungsten Arc Welding

GTAW torch is provided for the purpose of bypass current through the non-consumable electrode for GTAW–GMAW double electrode arc welding. Two torches are added to the GMAW system in order to provide two bypass loops for the melting current. The main current flows through the base material while bypass current flows through two GTAW bypass loops. This process is able to reduce the heat input without affecting the deposition rate of filler that subsequently leads to the reduction of heat affected zone and distortion of the workpiece without any effect on productivity [22]. However, it is difficult to make configuration of dual bypass GMAW with GTAW system due to its setup complexity.

5.3.4.2 Pulse Gas Metal Arc Welding

Pulse GMAW process is developed at Lanzhou University of Technology in which two pulsed type power is supplied to control base and bypass current at different required levels with two GMAW processes. The main and bypass currents are supplied to two different consumable electrodes of GMAW. This process results in stabilized arc even at low current with required low heat input in order to obtain dissimilar aluminum-galvanized steel joints. The spray transfer mode can be able to achieve at low heat with the help of pulsed bypass current that consequently result in quality joints [22, 23]. The deposition rate of this system can be claimed higher than GTAW-GMAW double electrode welding due to the consumable electrodes. However, further investigations are being carried out to prove the conceptual benefits.

5.3.4.3 Plasma-GMAW and Plasma-GTAW

The plasma arc welding torch is used as a bypass arc with its pilot arc advantage while GTAW/GMAW is used as a main arc system which is developed at the University of Kentucky. Pilot arc can avoid the delay time for establishment of the main arc to the bypass arc, which is required in another double electrode arc welding. Hence, burned through effect of the workpiece can be eliminated by this method. Significant reduction in heat input and arc pressure is reported without reducing melting speed in plasma-GMAW process [22].

5.3.4.4 Submerged Arc Welding-GMAW

Submerged arc welding-GMAW double electrode arc welding is developed by Adaptive Intelligent Systems LLC for the shipbuilding manufacturing. Submerged arc welding is used as main wire and GMAW as bypass filler wire in order to obtain benefits such as use of extra high current at high speed with higher deposition rate at low heat input. Submerged arc welding usually causes high heat input that results in heat affected zone and workpiece distortion, which can be remarkable improved by the application of this double electrode system. Weld bead geometry and heat input can be controlled easily with submerge arc welding-GMAW double electrode arc welding process [22].

5.3.5 Hot Wire Arc Welding

Hot wire gas tungsten arc welding is the advanced joining technique in which filler wire is preheated initially, and then added to the arc, in order to melt faster than the conventional method [24]. Separate resistive heating source is provided to preheat the filler wire. The heating current of this system is settled ideally in such a way that the filler wire reaches to its melting point as soon as it comes to the weld pool. The deposition rate of filler wire is improved through this method, which increases the productivity. Independent wire feeding allows flexibility of process control and its feed [24]. Hot wire GTAW can be applied to most of the metallic materials. Hot wire arcing GTAW is further development of hot wire GTAW process in which the filler is added in such a way that it creates a side arcing as shown in Fig. 5.8a. In this process, the filler wire is completely melted before it goes to the weld pool while in hot wire GTAW, filler wire melts at the weld pool. Side arc helps to increase the deposition rate significantly even than the hot wire GTAW as the wire is heated not only from wire heating power source. For higher conductive filler wires such as copper and aluminum, the excellent melting efficiency is reported

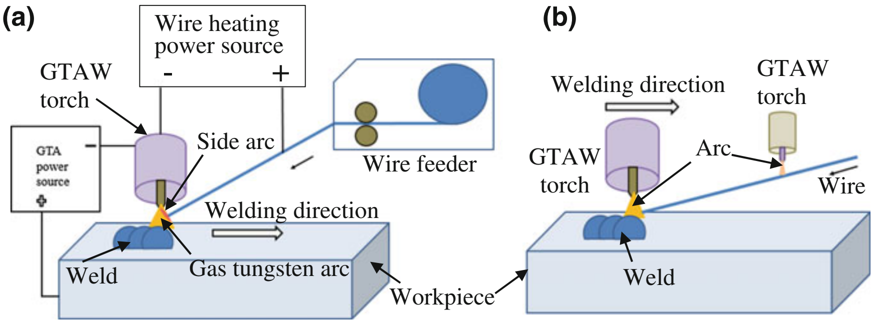


Fig. 5.8 **a** Hot wire GTAW with arcing and **b** arc assisted hot wire GTAW [22], with kind permission from Elsevier

through hot wire GTAW with arcing. A study conducted at the Beijing University of Technology has found that, there are three types of metal transfer such as free transfer, touching transfer and bridging transfer involved with hot wire GTAW with arcing. In free transfer, the metal separates from the filler wire before it makes contact with the weld pool. In touching transfer, the melted metal droplet initiates to form with a gap to the weld pool surface and travels into the weld pool after it makes contact to the surface periodically. In bridging transfer, the wire goes to the weld pool, even if it is solid [22]. However, a proper combination of melting current and wire position is required to obtain these modes.

Arc assisted hot wire GTAW is developed by researchers of Harbin Institute of Technology in order to obtain higher deposition rate than the hot wire GTAW. Figure 5.8b represents the arc assisted hot wire GTAW technique, in which pre-heating of wire is done through secondary gas tungsten arc. Separate parameters are able to control the temperature of wire that in turn leads to the enhancement of the deposition rate [22].

Other welding processes such as submerged arc, gas metal arc, plasma arc, laser and electron beam are also utilized for hot wire, but applications of the same are found to be limited [19, 24].

5.4 Advanced Beam Welding Processes

Beam welding processes are type of fusion welding techniques in which workpiece is being melted with the help of intense, focused heat provided through a beam of photons or electrons or plasma. Laser beam welding, electron beam welding and plasma beam welding are examples of beam welding processes. Advances of laser beam welding and electron beam welding are discussed here.

5.4.1 Laser Beam Welding

The laser is an extraordinary candidate, and widely applied in many fields of engineering for different applications. Laser beam welding is considered as one of the most versatile process in the area of manufacturing. Laser beam welding is developed for its different advantages such as precise process, excellent depth to width ratio, low weld heat input, small heat affected zone, rapid cooling, applied for complicated geometries. Recent developments of laser beam welding are presented in terms of ultra narrow gap laser welding, laser beam welding for plastics, non-metals, dissimilar materials, laser welding for repair applications and laser powder welding, under the subsections.

5.4.1.1 Ultra Narrow Gap Laser Welding

The ultra narrow gap is a type of advanced narrow gap welding used to join thick sections in a more economic way. In this welding procedure, the joint preparations are being prepared with one half of width of those in the conventional narrow gap between two workpieces which is to be joined with small included angles [25]. It is reported that, <2 mm of narrow width between workpieces to be joined can be considered as ultra narrow gap configuration [26]. This configuration requires less weld metal and less welding time to fill the cavity, which in turn increases productivity with material cost saving. The laser beam is most capable process to go into such small width groove as the laser beam diameter is very small. Additionally, laser beam welding is having a high power density and high precision control of process that perfectly suits for ultra narrow gap welding of thick sections. Ultra narrow gap laser beam welding offers low heat inputs, high welding speeds, lower levels of residual stresses and distortion, while consuming less filler material and power [27]. Defects such as lack of sidewall fusion, hot cracking, and porosity can be eliminated from the multiple-pass narrow gap laser beam welding of thick-section [26]. Process parameters such as joint design configuration, material transfer mode, current, laser power, laser-wire distance, welding speed, defocus of laser and laser beam diameter affects the output of the process [28].

5.4.1.2 Laser Beam Welding for Plastics

Plastic is a mixture of polymers that is either having homogeneous structure or heterogeneous structure. Properties of plastics such as reflection, absorptivity, melting point, thermal conductivity, and coefficient of thermal expansion affect its weldability [1]. Laser beam welding process is applied successfully to obtain sound joints of plastics. Since the evolution of diode lasers, plastics are actively investigated for its laser beam welding applications. Different types of lasers such as YAG, fiber and diode can be utilized under its low power defocused conditions in order to weld transparent materials of plastics, as the absorption and transparency can be controlled through concentration of substances such as carbon black [19, 29]. Suitable absorption additive has to be chosen for transparent plastic material that again depends on different conditions such as laser wavelength, demands on the color and transparency and economic aspects of the application. It is reported that, the transparent thermoplastics can be welded without the use of additional absorber in which diode lasers with wavelengths of 1500 nm or 2000 nm are recommended. However, such laser sources can be expensive [29].

5.4.1.3 Laser Beam Welding for Dissimilar Materials

Dissimilar materials are difficult to weld due to differences in its thermal, physical, chemical, metallurgical, and mechanical properties. Laser beam welding is one of the most feasible process for dissimilar joints because of precise control of the heat input, focused beam, flexible process, low distortion, quick heat dissipation, limited formation of brittle intermetallic compounds, and so on [19, 30–32]. Novel parameters of laser beam welding of dissimilar materials such as laser beam offset, dual beam laser, surface modification of workpiece, compatible filler wire, special edge preparation, wavelength and laser modulation are reported as the latest developments. Laser beam offset means displacement of laser beam towards particular base material according to its favorable properties, which can help to distribute the heat to both dissimilar base materials equally. Similarly, dual beam can provide equal distribution of heat. Filler material to laser welding of dissimilar materials can provide compatibility for excellent bonding with third suitable materials. Special joint preparation such as scarf joint configuration, close butt joint, and lap joint also provide favorable conditions for sound bonding. Control of laser modulation and wavelength provides suitable heat input that subsequently gives good conditions for dissimilar joints [31]. Dissimilar combinations like aluminum-steel, aluminum–copper, aluminum–magnesium, copper–steel, steel–Kovar, steel–nickel, dissimilar metal grades, and composite-metal joint can be successfully obtained through laser beam welding [31, 32].

5.4.1.4 Laser Welding for Repair Applications

Laser beam welding is suitable for different repair applications such as cladding of different material, repairing of damaged components, mold repair, repair through laser peening, under water laser welding and so on. Molds for plastic products and die casting of magnesium and aluminum alloys are subjected to strong thermo-mechanical loads that may lead to damage the mold surface in the form of fatigue cracks or wear. These defects can be repaired by laser welding using the ND-YAG lasers due to its characteristics like flexible method, less change of metal composition around repairing zone, accurate deposition of small volume of filler material, small heat affected zone, no distortion and able to operate at small thickness [33]. Extremely difficult material of nitride coated steel and chrome plated steel can be repaired by laser welding using heat pre-treating, re-melting and low alloyed filler wire [34]. In order to avoid replacement of steam circuit components of thermal power station, laser powder welding is employed through which coating can be applied with less processing time [35]. The details about laser powder welding are discussed in next Sect. 5.4.1.5.

5.4.1.5 Repair Using Laser Powder Welding

Laser powder welding is a variant of laser beam welding in which powder is fed to the shielded laser as shown in Fig. 5.9. The powder is being melted with the use of laser onto a substrate. This results in solid deposit as molten powder gets solidified [35]. Major advantages of this process are: (I) Liquation cracking is eliminated as the process draws low heat input and (II) Laser spot of very small size can produce highly accurate deposit onto a substrate. Besides these, the process is suitable for original part manufacturing. The functionally graded component can also be developed using varying powder composition. Dissimilar materials can be welded using laser powder welding (as for example, aluminum–steel [31]).

Another interesting development is hot wire laser welding, in which hot wire is fed to the laser instead of powder. Control of wire transfer and the initial temperature of the wire are two most important parameters of hot wire laser welding. Hot wire laser welding is employed in repairing purpose due to flexibility and low heat input technique [36].

5.4.2 Electron Beam Welding

Electron beam welding is the technique in which stream of electron is impinged on workpiece that transmits heat and causes joining due to melting and solidification.

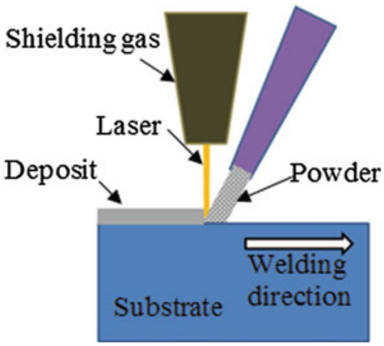


Fig. 5.9 Laser powder welding

This process requires a vacuum chamber to handle stream of the electron beam. Electron beam welding is capable to operate on ultra-thin thickness to a higher thickness for different materials such as plastics, aluminum, magnesium, steel, tungsten, nickel, molybdenum, zirconium, beryllium, dissimilar materials, composites, etc. [19]. The electron beam is most focused heat source among all welding processes, even compare to the laser beam welding, which is the biggest advantage of this process [37]. The electron beam welding is developed for repair applications, surface modification, non-vacuum process, high speed welding, and improved control system welding.

5.4.2.1 Electron Beam Welding for Repair Applications

Electron beam welding is adopted for repair applications of mechanical components due to its characteristics such as low distortion, high density heat input, and ability to weld dissimilar materials. Additionally, repairing thickness of deposition and fusion penetration can obtain, according to the requirements of the component due to good controllability of the process. Repair of large components such as bearing boxes, the rotor of a gas turbine, compressor blades and engines chamber can also be possible by electron beam welding [37].

Similar to laser powder welding and laser hot wire welding (as discussed in Sect. 5.4.1.4), external application of powder and filler wire is applied for the purpose of repair through deposition layer for different mechanical components such as roller bearing seats shafts, turbine, blades, die blocks and splines. Electron beam welding is having special advantage of minimizing dilution between base material and filler that in turn results in reduction of the thickness of deposition [19, 37].

5.4.2.2 Surface Modification Through Electron Beam Welding

Surface modification is conducted using a deflection system of single gun or lead multi-beam process which allows modifications of large surfaces. For the single gun set-up, contour path needs to be followed while for multi-beam type set-up having multi beams operates at the same time on the whole surface. Electron beam diameter, movement of beam and power density sophisticatedly controlled for the purpose of surface modification that subsequently affects the heating rate, surface microstructure, and modification depth [19, 37].

Surface modification through deposit layer can be achieved through the addition of filler material or powder (as mentioned in Sect. 5.4.2.1). Surface hardening and alloying are some other applications of surface electron beam welding [37].

5.4.2.3 Non-vacuum Electron Beam Welding

Non-vacuum electron beam welding is a technique in which beam is generated in vacuum and impinged to the workpiece which is kept in the atmosphere. Beam generator is excited with 175 kV voltage and transmitted to the workpiece by multi stage orifice assembly and special nozzle system. The pressure of 10^{-2} up to 1 mbar is kept for the pressure chamber which is connected to the beam generator chamber having vacuum 10^{-4} mbar that is evacuated and separated by pressure nozzles [19, 37]. This is high speed electron beam welding process in which productivity is increased significantly. However, one has to refer and apply the radiation protection guidelines before using this technique [37].

5.5 Sustainable Welding Processes

Sustainable welding processes are techniques in which workpiece materials are joined at minimum energy consumption, minimum material wastage, with minimum resources, at highest efficiency with maximum cost saving, highest quality with maximum environmental benefits (represented in Fig. 5.10). Solid state welding processes such as friction stir welding, magnetic pulse welding and ultrasonic welding fall under the categories of sustainable welding processes.

Fig. 5.10 Sustainable welding process aspects

5.5.1 *Friction Stir Welding*

Friction stir welding (FSW) is a type of solid state welding process, invented at The Welding Institute (TWI) initially for aluminum and its alloys. Developments of FSW for different materials such as plastics, composites, magnesium, titanium, nickel-based alloys, steel alloys and dissimilar materials are carried out on later stage because of its solid state nature. FSW is also known as "green process" due to many advantages such as no fumes generated, shielding gas is not required, and melting of material is not involved. Furthermore, energy benefits in terms of less power requirement (for example, 2.5% of less power required than laser welding), reduction in weight through enhancement of weldability of light weight material and saving of consumable materials are the other advantages [38, 39].

The FSW process principle is represented in Fig. 5.11. The non-consumable rotating tool made-up from hardened material, consist of pin and shoulder inserted into the workpiece, in such a way that the pin is totally inserted into the workpiece and shoulder generates friction through rubbing with the top surfaces of the workpiece. Frictional heat causes plastic deformation and stirring leads material flow, which consequently produces joint after transverse movement of the tool without the addition of external material [38–40]. Process parameters of FSW are summarized in Table 5.4.

Friction stir welding is further developed for its different variants such as friction stir spot welding, stationary shoulder FSW, friction bit joining, filling FSW, friction stir extrusion, under water FSW and friction crush welding. Some of these advances are discussed here as under.

5.5.1.1 Friction Stir Spot Welding

Friction stir spot welding (FSSW) is applied as an alternative of resistance spot welding in which tool is being kept in same position instead of its transverse speed at suitable rotational speed, like in FSW. FSSW is also one of the sustainable welding process through which energy consumption can be reduced up to nearly 99% compare to conventional spot welding (claimed by Mazda reported in [38]), while cost of installation can be saved up to approx. 40% relative to resistance spot welding [38, 39]. FSSW is capable to join highly conductive materials, non-metallic materials such as plastics and polymers as well as dissimilar materials. This can be operated with

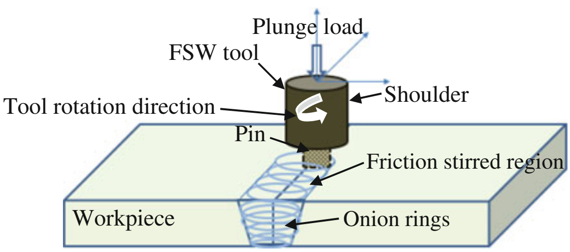


Fig. 5.11 Process principle of friction stir welding

Table 5.4 The important process parameters of FSW [38–44]

Tool design and material	Process parameters	FSW joint configurations	Workpiece material and thickness
Pin diameter, shoulder diameter, shoulder to pin diameter ratio	Rotational speed	Butt joint	Dissimilar materials
Pin shape and features (cylindrical, polygonal shapes, cone shaped, whorl pin, trifluet pin, trivex pin, thread-less pin, threaded pin,)	Welding speed	Lap joint	Metallic materials
Shoulder features (Concave, flat, convex, spiral, scoops, concentric circles)	Forces acting during process (axial force, transverse force, translational force)	T-joint	Refractory materials
Tool material (tool steel, tungsten carbide, nickel-cobalt alloys, tungsten-cobalt alloys, poly crystalline boron nitride)	Tilt angle	Multiple lap joint	Plastics and polymers
Tool developments (bobbin tool, dual rotation tool, skew stir tool, com stir tool, re-stir tool, retractable tool)	Pin offset (parameter of dissimilar joint)	Pipe joint	Reactive materials
FSW tool for repair application of casting defects	Workpiece material positioning (parameter of dissimilar joint)	Tube to tube-sheet metal joint	Ultra-thin thickness to higher section thickness (0.5 mm to 500 mm)

highly controllable robots in order to improve process efficiency. Recent developments of FSSW are refill FSSW, stitch FSSW, swing FSSW, and rotating anvil FSSW [45]. These advanced FSW processes are known for their capability to assist in avoiding key-hole formation at the end of the process.

5.5.1.2 Friction Bit Joining

Friction bit joining can be considered as advanced rivet joining technique in which consumable bit is inserted to the workpiece for the purpose of joining. The process is similar to the FSSW, but the tool is designed in such a way that the pin of tool acts as a bit. Friction between the bit and workpiece leads heat generation and subsequently bonding. Friction bit joining can also be applied for key-hole removal in FSW and FSSW [38, 39].

5.5.1.3 Friction Stir Extrusion

Friction stir extrusion is a new development for the dissimilar materials in which pin less tool is applied on the softer material to extrude material to the groove as shown in Fig. 5.12.

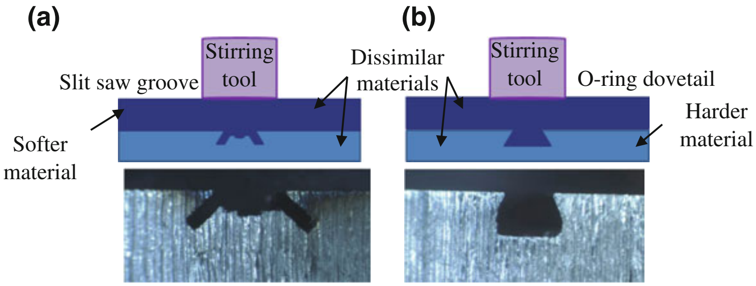


Fig. 5.12 Friction stir extrusion groove patterns: **a** slit-saw groove and **b** O-ring dovetail [46], with kind permission from Elsevier

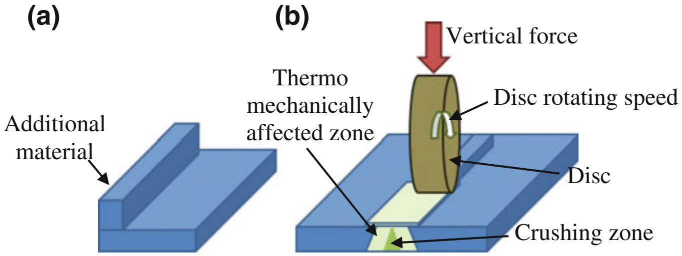


Fig. 5.13 Friction crush welding **a** workpiece preparation and **b** process principle [47]

Groove is required to be produced well in the advance on the harder material. This process is developed for the dissimilar combination of aluminum–steel and two different grooves such as slit-saw groove and O-ring dovetail. The quality joint is reported for slit-saw groove along with high strength and low amount of intermetallic compounds that to in a continuous layer form [46].

5.5.1.4 Friction Crush Welding

Friction crush welding is developed on the base of friction stir welding in which frictional heat and pressure is applied through disc as shown in Fig. 5.13b. Sheet metal edges are required to be prepared with extra material as shown in Fig. 5.13a. This extra material is crushed by means of rotating non-consumable disc with suitable pressure. Joining is established by plastic deformation of a material after the disc is traveled into a transverse direction. Concave shape is generally given to the disc surface in order to obtain defect free joint. Similar and dissimilar materials can be joined with this technique. Thickness of the workpiece is limited to thin sheets. Height of the additional material, disc design and its weight, vertical applied force, rotation and welding speeds of the tool are the important process parameters of friction crush welding [47].

5.5.2 *Magnetic Pulse Welding*

Magnetic pulse welding (MPW) is an environmental friendly process that uses the cleanest form of electromagnetic driving forces in order to join similar or dissimilar materials. MPW is under the category of sustainable welding technique, because of its characteristics such as no heat affected zone, no smoke, no radiation, high precision, no need of filler material, no distortion, no residual stresses and better repeatability. The mechanism for welding is similar to that of the explosive welding. The parameters such as collision angle and velocity are varying in the case of MPW while both of these parameters are kept constant for explosive welding. MPW improves quality of product and productivity through advantages such as solid state welding, less time operation, higher welding strength, process flexibility of combining the low cost and light weight dissimilar materials. Formation of brittle and hard intermetallic compounds is reduced to a great extent for dissimilar joints [48, 49].

MPW is a solid state welding process, in which electromagnetic forces are being applied between the coils and workpiece materials that are not in the contact with each other as shown in Fig. 5.14. Electromagnetic forces are applied with very short pulses, which are generated by a rapid discharge of capacitors. The high magnetic field is produced by pulse current along with high amplitude and frequency that subsequently creates an eddy current at one of the workpieces. This cause impact on another workpiece by high magnetic pressure created through repulsive Lorentz forces. Impact with sufficient collision velocity produces plastic deformation and results into the solid state bonding. Process parameters such as current, impact velocity, coil design, positions of tube, the gap between the coil and outer tube, impact angle and standoff distance are needed to be taken into the consideration to obtain successful weld. It is noted that, subsonic collision, sufficient impact velocity and pressure are the most important factors. Subsonic collision is required to achieve jetting condition. The high pressure regime is obtained

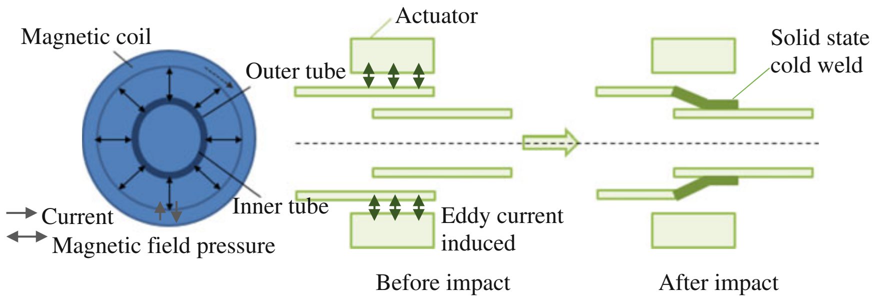


Fig. 5.14 Process principle of magnetic pulse welding [48], with kind permission from Springer

by optimum impact velocity. Optimum pressure allows proper plastic deformation of material and does not allow the melting and re-solidification of the material [48–50].

Applications

- MPW is most suitable process for dissimilar materials that includes dissimilar alloys of metals, dissimilar metals and metals to non-metals [50].
- To manufacture components of sheet metal products, drive shafts, and lightweight tubular structures [50]
- Applicable for all conductive materials [48–50].
- Sealing of tube with end plugs for metallic materials [50].
- Joining of materials applied to automobile and aerospace in order to reduce weight and improve strength [48].
- Applications in the nuclear industry like joining of refractory materials such as Niobium, Titanium, Molybdenum, and Zirconium [48].

5.5.3 Ultrasonic Welding

Ultrasonic welding is a solid state welding process in which frictional heat is being supplied by ultrasonic vibrations on workpieces to be joined. Bonding is established by shearing action and plastic deformation caused by ultrasonic vibrations without melting of material. Ultrasonic welding is having many advantages such as low energy requirement, fast automatic process, no filler wire needed, no shielding gas required, no oxide removal required, can able to join dissimilar materials and non-metallic materials [19, 51]. Therefore, ultrasonic welding is a sort of sustainable welding process. The basic set-up of ultrasonic welding is shown in Fig. 5.15. The major equipments of ultrasonic welding are transducer, booster, and sonotrode that generate ultrasonic vibrations. These vibrations are then transferred to the workpieces. Process parameters such as frequency, amplitude, pressure, and area are most important working conditions of ultrasonic welding [51]. Developments of ultrasonic welding are discussed in terms of ultrasonic seam welding and ultrasonic torsional welding along with its applications for plastics, polymeric composites, dissimilar materials and welding of workpieces having thickness variations [19].

5.5.3.1 Ultrasonic Seam Welding

Ultrasonic seam welding is also known as ultrasonic roll welding used to weld workpieces continuously with the help of the circular disk sonotrode and a transducer as shown in Fig. 5.16. The rotating disc is moved transitionally against the workpiece to produce vibrations. Long length sheets are easily joined with this

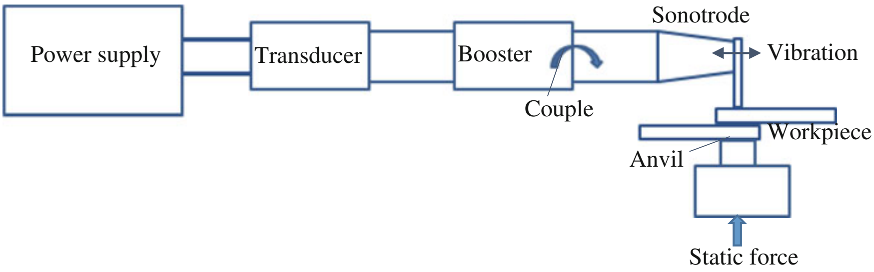
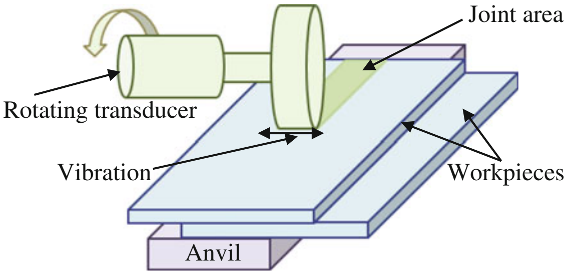


Fig. 5.15 Ultrasonic welding set-up of lateral drive [51]

Fig. 5.16 Ultrasonic seam welding [19]



technique. Additionally, this process finds extensive applications in joining of dissimilar materials such as foils of copper and aluminum.

Ultrasonic seam welding is a flexible process in which circumferential weld of round parts can be processed using same sonotrodes on one welding device. Moreover, thermoplastic fibers of textile industry can also be welded with ultrasonic seam welding.

5.5.3.2 Ultrasonic Torsion Welding

Ultrasonic torsional weld is also called as ring weld in which torsional motion is given to the specially designed horns and tooling in order to produce circular vibrations from sonotrode and welding tip. This process is applied at components where circular weld pattern are required and it is most suitable for the spot welding configurations. Therefore, this technique can be applied to the spot welding of automobile body components. Torsional movement of sonotrode and tooling is created using an opposite rotation of transducers as shown in Fig. 5.17. Number of transducers required depends on the need of power. Use of four transducers produces up to 10 kW power at 20 kHz frequency [19].

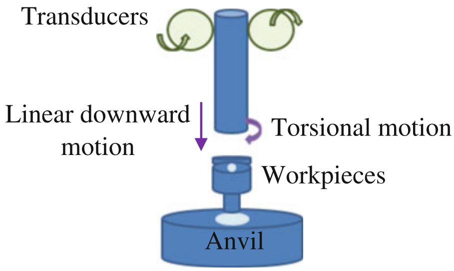


Fig. 5.17 Ultrasonic torsional welding [19]

Applications

Plastics and Polymeric composites

Ultrasonic welding operated at high frequency–low amplitude vibrations leads to interfacial heating and fusion welding of plastic and polymeric components at suitable axial pressure. Thermoplastics such as woven, non-woven fabrics, and coated materials can be ultrasonically welded by different novel techniques such as plunge welding, sequential welding, continuous welding, and scan ultrasonic welding. Important factors of ultrasonic welding of plastics are viscoelastic dissipation of energy, intermolecular diffusion, heating at the interface between two workpieces and ability to transmit vibrations to this interface. Ultrasonic welding is successfully applied to thin sections while thick parts of thermoplastics are difficult to weld by ultrasonic welding [52, 53].

Dissimilar materials

The solid state nature of ultrasonic welding provides a range of capabilities for dissimilar combination joints. Ultrasonic welding is an excellent method for joining of dissimilar materials having high thermal and electrical conductivities such as copper and aluminum [54]. It is feasible for all dissimilar metallic combinations. Additionally, dissimilar joints with non-metals such as ceramic–metal, glass–metal, and plastic–metal can be achieved in some cases using metallized coating or transition layer [19, 51].

Workpiece thickness variations

Ultrasonic welding is able to join thin workpieces such as 0.025–0.250 mm. This allows joining of multiple foils with thick substrate in a single weld. Joining of multiple wires with substrate is obtained through ultrasonic welding (for example, weld of multiple copper wires to aluminum connector) [19, 51].

5.6 Micro-Nano Joining

Micro-joining and nano-joining are adopted to manufacture miniature components, devices and systems such as micro-gears, micro-pumps, micro-turbines, micro-motors, battery packs and cells, micro-sensors, micro-transducers, nano-electronics, nano-structures, nurostimulators, endoscope, and micro-electro mechanical systems (MEMS), etc. [55]. There is no exact definition of micro-nano joining techniques. But, joining of micro-components are usually having dimensions less than 100 μm and similarly for the joining of nano-components are having dimensions of the order of 100 nm. Micro and nano level systems are very complicated for joining and welding due to irregularities in microstructures, chemical compositions, and surface layers within the same component or system. It is very important to remove surface oxides and contaminants from the surface which is subjected for welding. Additionally, fixturing and handling of micro-nano component, joint quality inspection, testing methods, process repeatability, and process capabilities are some of the challenges in micro-nano joining [55, 56].

Different approaches of micro-nano joining are discussed for fusion micro-welding, solid state micro-welding, wafer nano-joining and nano-structured joining as below.

5.6.1 Fusion Micro-Welding

Beam welding processes are well-controlled processes that are applied for different micro-welding applications. Practical applications from laser welding are possible through small beam diameters of different types of lasers such as laser diodes (0.8–1.1 μm), solid state Nd:YAG laser (1.06 μm), fiber laser (1.04–1.5 μm), thin disk laser (1.03 μm) and CO_2 laser (10.6 μm). Furthermore, other process parameters of laser welding, such as wavelength, travel speed, power density, beam velocity and time are required to be selected in such a way that optimum energy is transferred for the purpose of micro-welding. A selection of these parameters depends on the material of workpiece to be welded [for example: (1) Relatively large diameter of beam is required for polymer than the glass due to linear and non-linear absorption phenomena), (2) Power and wavelength requirements for materials like silver and copper are different such as 900 W at 1.06 μm and 300 W at 1.06 μm respectively, due to conductivity differences)]. Rapid travel speed and low power are recommended for micro-welding applications. Laser welding is applied for joining of lithium ion battery of 0.2 mm aluminum alloy, micro-spot welding of hard-disk suspension of computer, welding of watch gear to shaft, thin foil welding, micro-wire welding and micro-thickness sheets. Furthermore, novel laser micro-joining processes such as laser droplet welding, laser spike welding, shadow welding, ultra-short pulse laser welding and single mode fiber laser welding are used to extend special micro applications [55].

Electron beam welding is also a capable process for the micro-joining application in which beam spot diameter is kept from 0.1 to 1 mm in order to reach 10^6 to 10^7 W/cm^2 power density. Set-up of scanning electron microscope (SEM) is found promising tool for micro-welding application. This set-up is able to do positioning, joining and analysis of joint in a single device. Electron beam welding is used to weld MEMS, micro-systems, micro-components with materials of plastics, aluminum, magnesium, silicon and copper at an accelerating voltage of 10 to 40 keV, 10 μm beam current and 1–3 μm beam diameter. Electron beam welding can be utilized for multi beam, filler addition, and superposition for micro-joining [55].

Soldering and brazing are famous techniques adopted for micro-joining of wires in electronics industries. The main advantage of these processes is that the melting of base material is not present. Also, micro-component welding wherein dissimilar materials are involved can be effectively joined at reduced formation of intermetallic compounds [55, 56].

Gas tungsten arc welding and plasma arc welding techniques are found in some applications of micro-joining especially for the micro-spot welding. But, these techniques are not recommended as controlling the joining parameters for micro applications is difficult [55].

5.6.2 Solid State Micro Bonding and Welding

Solid state processes such as ultrasonic welding, FSW, diffusion welding, forge welding, and cold welding can be employed for the micro-joining. Solid state bonding processes are associated with large plastic deformation of materials. In solid state welding, heating and forging or only forging are applied to the micro-system. Micro-forge welding and micro-cold welding includes three bonding mechanisms such as contaminant displacement/interatomic bonding, decomposition of the interfacial structure and dissociation of retained oxides. In order to reduce oxidation, most of the time the solid state diffusion process is carried out in vacuum (10^{-3}–10^{-5} mbar) or in the presence of an inert gas for micro-component application [55, 56].

Modifications in the set-up of solid state welding processes are mandatory due to many problems such as pressure requirement, heat dissipation, complex geometry, materials variety, and tool manufacturing. These challenges in micro-FSW can be avoided by different approaches such as use of insulating anvil, precise manufacturing of tool and fixture and use of high rotational speed and low welding speed [56]. In case of ultrasonic micro-welding of plastics, it is reported that the machine operates around at 35 kHz with tool width 150–300 μm, up to 800 μm in depth, 500 μm in height, and 8 mm length [57]. Diffusion bonding set-up requires a small heating furnace and less pressure. Diffusion bonding takes much longer bonding time. However, the bonding is achieved with minimum deformation [56].

5.6.3 Nano-Joining

As mentioned, nano-joining implies the joining at the order of 100 nm, i.e., joining at molecular level. Repair of carbon nanotube through nano-joining is possible. It is reported that, the application of electron beam welding in transmission electron microscopy (TEM) using high accelerating voltage (of 1.25 MV) and high specimen temperature (at 800 °C) can be used for nano-joining. Under the effect of electron irradiation and annealing at their contact region, the welding is obtained. Similarly, scanning electron microscopy (SEM) can also be utilized for nano-joining of micro-to-nano-scale (50 to 900 nm). It is reported that, spot sizes of 50–125 nm (approximate) are possible at SEM that can melt areas up to 100 nm from 50 μm. Joining of materials such as polysilicon, nickel, Alumel, Chromel, and Tophet C is possible through direct SEM or TEM. Indirect SEM and TEM are able to give resolution in sub-nanometer and can create spot diameter less than 1 nm. Nano-surface can be manipulated through depositing contamination selectively using SEM or TEM [56].

Ion beam nano-welding, resistance nano-welding, ultrasonic nano-welding, and laser nano-welding are techniques through which nano-joining can be obtained. Multi-walled carbon nanotubes are joined by ion irradiation. Resistance welding and ultrasonic welding are possible on welding of nano-wire with substrate using sophisticated set-up and process parameters. Laser pulses can be utilized to weld nano-particles. It is reported that, gold nano-particles are welded by irradiating laser pulses of 532 nm and 0.2 mJ for 10 min on a carbon-coated copper TEM grid in order to have ohmic nano-contact [56].

Nano structure joining can be done similar like powder metallurgy in which nano-particles are combined together at the first stage and next it is pressed at optimum pressure and heat which leads to the joining. Silicon wafer bonding is another example of micro and nano-joining that can be done by different micro-nano joining methods such as anodic bonding, bonding via an intermediate layer of silicides and bonding via solder [56]. The selection of method is dependent on specific application of micro-nano system.

5.7 Hybrid Welding Processes

Hybrid welding processes are combination of two or more welding techniques through which process capabilities are extended significantly. Hybrid welding processes are found effective where individual process is incapable. Double electrode arc welding discussed in Sect. 5.3.5 can be considered as one of the examples of hybrid welding processes wherein the deposition rate is increased at low heat input. Hybrid welding concepts of laser assisted hybrid welding, hybrid arc welding processes and external energy assisted FSW are discussed in this section.

5.7.1 Laser Assisted Hybrid Welding

The laser beam has focused heat source and high density that produces higher depth of weld with small heat affected zone (see Fig. 5.18a). Laser beam welding can be performed at higher welding speed. Besides these advantages, laser welding has

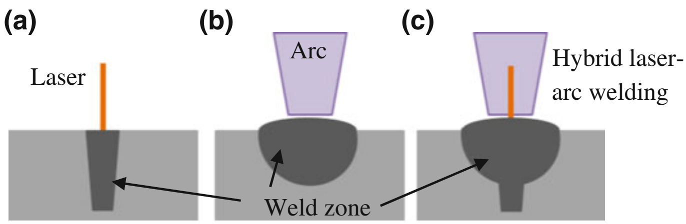


Fig. 5.18 **a** Weld bead of laser welding, **b** Weld bead of arc welding, and **c** Weld bead of hybrid laser-arc welding

some disadvantages such as higher power requirement and higher initial as well as service cost. These disadvantages can be minimized by hybrid laser-arc welding. Arc welding is operated at much low energy density and slow welding speed along with large heat source and low operating cost relative to laser welding that consequently results in shallow penetration and higher width (see Fig. 5.18b). Therefore, hybrid laser-arc welding serves advantages of both the process such as higher welding speed, improved weld quality, less deformation, an excellent gap bridging ability and better process efficiency (see Fig. 5.18c).

Additional process parameters such as distance between laser and arc, shielding arrangements, welding speeds and power level of arc and laser need to be taken into consideration along with individual basic process parameters.

Laser-arc welding concept is reported for laser-GTAW, laser-GMAW, and laser-plasma welding. Laser-GTAW hybrid welding can eliminate disadvantages of GTAW and laser welding, such as low penetration and absorptivity problems. It is reported that, higher process efficiency with deeper penetration is obtained through hybrid laser-GTAW technique. Similarly, laser-GMAW can solve distortion problems, improve weld bead profile, process performance, and improve weld strength. Laser-plasma hybrid technique improves process stability and weld bead profile [58].

5.7.2 Hybrid Arc Welding

Hybrid arc welding processes are those in which different arc welding processes are coupled in order to obtain benefits of each process. GTAW-GMAW and GMAW-Plasma arc welding are examples of hybrid welding techniques. GMAW-plasma welding can be used at different speeds at low current, low power density and high deposition rate that subsequently improves process capability and joint properties. GTAW-GMAW process is another hybrid process through which penetration level of GTAW is improved significantly with filler addition. Dual shielding can result into excellent properties of joint [19]. Hybridization in filler wire such as solid-flux cored, solid-metal cored improves process performances along with overall cost and time reduction [59].

5.7.3 Hybrid Friction Stir Welding

Hybrid approaches are applied to FSW technique in order to take benefits such as improve mechanical properties of joints, uniform heat generation and material flow, reduce load on the tools, and increase process parameters window. Electrically assisted FSW, laser assisted FSW, arc assisted FSW, ultrasonic energy assisted FSW, and cooling enhanced FSW are examples of hybrid FSW techniques [40, 60].

5.7.3.1 Electrically Assisted FSW

Electrically assisted FSW is a hybrid technique in which workpiece is subjected to resistance heating through electrical current. The Joule effect causes electro plastic heating that subsequently leads to the additional material softening to the workpiece. In this hybrid approach bulky set-up is not required like in arc assisted FSW and laser assisted FSW. This concept helps to reduce the forces generated on tool due to softening effect that in turn improve wear resistance and life of the tool. Increased welding speed of FSW is applicable as preheating of workpiece that softened the materials initially. Additionally, improved dissimilar joints can be obtained by temperature rise at single workpiece. However, electrically conductive materials are mandatory to provide resistance heating effect [60].

5.7.3.2 Laser Assisted FSW

Laser assisted FSW is another approach of hybrid FSW in which laser is applied as preheating source before the FSW tool in order to improve the process. The laser beam is a flexible and precise source of heating through which focused heat is supplied to the specific point. Preheating of dissimilar materials is done at specific material through flexible laser source. Properties of dissimilar joints can be significantly improved with this technique [40, 60].

5.7.3.3 Arc Assisted FSW

Arc assisted FSW is reported for GTAW assisted FSW and plasma assisted FSW for dissimilar combinations. The external torch of GTAW or plasma welding is attached in front of FSW tool for preheating purpose. In this technique, arc with shielding gas is supplied to a material which is harder than the other material [40, 60]. Shielding gas can prevent atmospheric contamination during preheating.

However, materials like copper affected by oxidation at higher preheating current and deteriorated joint properties of aluminum–copper joint [40]. This process can be applied to nonmetallic materials too.

5.7.3.4 Ultrasonic Energy Assisted FSW

Ultrasonic vibrations are applied similarly to the previously discussed process in order to preheat the workpiece. This process is advantageous in terms of solid state preheating where arc, laser, and shielding gases are not present. Therefore, this hybrid process can be considered as a sustainable hybrid FSW process. Ultrasonic energy assisted FSW is applied to dissimilar materials and similar materials [40, 60].

5.7.3.5 Cooling Enhanced FSW

Cooling enhanced FSW is a hybrid approach in which workpiece is welded under the effect of different cooling mediums such as water, liquid CO_2, and liquid nitrogen. The superior fine grain microstructure is obtained under this hybrid mode. Additionally, the formation of intermetallic compounds is significantly restricted due to cooling effect [40, 61]. However, forces acting on tool cannot be decreased as in thermally assisted FSW. Underwater FSW requires special purpose fixture where the workpiece is kept at under water. Cooling enhanced FSW is reported as an improved method for dissimilar welds by which the formation of intermetallic compounds has drastically reduced [62].

5.8 Summary

Recent developments of welding and joining techniques are discussed in this chapter. The special features of process background, parameters, capabilities, novel aspects, and variants are presented for recently developed welding and joining techniques. Developments in the area of fastening and bonding processes, arc welding processes, beam welding techniques, sustainable welding processes, micro-nano joining, and hybrid welding are covered. Advanced welding and joining techniques provides the tangible benefits such as favorable joint properties, synergistic mix of materials, significant reduction in the component cost, tremendous enhancement in productivity, excellent quality, ability to join dissimilar materials, repairability, attaining complex geometrical configuration, and the ability to deal with a variety of materials to manufacture new products.

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