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Developments and future prospects of welding technology for carbon fiber thermoplastic composites

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ABSTRACT

Carbon fiber reinforced thermoplastic composites (TPCs) attracted significant attentions from the aerospace, transportation, and defense industries, due to their high specific stiffness and specific strength, outstanding thermal stability and good damage resistance, etc. As the demand of TPCs significantly increased for aerospace applications, the development of advanced joining technologies for TPC components becomes critical to ensure the structural integrity of aviation structures. This paper provides a comprehensive review of the historical development and recent advancements in welding technologies for TPCs, including ultrasonic welding, induction welding, resistance welding, and laser welding. Special emphasis is placed on ultrasonic welding due to its growing prominence in the field. The characteristics of various types of welding technologies for TPCs have been systematically discussed. Simultaneously, the strengths of the TPC joints manufactured by different welding technologies have been summarized and compared. The future development trend and research focuses for the welding technologies of TPC components are also proposed.

1. Introduction

With the urgent global demanding for green economy, consumption reduction and energy conservation become the most crucial goals in the manufacturing fields [1,2]. Currently, the development of light-weighting products is considered to be one of the most effective routes to achieve these goals. Carbon fiber reinforced composites have been widely applied in aerospace, transportation and energy industries, owing to their high strength-to-weight ratio, good corrosion resistance and structural performance, etc. [3,4]. Their applications grew rapidly in the last several decades [5]. In recent years, carbon fiber reinforced thermoplastic composites (TPCs) have attracted widespread attentions due to their high specific stiffness and strength, outstanding thermal stability, good damage resistance and recyclability, etc. when compared with their thermoset counterparts [6–8]. In particular, significantly expanded applications of TPCs in the aviation industries has been foreseen. For instance, TPCs have been applied to manufacture large-scale main load-bearing aircraft components in the EU Clean-Sky 2 projects “Thermoplastic affordable primary aircraft structure (TAPAS)” and “Multi-functional fuselage demonstrator (MFFD)” (Fig. 1). Noteworthily, in many cases, TPCs would be hybrid used with carbon fiber reinforced thermoset composites (TSCs) and metals to fabricate large-scale aviation components [9]. Thus, the development of advanced light-weight joining techniques between the TPCs and TSCs, and even metals become critical [10].

Currently, the aviation composite structures are mainly joined by mechanical fastening techniques, including bolted joining [11,12], clinching [13–15] and riveting [16–18], etc. Among them, bolted joining is most commonly used due to the advantages of easy assemble, disassemble and inspection. However, the overall weight of the structural components is considerably increased as a large number of metal bolts are used. Galvanic corrosion could occur to the bolted joints, due to the large electrical potential at the composite/metal bolt interface [19,20]. Furthermore, there is a significant stress concentration around

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bolting holes due to the fiber discontinuity after the drilling process [21]. As semi-permanent joining techniques, the clinching (including hole-clinched joining [13,22], mechanical clinching [23,24], etc.) and riveting techniques (including self-piercing riveting [25,26], electromagnetic riveting [17,27], and friction riveting [16,28], etc.) have the advantages of high efficiency, more achievable automation and relatively low cost, when compared with the bolted joining technique. However, the piercing process normally generates many types of defects in the composites, such as fiber fracture, matrix damage and delamination [26,29]. It significantly detriments the joint strength and stability of the integrated structures. Thus, it is less than optimal to fabricate light-weight TPC aviation components using mechanical fastening techniques.

Adhesive bonding is deemed as a light-weight technique that has been widely used to join aviation TPC structures. It could avoid composite drilling and adding additional fasteners. To date, remarkable research efforts had been made to optimize the adhesive bonding technique. In specific, secondary bonding [30–32] and co-bonding [33–35] are the main adhesive bonding processes for TPCs, while co-consolidation is a specific joining technique for TPCs that is similar as the typical co-curing bonding process of TSCs [36–38]. To date, several studies have reviewed the literatures on the adhesive bonding of TPCs, and it has been demonstrated that the inherently low reactivity, surface energy and polarity of TPC surfaces results in poor interfacial bonding with traditional epoxy adhesives [39–41]. Thus, the necessary strict surface treatment to TPCs, as well as the long-time curing process and depredated performance of epoxy adhesives under extreme conditions limit their aviation applications.

On account of the “meltable” characteristics of thermoplastic resins, TPCs could be joined by various fusion bonding/welding techniques. During a welding process, the heat is applied to soften and melt the thermoplastic resins at the joining interface of TPC substrates. At the meantime, a pressure is applied to ensure intimate contact at the joining area and sufficient intermolecular diffusion of melted polymer chains. After the interdiffusion process is finished, the interface between TPC substrates disappears and the joint is formed [41,42]. The foremost advantage of welding in thermoplastic composites is that no additional metal fasteners, composite drilling and strict surface preparation process are required, resulting in light-weight components with typical excellent structure integrity. According to the heat generation mechanisms at the welding interfaces, the welding techniques can be classified as friction welding (e.g., ultrasonic welding, spin welding, vibration welding, stir welding, etc.), electromagnetic welding (e.g., resistance welding, induction welding, dielectric welding, microwave welding, etc.), and thermal welding (e.g., laser welding, hot plate welding, hot gas welding, infrared welding, etc.) [41,43]. In general, the ultrasonic welding [44,45], induction welding [46,47], resistance welding [48,49] and laser welding [50,51] techniques are the most applicable welding techniques for TPCs. Among them, ultrasonic welding is deemed as a clean welding technique that requires no additional implants, whereas resistance and induction welding processes rely on conductive elements [52]. Furthermore, ultrasonic welding can minimize thermal damage to the composite adherends and eliminate the need for induction or resistance elements made form dissimilar materials, making it one of the most attractive technique for joining TPCs [53,54].

Until now, significant advancements in the welding processes of TPCs and their hybrid joints had already been obtained. While for the welding process of TPC-TSC hybrid joints, the main challenges are to achieve the meltability of TSC surfaces and to avoid thermal decomposition of the thermoset matrix in the TSCs during the welding process [55]. That has been recently overcome by applying/co-curing a layer of thermoplastic films onto the TSC surfaces [56–58]. In joining TPCs directly to metals by welding techniques, the difficulty is the large difference in the melting temperatures between metals and TPCs. Recently, many studies attempted to enhance the joining strength of TPC-metal hybrid welded joints by applying various techniques, with different levels of success achieved [59–61]. However, most of the previous studies have primarily focused on optimizing welding parameters and analyzing the interfacial melting behavior of TPC joints. In particular, for the ultrasonic welding, comprehensive reviews on optimal interfacial structure design, heat generation uniformity, and optimization mechanisms remain lacking.

This work examines the development history and latest research progress in welding techniques for aerospace TPCs, with a primary focus on advancements in ultrasonic welding. Additionally, recent advancements in the resistance, induction and laser welding techniques of TPCs are briefly summarized. The technical characteristics, advantages and disadvantages of various welding technologies have been systematically

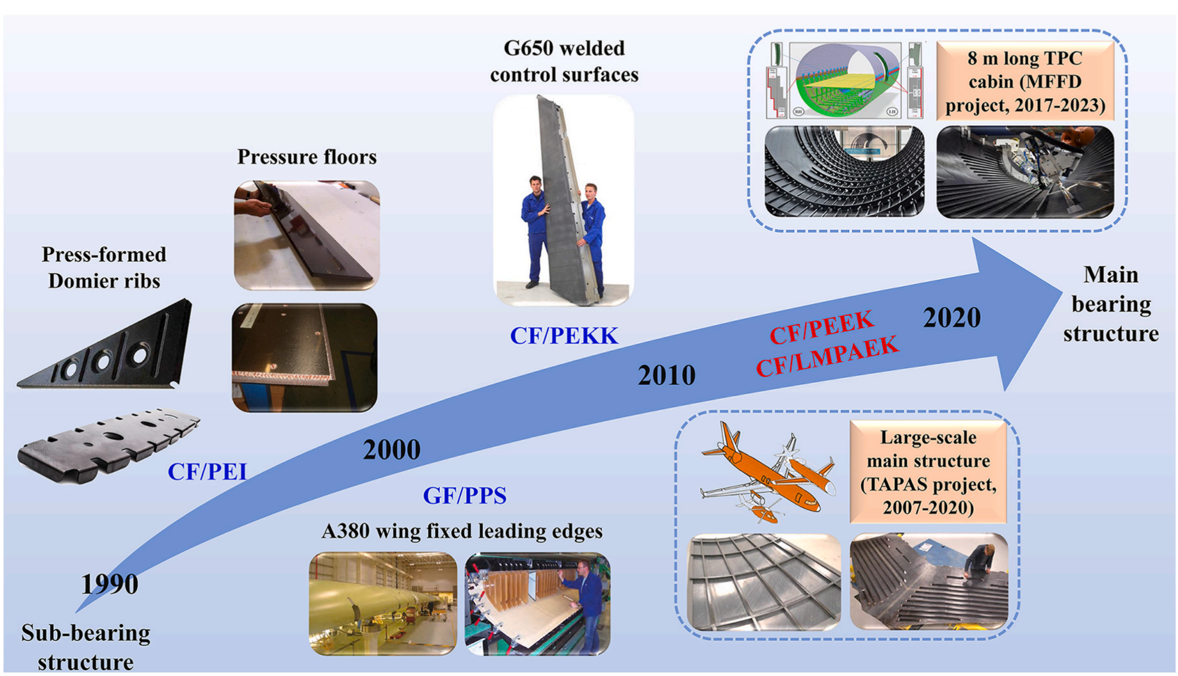

Fig. 1. Typical applications of thermoplastic composites in the field of civil aviation.

discussed. The achievements in the enhanced joint performance via optimizing the welding processes have been comprehensively compared and summarized. Moreover, the future prospects and application scenarios of the welding technologies for TPCs have been presented.

2. Ultrasonic welding

Ultrasonic welding possesses many advantages over the other welding techniques, such as lower joining time, simple operation, less damage of composite surfaces, good environmental protection and light-weighting joining, etc. [43]. Moreover, the ultrasonic welding process can be online monitored and intelligently controlled with a high degree of integration, and hence be considered to be an ideal joining technique for TPC components [62]. In recent years, its applications had been widely extended to the joining of advanced thermoplastics and their composite materials together with the rapid spreading demand of light-weight TPC structures in aviation industry.

2.1. Principle and critical parameters of ultrasonic welding

As schematically shown in Fig. 2(a), an ultrasonic welding equipment consists of ultrasonic generator, converter, booster, sonotrode and support platform, etc., while the functions of each part are summarized in Table 1. During the welding process, the high-frequency mechanical vibration can be effectively transmitted to the welding interface under a static compressive force, that triggers the heat generation and subsequent welding between TPC adherends. To concentrate heat generations at the welding interface, the energy directors (EDs) based on bulk thermoplastic resins that are identical or compatible with the TPC matrix are inserted into the welding interface [55]. The power and displacement versus time curves can be provided by the ultrasonic welding equipment, which offers the basis for analyzing the degree of thermoplastic resin melting at the interface. Based on the power and displacement versus time curves, the ultrasonic welding processes could be divided into five stages by Villegas et al. [63], namely interfacial heat generation (Stage I), local melting of the energy direction (Stage II), melting of the energy direction and resin extrusion (Stage III), resin melting of the composite surface (Stage IV) and resin melting inside the composite adherends (Stage V) (Fig. 2(b)). The identifications of welding stages can provide the basis for the process parameter optimizations and control of the welding process [64].

Table 1
Main functions of the above ultrasonic welding equipment structures [65].

Equipment structure	Main function
Ultrasonic generator	Convert the electrical power of 50–60 Hz into high-frequency electrical energy of 20–40 kHz (commonly 20 kHz for ultrasonic welding applications)
Converter	Convert the high-frequency electrical pulses into mechanical vibrations
Booster	Amplify the amplitude of the mechanical vibration obtained by the converter
Sonotrode	Transfer the mechanical vibration to the composite adherends
Adherend fixture	Hold the composite adherends in place to ensure good welding quality

The interface heat generation, i.e. stage I of the ultrasonic welding process has critical influences on the welding stages and the quality of welded joints. During the welding process, a high-frequency (commonly 20 kHz) ultrasonic vibration leads to intensive friction and heat accumulation at the contact area of the EDs and TPC adherends. The traditional EDs for ultrasonic welding are normally protruded bulk resins in a form of triangular, rectangular and semicircular shapes which were molded onto TPC surfaces. This type of EDs has small contact area with the adherends and hence the heat generation efficiency and uniformity

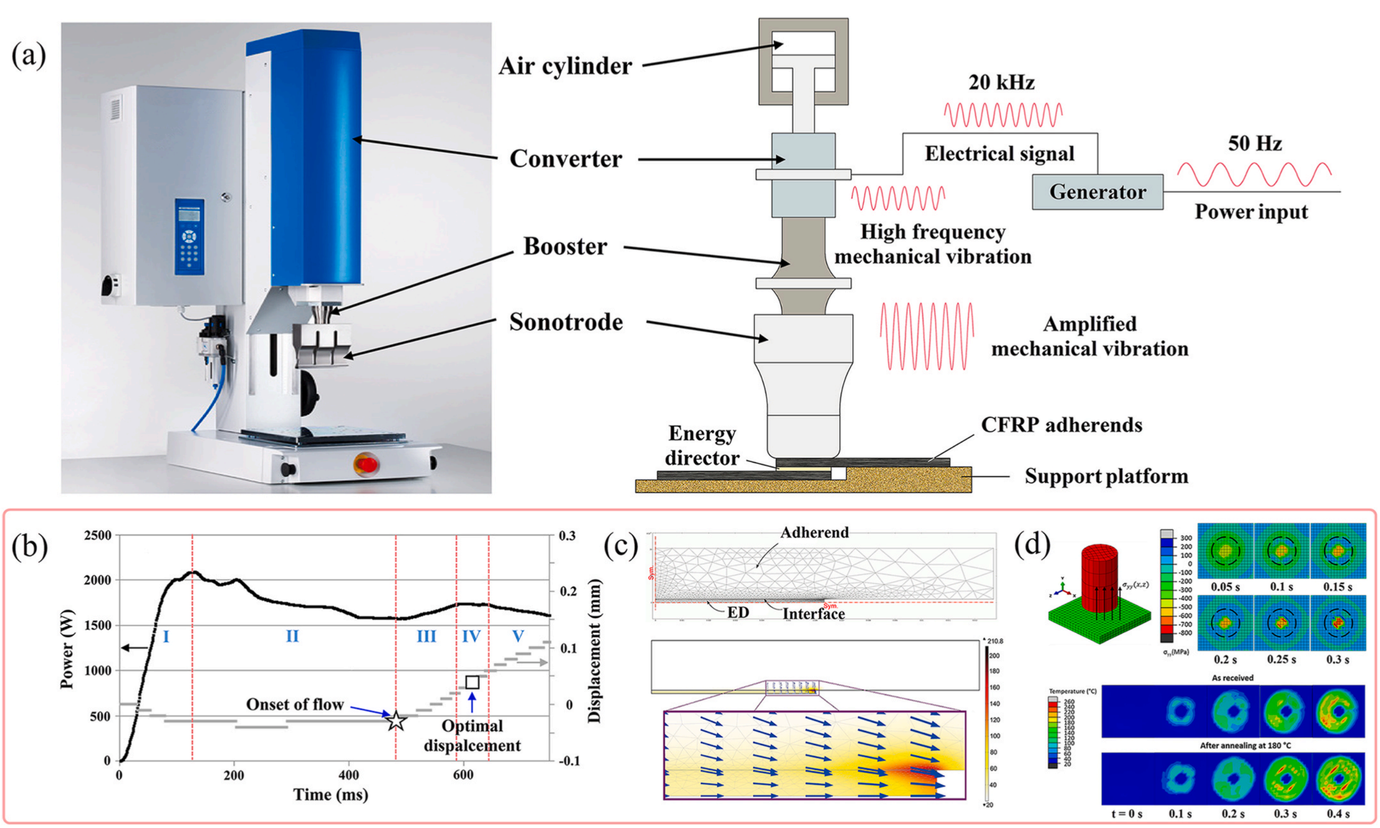

Fig. 2. (a) Schematic of the ultrasonic welding equipment structure [75]; (b) Representative power and displacement curves versus time during the ultrasonic welding process [64,76]; (c) and (d) Simulated results of the heat generation at the welding interface [73,74].

are relatively low. Moreover, the shape, size and orientation of EDs had significant influences on the heat generation and flow behavior of the melted resin at the interface [66–68]. Typically, extensive trials in the selection and design of traditional EDs are required to obtain high-quality welded joints. This issue had been nicely addressed by using a layer of flat thermoplastic films or meshes as EDs [69]. It was proved that flat EDs could enhance the levels and stability of frictional heat generation at the welding interface. Moreover, the sliding between the adherends reduces, and the frictional heat generation almost terminates as the temperature reaches T_g of thermoplastic resins. At that moment, the mutual friction between molecular chains of the melted resin rises and results in extensive viscoelastic heat generation. This phenomenon caused a high level of heat generation efficiency at the interface and provide high and consistent weld quality [70].

In stage II, the dissipated power versus time curves shows a stepwise decreasing trend with an almost constant welding displacement, which corresponds to partial melting and flow of thermoplastic resins at the interface [64]. After local ED melting completed in Stage II, the displacement of the sonotrode started to increase due to the melting and squeezing-out of melted resins in the stage III. Simultaneously, the power versus time curves raised again due to the increased mechanical impedance at the interface. In the stage IV of the welding process, the power versus time curves became relatively stable due to achieved balance between the power drop caused by the melting of adherend surfaces and power rise caused by the increased mechanical impedance after resin squeezing process [71]. Previous studies proved that the highest welding strength of the joints could be achieved if the welding process is terminated in the stage IV [71,72]. Once the ultrasonic welding process reached stage V, considerable heat transfer from the welding interface to the TPC substrates took place and over-heating at the edge of the welding interface due to the earlier onset of viscoelastic heat generation also occurred [73,74] (Fig. 2(c) and (d)). That would cause the thermal degradation of the epoxy matrix of the TSCs, and subsequently decrement the integrity of the welded joints.

Overall, carrying out effective regulation to welding parameters can achieve high-quality welded joints with good mechanical property. The critical welding parameters include control mode, frequency, amplitude and pressure, etc. Among them, the control mode can be divided into displacement-, time- and energy-controlled modes. The displacement-controlled mode is relatively stable due to the repeatable welding completion process [72]. Typical values and influences of different process parameters of static ultrasonic welding are presented in Table 2. Noteworthily, sequential and continuous welding processes were also developed for large-scale components with a long joining overlap [76, 77]. In this case, the sequential welding process can be controlled upon tailoring the welding position, sonotrode structure, etc., while the continuous welding can be optimized by adjusting the sonotrode structure, welding speed and pre-pressures, etc. [78,79]. Currently, both sequential and continuous welding techniques are still under development.

Table 2
Typical values and influences of the process parameters of static ultrasonic welding [43,80,81].

Process parameter	Typical value	Main influence
Welding displacement	Close to ED thickness	Determines the total energy input into the welding interface and the right time to complete the welding process
Welding time (s)	0.5–5	
Welding energy (J)	200–1500	
Frequency (Hz)	20–50	Affects the frequency of relative motion between adherends
Amplitude (μm)	50–85	Affects the intensity of relative motion between adherends
Welding pressure (N)	300–1500	Affects the vibration transfer from sonotrode to top adherends
Adherend thickness (mm)	0.5–6	Affects the vibration process and the attenuation behavior
Surface structure of the sonotrode	/	Affects the energy concentration at the welding interface

2.2. Ultrasonic welding of thermoplastic composites

Ultrasonic welding started to attract significant attentions by the academic and engineering community since the application of thermoplastic resins and their composites has grown rapidly in the aircraft primary structures. Villegas's group at Delft University of Technology firstly investigated the effects of critical parameters such as ED structure, pressure, amplitude, and welding control mode on the ultrasonic welding process of TPCs [66,67,72,82–84], and managed to enhance the joint strength by parameter optimization. A number of studies investigated the impacts of critical welding parameters on the temperature evolution at the welding interface and the weld strength, involving the use of polyetherimide (PEI) films as EDs (Fig. 3(a)). It was demonstrated that a shorter welding time could be obtained by optimizing the welding pressure and vibration amplitude, although a relatively high temperature close to 580 °C was achieved. This ensured sufficient diffusion of the molecular chains of melted PEI at the interface without matrix thermal degradation, resulting in a maximum lap shear strength (LSS) of about 49 MPa. Selected research advances in the ultrasonic welding of TPCs are presented in Table 3. It could also be found that the displacement-controlled mode was the most widely used, which exhibited normally the best joint strength [72].

A remarkable progress made by Villegas's group was that they introduced flat thermoplastic films as EDs for TPC ultrasonic welding. It was found that flat EDs led to more adequate heat generation and resin impregnation at the welding interface, when compared to traditional triangular, rectangular and semicircular EDs (Table 3). This could potentially widen the welding process window of TPCs, and hence offer more flexibility in parameter regulations [45]. However, the flat EDs led to more significant temperature differences between the edge and interior of the welding area, which negatively affected the uniformity of welding-line quality. This problem became more serious for the continuous ultrasonic welding, during which, significant flow and extrusion inhomogeneities of melted EDs occurred at the welding interface.

To overcome these issues, EDs based on thermoplastic meshes were developed in recent years by Jongbloed et al. for the spot ultrasonic welding process [86]. It could be found that high welding strength close to that of using flat EDs could be obtained (Table 3). It was also proved that the use of thermoplastic meshes as EDs could effectively avoid excessive resin melting and carbon fiber extrusion and improve the temperature uniformity at the welding line (Fig. 3(b)). However, un-melted resins often occurred at the center of the welding area while using mesh EDs, since it firstly melted from the edges of the welding area during the welding process. Thus, it is critical to supply a sufficient number of thermoplastic resins at the welding interface to prevent inhomogeneous welding-line microstructures. EDs based on thermoplastic meshes were also applied for continuous ultrasonic welding of TPCs [79,85,93]. It was proved that the mesh EDs underwent larger strains during welding process than flat EDs, resulting in better heat generation efficiently and more uniform resin melting at the interface (Fig. 3(c)). That significantly mitigated the non-uniformity of heat generation and ED extrusion phenomenon at the interface. However, the LSS of continuously welded joints was remarkably lower than that of statically welded joints, which was attributed to the pore defects within the welding area. More recently, ultrasonically welded TPC joints incorporating thermoplastic embossed EDs have been further developed. This approach has been shown to enhance the temperature distribution uniformity at the welding interface to some extent, thereby improving the quality of TPC welded joints [81,92]. However, the heat generation efficiency still requires further optimization.

Notably, continuous ultrasonic welding was successfully implemented in 2024 for joining the right longitudinal seam of upper and

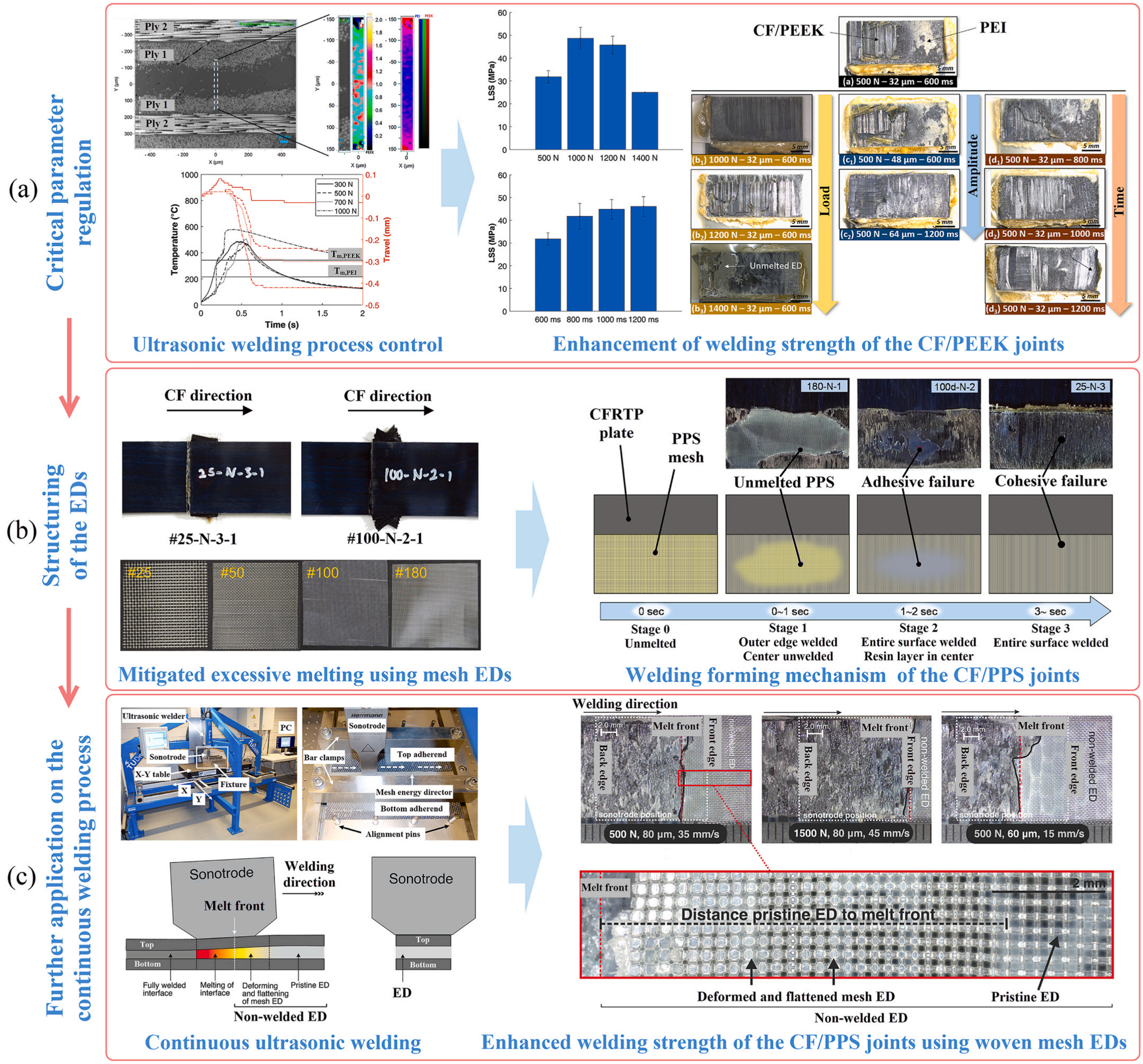

Fig. 3. (a) Enhanced welding strength of the CF/polyetheretherketone (PEEK) joints by critical ultrasonic welding parameter regulation; (b) Mitigated excessive melting behavior and improved welding strength of CF/Polyphenylene sulfide (PPS) joints by applying structured EDs; (c) Enhanced welding strength of CF/PPS joints obtained by continuous ultrasonic welding process using woven mesh EDs [45,85,86].

lower fuselage shells of the MFFD, forming an integrated fuselage section measuring 8 m in length and 4 m in diameter [94]. This achievement represents the largest TPC aircraft fuselage segment to date, highlighting the significant potential of ultrasonic welding for large-scale aviation applications. To fully realize this potential, further systematic studies are required to ensure the stability and reliability of ultrasonic welding of TPC structures, particularly in sequential and continuous ultrasonic welding. In particular, given the rapid processing time and high parameter sensitivity of ultrasonic welding, establishing a reliable strategy or guideline is crucial to achieving consistent welding quality and joint strength. Such guidelines can serve as the foundation for online monitoring and intelligent control of ultrasonic welding in aircraft TPC structures. Furthermore, optimizing the surface structure and resin-rich layer of TPCs, along with the use of structured thermoplastic EDs, may serve as effective strategies to enhance joint performance and broaden the optimal processing window. These advancements can further improve the applicability and reliability of ultrasonic welding in aerospace manufacturing.

2.3. Ultrasonic welding of thermoplastic to thermoset composites

Ultrasonic welding had been recently extended for the joining of hybrid TPC-TSC structures, considering the wide application potentials of these hybrid joints in large-scale aviation components [9]. However, the foremost challenge was that the TSCs based on highly cross-linked thermoset matrix are not meltable or weldable. This could be overcame by applying a thermoplastic resin layer, i.e. coupling layer (CL) onto the TSC surfaces by a co-curing process [56,57,95–97]. A number

Table 3
Summary of selected researches on the ultrasonic welding of TPC-TPC joints.

Year	Joint adherend	ED	Factors studied	Control mode	Welding pressure	Amplitude (μm)	Time (s)	Optimal strength	Ref.
2010	CF/PEI	Triangular PEI	Multiple transverse EDs	Time	4.0 MPa	50.0	3.500	40.1 MPa	[82]
2014	CF/PEI	Flat PEI (0.25 mm)	Welding pressure and amplitude	Displacement	300 N	86.2	0.724	37.3 MPa	[72]
2015	CF/PPS	Triangular/Flat PPS (0.4 mm)	ED type	Displacement	500 N	86.2	~0.500	37.1 MPa	[66]
2016	CF/PPS	Flat PPS (0.08 mm)	Joint Structure	Displacement	1000 N	86.2	NA	36.5 MPa	[83]
2017	CF/PPS	Triangular PPS	ED type	Displacement/ Energy	500 N	86.2	0.434	34.2 MPa	[67]
2017	CF/PEI	Flat PEI (0.06, 0.25, 0.5 mm)	ED thickness	Displacement	500 N	86.2	0.650	37.3 MPa	[84]
2018	CF/PPS	Flat PPS (0.25 mm)	Welding control mode	Displacement/ Energy	1500 N	60.8	~0.500	7037.5 N	[76]
2018	CF/PPS	Flat (0.08 mm) /Mesh PPS (0.20 mm)	ED type	NA	500 N	82.5	~0.550	33.7 MPa	[77]
2019	CF/PEEK	Flat PPS (0.45 mm)	Welding time and application of EDs	Time	0.3 MPa	25.0	0.900	28 MPa	[87]
2020	CF/Elium®	Flat Elium® (0.5 mm)	ED type	Time	0.4 MPa	49.0	1.000	18.86 MPa	[68]
2020	CF/PPS	Mesh PPS (0.2 mm)	Welding pressure and amplitude	Time	1500 N	80.0	~0.960	38.0 MPa	[85]
2021	CF/PEEK	Flat PEEK (0.24 mm)	Fiber orientation	Displacement	3.1 MPa	86.2	0.340	37.4 MPa	[88]
2021	CF/PPS	Mesh PPS (0.51 mm)	Mesh size of the EDs	Time	1.1 MPa	NA	3.000	34.1 MPa	[86]
2022	CF/PEEK	Without ED	Welding energy	Energy	150 N	56.0	~0.750	5000 N	[89]
2023	GF/PPS	Flat PPS (0.37 mm)	Displacement	Displacement	500 N	53.2	NA	18.4 MPa	[90]
2024	CF/PEEK	Embossed PEEK	Surface structure and welding time	Time	0.3 MPa	70.0	1.500	~8000 N	[81]
2024	CF/PEEK	Embossed PEEK	ED structure and welding time	Time	800 N	72.4	1.000	39.6 MPa	[91]
2024	CF/PEI	PEI	Thickness of ED and extra resin layer on the TPC surface	Displacement	1000 N	80.0	0.520	45.9 MPa	[92]

of studies had reported that CL-topped TSCs were more sensitive to the welding parameters than TPCs (see Fig. 4(a)). This is mainly because of the matrix of TSCs (typically being epoxies) are more prone to thermal decomposition during the welding process [58]. Moreover, the TSCs based on brittle matrix are easier to fail under the large peel stress concentration at the edge of the welding overlap. Consequently, the ultrasonic welding processing window of the TPC-TSC joints is relatively narrower.

Previous studies mainly focused on the effects of the processing parameters, the ED and CL thicknesses on the ultrasonic welding process of TPC-TSC joints [55,98]. Table 4 presents the selected research advances in the TPC-TSC ultrasonic welding. One can observed that relatively larger welding pressure and amplitude were desirable for the ultrasonic welding of TPC-TSC hybrid joints. This was done to shorten the welding time and consequently mitigate the risk of thermal decomposition of the TSC matrix. In general, it is well accepted that applying EDs led to better heat generation efficiency at the welding interface and higher strength of the TPC-TSC joints, as shown in Fig. 4(b) [55]. Additionally, the optimal process window could be broadened by applying thicker CLs, since it acts as an effective thermal barrier to avoid the thermal decomposition of the TSC matrix, see Fig. 4(c) [98].

To address the greater sensitivity of CL-topped TSCs to welding parameters compared to TPCs, structured EDs fabricated from thermoplastic films have been developed in recent years for ultrasonic welding of TPC-TSC joints. Studies have shown that the use of structured hollow-mesh EDs with uniformly distributed holes improves temperature distribution uniformity across the welding interface, resulting in more consistent welding lines and preventing thermal decomposition of the resin matrix in TSCs [105]. This, in turn, enhances the welding-line quality and joint strength of TPC-TSC welded structures. Moreover, temperature distribution uniformity can be further optimized by employing variable-flexibility structured hollow-mesh EDs, which feature increased flexibility at the edges to mitigate overheating, a common issue in the peripheral regions of the welding area [106].

The development of ultrasonic welding process for the TPC-TSC hybrid welded joints is still in its early stage, with no reported engineering applications to date. In fact, research on this topic remains limited. To advance this technique, several challenges inherent to conventional ultrasonic welding must be addressed, including non-uniform heat generation at the welding interface, pore defects caused by trapped air, fiber squeezing and bending, and thermal decomposition of the resin matrix. Optimizing the ED structure presents a promising approach to mitigating these issues. Additionally, it is essential to develop methodologies for preventing thermal decomposition of the TSC matrix by refining process parameters and tailoring the thickness and structure of CLs. Furthermore, systematic studies on the sequential and continuous ultrasonic welding process for TPC-TSC hybrid joints are needed, along with advancements in industrial automation, to facilitate their application in large-scale aerospace structures.

2.4. *Ultrasonic welding of thermoplastic to metal*

With the significantly increased demands of TPCs and light-weight alloys for aviation applications, high-quality TPC-metal hybrid joints have been attractive development goals over the last few decades [107–109]. Table 5 presents the selected research advances in the ultrasonic welding of TPC-metal joints. It could be found from that the welding pressure was commonly lower than that of TPC-TPC/TSC welded joints, and the EDs or CLs were not generally applied. In such a case, only TPC side melted and filled the pores and structures of the metal surfaces during the welding process. Therefore, the obtained TPC-metal joint strength is typically low, compared to that of the ultrasonically welded TPC-TPC and TPC-TSC joints in Tables 3 and 4 That was attributed to the intrinsic low surface energy of thermoplastic resins and hence poor chemical adhesion with the metal substrate at their interface. Thus, it is necessary to apply appropriate surface treatment to the metal substrate prior to the ultrasonic welding process.

In general, the strength of the ultrasonically welded TPC-Al joints could be enhanced by optimizing the surface micro-structures of the Al adherend, which was achieved by using various machining methods, including laser ablation, 3D printing and micro-forming techniques [112]. It was proved that the welding strength of the TPC-Al hybrid joints was comparable to the reference adhesive bonded joints with a much shorter process time when the Al substrate was laser ablated

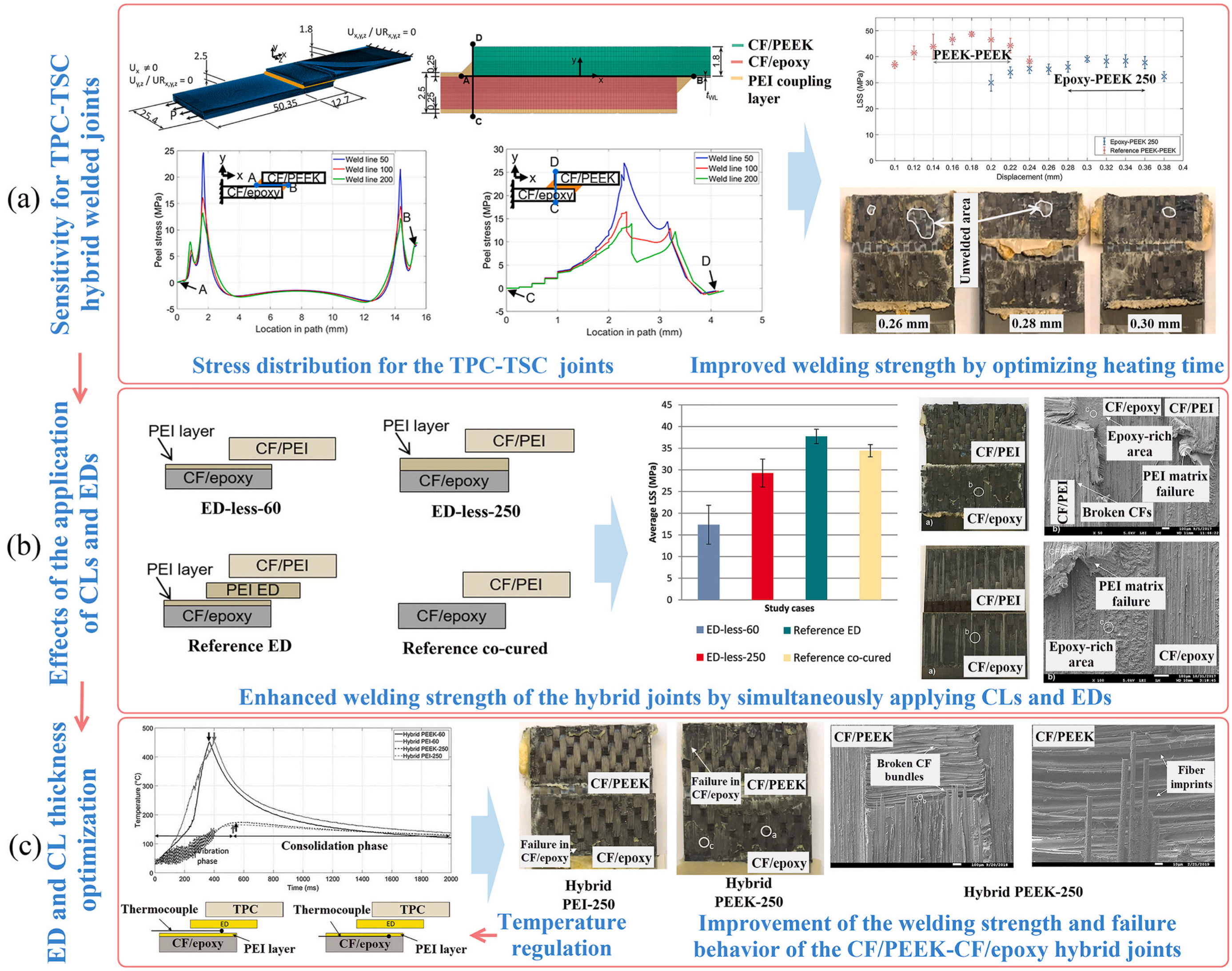

Fig. 4. (a) Stress distribution for the CF/PEEK-CF/epoxy hybrid welded joints and sensitivity of the welding strength for the hybrid welded joints to the heating time; (b) Effects of the application of CLs and EDs on the welding strength of the CF/PEI-CF/epoxy hybrid welded joints; (c) Improvement of the welding strength and failure behavior of the CF/PEEK-CF/epoxy hybrid joints by the optimization EDs and CLs [55,58,98].

(Fig. 5(a)). Additionally, the ultrasonically welded hybrid TPC-Al joints exhibited a cohesive failure within the welding area, indicating good interface adhesion. Nevertheless, excessive weakening of the composite adherends due to deep laser-ablation is still considered to be an issue. Moreover, the joint strength was still not comparable with the requirements of primary load-bearing aircraft structures. This was mainly because of the joint strength was dominated by mechanical interlocking without chemical interactions at the TPC/Al interface. Additionally, the environmental ageing resistance and fatigue properties of this type of joints would also be an issue for long term aerospace applications. Recently, the ultrasonic welding of TSC-Al joints was also carried out by some researchers [116]. In particular, a layer of PA6 film was applied onto the surface of the TSCs through a co-curing process, that was considered as a functional surface layer to realize their weldability during the ultrasonic welding process (Fig. 5(b)). It had been proved that the thermoplastic resins at the welding interface could be fully extruded by regulating the critical parameters of the ultrasonic welding process. In that case, the carbon fibers were in direct contact with the Al substrate and locally embedded in the surface microstructures of the Al substrate within the TSC-Al joints. Moreover, the contact surface of the Al was plastically deformed, therefore enhancing the welding strength of TSC-Al hybrid joints.

The current ultrasonically welded TPC-metal joints exhibit relatively low joint strength and poor mechanical stability due to the absence of chemical interactions at the TPC/metal interfaces. To address this limitation, developing appropriate surface treatment processes for metal adherends that enahnce chemical or hydrogen bonding at the interface is crucial. Further research should focus on establishing and investigating interfacial bonding mechanisms and corresponding enhancement methods between metals and thermoplastic resins. Additionally, the sequential and continuous ultrasonic welding processes for TPC-metal hybrid joints must be developed to meet the demands of assembling large-scale TPC-metal components. Furthermore, the interface formation mechanisms underlying ultrasonic welding of TPC-metal hybrid joints remain unclear and should be further explored through modeling and numerical simulation approaches.

3. Resistance welding

Resistance welding is a relatively mature welding technique for the bonding of TPCs. A conductive element is placed at the overlapping area of two TPC adherends, and then connected with an electric power supply. During the welding process, resistance heating is generated as the electrical current passing through the conductive element, see Fig. 6

Table 4
Summary of selected researches on the ultrasonic welding of TPC-TSC joints.

Year	Joint adherend	ED	CL	Factors studied	Control mode	Welding pressure	Amplitude (μm)	Time (s)	Optimal strength	Ref.
2015	CF/PEEK-CF/epoxy	Flat PEEK (0.25 mm)	PEEK (0.25 mm)	Welding pressure and amplitude	Displacement	1500 N	90.0	0.460	29.6 MPa	[99]
2018	CF/PEEK-CF/epoxy	Flat PEEK (0.25 mm)	PEI (0.06 mm)	ED type	Displacement	1500 N	86.2	NA	44.8 MPa	[100]
2018	CF/PEEK-CF/epoxy	Flat PEI (0.25 mm)	PEI (0.05 mm)	Composite adherend type	Displacement	2000 N	73.4	0.421	28.6 MPa	[101]
2019	CF/PE-CF/epoxy	Flat PEI (0.25 mm)	PEI (0.06 mm)	The use of EDs and CL thickness	Energy	1500 N	86.2	~0.300	37.7 MPa	[55]
2020	CF/PEI-CF/epoxy	Flat PEEK (0.25 mm)	PEI (0.25 mm)	ED type and CL thickness	NA	1500 N	86.2	~0.600	40.8 MPa	[98]
2021	CF/PEEK-CF/epoxy	Flat PEEK (0.25 mm)	PEI (0.175 mm)	Welding pressure and amplitude	Displacement	800 N	86.0	~0.600	40.2 MPa	[57]
2021	CF/PEEK-CF/epoxy	Flat PEEK (0.25 mm)	PEI (0.175 mm)	CL thickness	Displacement	1200 N	86.0	0.461	39.1 MPa	[95]
2022	CF/Elium®-CF/epoxy	Flat PMMA	PMMA	Welding time and pressure	Time	0.5 MPa	75.0	2.000	8.56 MPa	[102]
2024	CF/PEI-CF/epoxy	Flat PEI	PEI (0.900 mm–0.250 mm)	ED and CL thickness	Displacement	1000 N	80.0	0.497	35.3 MPa	[103]
2024	CF/PEI-CF/epoxy	Flat PEI	PEI (0.175 mm)	ED thickness and displacement	Displacement	1000 N	80.0	0.498	39.4 MPa	[104]
2025	CF/PEI-CF/epoxy	Structured PEI	PEI (0.250 mm)	ED structure and displacement	Displacement	1000 N	80.0	0.351	38.2 MPa	[105]
2025	CF/PEI-CF/epoxy	Structured PEI	PEI (0.175 mm)	ED structure and displacement	Displacement	1000 N	80.0	NA	40.3 MPa	[106]

Table 5
Summary of selected researches on the ultrasonic welding of TPC-metal joints.

Year	Joint adherend	ED	Surface layer	Factors studied	Control mode	Welding pressure	Amplitude (μm)	Time (s)	Optimal strength	Ref.
2009	CF/PA6-AA5754	/	/	Alloy composition	Energy	140 N	38.0–42.0	NA	31.5 MPa	[110]
2013	CF/PA6-Al	/	/	Alloy composition and heat treatment	Energy	NA	38.0–42.0	NA	58 MPa	[111]
2018	ABS-M30i-metal cellular	/	/	Welding time	Time	0.15 MPa	147.0	0.300	17.7 MPa	[60]
2019	GF-CF/PEEK (PPS) -AA5024	/	/	Welding pressure and amplitude	NA	300 N	40.0	0.520	8310 N	[61]
2019	CF/PA6-Al6061	Flat PA6 (0.24 mm)	/	Heat treatment of the alloy	Displacement	500 N	34.5	~1.000	~15 MPa	[112]
2020	CF/PEEK-AA5024	/	/	NA	Energy	NA	NA	NA	64 MPa	[113]
2021	CF/PA12-AA6061	/	PA11 (0.5 mm)	Surface treatment, time, and pressure	Time	0.5 MPa	NA	0.900	14.52 MPa	[114]
2023	CF/PA66-AA6061	Embossed PA66	PA6	Surface treatment and the use of ED	Time	600 N	60.0	0.600	31 MPa	[108]
2024	CF/PA6-5052 Al	/	/	Time and temperature compensation	Time	0.3 MPa	39.0	1.500	2480.4 N	[115]

(a). The thermoplastic resins at the bonding interface would then melt as the interface temperature gradually increase above their melting points, that initiated the interdiffusion of melted polymer chains under pressure until the interface fully connected.

Since 1990s, a large number of studies had investigated the impacts of resistance welding parameters, such as welding current, heating time and welding pressure on the welding quality of CF/PEEK, CF/PEI CF/PA, CF/PPS and CF/polypropylene (PP) joints [117–128]. As expected, the welding current and heating times had significant influences on the heat generations at the welding interface and hence affected the joint strength. In general, a relatively low welding current and short heating time led to non-sufficient melting of the welding interface [129], while excessive welding current or heating time could lead to joint strength reduction due to resin overheating or even decomposition. The application of a proper welding pressure to the joining area could promote composite deformation, molecular diffusion and extrusion of air at the interface during the resistance welding process, which is considered to be necessary for consistently producing sturdy and ideal TPC joints [130]. It was proved that decreased joint strength could be obtained by applying low welding pressure, which could be attributed to a large number of voids formed at the welding interface. In contrast, the porosity could be effectively eliminated as the welding pressure increased. However, if the welding pressure was too high, the final thickness of TPC substrates was somewhat lower than the initial value due to the excessive deformation of carbon fibers and squeeze flow of matrix resins in TPCs during the welding process. In this case, the mechanical performance of TPC joints, especially fatigue properties, would significantly drop.

The material and form of the conductive element is another key factor that had prominent effects on the welding quality and controllability of the resistance welded TPC joints [131–133]. To date, carbon fiber prepregs and metal meshes are the most prevalent conductive elements for the TPC resistance welding in the literatures and for the engineering applications. In 1988, researchers begun to use composite prepregs as conductive elements for the resistance welding, such as CF/PEEK, CF/PEI and CF/PP prepregs, etc. [119–121,134–137]. However, the resistivity within the carbon fiber prepreg exhibited a large scatter, which led to non-uniform current and heating generation at the

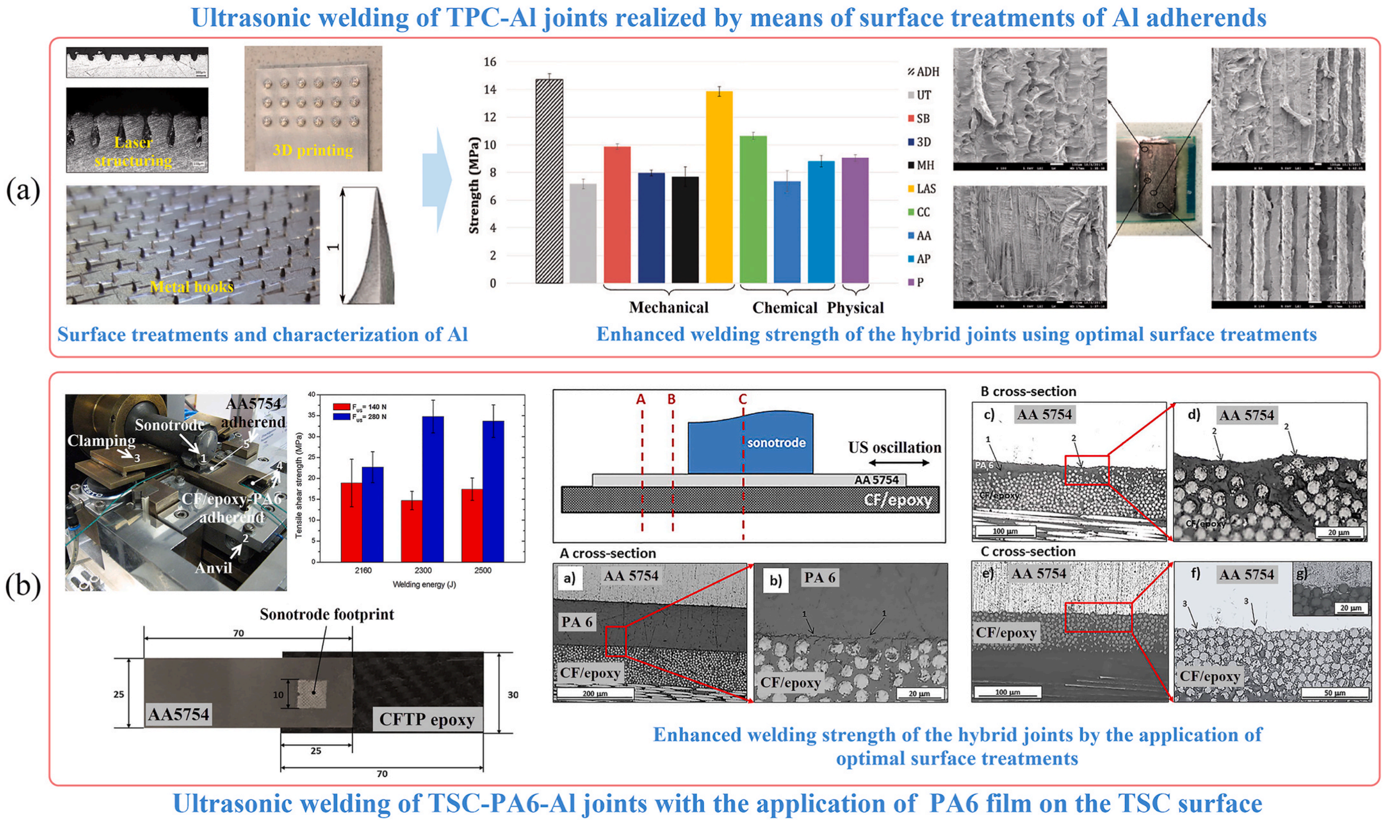

Fig. 5. (a) Enhanced welding strength of CF/PA6-Al welded joints by optimal surface treatments of Al; (b) Enhanced welding strength of CF/epoxy-Al welded joints using PA6 film on TSC surfaces [112,116].

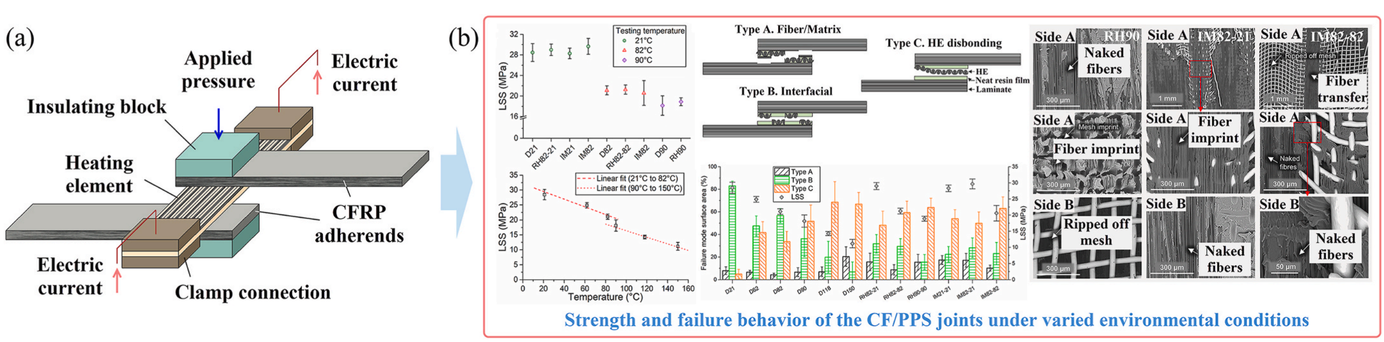

Fig. 6. Schematic of (a) the resistance welding and strength and (b) corresponding failure behavior of the CF/PPS welded joints [128].

welding interface. This caused local overheating and resin decomposition within the bonding area and subsequently detriment the welding strength of TPC joints. To improve the consistent quality of conductive elements and consequently achieve reliable performance of welded joints, comparative researches between the above types of carbon fiber prepreg and metal mesh conductive elements had been performed since 2000s [138,139]. It was found that the use of stainless-steel mesh as conductive element led to better heating consistency at the welding interface and higher strength of TPC joints than the carbon fiber prepreg conductive element. Moreover, good bonding between the mesh conductive elements and thermoplastic resins was observed on the fracture surfaces of TPC joints [140,141]. However, it is noteworthy that the stainless-steel meshes remained in the welds could negatively affect the mechanical performance of the TPC joints under long term hydrothermal ageing, thermal cycling and fatigue loading conditions. For instance, obvious debonding of heating element from the matrix was observed for the resistance welded TPC joints under severe environmental conditions with high testing temperature and humidity (Fig. 6(b)) [128]. Simultaneously, the failure mode of the TPC joints also involved the debonding of the fiber/matrix interface within the composite substrate. These interfacial debonding phenomena resulted in considerably degraded LSS of the TPC joints. Recently, seveal researchers have explored the use of carbon nanotube (CNT) web/film and CNT-modified thermoplastics as conductive elements in welding processes [142–147]. Among these approaches, CNT-modified thermoplastics, which exhibit superior interfacial compatibility with TPC substrates, have shown particular promise in enhancing the uniformity of heat generation. For example, resistance welding using CNT-modified thermoplastics as conductive elements demonstrated a highly uniform temperature distribution around the heating element, with a typical temperature variation of less than 5 °C [145]. This improved uniformity resulted in enhanced welding-line quality and a significant increase in the LSS of TPC joints-up to 2.3 times higher than that of joints without CNT-modified thermoplastics at the welding interface [146]. Such advancements may not only improve joint performance but also reduce welding time, thereby increasing overall process efficiency. However, the significant CNT agglomeration and poor CNT/resin interface adhesion could negatively affect the TPC joint strength. Accordingly, further development and systematic studies on the topic of resistance welding using CNT based resistance elements are still needed.

Overall, after a few decades of development, resistance welding has been successfully applied for the joining of thermoplastic pipes, medical devices, and wind turbine blades, etc. For example, the skin and ribs of wing leading edges in Airbus A340 and A380 were resistance welded together using metal meshes as conductive elements [125,127]. However, the compatibility between the conductive elements and TPCs and the homogeneity of heating generation at the welding interface are difficult to be simultaneously improved. Accordingly, the development of novel conductive elements with physical and chemical properties similar to those of TPCs represents a key trend in advancing resistance welding techniques. Additionally, despite progress in industrial automation, automated resistance welding remains at a relatively low maturity level and requires further development. Moreover, previous research has primarily focused on static resistance welding, which poses feasibility challenges for large-scale or high-aspect-ratio components, such as joints and stringers in aircraft structures. To address these limitations, continuous resistance welding has emerged as a promising approach for future advancements, offering improved feasibility for large-scale applications.

4. Induction welding

Induction welding is a non-contact technique that uses electromagnetic induction to heat TPCs. A radio-frequency electric current is applied to an induction coil, which generates a high-frequency electromagnetic field that acts on the electrically conductive elements in the TPCs, as shown in Fig. 7(a). Three typical heating generation mechanisms have been reported, including Joule losses due to intrinsic resistance heating of fibers, dielectric heating due to the movement and line up of molecules between the fibers and contact resistance heating that occurs on the high fiber-fiber contact points [148]. During the induction welding process, the thermoplastic resins at the welding interface would be melted as the heat accumulation and then the molecular chain entanglement initiates under pressure until the welding interfaces fully connected.

Induction welding has been widely applied for joining the TPCs in the last two decades, and a large number of studies systematically investigated the effects of welding parameters on the welding quality and joint strength [43]. In general, the input power, frequency and welding pressure are found to be the critical processing parameters [149]. Among them, the input power has direct effect on the welding time. A low level of input power normally results in relatively poor heat generation efficiency at the welding interface and consequently a long welding time [150–152]. However, an overhigh input powder could cause overheat of the TPCs and massive resin extrusions, which reduce the welding quality and strength of TPC joints. Frequency is another critical parameter that had significant influences on the welding process and quality. As the frequency increased, the heat generation efficiency at the welding interface could be correspondingly improved, thus leading to shorter welding time [153]. Nevertheless, applying an over high frequency would increase the overheating risk of the TPC adherends. In addition to that, a moderate welding pressure is also essential to sufficiently squeeze out the trapped air at the welding interface and ensure a good welding quality [154]. It should be aware that if the welding pressure is too high, the resin melt at the interface would be excessively squeezed out and detriment the welding strength of TPC joints.

Similar as resistance welding, the graphite and carbon fibers can also be used as conductive elements instead of metal ones, while the large resistivity difference between these conductive elements and the matrix of the TPCs led to considerably uneven heating generation at the welding interface [149]. Consequently, local overheating could easily occur within the welding interface and generate defects, such as fiber bending and pores due to resin decomposition. To overcome this issue, new conductive elements composed of thermoplastic resins and ferromagnetic particles (e.g. iron) had been developed [155,156]. These conductive elements significantly shortened the welding time and promoted the weld quality, as compared to that of ordinary ones. However, the presence of ferromagnetic particles formed small cracks within the welding region and negatively affected the strength of TPC joints. It should be noted that the edge effect and local heating effect could also cause noticeable defects within the joints, especially for the induction welding of large-scale components. Hence, it is key to further improve the stability of induction welding for TPCs. With these purposes, researchers managed to improve the welding uniformity and stability of TPC joints by applying a layer of thermoplastic films on the TPC substrates (see Fig. 7(b)). Furthermore, an accurate modeling of temperature distribution in TPC adherends during the welding process was performed according to the electromagnetic field. The heat transfer, and melting and crystallization of the resins at the interface during the welding process of TPCs could be then regulated for expanding the optimal processing window.

Until now, induction welding has been successfully applied for the joining of large-scale TPC structures, such as the empennage of Gulfstream G650, taking advantage of higher welding strength than resistant welded joints [125,157]. Nevertheless, the metal conducting element that possessed significant different physical and mechanical properties as the TPC adherends would remain in the welded joints, while the uniformity of the heating generation is relatively poor by using graphite or carbon fiber conductive elements. These issues limit the further aviation applications of induction welding for the aviation TPC structures. Thus, the development of conductive elements with high heat generation efficiency and strong compatibility with TPCs has become a key focus in advancing induction welding techniques. Additionally, the dominant heat generation mechanism among the three proposed

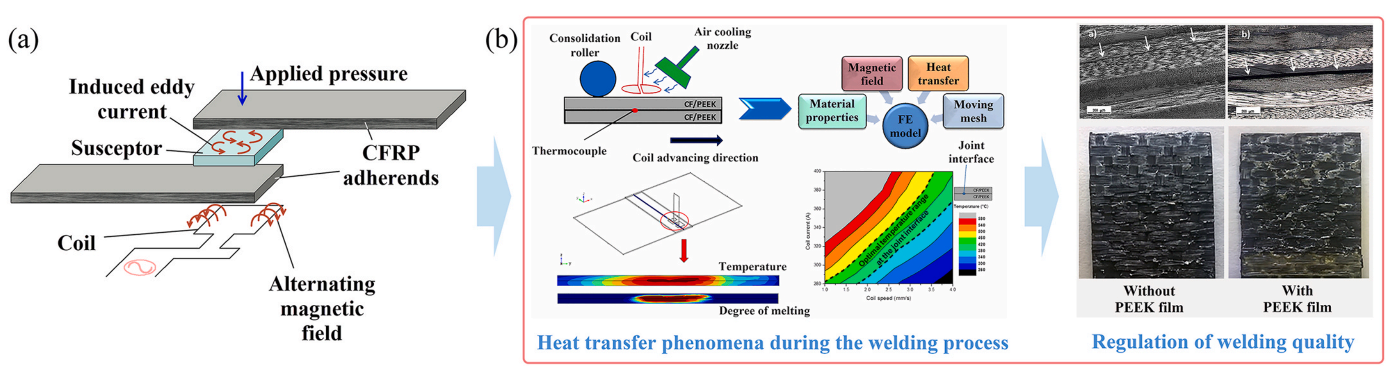

Fig. 7. Schematic of (a) the induction welding and heat transfer and (b) enhanced welding quality of the CF/PEEK welded joints [149].

mechanisms in induction welding remains unclear and requires further investigation. Another critical aspect for the advancement of induction welding is process modeling, which is still in its early stages and requires further refinement. A well-developed modeling framework could provide a deeper understanding of heat generation mechanisms and help establish optimal processing windows by evaluating the effects of key parameters on joint quality.

5. Laser welding

As another non-contact welding technique, laser welding is also an attractive technique for the welding of TPCs. It exhibits considerable advantages over the other techniques, such as fast welding speed, low mechanical stress and no requirements of conductive elements, etc. [158,159]. Laser transmission welding has been considered as the most widely studied laser welding technique for the joining of TPCs. Fig. 8(a) presents the illustration of the laser transmission welding process. During the welding process, the laser energy primarily passes through the upper laser-transparent adherend and then transmitted to the lower laser-absorbent adherend [160,161]. Subsequently, the laser energy can be absorbed and converted to thermal energy. That results in the melting of the thermoplastic resins and subsequent molecular diffusion at the welding interface.

With the development of laser sources, the laser welding technique began to be widely applied for the joining of thermoplastic materials in the 1990s. Four laser types have been mainly applied at present for the welding of thermoplastic materials, e.g., CO_2 laser [162,163], diode laser [164,165], Nd:YAG laser [166,167], and fiber laser [168,169]. These laser sources are represented in Table 6 in terms of their wavelength, efficiency, beam quality, etc. [161,170]. In general, no laser adsorber is required during a fiber laser welding process, since the laser radiation is easily absorbed by the thermoplastic resins in this case. The application of adsorbers would be necessary for the other laser systems, and carbon black is the most commonly used absorber material [171–173]. It is worth noting that both excessive amounts of adsorber and laser exposure time would negatively affect the mechanical performance of the welded joints owing to the serious surface damage caused by the laser beam. For instance, it was proved that applying high amounts of adsorber (0.5–1.0 wt%) and laser exposure time (30 s) would result in the generation of visible holes and burn areas within the welded joints [174]. Therefore, it is critical to precisely optimize the amount of adsorber and laser exposure time for greater welding quality of the joints.

Since the carbon fibers can absorb and reflect the laser beamline, the carbon fiber reinforced TPCs are not laser transparent [176]. Moreover, the application of semi-crystalline thermoplastic matrix, e.g., PEEK, PPS, low-melt polyaryletherketone (LMPAEK), polyetherketoneketone (PEKK), could interfere with the transmission of the incident laser beam [177]. As a result, the laser welding of two carbon fiber reinforced TPCs remains a great challenge. In recent years, the laser welding method for the hybrid joints between TPCs and light-weight alloys has been primarily proposed and exhibited outstanding application prospects, which is summarized in Table 7 [178]. During the laser welding process of TPC-metal joints, the laser energy can be absorbed by the upper metal adherends, leading to the generation of heat at the welding interface. Whereafter, the heat would be transmitted to the TPC surface, and results in the melting of the matrix resins and attachment onto the metal surfaces. Consequently, TPC-metal joints were obtained under an external pressure after the solidification process. Laser power, welding speed and welding pressure are the main parameters that have significant influences on the laser welding strength of the TPC-metal joints, which have been summarized and compared in Table 7 [179]. In general, the strength of the laser welded joints firstly increased and then decreased as the laser power and welding speed gradually increased [180,181]. Too high laser power and low welding speed would result in the thermal damage to TPC surfaces. Moreover, an optimal welding pressure could improve the filling behavior of thermoplastic resins on metal surfaces, while pore defects and cracks would be generated at the welding interface by applying an excessive welding pressure [182]. It is noteworthy that the laser welding process is highly sensitive to the welding parameters and the welding process window is typically narrow.

Studies have found that there are three main joining mechanism between the TPCs and metals, including mechanical interlocking, physical bonding and chemical bonding [50]. Among them, mechanical interlocking is considered as the dominant influence for improving the strength of TPC-metal welded joints. Therefore, it is required to perform an appropriate surface treatment to the light-weight alloys prior to the laser welding process. To enhance the laser welding strength of the TPC-metal hybrid joints, numerous effective strategies have been applied, e.g., metal surface micro-texturing [183,190], introducing chemical bonding at their interface [191,192], surface cleaning of TPCs [193,194] and amount improvement of resin melts at the welding interface [187,195], etc. For example, the improvement in the surface roughness of the Ti–6Al–4V (TC4) surface and hydrogen bonds between the TC4 and TPC surfaces had successfully achieved by simultaneously applying micro-arc oxidation (MAO) and silane coupling agent (SCA) treatments, as shown in Fig. 8(b). Accordingly, the maximum interfacial bonding force of the laser welded TPC-TC4 joints had been remarkably improved by 77.1 % when compared with that of the welded joints without MAO or SCA treatments.

The laser welding technique has been successfully applied for the joining of TPCs in the aviation industry after a few decades of development. For instance, the left longitudinal seam joining of the upper and

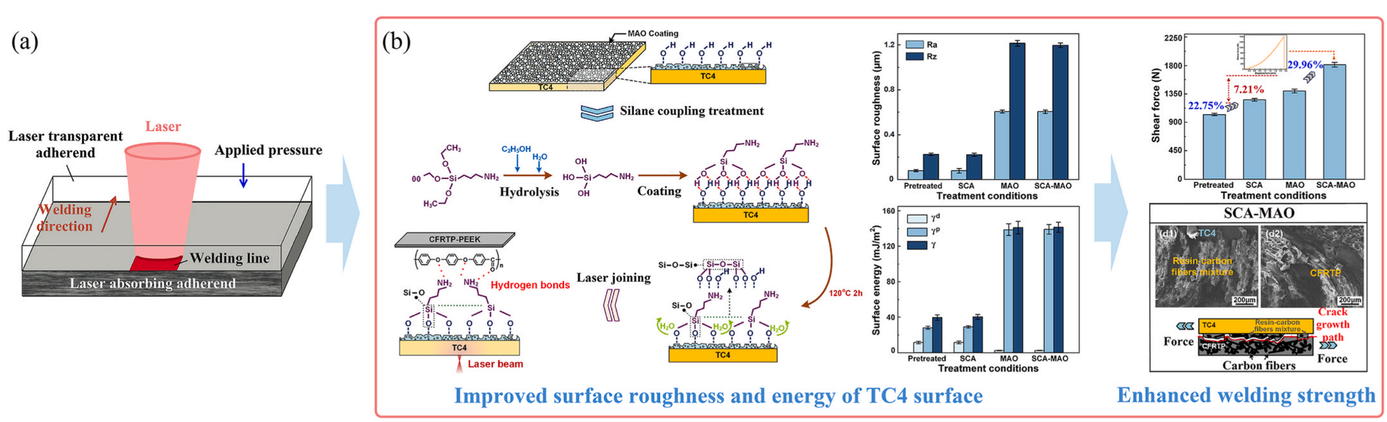

Fig. 8. Schematic of (a) the laser welding and (b) improved surface and energy of TC4 surface and correspondingly enhanced welding strength of the TPC-TC4 hybrid joints [175].

Table 6
Laser system types for the welding of thermoplastic materials.

Laser system	Type	Wavelength (nm)	Efficiency (%)	Beam quality	Application of the absorber
CO_2 laser	Gas laser	10600	5–10	High	Necessary
Diode Laser	Semiconductor laser	780–980	30–60	Low	Necessary
Nd:YAG laser	Solid-state laser	1064	3–5	High	Necessary
Fiber laser	Solid-state laser	1000–2100	20–50	High	Unnecessary

Table 7
Summary of selected researches on the laser welding of TPC-metal joints.

Year	Joint adherend	Laser system	Factors studied	Laser power (W)	Welding speed (mm/s)	Welding pressure	Optimal strength	Ref.
2016	CF/PA6-A6061	Fiber laser	Surface treatment to the A6061 surface	800–2000	4	NA	41.8 MPa	[183]
2018	PEEK-Al-Mg alloy	Diode Laser	Laser power	200	NA	1.0 MPa	30 MPa	[184]
2018	CF/PA6T-Steel	Fiber laser	Surface treatment to the steel surface	700	12	NA	30.8 MPa	[185]
2019	CF/PPS-TC4	CO_2 laser	Laser power	700	0.8	0.5 N m	2052 N	[162]
2020	CF/PEEK-TC4	Fiber laser	Welding speed	750	0.8	NA	2024 N	[186]
2021	CF/PEEK-6061 alloy	Fiber laser	Laser power and welding speed	1100	5	0.5 MPa	23.8 MPa	[187]
2022	CF/PEEK-AZ31B alloy	Fiber laser	Laser power	700	15	0.5 MPa	1714.17 N	[180]
2022	GF/PA6-SUS444	NA	Welding speed and defocus distance	900	11	NA	1785.9 N	[181]
2022	CF/PA6-Steel	Fiber laser	Laser power	700	5.5	NA	3855 N	[188]
2022	CF/PEEK-Ti6Al4V	Fiber laser	Clamping pressure	2000	15	0.8 MPa	3821.4 N	[182]
2022	CF/PEEK-Ti6Al4V	Fiber laser	Laser power and welding speed	2000	45	NA	10195.6 N	[189]

lower 8-m-long and 4-m-diameter fuselage shells of the MFFD has been successfully achieved by a CO_2 laser welding process. However, fabricating high-quality TPC-TPC and TPC-TSC welded joints remains a significant challenge with current laser welding techniques. Additionally, the weak chemical bonding between TPCs and light-weight alloys results in relatively low joint strength and poor mechanical stability of the joints. To address this, developing optimized surface treatments for lightweight alloy adherends is essential to promote interfacial chemical bonding. Further studies are also needed to elucidate the mechanisms of interfacial bonding formation and enhancement between TPCs and lightweight alloys. To further improve joint performance, integrating additional energy fields into the laser welding process, such as ultrasonic-assisted laser welding, presents a promising approach. This hybrid technique could enhance welding strength by increasing the contact intimacy between the resin and metal substrates while promoting chemical bonding at the interface. Furthermore, numerical simulations of heat transfer, melting, and interfacial bonding in TPC-metal laser welding should be conducted to accurately predict thermal damage, interface penetration, and joint strength, thereby refining the process parameters and improving weld quality.

6. Comparison of welding techniques

A comparative analysis of various welding and adhesive bonding

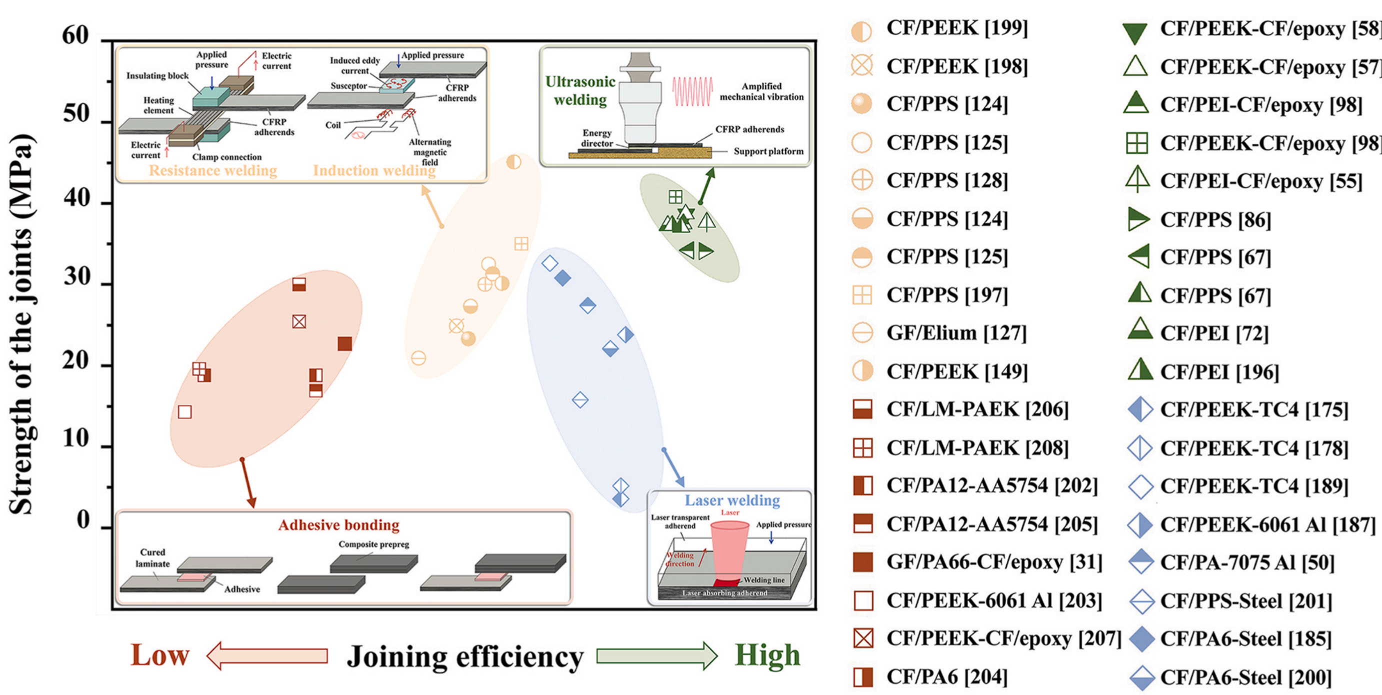

Fig. 9. A comparison of various welding techniques and adhesive bonding in terms of the efficiency and TPC joint strength.

techniques, considering their impact on joining efficiency and joint strength, is presented in Fig. 9. In general, friction welding (e.g., ultrasonic welding) [55,57,58,67,72,86,98,196], electromagnetic welding (e.g., resistance and induction welding) [124,125,127,128,149, 197–199], and thermal welding (e.g., laser welding) [50,175,178,185, 187,189,200,201] techniques exhibited significant advantages in both joining efficiency and strength compared to adhesive bonding [31, 202–208]. Among these, ultrasonic welding technique demonstrated superior performance in terms of efficiency and joint strength. Specifically, while the welding times for resistance, induction, and laser welding processes typically exceeded 10 s, ultrasonic welding can be completed in less than 1 s, as described in Tables 3–5 [43,100].

A more detailed comparison of various welding techniques, including their advantages, disadvantages, and applications, is summarized in Table 8. The ultrasonic welding technique stands out as a high-quality, high-efficiency, and lightweight joining method for aviation TPCs. Additionally, it minimizes surface damage to composite substrates. However, its industrial application is constrained by the underdevelopment of continuous ultrasonic welding and limitations on composite substrate thickness. Given its high automation potential relative to other welding technologies, further research is needed to advance the sequential and continuous ultrasonic welding process for TPC joints to meet the demands of large-scale TPC component assembly.

7. Conclusions and outlook

In recent years, the TPCs have attracted widespread attentions in aviation industry due to their excellent mechanical performance, outstanding thermal stability and good damage resistance. For instance, TPCs have been applied to manufacture large-scale main load-bearing aircraft components in the EU Clean-Sky 2 projects "TAPAS" and "MFFD". Notably, the TPCs were generally hybrid used with TSCs and metals to prepare large-scale components. Thus, it is critical to develop advanced light-weight joining techniques between TPCs and metals/TSCs. The development history and latest research advancements in welding techniques for TPCs were systematically reviewed in this paper, with a particular emphasis on ultrasonic welding. Additionally, the development and research trends for TPC welding technologies were proposed.

Welding techniques offer outstanding potential for joining TPCs due to their excellent joining strength and high productivity. Among these techniques, resistance welding has been successfully applied for the joining of TPCs after decades of development. However, achieving both high compatibility between conductive elements and TPCs and uniform heat generation remains challenging. Therefore, an optimized resistance welding technique utilizing novel conductive elements with similar or identical physical and chemical properties to TPCs should be developed. Additionally, further advancements in industrial automation for resistance welding are necessary. Moreover, the development of continuous resistance welding has emerged as a promising direction for future research.

Induction welding has also been successfully applied for the joining of TPCs, offering higher welding strength compared to resistant welding. However, the presence of metal conductive elements in TPC joints and the non-uniform heat generation at the welding interface when using graphite or carbon fiber conductive elements limit its aerospace applications. Therefore, the development of conductive elements with high heat generation efficiency and strong compatibility with TPC adherends is a key research direction for advancing induction welding. Additionally, the modeling of the induction welding process is another critical development trend, as it enables a deeper understanding of heat generation mechanisms and helps establish processing window boundaries for optimized welding performance.

Laser welding exhibits considerable advantages of fast welding speed, low mechanical stress and no requirements of conductive elements, etc. Among them, laser transmission welding is the most widely studied for the joining of TPCs. Nevertheless, the carbon fiber reinforced TPCs are not laser transparent, hence it is still a great challenge to join two carbon fiber reinforced TPCs by the current laser welding process. In recent years, with the process by which laser energy can be absorbed by the upper metal adherends and generate heat at the welding interface, the laser welding method has been proposed for the TPC-metal hybrid joints and exhibited outstanding application prospect. However, the lack of chemical bonding at TPC/metal interfaces would result in the relatively low welding strength and poor mechanical stability of the hybrid joints. Therefore, it is essential to develop optimal surface treatment processes for lightweight alloy adherends to enhance the chemical bonding strength at the welding interface. Additionally, the heat transfer, melting, and interfacial bonding processes during laser welding should be modeled and numerically simulated. This approach will enable accurate predictions of thermal damage, welding interface penetration, and welding strength, facilitating better control over the welding process and optimizing joint performance.

Ultrasonic welding offers numerous advantages over other welding techniques, including significantly reduced joining time, the elimination of TPC surface treatment requirements, minimal damage to TPC surfaces, and strong environmental benefits, etc., making it an ideal choice for joining TPC components. In recent years, its application has been extended to the joining of TPCs, showing its potential. However, further systematic studies are still required to ensure the stability of ultrasonically welded TPC structures, especially for the sequential and continuous ultrasonic welding. Developing a reliable strategy or guideline to

Table 8
Comparison of various welding techniques [209].

Type	Heat generation mechanism	Advantage	Disadvantage	Thickness	Typical applications
Ultrasonic welding	Friction and viscoelastic heat caused by high-frequency (20–40 kHz) mechanical vibration	Quick joining process; Less surface damage; Light-weight	Continuous welding still in development	Lower than 6 mm for upper adherend	CF/PEI parts to CF/PEI floors for G650 (GKN Fokker); CF/PEEK hinge and clips to CF/PEEK C-frames (TU Delft)
Resistance welding	Electric current passes through resistive element causes heat and melting	Heat generated only at the interface; High-efficiency for long welds	Requires a resistive element which stays in the welding line	No limit	CF/PPS main landing gear door for Fokker 50 turboprop and GF/PPS fixed leading edge for Airbus A340/A350/A380 (GKN Fokker)
Induction welding	Joule losses due to resistance heating of fibers; Dielectric heating due to molecule movement and line up between fibers; Contact heating occurred on high fiber-fiber contact points	Susceptor only required with non-conductive fiber composites	Harder to focus heat at the welding line; Requires an induction element	Lower than 5 mm per side	CF/PPS rudder Gulfstream for G650 and CF/PPS elevator for Dassault Falcon 5X (GKN Fokker)
Laser welding	Laser radiation passes through a laser transparent part and generates heat in a laser absorbent part; Laser energy is absorbed by upper metals and generates heat at the interface	Quick joining process for long welds	Hard to join two TPCs; Low TPC-metal joint strength; Easier surface damage to composites	Demonstrated 2.4 mm	GF/PEEK L bracket to CF/PEEK laminate; Polyamide (PA) aerospace attachment pin to CF/PA baseplate; GF/PEI hat-stringer stiffeners to GF/PEI skins (KVE, LZH, TenCate et al.)

ensure consistent welding quality and joint strength is essential. This will form the foundation for the online monitoring and intelligent control of the ultrasonic welding process for aircraft TPC structures. Additionally, optimizing the surface structure and resin-rich layer of TPCs represents an effective approach to further enhancing the welding strength and expanding the optimal processing window.

The ultrasonic welding technique for TPC-TSC joints is still in its infancy, with limited research on this topic, and no reported engineering applications to date. To advance this technique, common challenges in the conventional TPC-TPC ultrasonic welding process must be addressed, such as non-uniform heat generation, pore defects from trapped air, carbon fiber squeezing, and thermal decomposition. A method for preventing thermal decomposition of the TSC matrix should also be developed by optimizing process parameters and adjusting the thickness and structure of the CLs. Furthermore, it is essential to explore the sequential and continuous ultrasonic welding processes for TPC-TSC hybrid joints, with a focus on developing advanced industrial automation. This will enable the broader application of ultrasonic welding in relatively large aerospace structures.

With the significantly increased demands of TPCs and light-weight alloys in aviation industry, high-quality TPC-metal hybrid joints have been attractive development goals in recent years. An appropriate surface treatment of metal adherends is required prior to TPC-metal ultrasonic welding process. However, current TPC-metal ultrasonically welded joints possess typically low strengths due to the lack of chemical interactions at the TPC/metal interfaces. Therefore, it is essential to develop novel surface treatments for metal adherends that facilitate the introduction of chemical bonding at the interface. The mechanisms of interfacial bonding and methods for enhancing these interactions require further investigation. Additionally, the sequential and continuous ultrasonic welding processes for TPC-metal hybrid joints should be further optimized. Moreover, simulation methods could be employed to better understand the interface generation mechanisms during ultrasonic welding.

CRediT authorship contribution statement

Jiaming Liu: Writing – original draft, Investigation. **Dong Quan:** Writing – review & editing, Project administration, Funding acquisition. **Gennaro Scarselli:** Resources, Conceptualization. **Rene Alderliesten:** Visualization, Resources, Conceptualization. **Hao Wang:** Writing – review & editing, Supervision, Conceptualization. **Guoqun Zhao:** Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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