



A review on recent developments in ultrasonic welding of polymers and polymeric composites

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Abstract

The review, titled “A Review on Recent Developments in Ultrasonic Welding of Polymers and Polymeric Composites,” comprehensively examines advancements in ultrasonic welding within the last decade. Employing a meticulous material-by-material approach, the study delves into the evolution of ultrasonic welding techniques, focusing on diverse advanced materials. Notably, the review encompasses significant developments in ultrasonic welding applied to carbon fiber–reinforced polymers such as PEEK, PA, PPS, and PEI, as well as glass fiber–reinforced polymers (GFRP). Additionally, the review extends its purview to various thermoplastics, including ABS, PP, and PE. The review synthesizes a nuanced understanding of the challenges and innovations associated with ultrasonic welding in diverse polymer and composite contexts by systematically analyzing each material category. This inclusive examination facilitates a holistic comprehension of the advancements made in ultrasonic welding technology, offering valuable insights for researchers, practitioners, and industry professionals. The review is a timely and comprehensive resource for those seeking to stay abreast of the latest developments in ultrasonic welding, fostering continued progress and innovation in polymer and polymeric composite joining methodologies.

Keywords Ultrasonic welding · Thermoplastics · Thermoplastic composites

Nomenclature

USW	Ultrasonic welding	ED	Energy director
PEEK	Poly-ether-ether-ketone	HAZ	Heat-affected zone
PA	Polyamide	SSUW	Single-sided ultrasonic welding
PPS	Poly-phenyl sulfide	DoS	Degree of crystallinity
PEI	Poly-ether imide	ESW	Energy controlled sequential ultrasonic welding
F RTP	Fiber-reinforced thermoplastic polymer	DSW	Displacement-controlled sequential ultrasonic welding
CFRP	Carbon fiber–reinforced polymer	MSW	Multiple equispaced ultrasonic welding
GFRP	Glass fiber–reinforced polymer	MMF	Multiple equispaced mechanical fastening
ABS	Acrylonitrile butadiene styrene	D _p	Detachment pressure
PP	Polypropylene	MWCNT	Multi-walled carbon nanotubes
PE	Polyethylene		
FFF	Fused filament fabrication		
LSS	Lap shear stress		

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1 Introduction

In today's era of technological advancement, the perpetual demand for innovative materials remains evident. Traditional metals, once prevalent in various engineering sectors such as automobile and aerospace, are gradually becoming obsolete due to the progress made in these fields. The emergence of composite materials has played a pivotal role in replacing metals, demonstrating superior characteristics such as an impressive strength-to-weight ratio, dimensional stability in diverse environmental conditions, and immunity to rust [1]. Among the various applications of composite materials, the performance automobile industry, particularly sports cars, stands out as a significant adopter. Components like panels, frames, and interior parts, which were conventionally crafted from metals, are now predominantly manufactured using composite materials. This shift reduces weight and enhances overall performance [2]. Leading car manufacturers such as BMW and Bugatti have highlighted flagship models extensively incorporating composite materials.

The composition of a composite involves arranging reinforcement within a matrix medium. In the realm of polymeric composites, the matrix comprises either thermoplastics or thermoset polymers [3]. Various composites exist depending on the matrix type, reinforcement, and arrangement. While composite materials serve diverse purposes in modern life, this discussion will primarily focus on fiber-reinforced composites. Fiber-reinforced polymeric composites are renowned for their myriad industrial applications, utilizing thermoplastic or thermoset matrix systems. Notably, thermoplastic composites surpass their thermoset counterparts in several aspects. They exhibit exceptional vibration absorption, increased resistance to impact loading, high productivity, greater tolerance towards damage and fracture toughness, recyclability, reformability, and cost efficiency [4]. The exploration of ultrasonic welding to join dissimilar materials, especially metals, to fiber-reinforced thermoplastic composites or FRTP by Liu et al. [5] encompasses four key aspects: the welding process, joining mechanism, mechanical properties, and galvanic corrosion. While the current understanding of these facets is summarized, it becomes apparent that certain aspects, particularly the chemical bonding mechanism underlying ultrasonic welding of dissimilar material, still need to be clarified. The existing literature also reveals a gap in modeling and numerical simulation, attributed to the challenge of formulating the metal/FRTP interface interaction.

In a similar attempt, Li et al. [6] addressed the intricacies of ultrasonic welding of industrial thermoplastic composites, with emphasis on employing energy directors

(ED), which includes creating macroscopic or microscopic grooves and protrusions on the adherend surface to enhance joint strength. However, the stability and quantitative analysis of the effects of these surface modifications warrant further investigation. This review again underscores that the field of joining dissimilar materials, especially metals, to fiber-reinforced thermoplastic composites or FRTP using ultrasonic welding holds significant potential for development, with many opportunities for future research and advancements.

In a related context, ultrasonic welding is a distinctive joining process characterized by high speed and robust joint strength. Our review extends beyond the metal/FRTP hybrid structures to encompass the latest advances in ultrasonic welding technology tailored explicitly for fiber-reinforced thermoplastic composites. Comparative analysis with conventional mechanical and adhesive bonding methods accentuates the advantages of ultrasonic welding in this domain. This comprehensive review not only assesses the ultrasonic welding process' advantages and disadvantages in comparison to other welding methods but also delves into the influence of ultrasonic welding parameters on welding quality. Furthermore, it explores the nuances of ultrasonic welding of dissimilar materials, addressing the critical aspects of quality inspection and repair in the context of ultrasonic composite welding. The review concludes by offering an insightful analysis of the research status and future development prospects of ultrasonic welding for thermoplastic composites. Through our material-by-material approach, this review article contributes a unique perspective to the evolving landscape of ultrasonic welding in the realm of thermoplastics and thermoplastic composites.

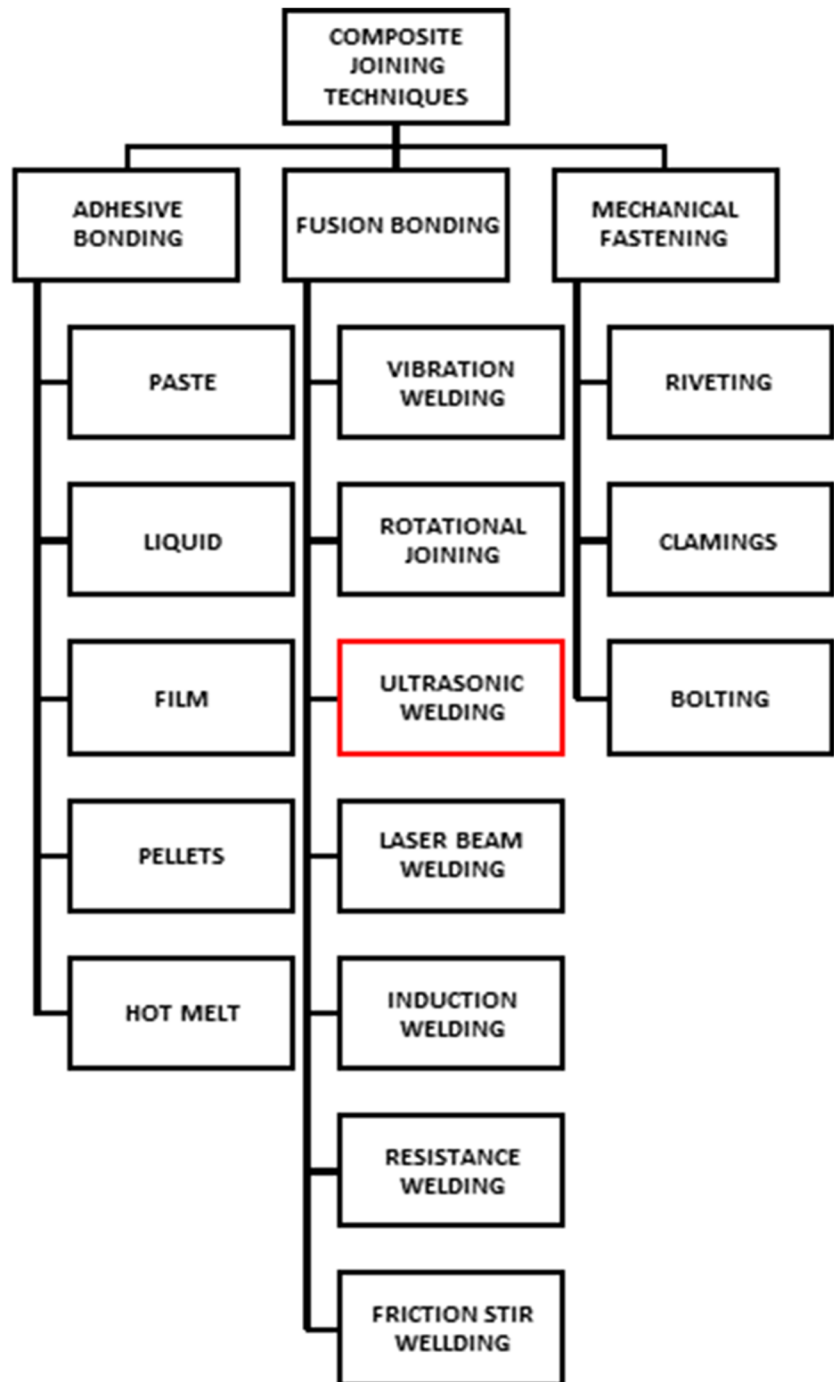
2 Joining techniques for composite materials

Molds or assembly operations are employed when making complex structures like door panels or an automobile's interior. Being complex and costly, molds are rarely used with composites on a large-scale production. Another way is to assemble or enter small parts using various available methods, as shown in Fig. 1. Each of these techniques has advantages and limitations, as commented below.

2.1 Mechanical fastening

In the dynamic landscape of modern industrial and commercial applications, mechanical fastening techniques play a crucial role in joining thermoplastics and thermoplastic composites [7]. The physics of mechanical fastening revolves around creating a robust connection through the interaction of forces between the fastener and the materials

Fig. 1 Classification of joining techniques for composite materials



being joined [8]. In thermoplastics and thermoplastic composites, considerations include material elasticity, thermal expansion coefficients, and the ability to withstand mechanical stresses associated with fastening [9]. Threaded engagement in screws and bolts relies on friction to prevent self-loosening, while riveting involves plastic deformation of the rivet material for a secure joint. Nuts, bolts, clips, and fasteners depend on mechanical interlocking between mating components, ensuring stability. Press-fit assemblies

leverage interference fits, utilizing material elasticity for a secure bond [10].

The methodology of mechanical fastening involves precise techniques to ensure a reliable and durable connection. Surface preparation is crucial, involving cleanliness, alignment of components, and appropriate hole diameters [11]. The choice of fastener type is influenced by factors like application, load-bearing requirements, and environmental conditions [12]. For threaded fasteners, torque specifications

are critical for achieving the desired clamping force without damaging materials [13]. Riveting requires careful hole alignment and selection of the appropriate rivet size. Precision in interference fits is crucial for press-fit assemblies to balance secure connections without causing material damage.

While the advantages of mechanical fastening, including versatility, reversibility, and quick assembly, position it as a valuable tool in manufacturing, carefully considering potential disadvantages, such as stress concentrations and corrosion risks, is essential for optimal application [14]. As industries continue to evolve, mechanical fastening techniques will remain fundamental to assembly processes, adapting to meet the ever-changing demands of modern manufacturing [15].

2.2 Adhesive bonding

Adhesive bonding relies on intricate molecular interactions, particularly critical in the context of thermoplastics and thermoplastic composites. The high molecular mobility of these materials requires a nuanced understanding of surface energy, molecular structure, and wetting properties [16]. Adhesion occurs through mechanical interlocking, molecular forces, and, in some instances, chemical bonding [17]. The viscoelastic nature of thermoplastics allows for flow and deformation during bonding, fostering intimate contact between the adhesive and substrate [18].

Adhesive bonding methodology involves essential steps. Surface preparation enhances surface energy, including cleaning and pre-treatment [19]. Choosing the appropriate adhesive is vital, considering compatibility with the substrate, environmental conditions, and the intended application. Various adhesives, including thermoplastics and reactive types like epoxies, are selected based on their unique properties. Precise adhesive application, ensuring uniform coverage, is fundamental [7]. Techniques such as heat, pressure, or curing agents may initiate bonding, with the curing time carefully controlled for optimal adhesive strength development [20].

Adhesive bonding finds diverse engagement across automotive, aerospace, electronics, medical, and construction

industries. In automotive manufacturing, adhesive bonding is an alternative to traditional mechanical fastening, reducing weight and improving structural integrity [21]. Aerospace utilizes adhesive bonding for lightweight structures, enhancing fuel efficiency [22]. The electronics industry benefits from adhesive bonding in assembling compact and intricate components, ensuring electrical insulation and mechanical stability [23]. In the medical sector, the biocompatibility of certain adhesives supports the assembly of medical devices. Construction industries include bonding thermoplastic materials and contributing to fabricating durable and weather-resistant structures [24].

Adhesive bonding uses bonding agents in solid, pellet, or film, i.e., hot-melt adhesives, liquid, i.e., general-purpose adhesives, paste, i.e., epoxy-based adhesives at the interfacial surface of joining components, similar or dissimilar with uniform strength and negligible stress concentration due to absence of holes under the influence of breaking loads. Mechanical fastening techniques like riveting and bolting are metals' most common joining techniques. These are generally avoided in the case of composites owing to fiber destruction due to holes, which are the load-bearing structures in fiber-reinforced composites [25]. Many advantages of adhesive bonding and mechanical fastening techniques are documented in Table 1.

For manufacturing large and intricate parts, adhesive bonding and mechanical fastening are being used on a large scale, yet issues regarding the toxic nature of several adhesives and the susceptibility of mechanical fasteners to rust are of great concern. These techniques employ external agents for bonding components, often hampering the surrounding material's mechanical or chemical properties. Table 2 describes a few common drawbacks of adhesive bonding and automated fastening techniques.

General-purpose or structural adhesives should be carefully handled due to their varying degrees of toxicity. Though on an industrial scale, robotic arms are extensively used in applying these adhesives still, there are several applications such as plumbing which require applying these adhesives by the worker himself, exposing him to toxic fumes produced by some of the adhesives like PVC cement or methyl ethyl ketone. Due to hydrolytic degradation,

Table 1 Advantages of adhesive bonding and mechanical fastening techniques

S. No	ADHESIVE BONDING	MECHANICAL FASTENING
1	Increased stress resisting area [26]	Easy automation [27]
2	Continuous joint area improving rigidity [28]	Minimum space required for tools [29]
3	Increased fatigue strength [28]	Minimal steps required for installation [27]
4	Vibration dampening and shock absorption capability [30]	No constraints over work direction [21]
5	Ease in Joining complex and intricate shapes	Applicable on every material [29]
6	Enhanced resistance towards corrosion	Easy maintenance

Table 2 Drawbacks of adhesive bonding and mechanical fastening techniques

S. No	ADHESIVE BONDING	MECHANICAL FASTENING
1	Toxicity of several general-purpose adhesives [31, 32]	Increases the overall weight of the structure
2	Adhesive bonding is mainly influenced by its surrounding environment. [33]	Highly susceptible to rust and corrosion [34]
3	Requirement of surface preparation before application of adhesives [35]	The requirement of holes causes stress concentration [36]
4	Long curing time [33]	Mechanical fastening via screws and bolts are temporary joints which are susceptible to loosening [36]
5	The suitability of adhesive depends upon adherends and application	

adhesives have a limited shelf life and lose their bonding strength exponentially beyond the expiration date [31].

Contrary to adhesives and mechanical fasteners, fusion bonding utilizes the diffusion phenomenon at the joining interface to form a fused union. Application of heat, pressure, or sometimes both are the driving factors for attaining a fusion bond. Fusion bonding techniques are listed in Fig. 1, and anyone can choose to weld thermoplastic composite parts. This article provides a detailed review of the latest advancements in joining polymer composites using ultrasonic welding techniques.

2.3 Fusion bonding technique

The physics of fusion bonding revolves around the controlled application of heat to create a molten state at the joint interface. This process capitalizes on the material's ability to undergo reversible phase transitions in thermoplastics. As heat is applied, the polymer chains within the thermoplastics gain enough energy to transition from a solid to a molten state. These materials return to a solid state upon cooling, resulting in a fused joint [37]. The effectiveness of fusion bonding is contingent on achieving the precise temperature necessary for melting without causing degradation of the thermoplastic material. Understanding the heat transfer mechanisms involved in each fusion bonding technique is crucial for optimizing the process [38].

The methodology of fusion bonding techniques is intricately linked to the specific type employed. However, common steps include surface preparation; ensuring clean and properly prepared surfaces is fundamental for successful fusion bonding. Any contaminants or irregularities on the surfaces can compromise the quality of the bond. Secondly, a controlled application of heat is a critical step. Whether through a hot plate, ultrasonic vibrations, rotational friction, infrared radiation, or electromagnetic fields, achieving the precise temperature for melting without degradation is essential [39]. Once the thermoplastic materials, or the matrix material, in the case of thermoplastic composites, reach the molten state, they are brought into contact to allow for fusion. Depending on the specific fusion bonding technique, this can involve pressing,

rotating, or other methods. After fusion, the joint can cool and solidify, creating a solid molecular-level bond between the thermoplastics.

While fusion bonding techniques offer several advantages, they have limitations. Thus, the advantages and disadvantages of fusion bonding techniques are mentioned below. Among various fusion bonding techniques, ultrasonic welding is versatile and efficient, offering unique benefits that make it well-suited for diverse industrial areas. This advanced joining technique employs high-frequency ultrasonic vibrations to create molecular-level bonds between thermoplastic materials. Below are key factors contributing to the standout nature of ultrasonic welding compared to other fusion bonding methods.

Advantages	Disadvantages
Fusion bonding creates strong molecular-level bonds, ensuring robust joints that withstand various stresses	Fusion bonding is typically restricted to thermoplastics and may not be suitable for specific materials or composite structures
The process is often highly efficient, with rapid heating and cooling cycles contributing to quick assembly	Each fusion bonding technique often requires specialized equipment, contributing to initial setup costs
Unlike adhesive bonding or mechanical fastening, fusion bonding typically requires no additional materials, reducing costs and potential points of failure	Achieving and maintaining the precise temperature for melting without degradation is crucial, making the process sensitive to temperature fluctuations
Fusion bonding techniques provide consistent and uniform bonds, minimizing variability in joint strength	Depending on the technique, fusion bonding may leave visible seams or marks on the joined surfaces, which may be undesirable in specific applications

The ultrasonic welding technique outperforms other fusion bonding techniques due to the reasons conferred below:

- Ultrasonic welding is more appropriate for automation and mass production due to very short weld times compared to resistance, induction, and arc welding processes.

- Minimal surface damage occurs at the welding interface during ultrasonic welding, unlike in friction welding processes.
- No fillers or heating agents are required at the weld interface, unlike in the resistance or induction welding process.
- Burning or degradation at the weld interface is absent; thus, no fuming or sparking is evident in ultrasonic welding, unlike in laser welding, making it more apt to join thermoplastic components.
- Both spot and continuous seam welding can be performed using the ultrasonic welding technique.

In conclusion, ultrasonic welding stands out among fusion bonding techniques due to its exceptional speed, precision, minimal thermal impact, simplicity, versatility, and environmental friendliness. These attributes make it a preferred choice in industries where efficiency, consistency, and adaptability are paramount. Whether in the automotive, electronics, medical, or packaging sectors, ultrasonic welding continues to demonstrate its prowess in creating robust and reliable bonds in the ever-evolving manufacturing landscape.

3 Ultrasonic welding

Ultrasonic welding is a sophisticated fusion bonding technique that harnesses high-frequency ultrasonic vibrations to create seamless molecular-level bonds between thermoplastic materials. Widely adopted across diverse industries, this method is celebrated for its efficiency, precision, and versatility. At its core, ultrasonic welding involves the application of ultrasonic vibrations, typically ranging from 20 to 70 kHz, to thermoplastic materials placed in intimate contact. The vibrations generate localized heat at the joint interface, causing the thermoplastics to reach their melting point. As the materials fuse, a robust and durable bond is formed. The entire process occurs within seconds, from heating and joining to cooling, making ultrasonic welding exceptionally swift.

Ultrasonic welding has numerous engagements in automotive [40], aerospace, medical, electronic, and electrical divisions, and many other industrial sectors. The requirement of lightweight materials in automotive and aerospace design to increase efficiency by reducing energy consumption overlooks the use of fasteners or bolted joints as they add extra weight, and due to the requirement of pre-welding preparations followed by a long curing cycle of adhesive joints, ultrasonic welding is the chosen option for large-scale production in these industries. Ultrasonic welding is already used for mass production in the textile industry [41]. Being an eco-friendly process, medical chipsets, personal protective clothing, and masks are assembled by ultrasonic

welding in medical sectors [42]. For packaging, Khem Lev et al. [43] successfully assembled a novel unit dose packet using ultrasonic welding. Ultrasonic welding is also used to create batteries and other electronic parts. This technique also applies to electrical connections in motors and capacitors [44].

Additive manufacturing processes and other widely used batch-wise, small-scale, or user-specific manufacturing processes, including the FFF method or 3D printing, are celebrated for their ability to create intricate and complex geometries. However, the layer-by-layer nature of these processes often introduces challenges when joining individual components into a cohesive and robust structure [45]. Traditional methods such as adhesives or mechanical fastening may only sometimes align seamlessly with the intricacies of 3D-printed parts, necessitating advanced joining techniques. Ultrasonic welding proves advantageous in assembling multi-part 3D-printed structures. Whether creating intricate mechanical components or larger assemblies, ultrasonic welding provides a reliable means of joining different printed parts [46]. This is particularly beneficial in industries such as aerospace and automotive, where complex structures often comprise multiple 3D-printed components. The medical sector, leveraging the capabilities of 3D printing, usually requires the assembly of intricate medical devices and prosthetics. Ultrasonic welding ensures the secure joining of 3D-printed parts in a manner that maintains the integrity and sterility of the final product. The non-invasive nature of ultrasonic welding is advantageous for medical devices that demand precision and cleanliness. With the increasing integration of electronics into 3D-printed products, such as smart wearables and customized electronic housings, ultrasonic welding provides a method for securely encapsulating electronic components [47]. The technique facilitates the creation of seamless, hermetically sealed enclosures, ensuring functionality and durability in electronic assemblies.

3.1 Concept of ultrasonic welding technique

As the name suggests, ultrasonic welding utilizes vibrations with frequency in the ultrasonic range, i.e., 20–40 kHz, and amplitude in the range of micrometers. These mechanical vibrations cause heating and wetting at the joint interface due to surface friction and the viscoelastic nature of adherents, which takes not more than a few seconds to complete, giving ultrasonic welding an edge over other fusion bonding techniques.

The whole ultrasonic welding can be summarized into six sub-processes [48];

- Frictional heating at the joint interface
- Viscoelastic heating of adherents
- Heat transfers along with the interface

- Flow of interfacial boundary
- Inter-molecular diffusion and chain entanglement
- Cooling and re-solidification of surfaces

The ultrasonic welding process starts with applying ultrasonic vibrations, causing frictional heating of joining surfaces. This phenomenon is the principal reason for weld formation under ultrasonic metal welding, yet in the case of polymers, frictional heating fades soon after the process starts, and viscoelastic heating takes over [6]. In polymers, viscoelastic heating plays a vital role in joint formation during ultrasonic welding. The viscoelastic nature of plastic materials can be represented using the Voigt-Kelvin model, as shown in Fig. 2 [7].

The heat generated due to friction and viscoelastic behaviors in metals or polymers is transferred along the joint interface, causing wetting of the surface; at this stage, vibration amplitude causes squeeze flow, which diminishes the interfacial boundaries due to inter-molecular diffusion at the joint interface. The vibrations are terminated at this point, and the newly formed joint can cool and solidify [49].

3.2 Ultrasonic welding apparatus

A significant ultrasonic welding apparatus is available in two configurations: ultrasonic spot welder and ultrasonic continuous welder (shown in Fig. 3a and b). A considerable difference is visible in the ultrasonic welding stack. In an ultrasonic spot-welding apparatus, the transducer and

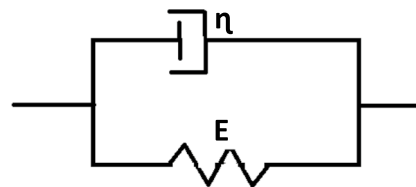
booster assembly are connected to the welding horn, which is stepped cylindrical or stepped cuboidal. The transducer and booster assembly are attached to a roller in a continuous ultrasonic apparatus. This roller rolls along the weld line, applying weld pressure and ultrasonic vibrations, thus forming a continuous weld. Continuous ultrasonic welding techniques are extensively used in the textile industry [50].

A basic ultrasonic welding apparatus consists of the following parts:

- An ultrasonic generator for supplying required energy to the ultrasonic stack.
- A microprocessor control system and user interface panel to monitor and control the whole welding process.
- Ultrasonic welding stack, which consists of:
 - **A transducer** for converting electrical energy from the generator to vibrations of the required frequency.
 - **A booster** for tuning the mechanical vibrations supplied by the transducer.

Boosters, also known as amplitude transformers, are essential components that connect the ultrasonic transducer to the welding horn. They serve the purpose of magnifying the amplitude of the vibrations generated by the transducer. Several types of boosters, such as half-wave boosters and full-wave boosters, are employed based on the specific requirements of the welding application. **Half-wave boosters** are designed to resonate at one-half of the operating frequency, effectively doubling the amplitude. They are a

Fig. 2 Schematic illustration of a viscoelastic solid using the Voigt-Kelvin model



η - viscosity of material

E - Young's modulus of material

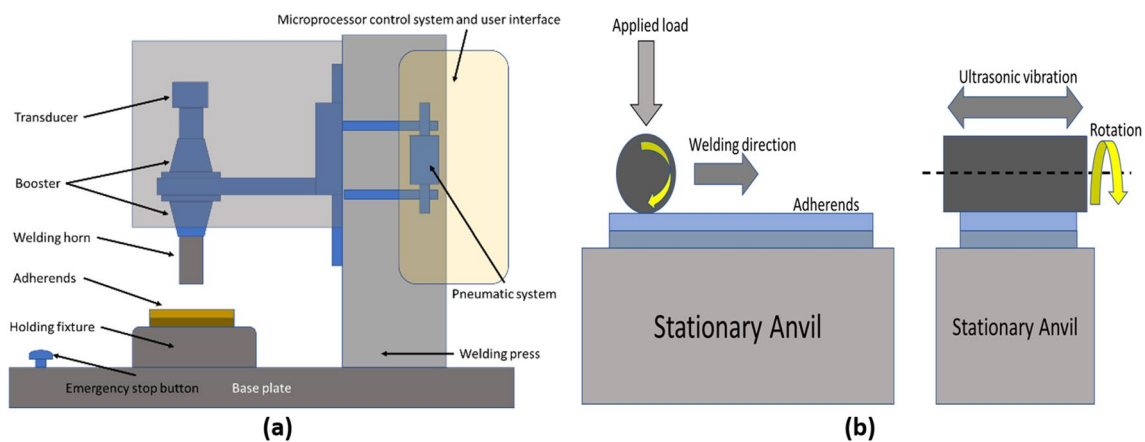


Fig. 3 Schematic representation of **a** ultrasonic spot welding machine and **b** continuous ultrasonic welding [51]

fit where high amplitude is critical, such as welding thick or dense materials. **Full-wave boosters** operate at the same frequency as the transducer, providing a one-to-one amplitude ratio. They are often used when maintaining the original frequency, which is essential for welding. Based on the design, boosters can be further classified as:

Step boosters: Characterized by a stepped design, these boosters allow for the adjustment of amplitude levels by altering the step height. They provide versatility where fine-tuning amplitude is crucial.

Continuous boosters: These boosters have a smooth, continuous design, offering a constant amplitude level. They are preferred for requiring consistent and sustained energy transfer.

The horn, or sonotrode, is the component directly in contact with the welded materials. Its shape and size influence the amplitude of the ultrasonic vibrations, and this phenomenon is known as horn gain. The horn is a mechanical transformer transmitting vibrational energy to the workpiece.

The equation that governs the relationship between booster gain (G_b), horn gain (G_h), and transducer gain (G_t) to calculate the overall gain (G_o) is expressed as:

$$G_o = G_t * G_b * G_h$$

This equation highlights how the gains of the transducer, booster, and horn collectively contribute to the overall amplification of the ultrasonic vibrations during the welding process.

The impact of horn shapes includes conical horns, which are tapered and slender; conical horns are effective for precision welding. They provide controlled energy concentration appropriate for joining small and intricate components. On the other hand, exponential horns feature a gradual taper distribution. Energy more evenly across the surface. Exponential horns are ideal for requiring uniform welds on larger surfaces. Finally, the amplitude of ultrasonic vibrations

determines the energy transferred to the materials during welding. Higher amplitudes are often needed for welding denser or thicker materials. Adjusting booster types, horn shapes, and overall gain allows for precise control over the amplitude dynamics, enabling optimal welding results. A fixture to hold the adherends together.

3.3 Ultrasonic welding parameters

1. Weld time is when vibration is applied to the adherends [52].

2. Unlike weld time in ultrasonic spot welds, weld speed is also used in continuous ultrasonic welding. This parameter informs the speed at which the sonotrode translates while forming the weld [53].

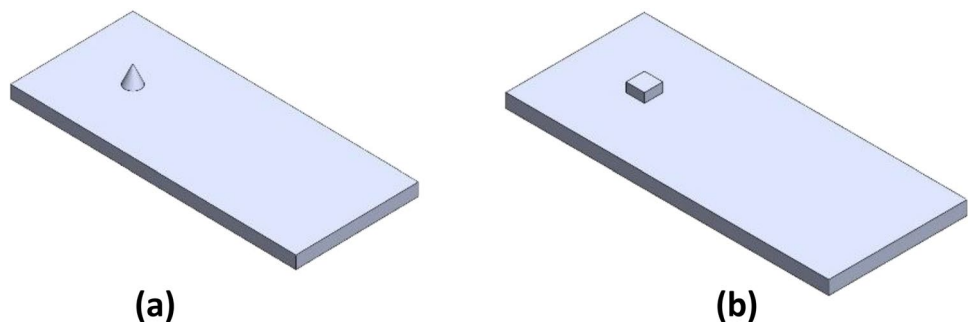
3. Weld pressure is the amount of pressure applied on adherends by the sonotrode [53].

4. Weld amplitude and frequency is the value of amplitude and frequency for the vibrations applied. Welding frequency, amplitude, and weld pressure are responsible for heat generation via surface friction and the viscoelastic nature of adherends, which plays a vital role in weld formation [54].

4 After the weld is made and vibrations are terminated, adherends are kept under a pre-defined pressure called hold pressure for a brief period termed as hold time [55].

6. Energy directors (ED), i.e., an independent or co-cured thermoplastic film with or without geometrical protrusions for preferential heating during welding [56]. Energy directors play a pivotal role in ultrasonic welding as focal points for transmitting ultrasonic vibrations. These specialized features are strategically incorporated into the design of components to enhance precision and promote strong, reliable bonds [57]. This article delves into energy directors' nature, purpose, and types employed in ultrasonic welding

Fig. 4 a Conical point type ED.
b Flat point type ED



processes. Based on their geometric shapes, EDs can be differentiated as follows:

Point energy directors: as depicted in Fig. 4a and b

Conical points: These are raised, conical features strategically placed at the joint. Conical points concentrate the energy in a specific area, allowing precise control over the welding process.

Flat points: Flat points are raised, flat features designed to create a broad melting zone. They are apt where a larger bonding area is required.

Line energy directors: as depicted in Fig. 5a and b

Raised ribs: These are continuous, raised features running along the joint line. Raised ribs provide a line of concentrated energy, acceptable for creating long continuous welds.

Parallel grooves: Parallel grooves are depressions or channels along the joint line. They guide and concentrate the ultrasonic vibrations, ensuring a consistent weld across the entire length.

Combination energy directors:

Mixed patterns: Some applications benefit from a combination of point and line energy directors. Mixed patterns allow for tailored welding solutions, adapting to the specific geometry and requirements of the joined components.

7. Several control modes are used for spot/plunge ultrasonic welding. These control modes include weld time, energy, horn distance, and maximum power output. In **time control mode**, ultrasonic vibration is applied for a fixed time interval. In **energy control mode**, the power dissipated in the ultrasonic transducer is measured and integrated over time as soon as the ultrasonic vibration starts until a desired

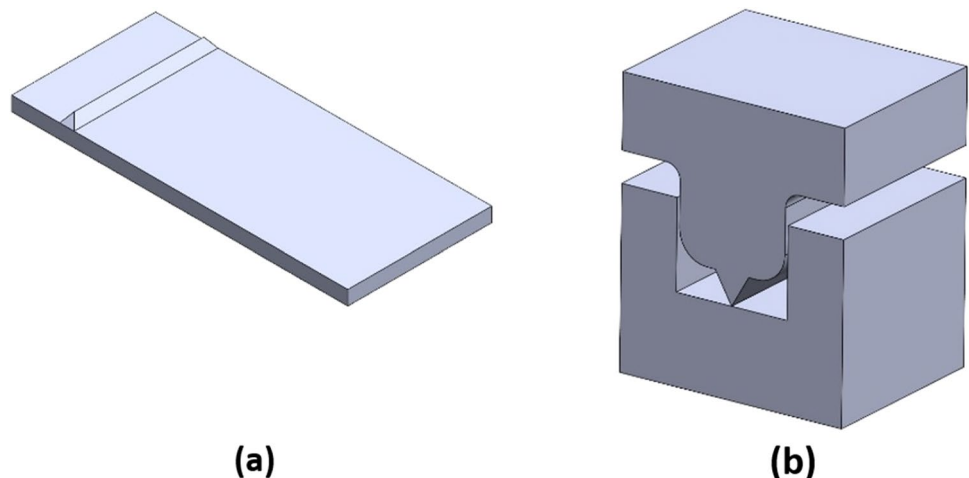
energy level is attained and the ultrasonic vibration is terminated. In **displacement control mode**, the application of vibration depends upon the plunge position of the horn. In peak **power control mode**, vibrations terminate the instance when power reaches a preset value. In addition, **microprocessor control mode** is also present in high-end ultrasonic set-ups in which a dedicated computer supervises different above-mentioned weld inputs and terminates the welding process according to them, thus increasing the repeatability of welded joints during mass production [58].

4.1 Strengths and limitations of ultrasonic welding

Ultrasonic welding stands out as a highly advantageous fusion bonding technique, offering a range of benefits that contribute to its widespread adoption across diverse industries. From its precision in creating strong molecular-level bonds to its efficiency in rapid assembly, ultrasonic welding has become a preferred choice for manufacturers seeking reliable and efficient joining solutions. Here are some critical advantages of ultrasonic welding:

1. **Speed and efficiency:** One of the most notable advantages of ultrasonic welding is its speed. The welding process, including heating, joining, and cooling, takes place in seconds. This rapid cycle time is particularly advantageous in high-volume production environments where efficiency is paramount. Manufacturers benefit from increased productivity and shorter manufacturing cycles [59].
2. **Precision and consistency:** Ultrasonic welding offers unmatched precision in creating bonds at a molecular level. The controlled application of high-frequency ultrasonic vibrations ensures uniform heating and melting of the joint interface. This precision results in consistent and reliable bonds, minimizing variability in joint

Fig. 5 a Raised rib type ED. b Parallel grooves type ED



strength. The repeatability of the process enhances the overall quality of the assembled components [60].

3. **No consumables or additional materials:** Unlike some other bonding techniques that require adhesives, solvents, or mechanical fasteners, ultrasonic welding typically requires no additional consumables or materials. This simplicity reduces material costs and eliminates the need for extra processing steps. The absence of consumables also contributes to a cleaner and more environmentally friendly manufacturing process [50].
4. **Minimal thermal impact:** Ultrasonic welding operates with minimal thermal impact on the surrounding areas of the joint. The focused application of ultrasonic vibrations generates localized heat at the joint interface, preventing extensive heat transfer to the rest of the materials. This characteristic is crucial for preserving thermoplastic materials' structural integrity and properties that may be sensitive to heat-induced degradation [61].
5. **Versatility in material compatibility:** Ultrasonic welding exhibits exceptional versatility in bonding various thermoplastic materials. The technique accommodates a wide range of material compositions, from common plastics like polyethylene and polypropylene to specialized engineering plastics. This versatility makes ultrasonic welding applicable across industries with diverse material requirements [42].
6. **Environmentally friendly:** The eco-friendly nature of ultrasonic welding is attributed to the minimal use of consumables and the energy-efficient operation of the process. With a growing emphasis on sustainability and reduced waste, ultrasonic welding aligns with environmentally conscious manufacturing practices. The absence of adhesives or solvents further contributes to a cleaner and greener production environment.
7. **Engagement across industries:** Ultrasonic welding finds applications in various industries, showcasing its adaptability. Ultrasonic welding addresses diverse manufacturing needs, from automotive manufacturing for assembling interior and exterior components to the medical sector for creating sterile and secure bonds in medical devices. Its ability to create intricate joints makes it precise for electronics, packaging, and consumer goods.

As none of the manufacturing processes known to make is perfect, ultrasonic welding carries its disadvantages, some of which are documented below:

Limitations on the materials: Ultrasonic welding is appropriate for some thermoplastics but not others. Less moisture is needed for the materials that the ultrasonic welding process welds [20].

Due to its specified power output, the thickness of adherends that can be joined via USW depends highly on the transducer. Furthermore, mechanical vibration energy cannot quickly vibrate thick materials, rendering ultrasonic vibration an inadequate welding approach for thicker materials.

Every new project for an ultrasonic welding application requires specialized tooling as part of the custom manufacturing requirements of the process.

High initial outlay: The cost of ultrasonic welding equipment is more than that of traditional welding equipment, and the price only rises when automation is added.

5 Ultrasonic welding of different polymeric composites

5.1 Carbon fiber–reinforced poly-ether-ether-ketone (CF/PEEK)

The application of thermoplastic composites has shown a tremendous increase in the last decade or half, especially in the aerospace industry. CFRPs, being strong yet lightweight with a remarkably high shelf life, have successfully challenged the use of metals and their alloys in producing many aerospace parts. CF/PEEK is one of many CFRPs currently used in making clips and brackets for commercial airplanes by many reputed aerospace industries, such as Airbus and Boeing [62]. Compared to unreinforced PEEK, carbon fiber offers a much higher thermal conductivity, lowering its thermal expansion rate. Carbon PEEK has the potential to service in some of the most challenging working conditions, experiencing extensive mechanical loading and environmental variations, since it has the best mechanical property retention up to 300 °C and the most substantial chemical resistance of any semi-crystalline plastic [63]. Exceedingly high mechanical strength at 250 °C offers outstanding wear and abrasion resistance and excellent resistance to hydrolysis in steam and boiling water. CF/PEEK also has an elevated level of chemical resistance to bases, acids, and organics—superior dielectric with minimal loss at high frequencies and temperatures. At room temperature, CF/PEEK is one of the most robust thermoplastic composites [63].

Table 3 comprehensively reviews recent developments in joining CF/PEEK using the ultrasonic welding technique. The relationship between weld time, weld pressure, and weld amplitude to achieve the highest weld strength in terms of ultimate lap shear stress or load (LSS) is intricate, and achieving the best combination requires a tailored approach. A balance between these parameters is necessary to ensure solid and reliable welds while avoiding potential issues such as material damage or degradation. The optimization process is highly application-specific,

Table 3 Ultrasonic joining of CF/PEEK

YEAR AND REF	AUTHORS	FACTORS CONSIDERED	WELDING PARAMETERS			OPTIMIZED LAP SHEAR STRENGTH (LSS)
			TIME	FORCE/PRES-SURE	AMPLITUDE	
2021 [64]	Tsiangou et al	Heating time	461 ms	1200 N	86 μ m	39.1 \pm 1.3 MPa
2021 [62]	Tsiangou et al	Welding force, amplitude	471 s	800 N	86 μ m	40.2 \pm 2 MPa
2020 [65]	Tsiangou et al	ED Material and thickness	Displacement control	1500 N	86.2 μ m	40.8 MPa
2020 [66]	Brito et al	Adherend alignment angle	Displacement control	500 N	86.2 μ m	50.81 \pm 2.25 MPa
2019 [67]	Tao et al	Weld time	0.9 secs	0.3 MPa	25 μ m	28 MPa
2018 [68]	Villegas et al	Weld strength	Displacement control	2000 N	73.4 μ m	28.6 MPa

and continuous monitoring and refinement are vital to maintaining high weld quality in ultrasonic welding processes. A brief insight into the documented research is also provided to understand better the research work done.

Thermosets or thermoset composites like CF/Epoxy cannot be welded to thermoplastics or thermoplastic composites like CF/PEEK because they cannot be re-melted and burnt with the heat produced during ultrasonic welding. This requires a PEI coupling layer. Tsiangou et al. [64] and Villegas et al. [68] studied the joining mechanism involved in joining thermoplastic composites (CF/PEEK) to epoxy-based carbon fiber–reinforced thermoset composites using the USW technique; heating time here referred to the time in which ultrasonic vibrations caused the weld interface to heat. Increasing heating time when joining CF/Epoxy to CF/PEEK led to a decrease in weld line thickness due to shared flow of the PEEK ED and the PEI coupling layer on CF/Epoxy. However, increasing the heating time caused the weld strength to rise to an optimum value and decrease.

Building upon the preceding research, the study extended its inquiry into the impact of welding force and amplitude on the joining of CF/Epoxy to CF/PEEK. The experiments revealed noteworthy insights: a reduced welding force or vibration amplitude correlated with an increased heating time, consequently elevating temperatures within the coupling layer and CF/Epoxy adherend. Conversely, simultaneous escalation of both parameters yielded weakened welds due to heightened thermal degradation. Striking a delicate balance, the investigation identified an optimal combination of 800 N weld force and 86 μ m amplitude, resulting in welds with the highest strength. However, it was observed that even at these optimized welding parameters, certain regions on the CF/Epoxy adherend exhibited signs of thermal degradation. This nuanced understanding underscores the intricate interplay of welding parameters and their consequential effects on weld strength and material integrity. It paves the way for fine adjustments in ultrasonic welding processes for enhanced outcomes in joining CF/Epoxy to CF/PEEK [62].

Expanding on the investigation, the study delved into the influence of electrode design (ETD) materials, specifically PEEK or PEI (poly-ether imide), on weld strength when joining CF/Epoxy, employing PEI as the coupling to CF/PEEK. The findings unveiled a notable disparity in outcomes: utilizing a loosely applied PEEK film as the ETD yielded an augmented weld strength of 40.8 MPa, accompanied by a mere 20% overlap area exhibiting unwelded regions. In contrast, employing a PEI film as the ETD resulted in a higher unwelded area of 50% and a reduced lap shear strength (LSS) of 31.8 \pm 2.9 MPa. Despite both composite adherend materials exhibiting similar failure modes, the discrepancy in lap shear strength was linked to the incongruity between the strengths offered by PEEK and the epoxy resin, exacerbated by the extent of unwelded zones. This nuanced exploration sheds light on the subtle role of ETD materials in ultrasonic welding, providing valuable insights for optimizing the process when joining CF/Epoxy with PEI coupling to CF/PEEK [65].

Brito et al. emphasized how the angle between adherends affected the ultrasonic welding of CF/PEEK adherends with flat energy directors (ED). To get a wide variety of angles, the welding jig's top clamp's location and the thickness of the supporting base were adjusted. The key findings were that the maximum power consumption and the homogeneity at the weld interface reduced as this angle increased, thus increasing the time required for the ED to start flowing. In addition to the angle, the clamping distance impacted these findings since it affects the top adherend's compliance with the pressing ultrasonic horn and, as a result, the absolute amplitude communicated to the ED and used to generate heat. A clamping distance of 50 mm was sufficient to reduce the effects of misalignment, providing high weld strength and uniform weld quality at a welding force of 500 N, even under significant adherends misalignment. [66].

Tao et al. emphasized the discrepancies in weld strength upon welding CF/PEEK with or without flat ED. When welding CF/PEEK without ED, weak joints with LSS less than 14.4 MPa were attained with cracks, voids, and fusion

flaws on PEEK resin at the weld interface due to insufficient heating at weld times of 0.7 to 0.9 s. On the contrary, incorporating flat ED resulted in the formation of welds with fewer flaws and an increased strength of 28 MPa. Further instantaneous weld interface temperature measurements suggested that the presence of ED decreased the time taken by resin at the weld interface to reach a melting point of 343 °C from 0.23 to 0.17 s when compared with the same without using ED due to increased viscoelastic strain thus lowering HAZ as a part of heat produced is utilized in melting ED; the heat-affected zone (HAZ) in the case of USW refers to the region of the materials being joined that undergoes thermal changes during the welding process [67].

5.2 Carbon fiber–reinforced nylon or polyamides (CF/N or PA)

Nylon is another name given to plastics under the polyamide group. CF/N6 or CF/PA6 and CF/N66 or CF/PA66 find their application in aerospace modeling and parts, automobile parts, civil construction, sports equipment, and many other civilian and technical applications. Nylon and Nylon 66, when paired with varying percentages of carbon fiber, provide high stiffness and elevated strength. With excellent strength-to-weight ratio and low thermal expansion, these CFRPs have high dimensional stability and are specially used for making dynamically stressed parts.

Chen et al. performed SSUW or single-sided ultrasonic welding (shown in Fig. 6) of 2.5-mm-thick CF/N6 composite outperformed conventional ultrasonic welded joints in terms of heat generation, weld area, and weld strength for the suspension distance of 11 mm, which is more as compared to horn diameters of 10 mm. This was due to severe contacts between clamps and suspended surfaces as a result of the bending deformation due to the forces generated, as shown in Fig. 6, producing a high value of interfacial and intermolecular frictional heat generated at the suspended weld

zone during the weld cycle as compared to conventional ultrasonic welding process [76].

Using a similar process, Zhi et al. analyzed the lap configuration weldability of a 4-mm-thick carbon/nylon 66 composite. Under ultrasonic vibration at nominal weld parameters, the weld formation started at the surfaces closer to the edge of the horn. It propagated towards the center, showing pores and unwelded zones, decreasing the strength of the welds, and leading to an interfacial fracture. Further analysis suggested that these issues can be resolved by optimizing the weld parameters [69]. In another study, Zhi et al. analyzed the consequence of moisture content in adherends i.e., 30% CF/PA66 on ultrasonic weld strength. Results show an adverse effect of increasing moisture content in adherence, resulting in voids and severe deformation in the fusion zone, causing interfacial fracture when subjected to shear load during lap shear tests [80].

Gao et al. conducted a study on single-sided ultrasonic welding (SSUW) for fusing 4-mm-thick carbon fiber-reinforced polyamide 66 (CF/PA66). Emphasizing the pivotal role of weld time and horn pressure, they optimized weld parameters (Table 4) to mitigate upper adherend surface indentation and weld interface porosity. The focus was on preventing premature weld failure caused by excessive heat due to improper weld time and pressure combinations. Their systematic approach balances these factors, enhancing weld integrity and longevity. The study provides crucial insights for precision in SSUW processes, particularly in joining composite materials like CF/PA66 [75].

Zhang et al. applied ultrasonic vibrations to repair partially uncured adhesive bonded 2.3-mm-thick injection-molded Nylon 6 (Cf/PA6) plates reinforced with 30% short carbon fiber. Microstructural analysis showed that ultrasonic vibrations effectively re-joined the defective adhesive bonds by fusing the carbon fibers to the PA6 matrix through viscoelastic and frictional heating, thus recovering 90% of the fully adhesively joined strength. This process required

Fig. 6 Schematic representation of single-sided ultrasonic welding (SSUW)

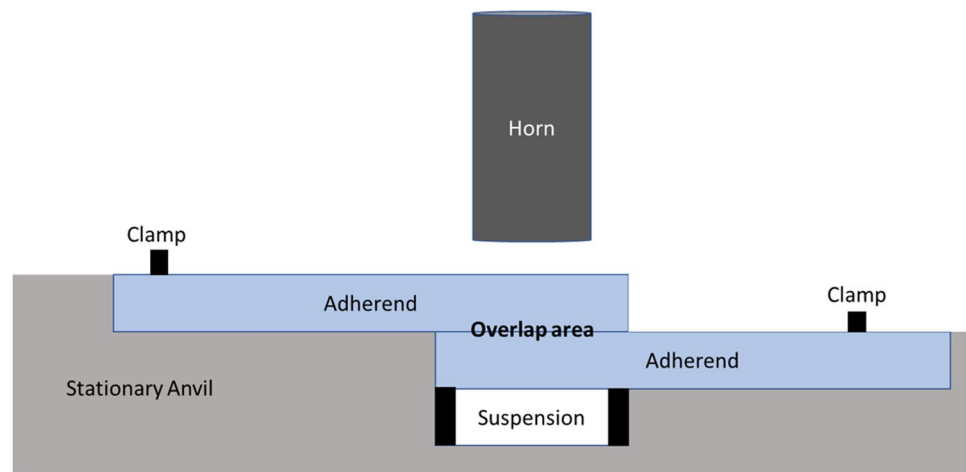


Table 4 Ultrasonic joining of carbon fiber–reinforced nylon or polyamide composites

YEAR AND REF	AUTHORS	FACTORS CONSIDERED	WELDING PARAMETERS			OPTIMIZED LAP SHEAR STRENGTH (LSS)
			TIME	FORCE/PRESSURE/ENERGY	AMPLITUDE	
2021 [69]	Zhi et al	Welding quality	2.1 s	0.15 MPa	NA	5.2 kN
2020 [70]	Zhang et al	Use of USW to repair adhesive joint	0.9 s	623 MPa	25 μ m	11.5 MPa
2020 [71]	Tutunjian et al	Temporal and spatial temperature development	3 s	19.5 MPa	28 μ m	NA
2019 [72]	Lee et al	Degree of crystallinity and ratio of the phases of Nylon 6	Energy control mode	800 J	50 μ m	23.69 MPa
2019 [73]	Goto et al	Effect of weld energy	Energy control mode	800 J	90 μ m	40 MPa (LSS2)
2018 [74]	Li et al	Blank holding force	Microprocessor control	1200 J	35 μ m	~4 kN
2018 [75]	Gao et al	Weld time, horn pressure	Time control mode	NA	NA	5.2 kN
2018 [76]	Chen et al	Heat generation	1.3 s	0.3 MPa	NA	~1000 N
2017 [77]	Wang et al	Bonding efficiency, weld area, horn indentation	Energy control	200 N	35 μ m	3.38 kN
2017 [78]	Wang et al	Effect of interfacial preheating	Energy control mode	NA	NA	3.2 kN (approx.)
2017 [79]	Wang et al	Effect of welding energy	Energy control mode	1000 J	35 μ m	~40 MPa
2017 [80]	Zhi et al	Consequence of moisture content on weld strength	Displacement control mode	0.17 MPa	25 μ m	6.3 kN

adjusting the ultrasonic horn just above the defective adhesively bonded area supported by the anvil [70].

Tutunjian et al. developed a 2D explicit model to simulate the temporal and spatial evolution of the temperature in an ultrasonic weld site between two laminates made of fiber-reinforced thermoplastic CF/PA66. Fem model, along with experimental investigation, suggested frictional heating to be the driving factor in increasing the weld interface temperature until the matrix starts to flow; as the flowing temperature is achieved, rapid heating is observed due to viscoelastic heating overtaking friction. Indeed, with the influence of extended weld time, this fast heating leads to matrix deterioration due to molecular breakdown [71].

Lee et al. investigated the impact of degree of crystallinity (DoS) on the weld strength of ultrasonically welded 30% carbon fiber–reinforced PA6. To heighten the DoS, composite coupons in their as-received state underwent an annealing process at varying temperatures before the ultrasonic welding procedure. The outcomes demonstrated a significant improvement in the viscoelastic and mechanical characteristics of the adherend material following annealing, consequently enhancing the resulting weld strength. This study not only elucidates the pivotal role played by DoS in

influencing the quality of ultrasonic welds but also highlights the efficacy of the annealing process as a strategic means to augment the overall performance of the welded joints in 30% carbon fiber–reinforced PA6 [72].

Goto et al. introduced two sets of material characterization parameters for the analysis of ultrasonic weld quality and efficiency in cross-ply and twill woven CF/PA6 composite plies, with and without a flat electrode design (flat ED). The first set, consisting of lap shear strength-1 (LSS1) and cross tensile strength-1 (CTS1), was instrumental in determining weld efficiency. LSS1 was calculated by dividing lap shear strength and cross tensile strength by the total overlap area during ultrasonic welding. Conversely, the second set, comprising LSS2 and CTS2, was calculated by dividing lap shear strength and cross tensile strength by the actual welded area during ultrasonic welding, serving as parameters to evaluate weld quality. The application of flat ED proved to be a significant factor in influencing weld quality and efficiency. Flat ED enhanced weld quality for cross-ply laminates by increasing joint strength per unit area. Conversely, in twill-woven laminates, the use of flat ED improved weld efficiency by expanding the weld area. This nuanced distinction underscores the versatile impact of

flat ED, showcasing its differential influence on ultrasonic welding outcomes depending on the specific configuration of composite plies [73].

Li et al. presented a novel approach for joining 30% carbon fiber–reinforced PA6 without using Eds by employing a reusable annular clamp known as a blank holder as a component of the weld tool to impart a variable force on the composite sheets known as the empty holding force (BHF). This investigation was directed to ease the repeatability of the ultrasonic welding technique without using EDs. The outcomes demonstrate that the weld formation was significantly impacted by the duration for which BHF was applied. For all of the research’s experimental scenarios, the crucial release time and energy consumption were roughly 0.8 s and 300 J, providing a maximum weld strength of 4 kN [74].

Wang et al. analyzed and simulated the shear loading phase in the ultrasonic bonding phenomenon in thermoplastic composites using a surface-based cohesive model [79]. In continuation, when joining 30% CF/PA6 coupons, the bonding occurred between the matrix part of either adherends or carbon fibers. It was reinforced in the direction of matrix flow during the ultrasonic welding process. Favorable welding conditions facilitate this flow. In contrast, defects like pores occur at the weld interface due to very high weld temperature and pressure when welds are performed beyond

a favorable weld parameter window [77]. By this analysis, Wang et al. [78] projected the claim of preheating ultrasonic weld interface while welding 30% CF/PA6. Results show that preheating the weld interface before welding caused the interfacial layers to soften to a favorable extent, thus increasing weld strength by converging the weld energy provided by the ultrasonic horn. Meanwhile, preheating for an extended interval developed porosity at the weld interface, thus deteriorating weld strength.

5.3 Carbon fiber–reinforced poly-phenylene sulfide (CF/PPS)

Polyphenylene sulfide (PPS) is a semi-crystalline thermoplastic with outstanding thermal stability, mechanical strength, resistance towards elevated temperature and corrosive chemicals, high-flowability, excellent dimensional stability, and conductivity towards current. PPS, when filled with fibers and fillers, lowers its intrinsic brittleness, making it a preferred matrix for composite materials.

As mentioned in Table 5, Tanabe et al. employed a carbon fiber–reinforced energy director with varying % fiber volume (0–50%, in step 10) to examine the joining strength and ultrasonic spot-welding behavior of CF/PPS. According to the experimental findings, the volume percentage of carbon

Table 5 Ultrasonic welding of CF/PPS

YEAR AND REF	AUTHORS	FACTORS CONSIDERED	WELDING PARAMETERS			OPTIMIZED LAP SHEAR STRENGTH (LSS)
			TIME	FORCE/PRES-SURE	AMPLITUDE	
2017 [80]	Tanabe et al	Effect of loose carbon fibers as ED	1 s	0.9 kN	NA	50.1 MPa
2022 [81]	Kirby et al	Void content in the USC process	3 s	NA	NA	Minimum void %
2020 [82]	Takeda et al	Welding conditions, ED coarseness	3 s	1.1 MPa	NA	34 MPa
2020 [83]	Zhao et al	Spot spacing and number of spots	NA	1500 N	60.8 μ m	14 kN [4]
2020 [84]	Jongbloed et al	Difference and similarities between USW and CUSW	0.435 S	500 N	60 μ m	38 MPa
			35 mm/s	NA	80 μ m	28 MPa
2020 [85]	Jongbloed et al	Effect of ED profile	40 mm/s	500 N	82.5 μ m	18.8 MPa
			45 mm/s			33.7 MPa
2018 [86]	Jongbloed et al	Weld uniformity	45 mm/s	500 N	82.5 μ m	18.8 \pm 6.2 MPa (FED) 33.7 \pm 2.4 MPa (MED)
2018 [87]	Zhao et al	Weld uniformity for sequential USW	Displacement control mode	1500 N	60.8 μ m	7.03 \pm 0.46 N (DSW)
			Energy control mode			5.8 \pm 0.7 kN (DSW)
2016 [88]	Senders et al	Zero-flow welding	Displacement control mode	1000 N	85 μ m 49 0.5 μ m	30.7 \pm 4.3 MPa 31.9 \pm 0.9 MPa
2016 [89]	Villegas et al	Melting flow of ED, weld strength	Displacement control mode	500 N	86.2 μ m	37.1 \pm 1.3 MPa (flat ED)

fiber in the energy director in conjunction with weld force (0.1, 0.5, 0.9 kN) had a considerable impact on the behavior of ultrasonic welding. Joints welded at a welding force of 0.9 kN with 10% fiber volume in EDs produced the strongest welds with a tensile shear strength of 50.1 MPa [80].

Kirby et al. [81] presented a 2D model to simulate the ultrasonic consolidation process of PPS resin with dry-woven carbon fiber. This model incorporates mathematical formulation involving viscoelastic heating, varying material properties, and matrix phase, respectively, thus reducing multiple experimental iterations. Results suggest the presence of voids is equivalent to 2.43% of the total overlap area due to insufficient melting of resin at welding time less than 1750 ms; the voids were reduced to 0.83% when welding time was increased to 3000 ms. This decrease is due to sufficient heat generation at the weld interface, causing favorable flow and impregnation rate of resin matrix and carbon fiber reinforcement, thus facilitating the overall consolidation process [81].

Takeda et al. investigated the viability of using a coarse resin mesh sheet as an ED with varying coarseness to weld CF/PPS ultrasonically. This work highlighted the combined influence of welding parameters and coarse EDs on weld strength. Fractographical observations show incomplete melting at the center at weld time of 1 s due to low heat generation. In contrast, with increased weld time, welded layers' defects like adhesive and cohesive failure were evident. The welded samples with the coarsest resin mesh demonstrated a single-lap shear strength of 34 MPa and a coefficient of variation of 0.1 due to high heat generation and complete melting of ED resin [82].

Zhao et al. [87] studied the effect of welding modes on weld strength. They investigated how the ultrasonic sequential welding process could be made more reliable for mass production by improving its repeatability. Ultrasonic sequential welding refers to a multiple-spot ultrasonic welding process. This study compares energy control (ESW) and displacement control ultrasonic welding (DSW) based on consistency in weld strength while welding CF/PPS at a constant set of weld parameters. Results show the superiority of displacement control ultrasonic sequential welding as the welds achieved were more persistent regarding weld area and strength than those performed via the energy control method. In addition to this work, using similar material, a comparative study between multi-spot ultrasonic welds (MSW) and multi-mechanical fastener (MMF) joints to investigate the effects of spot spacing and spot count on secondary bending. Consequently, the strength of multi-spot welded joints was performed by Zhao et al. [83]. Results show the superiority of MSW joints on MMF joints regarding load-bearing capacity due to reduced secondary bending.

Jongbloed et al. [86] aimed at enhancing the weld uniformity of continuous ultrasonically welded connections

of CF/PPS composites. To accomplish this, a comparative study was performed between the effect of conventionally used flat EDs or flat EDs (0.08 mm thickness) and a novel woven mesh of 0.2 mm thickness. Results show a notable increase in joint strength and uniformity mainly because of better contact area and even heat distribution compared to flat EDs, thus enhancing weld uniformity and strength. The same research group performed further studies to assess the effect of ED shape upon weld uniformity based on its "Compliance," which is inversely proportional to the contact area and material modulus and proportionate to the energy director thickness. Woven mesh-type EDs with greater compliance than flat EDs generated more heat at the weld interface with uniform distribution, thus enhancing the weld strength and uniformity [85]. Another study aimed to differentiate between the effect of heat generation at weld interfaces in static and continuous welding. Experiments were performed by varying weld force (500, 1500 N) and vibration amplitude (60, 80 μm) at varying weld speeds and time for continuous and static processes. Results suggest the non-welded area beneath the sonotrode is constant for the ongoing process as materials at different phases coexist instantly. In contrast, in the static process, the non-welded zone eventually shrinks to zero as phase changes in adherend material at the weld interface happen sequentially [84].

Koutras et al. investigated the effect of longer and shorter welding periods with parameters, i.e., 1000 N, 86.2 μm and 300 N, 52.8 μm respectively upon weld quality in terms of its degree of crystallinity while joining CF/PPS using the USW technique. Weld time was kept constant at 400 ms for both mentioned weld parameters, and weld interface temperature was measured via thermocouples to calculate the cooling rate. Further differential scanning calorimetry (DSC) and fast scanning calorimetry (FSC) techniques were performed on welded samples to measure their degree of crystallinity and cooling rate-dependent crystallinity. Results show enhanced crystallinity in shorter welding periods, i.e., low weld force (300 N) and amplitude (52.8 μm) due to slow cooling and strain-induced crystallization [90].

To reduce the squeezing flow effect brought on by the application of welding pressure during ultrasonic spot welding as well as continuous welding of CF/PPS, Senders et al. [88] designed a novel zero-flow welding approach. The suggested method can provide robust welds before any squeezing flow occurs at the interface. Due to the simultaneous melting of the adherents' matrix and the energy director, it is made possible using very thin, flat energy directors. The outcomes demonstrate the viability and point to the potential for extremely quick high-strength welding between thermo-plastic composite plates.

Villegas et al. employed a triangular energy director co-cured on the adherend surface while joining CF/PPS by the USW method. This study comparing the time required to

melt flat ED with that of triangular ED showed a considerable discrepancy; triangular EDs were found to melt twice as fast as their flat counterparts, yet the weld time required to attain a strong weld remained similar for both EDs. Experiments suggest that in the case of triangular EDs, heat generation originated at the apex, and with the application of weld pressure, ED resin squeezed out of the weld interface; thus, additional time was required to heat and re-melt the new resin-rich layer, forming a fully welded strong weld [89].

5.4 Carbon fiber–reinforced poly-ether imide (CF/PEI)

Poly-ether imide (PEI) is well-known for its excellent thermal properties in polymers. PEI is an amorphous thermoplastic that produces a product that can withstand higher temperature conditions without losing its dimensional stability when used as matrix material and carbon fibers to make composite structures. Table 6 provides insight into recent developments in joining CF/PEI using the ultrasonic welding technique.

Tsiangou et al. investigated the difference in welding strength of CF/Epoxy to CF/PEI when using co-cured PEI with varying (250 μm and 60 μm) as ED. As a reference, the results were compared with weld strength achieved by employing loose EDs with similar thicknesses. Results show enhanced weld strength (37.7 \pm 1.6 MPa) achieved by using loose EDs (250 μm) due to favorable frictional heating and lowered thermal degradation of plastic resin. In contrast, co-cured thin PEI layers (60 μm) resulted in inferior welds with a strength of 17.3 \pm 4.5 MPa due to overheating and matrix destruction [91].

On a similar note, Palardy et al. considered the effect of ED thickness on ultrasonic weld strength when joining CF/

PEI. An extensive analysis was performed to identify an optimized thickness for flat EDs. Results show that when using EDs with 0.06 mm thickness, both adherends and Ed are heated together rapidly from the beginning of the welding process, and optimum weld strength (32.9 \pm 2.2 MPa) occurred at a weld time of 475 ms requiring very minute sonotrode displacement showing signs of overheating due to rapid heat generation. Thus, it was suggested that displacement control mode must be omitted while ultrasonically welding CF/PEI using thin EDs. In the case of using thick EDs (0.25 mm, 0.5 mm), ED melted before adherends showing distinct phases of USW showing flash squeezed beyond weld interface providing welds with strength 37.3 \pm 0.9 and 36.5 \pm 1.8 MPa, respectively, with welding times of 565 ms and 605 ms, respectively [92]. In continuation, resin flakes and voids were seen when employing the thinnest energy directors, indicating thermal degradation based on the study of the fracture surfaces. These findings imply that thin energy directors are less effective at generating preferential heat at the weld line than more significant EDs (i.e., 0.25 mm), which results in less consistent weld quality [93].

Villegas et al. used a microprocessor-controlled ultrasonic welder to give a detailed experimental examination of the alterations and weld interface heating mechanisms along with their interaction with the wasted power and the sonotrode displacement. The primary goal of this study is to increase knowledge, enabling simple process monitoring and, ultimately, weld quality monitoring through feedback from the ultrasonic welder [95]. Continuing previous work, Villegas presented a simple yet innovative method to join CF/PEI coupons using ultrasonic welding in optimum processing conditions. This work provided a pathway to find optimum ultrasonic welding parameters for any thermoplastic composite. This optimum processing condition was

Table 6 The ultrasonic joining of CF/PEI

YEAR AND REF	AUTHORS	FACTORS CONSIDERED	WELDING PARAMETERS			OPTIMIZED LAP SHEAR STRENGTH (LSS)
			TIME	FORCE/PRESSURE	AMPLITUDE	
2019 [91]	Tsiangou et al	Requirement of loose ED	Displacement control mode	1500 N	86.2 μm	37.7 MPa
2017 [92]	Palardy et al	ED Thickness	Displacement control mode	500 N	86.2 μm	37.3 \pm 0.9 MPa (0.25 mm ED)
2016 [94]	Villegas et al	Weld strength	Displacement control mode	300 N	86.2 μm	37.3 \pm 1.6 MPa
2015 [93]	Palardy et al	ED thickness (0.06 mm)	Displacement control mode	500 N	86.2 μm	32.9 \pm 2.2 MPa
		0.25 mm				37.3 \pm 0.9 MPa
		0.5 mm				36.5 \pm 1.8 MPa
2015 [95]	Villegas	Transformation and heating mechanism at the weld interface	Displacement, power control mode	300, 500, 1500 N	51.8, 86.2 μm	NA

assessed using microprocessors while joining coupons using displacement control mode. Flat EDs were used to achieve preferential heating at the weld interface. The combined contribution of data acquisition and welding in displacement control mode using flat EDs provided high-strength joints, thus providing optimum welding parameters (Table 6) [94].

5.5 Glass fiber–reinforced polymer composites

Glass fiber–reinforced polymers or GFRPs are extensively used in the marine industry, i.e., construction of boats, civil construction industries for making ladders, handrails, platforms, etc., in oil and gas industries for transporting fluids, and many more. Though inferior to carbon fibers in terms of mechanical strength and electrical conductivity, GFRPs make it up owing to their low production cost and cheap maintenance. Table 7 comprehensively reviews recent research on GFRPs as a critical component.

Dobrata and Lazar conducted an optimization study for ultrasonic welding parameters when joining polytetrafluoroethylene and PBT-GF30 (70% polybutylene terephthalate and 30% fiberglass) (e-PTFE). This article investigates welding a membrane-type portion made of e-PTFE with a thickness of 0.3 mm and a plate-type portion made of PBT-GF30 with a thickness of 2.1 mm. This study considered the membrane's detachment pressure (DP) to be at least 4 bar for the welded joints to be technically compatible. Optimized results show a detrimental effect of welding pressure or force upon detachment strength of the adherends as this force tends to reduce the

thickness of the membrane at the weld line, whereas increasing other parameters with favorable correlation with each other like weld time and amplitude resulted in strong welds [96].

In this study, Li et al. explored the use of multi-walled carbon nanotube-reinforced polypropylene (MWCNT/PP) films as flat EDs to join glass fiber/polypropylene (GF/PP) composite plates in a single-lap configuration via ultrasonic welding. Further, these MWCNT/PP films were used in damage monitoring at the weld interface via a change in the electrical resistance of the joint. To weld GF/PP adherends, three MWCNT concentrations (15, 20, and 25 wt. percent) above electrical percolation were selected. Lap shear strength (LSS) testing and fractography analyses were used to compare weld quality and assess the impact of MWCNT content on the welding process. Therefore, the electrical resistance increases dramatically when the weld interface is destroyed. This study summarizes that the weld specimen demonstrates a minor increase in weld lap shear strength and a significant increase in electrical resistance with each degree of fracture in the weld contact [98].

In an experimental study done by M.A.A Alrubaie, the ultrasonic weld quality was assessed to determine the effects of the orientation of the outer layer of polypropylene (PP) reinforced with E-glass fiber laminate (GF/PP) and the impact of the fiber volume percentage. GF/PP laminates had a 90° outer layer orientation or were unidirectional. When paralleled with the shear strength achieved with flat EDs at similar weld parameters, the high welding energy, low amplitude, welding pressure, hold

Table 7 Ultrasonic joining of GFRPs

YEAR AND REF	AUTHORS	ADHERENDS	FACTORS CONSIDERED	WELDING PARAMETERS			OPTIMIZED LAP SHEAR STRENGTH (LSS)
				TIME	FORCE/PRES-SURE	AMPLITUDE	
2021 [96]	Dobrata and Lazar	PBT/GF30-e-PTFE	Welding time, force, holding time	450 ms	70 N	30 μ m	4.5 bar (D_p)
2020 [97]	Kumar and Omkumar	GF/PA	Effect of Welding time, force, and holding time on weld dimension	550, 580, 600 ms	400 kPa	NA	NA
2020 [98]	Li et al	GF/PP	Damage detection capability of MWCNT/PP films	4 s	1000 N	38.1 μ m	14.9 MPa
2020 [99]	M.A.A Alrubaie	GF/PP	Outer layer orientation and fiber volume fraction	Energy control mode	103.4 kPa	NA	13.03 MPa
2015 [100]	Nikoi et al	GF/PP	Weld time, pressure, and amplitude	0.4 s	1.5 bar	30–33 μ m	1.255 KN

time, and hold pressure of a unidirectional GF/PP with the lowest fiber volume fraction were found to achieve an optimum weld with high shear strength [99].

In the work done by Nikoi et al., polypropylene composites reinforced with glass fiber are joined using the ultrasonic welding procedure. A second-degree model was created to calculate the weld failure force inside an experimental design space, which considered the weld's tensile shear strength to be most significantly influenced by amplitude, welding time, GF quantity, and air pressure. Unlike results in [96], this work shows that up to 2 bars of pressure rise can cause strength to diminish, but after this point, strength increases, and strength suffers as welding duration and amplitude increase. Also, strength is decreased when GF content is increased by more than 20%. Maximum strength may be attained at 30–33 micron amplitude, 0.4 s welding time, 10% GF, and 1.5 bar pressure based on interaction effects [100].

Kumar and Omkumar [97] conducted an application-focused optimization study to weld glass fiber-reinforced polyamide (GF/PA6) parts using ultrasonic welding with vibration amplitude, weld pressure, hold time, and weld time as varying weld parameters. Both experimental and statistical studies were performed to investigate their effect on assembly dimensions. Statistical studies via the ANCOVA method showed a linearly proportional relationship of weld energy and horn travel to assembly height, i.e., the distance between horn tip and weld interface, in time control mode welding. Hence, varying these two parameters, an optimum assembly height of 0.5 mm was

deduced by statistical means and further validated by conducting experiments.

6 Ultrasonic welding of thermoplastics

On account of microstructural orientation, thermoplastic polymers are categorized as amorphous and semi-crystalline [101]. Joining thermoplastics via welding requires a certain amount of heat generation to induce viscous flow between adherend surfaces. In amorphous plastics, the ultrasonic welding technique can quickly generate the necessary amount of interfacial heat by using wide combinations of high frequency, low amplitude vibrations, and load application. Semi-crystalline polymers, on the other hand, require vibration with higher amplitude when compared to their amorphous counterparts due to their vibration absorption capability [4]. Table 8 provides a comprehensive review of recent research on ultrasonic welding of thermoplastic polymers.

In the study performed by Rajput et al. [102], weld time, hold time, and amplitude of peel strength during ultrasonic welding (USW) of polypropylene were examined. Taguchi's methodology was adopted to conduct the required experiments using the L9 orthogonal array. Further, ANOVA has also been used to assess how the process mentioned above variables affect peel strength. Results show vibration amplitude as the most manipulating factor affecting weld peel strength, followed by weld time and hold time. The ideal weld time, hold time, and amplitude for the welded specimen with the greatest peel strength are 1200 ms, 900 ms, and 75 μm ,

Table 8 Ultrasonic joining of thermoplastic polymers

YEAR AND REF	AUTHORS	ADHERENDS	FACTORS CONSIDERED	WELDING PARAMETERS			OPTIMIZED LAP SHEAR STRENGTH (LSS)
				TIME	PRES-SURE/FORCE	AMPLITUDE	
2020 [102]	Rajput et al	PP	Weld time, hold time, amplitude	1200 ms	3000 N	75 μm	NA
2019 [103]	Raza et al	ABS PP	Optimization of weld parameters	0.9 s 1.5 s	25 MPa	18.9 μm	31.21 MPa 22.36 MPa
2019 [104]	Kuratani et al	Polyacetal resin	Effect of contact area with fixture	0.5 s	NA	30 μm	NA
2019 [105]	Natesh et al	PC-ABS blends	Amplitude, pressure, and time	3.35 s	4.03 bar	33.14 μm	6.02 MPa
2018 [55]	Thang et al	ABS HDPE	Effect of height and angles of ED	NA	NA	60 μm	NA
2017 [106]	Chinnadurai et al	PP	Adherend behavior towards USW	5 s	900 kPa	50 μm	30 MPa (approx.)
2016 [107]	Parmar et al	ABS	Modeling of experimental data for USW of ABS	1.25 s	1.5 bar	96.82 μm	6.05 MPa

respectively. Results show an increase in the S/N ratio of weld peel strength with an increase in the weld and hold time, whereas, in the case of increasing amplitude, peel strength increases in the range of 60–75 μm and decreases after that.

Raza et al. [103] used L-8 Taguchi experimental design to optimize the weld parameters for ultrasonic welding of acrylonitrile butadiene styrene (ABS) to ABS and polypropylene (PP) to PP using injection-molded triangular and semi-circular EDs. For ABS, it was discovered that ED profile and vibration amplitude were more significant than hold time; however, for PP, no weld factor was shown to be necessary. This study revealed triangular ED as the top contributor in realizing the highest lap shear strength for both ABS and PP compared to semi-circular ED. Microscopic inspection has indicated that the primary sources of brittle fracture for ductile thermoplastics are rock-like, horn-like, and crazing fibrils, resulting in voids and cracks in both ABS and PP. After carrying out the validation trials for both ABS and PP, a noteworthy enhancement in the weld strength or (LSS) was made, reaching 31.21 MPa (104% of the parent ABS shear strength) and 22.36 MPa (319% of the parent PP shear strength), respectively.

Kuratani et al. [104] performed a computational study to examine the impact of the joint interface's dynamic behavior on heat generation at the interaction between the bottom component and the welding fixture when joining components made of polyacetal resin. Using finite element dynamic contact analysis, the displacements and elastic strains of the interface were simulated and linked for various contact areas. The findings demonstrate that when the natural frequencies of the bottom component and the fixture approach the horn vibration frequency, the displacements and strains at the weld interface are minimal. In contrast, the displacements and strains are significant when the lower element has no natural frequency close to the horn vibration frequency. Thus, the dynamic behavior of the interface is influenced by the contact area since its dynamic behavior is dependent on the natural frequencies of the parts that will be linked. In contrast, the contact area can readily raise the natural frequency of the lower component.

Natesh et al. [105] employed NSGA-II (Non-dominated Sorting Genetic Algorithm) in conjunction with artificial neural networks to optimize the weld strength and heat generation at the weld interface when ultrasonically joining PC/ABS blends using an injection-molded triangular ED by considering three weld parameters, namely amplitude, pressure, and weld time. Optimized results show that vibration amplitude is the most influencing factor on weld strength, whereas weld pressure has the maximum impact on heat generation. The welding parameters of amplitude (33.14 μm), pressure (4.03 bar), and weld duration (3.35 s) resulted in a weld strength of 6.02 MPa. The welding parameters of amplitude (40.89 μm), pressure (4.29 bar), and welding time of 4.52 s are used to reach a maximum temperature of 146.20 $^{\circ}\text{C}$.

Thang et al. [55] examined the impact of various triangular ED heights (0.5–1.75 mm) on the temperature distribution at the weld interface. Transient thermal analysis mimics experiments employing 3D samples of high-density polyethylene (HDPE) and acrylonitrile butadiene styrene (ABS). The outcomes of a simulation of the temperature distribution at different ED heights and angles at different welding amplitudes (40, 50, 60 μm) show that the weld interface temperature is influenced by both welding amplitude and ED height, with increasing welding amplitude and ED height strongly growing MIT (maximum interfacial temperature). On the other hand, the contact temperature was less affected by the ED angle. The simulation's depiction of temperature distribution revealed that the apex of the ED, where the energy was concentrated, had the highest interface temperature. Amorphous polymers are better suited for ultrasonic welding than semi-crystalline ones because they can effectively transfer ultrasonic vibrations. In other words, ABS has a better energy absorption ratio than HDPE.

The evaluation of the behavior of polypropylene during the ultrasonic welding process has been the main focus of the study performed by Chinnadurai et al. [106]. Results from differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) revealed that the mass loss of the molded and welded propylene materials differed by an exceedingly small amount. Additionally, the SEM pictures demonstrated that void formation is closely correlated with vibration amplitude. This indicates that the lap joint interface strength is more muscular when the tendency of invalid formation is reduced, and the weld strength and bond integrity are higher for higher vibrations. Plotting the stress–strain curve of the material for three different ultrasonic welding configurations showed that as the critical process variables, pressure, time, and vibration amplitude, are increased, the weld strength and hardness increases, but the ductility of the welded polypropylene samples decreases.

Parmar et al. [107] performed an experimental study to establish a relationship between joint strength and welding parameters welding (welding pressure, welding time, amplitude) when ultrasonically welding ABS (acrylonitrile butadiene styrene). Analysis of variances was used to identify crucial welding parameter states, and the response surface methodology's center composite approach was used to optimize the parameters that affect joint strength. According to the findings, the welding strength is most influenced by the amplitude value, followed by the quantity of weld pressure. Welding strength continues declining with fixed amplitude and welding time values after 0.3125 bar. This is because an increase in pressure decreases the relative motion between surfaces, which results in a smaller area of contact and, thus, a weaker bond. A maximum of 6.05 MPa was the optimized weld strength at 1.5 bar weld pressure, 1.25-s weld duration, and amplitude of 96.82 μm .

Apart from welding thermoplastic plates, several studies on applying ultrasonic welding techniques in joining 3D-printed thermoplastic plates have also been conducted in the last half a decade. Under the same survey, “Direct joining of 3D-printed thermoplastic parts to SLM-fabricated metal cellular structures by ultrasonic welding” was performed by Tang et al. [108] where 3D-printed ABS-M30i polymer parts were joined with metal cellular structured parts using ultrasonic welding technique resulting in enhanced micro-mechanical interlocking between adherend parts. On the same note, the hybridization of ultrasonic vibrations along with the fused filament fabrication technique was performed by Tofangchi et al. [109], documenting a 10% increase in interlayer adhesion in the printed parts.

7 Conclusion

In conclusion, the review of recent developments in ultrasonic welding of polymers and polymeric composites provides a comprehensive and insightful examination of advancements in the field over the past decade. The material-by-material approach adopted in this review offers a nuanced perspective on the evolution of ultrasonic welding techniques. By scrutinizing critical materials such as carbon fiber PEEK, carbon fiber PA, carbon fiber PPS, carbon fiber PEI, various GFRP, and common thermoplastics like ABS, PP, and PE, the review underscores the diversity and specificity required in welding methodologies.

The synthesis of findings from multiple studies reveals a dynamic landscape of innovations, addressing challenges and optimizing processes for each material category. The intricate balance between weld parameters, such as time and pressure, is a critical factor influencing weld quality. Moreover, integrating advanced materials like carbon fibers demonstrates the industry’s commitment to enhancing structural integrity and performance. As the review navigates through various studies, it highlights successes and identifies areas for future exploration, emphasizing the continual evolution of ultrasonic welding technology. The collective insights contribute to a richer understanding of the nuanced requirements of different materials, fostering advancements that hold promise for the broader field of polymer and composite welding in the years to come.

8 Future scope

The future scope of ultrasonic welding in polymers and polymeric composites encompasses several unexplored avenues that merit focused research and investigation. Despite extensive scrutiny in the past decade, certain critical areas still need to be explored.

One promising area involves joining thermoplastics and their composites under varying thermal conditions and surrounding media. Exploring ultrasonic welding’s efficacy in connecting polymer or polymeric composite pipes presents another intriguing dimension, considering the limited studies since [110]. CF/PEEK, a material under scrutiny for cryogenic fuel tanks, opens an uncharted realm. Despite its potential use by NASA, ultrasonic welding as a joining method for cryogenic applications needs more exploration. Investigating the welding of thermoplastics or their composites in very low temperatures, including cryogenic conditions, through the ultrasonic joining technique promises novel insights [111]. Furthermore, applying ultrasonic welding in water storage containers and pipes for domestic water transport using thermoplastics like PP, PE, and ABS requires more comprehensive comparative research. Additionally, addressing the research gap in joining dedicated GFRPs underwater becomes imperative, offering solutions for the rapid repair of submerged components without offshore interventions [112]. For electrically conductive CF/PEI, widely used in electronic components, a significant research direction involves investigating changes in electrical and thermal conductivity in the weld interface before and after ultrasonic joining [113]. Similarly, exploring the viability of ultrasonic welding for on-site repair of CF/PPS components in oil and gas industries, considering the presence of oil or other gases in the weld interface, still needs to be explored. Finally, delving into the effects on mechanical properties and microstructure evolution of 3D-printed CF/PA when welded using ultrasonic welding technique presents an uncharted territory [47]. Overall, these unexplored domains offer rich potential for advancing the application of ultrasonic welding in diverse and critical sectors.

Author contribution In the collaborative effort of this work, H. Chelladurai and K. Ponappa played critical roles in conceiving ideas and refining the manuscript’s format. Meanwhile, Sandeep Bose took charge of sourcing information and composing the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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