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Review Article

Advantages and Application Challenges of Composite Material Repair Methods Used in Aircraft

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Abstract: With the development of fiber-reinforced composite materials, composites have become indispensable in modern aircraft structures. Aircraft receive damages from impacts or environmental conditions throughout their service life. Since replacing a damaged composite with a new one is an economically costly task, appropriate repair techniques are keeping its importance. It is possible to restore structural integrity by repairing the damaged part. In addition, since composites are difficult to recycle, their repair contributes to sustainability by reducing the amount of waste material. Although systematic repair methodologies have been well established for thermoset matrix composites, a clear and standardized roadmap for thermoplastic composites has yet to be developed. In this article, damages in composite materials used in today's aircraft, their detection, evaluation and repair methods have been examined. In addition, studies from the literature on ultrasonic, resistance and induction welding methods, which are among the welded repair methods of thermoplastic matrix composites, which have been used increasingly in recent years, have been presented. The advantages of repair methods and the difficulties encountered in application have been evaluated.

Keywords: *Composite repair, Repair, Fusion bonding, Thermoplastic composite, Aircraft*

I. INTRODUCTION

With the advancement of polymer matrix composite materials, these materials have become capable of meeting many of the performance requirements of modern aircraft. Their low specific weight, combined with high strength as well as excellent fatigue and corrosion resistance, has made them indispensable in aerospace applications (Çalışkan et al., 2021). Aluminum alloys were used for aerospace structures in the 1920s. They were first used in military aircraft in the 1960s, and their use in civilian aircraft gradually increased in the 1970s. Composites are preferred in many load-bearing and non-load-bearing areas of new-generation aircraft. The use of composites in today's military and civil aircraft accounts for approximately half of the total weight of the aircraft (Barroeta Robles et al., 2022). In Figure 1, the Boeing 787 aircraft consists of 50% composite, 20% aluminum, 15% titanium and 10% steel material by weight (Budhe et al., 2018). Aircraft engine emissions are released directly into the troposphere and stratosphere, thus impacting climate change. The use of composite materials has contributed to aircraft weight reduction, thus saving fuel and reducing emissions (Katnam et al., 2013).

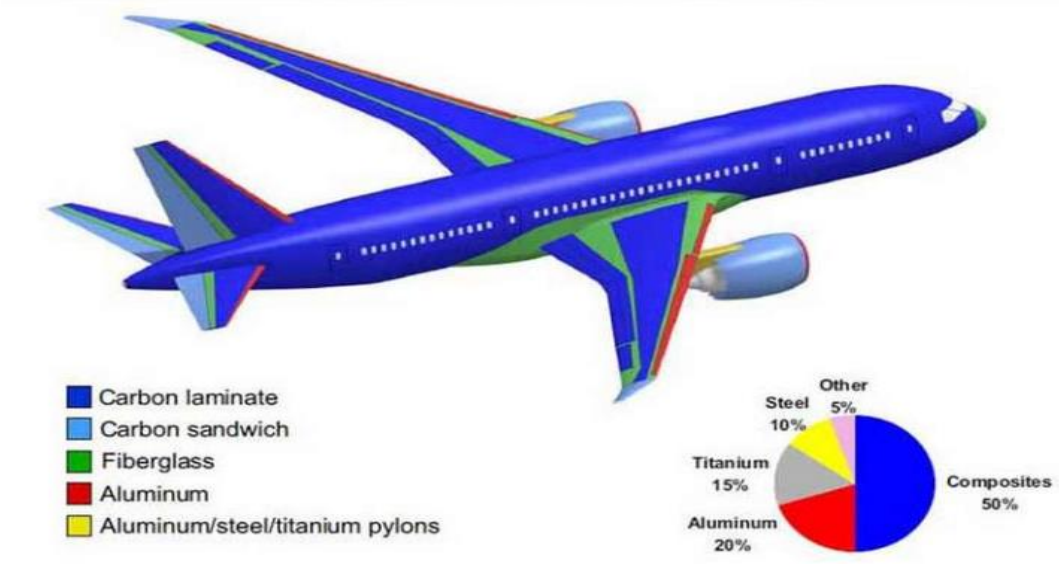


Figure 1. Weight ratios of materials used in the Boeing 787 aircraft (Hale, 2014).

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Composite structures are subject to damage from impact and environmental conditions throughout their service life. These materials are highly susceptible to impact damage. Impact damage can lead to fiber breakage, matrix cracking, and delamination. These damages significantly reduce the load-carrying capacity of the composite structure, shortening its service life (Collombet et al., 2015). The damaged composite needs to be replaced or repaired in the damaged area. Because replacing a damaged composite part is a financially expensive undertaking, repairing the damaged area is generally preferred. In addition, the time required to return the damaged aircraft to service is also very important. It has been reported that the unplanned daily cost of a passenger aircraft to the airline is approximately 100 thousand US dollars (Barroeta Robles et al., 2022) . Composites used in aircraft are divided into two types, thermoset and thermoplastic, based on the matrix element. While thermoset matrix composites are widely used in the aviation industry, the use of thermoplastic composites has also increased in recent years. Thermoplastic matrix composites used in aircraft and their areas of use are given in Table 1 (Barroeta Robles et al., 2022; Budhe et al., 2018; Reis et al., 2020). Thermoplastic polymers have better shock absorption than thermosets and are less likely to develop microcracks. Thermoplastics can also be remelted and reshaped. These properties provide great advantages in the repair of damaged areas of thermoplastics (Ageorges & Ye, 2001; Reis et al., 2020).

Table 1. Thermoplastic matrix composites and their applications (Barroeta Robles et al., 2022; Budhe et al., 2018; Katnam et al., 2013; Reis et al., 2020).

Name	Reinforcement material	Where used
PEEK (Polyetheretherketone)	Carbon	Cockpit floor (A400M) Support and fastening parts (A350) Access doors (A220)
PEKK (Polyetherketoneketone)	Carbon	Control panels (G650)
PPS (Polyphenylene sulfide)	Carbon	Landing gear hatch (Fokker 50) Seat backrests (B787, A350) Rudders (G650)
PEI (Polyetherimide)	Glass	Seat base (Tod's Aerospace)
	Carbon	On the cargo compartment floor (Fokker 70, Fokker 100) Floor panels (G550) Side wall fastening rails (A330, A340)

The purpose of this review study is to provide a comprehensive examination of current welding-based repair methods developed for thermoplastic matrix composite materials, which are increasingly utilized in the aviation industry, and to present the existing body of knowledge in literature within an integrated framework. Although systematic repair procedures for thermoset composites have been established over many years, there is still no standardized and industrially applicable methodology for the repair of thermoplastic composites. While numerous experimental investigations have been conducted on welding-based repair techniques for thermoplastic composites such as resistance welding, ultrasonic welding, and induction welding, most of these studies primarily focus on fundamental process parameters. Consequently, critical aspects such as comparative analyses of different welding methods and systematic evaluations of the mechanical performance of repaired structures remain limited in the literature.

The scope of this study is to conduct an in-depth analysis of the existing research on welded repair of thermoplastic composites and to comparatively assess the practical challenges, advantages, and effects of these techniques on performance outcomes. By consolidating the dispersed knowledge available in the literature, the study aims to provide an evaluation that not only guides future academic research but also serves as a foundation for industrial applications. Within this context, recent studies on resistance, ultrasonic, and induction welding methods have been reviewed, and their comparative results in terms of mechanical strength, joint quality, process efficiency, and post-repair performance have been discussed.

Accordingly, the second section of this review addresses the types of damage commonly observed in composite materials used in aerospace structures, along with the methods employed for their detection and assessment. The third section systematically presents the repair methods for thermoset and thermoplastic matrix composites, with particular emphasis on welding-based repair techniques. By filling the existing gap in the literature, this study aims to provide a comprehensive evaluation of welded repair approaches for thermoplastic composites and to contribute a scientific foundation for future standardization efforts in this field.

II. DAMAGE FORMATION, DETECTION AND EVALUATION

The anisotropic structure of polymer matrix composites causes them to exhibit more complex and diverse damage mechanisms than metals. Early detection and accurate assessment of damage are vital to the safe use and long service life of these materials. Advanced non-destructive testing methods and numerical modelling play a critical role in optimizing the performance of polymer matrix composites (Ashforth et al., 2023).

A. Damages

Composite parts in aircraft are subject to damage from impact and/or environmental factors throughout their lifespan. A large portion of this damage is caused by impact damage, such as bird strikes, hail, and dropped equipment during maintenance. Environmental factors that cause damage include humidity, UV rays, and temperature fluctuations (Dubinskii et al., 2019).

The types of damage that occur generally include matrix cracks, delamination (separation of the internal layers of the structure), and fiber fracture. Low-energy impacts can cause matrix cracks, which in turn trigger delamination. Delamination reduces the structure's compressive strength. High-energy impacts, however, cause fiber fractures. The disruption of fiber continuity causes a sudden decrease in the structure's load-carrying capacity (Raju & O'brien, 2008). Damage formation and types in composite structures are shown in Figure 2. (Barroeta Robles et al., 2022).

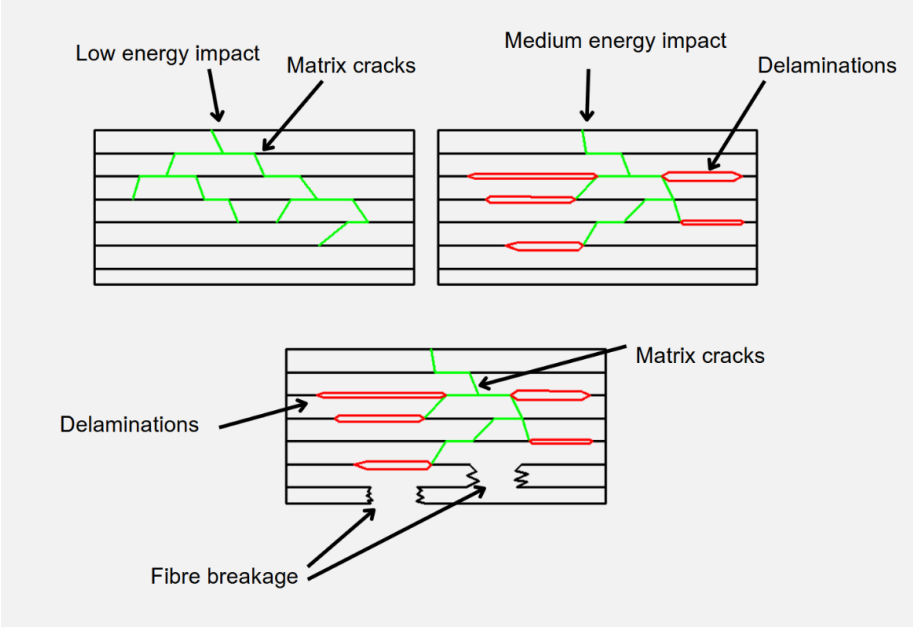


Figure 2. Damage formation and types.

B. Determination Of Damages

Non-destructive testing techniques are widely used to detect damage in composite structures. The simplest of these techniques is visual inspection (Erdem, 2024). Surface cracks, dents and colour changes can be detected by visual inspection. However, internal defects cannot be detected by visual inspection. Another practical and economical method used to detect damage is the tap test. The tap test involves striking the material with an object such as a coin or hammer to create sound waves. The acoustic waves obtained are compared with those from the area believed to be defect-free and interpreted accordingly. Tap testing is not a suitable method for deep faults (Cambaz, 2024). While ultrasonic tests are used to detect delamination and internal cracks, x-ray tomography methods are used for 3D damage analysis and disruptions in fiber distribution. The methods suitable for detecting damage are summarized in Table 2.

Table 2. Damage type and methods suitable for its detection (Ashforth et al., 2023; Darwish & Shivakumar, 2014; Reis et al., 2020).

Damage type	**Appropriate methods**
Surface cracks	Visual inspection Thermography
Delamination	Ultrasonic testing Thermography
Internal cavities	X-ray tomography
Fiber breakage	X-ray tomography
Humidity control	Dielectric measurements

C. Damage Assessment

After determining the type, extent, and location of the damage, it must be determined whether the damage is within the limits permitted for safe operation of the aircraft. If the damage is within the limits permitted for safe operation,

cosmetic maintenance has been completed. More extensive damage requires structural repair. Penetration damage requires structural repair. The level of damage identified during periodic inspections must remain within limits that do not compromise the structure's integrity. Acceptable minor defects may include small scratches, slight delamination, or minor porosity. More significant visible damage such as impact marks, deep gouges, bond separation, or extensive delamination can typically be detected by maintenance or operations personnel (Tsokanas et al., 2025). If the damage detected exceeds the allowable limits, repairs must be performed in accordance with the aircraft's structural repair manual. If the repair exceeds the repair limits specified in the structural repair manual, the part must be replaced. Furthermore, an analysis must be made to determine whether the repairs provide the required structural strength. Repairs that do not meet the required strength must be replaced (Ashforth et al., 2023; Wang et al., 2009).

III. REPAIR METHODS

A. Repair of Thermoset Matrix Composites

After the aircraft's damaged structure is assessed and evaluated, if structural repair is deemed necessary, the repair process begins. To ensure the aircraft remains in service, the damaged structure is removed and replaced with a replacement part. In-situ repairs are performed on the fuselage and wing structures. Repair techniques can be broadly divided into two categories: patchless and patch repair. Patchless repair involves filling the damaged area with resin. Patch repairs, on the other hand, involve one-way or two-way repairs using mechanically bonded repairs such as bolts and/or adhesives (Collombet et al., 2015; Dindar & Ağır, 2021; Kaman & Cetişli, 2011).

A.1. Patchless Repair (Resin Transfer)

It's a method used to repair superficial defects or small adhesion failures between layers. Resin is transferred to the defective area, restoring local strength and continuity. The resin penetrates between the fibers, filling the voids, and after curing (hardening), the repaired area gains mechanical strength close to the original structure. The resin transfer method is particularly suitable for in-situ repairs of large parts and is characterized by uniform resin distribution and low void ratios (Samancı & Avcı, 2007). The patchless repair technique, as shown in Figure 3, involves two holes drilled into the damaged area: one for resin transfer and the other for ventilation or vacuum (Cambaz, 2024; Gong et al., 2015).

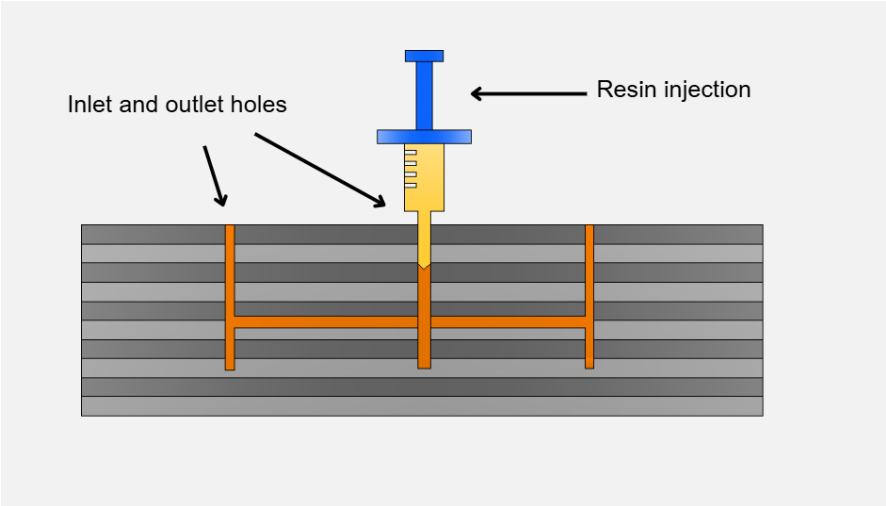


Figure 3. Resin injection.

A.2. Patch Repair

Patch repair techniques are used to repair damage that is too extensive to be repaired with resin filling. This involves cutting out the damaged area and applying a patch. This is done using a mechanically attached patch and/or adhesive (Soykök, 2023).

A.2.1. Mechanical Bonded Patch Repair

In this repair method, the defective area is cut out from the main structure and then covered with a patch using pins or bolts. Although this technique is reliable and does not require surface preparation, tear, slip and crush stress concentrations occur around the holes opened for the fasteners, negatively affecting the life of the main structure and the repair patch. Additionally, the fasteners add extra weight to the structure. If this repair method is chosen, the aerodynamic requirements of the aircraft must also be considered. Figure 4 shows a mechanically bonded repair (Erdem, 2024; Uslu, 2020).

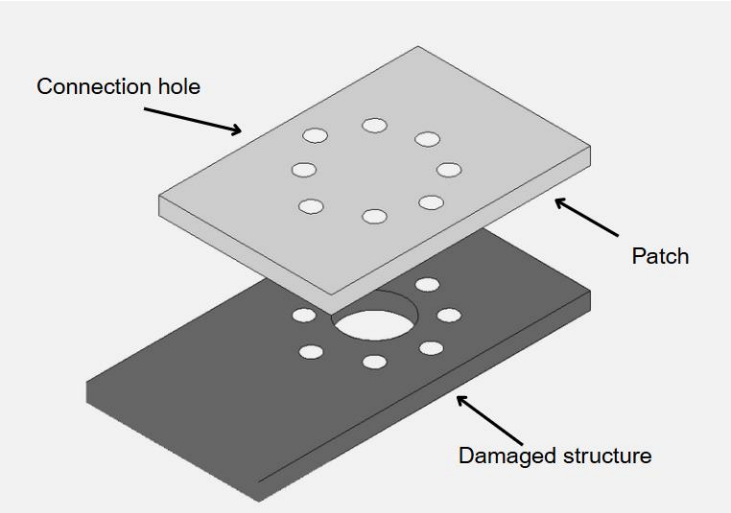


Figure 4. Mechanically bonded patch repair.

A.2.2. Patch Repair with Adhesive

There are many different application techniques for this method, which is based on bonding the patch to the damaged main structure using adhesive, as shown in Figure 5. These include single-sided patching, double-sided patching, stepped patching and angled patching. The easiest of these techniques is single-sided patching. The damaged area is removed, and the void is filled with resin and chopped fibre. The prepared patch is then adhered to the area to be repaired. Due to its asymmetrical geometry, it negatively affects the strength of the connection, but this negative effect has been eliminated by the double-sided patch method, which is a symmetrical repair process. When examining the strength of carbon fibre/epoxy composite plates containing cracks after single-sided and double-sided repairs, it has been noted that double-sided repairs demonstrate significantly superior performance (Erdem, 2024; Uslu, 2020; Yücel et al., 2019). However, for the double-sided repair method, it is necessary to have access to the other side of the part, which is generally not possible in aviation structures. For these reasons, angled or stepped repair techniques are more suitable in the aviation field. They provide smoother load transfer without causing stress concentrations. They also strengthen the structure without adding additional weight. These techniques are named according to the removal geometry of the damaged area (Gong et al., 2015; Liu et al., 2016). It has been reported that it is possible to recover the strength of the structure by 70% to 100% with angled and stepped repair methods. It has been concluded that angled repair is more suitable for load-bearing structures because the angled repair method causes less stress concentration than stepped repair (Çetinkaya, 2017; Dindar & Ağır, 2021; Evren, 2024; Kepir et al., 2022; Olajide et al., 2017). In repairs performed with angled repair, the patch angle has been reported to vary between 3° and 7°, with the optimum patch angle being 3° (Wang & Gunnion, 2008). Because a large area must be removed from the main structure to achieve the optimum patch angle, the angled repair method is not recommended for repairing thin fragments (Darwish & Shivakumar, 2014). Erdem (2024) investigated the mechanical performance of composite materials with pin-hole crack repairs using patches. He concluded that double-sided repairs provided significantly superior performance compared to single-sided repairs.

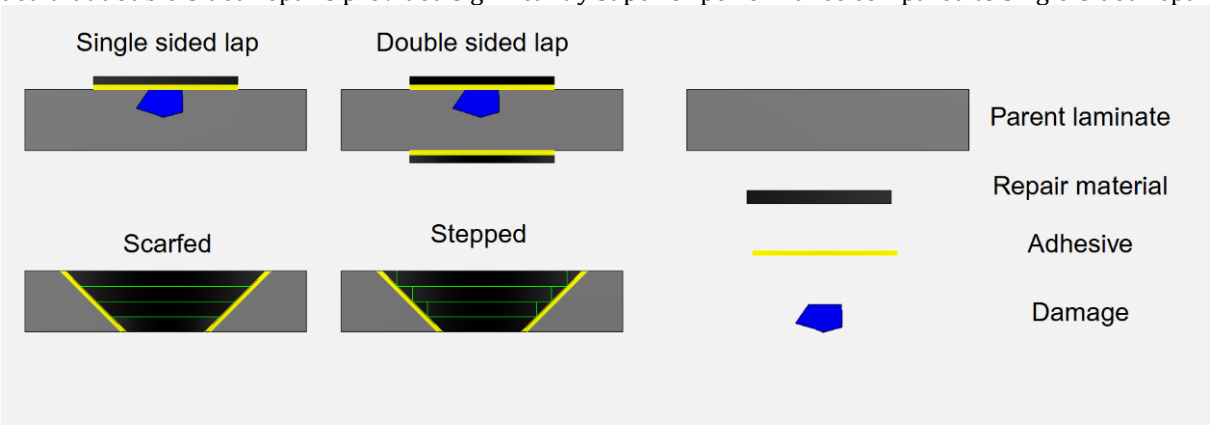


Figure 5. Patch repair with adhesive.

B. Repair of Thermoplastic Matrix Composites

The most important advantage of thermoplastic matrix composites over thermosets is that they can be melted and reshaped at the appropriate temperature and pressure, making repairs easier. They can be repaired using fusion bonding methods without the need for surface preparation. The heating process for thermoplastic composites can be performed

using various fusion bonding methods. These methods are shown in Figure 6. The most commonly used welding techniques are ultrasonic welding, induction welding, and resistance welding (Yousefpour et al., 2004).

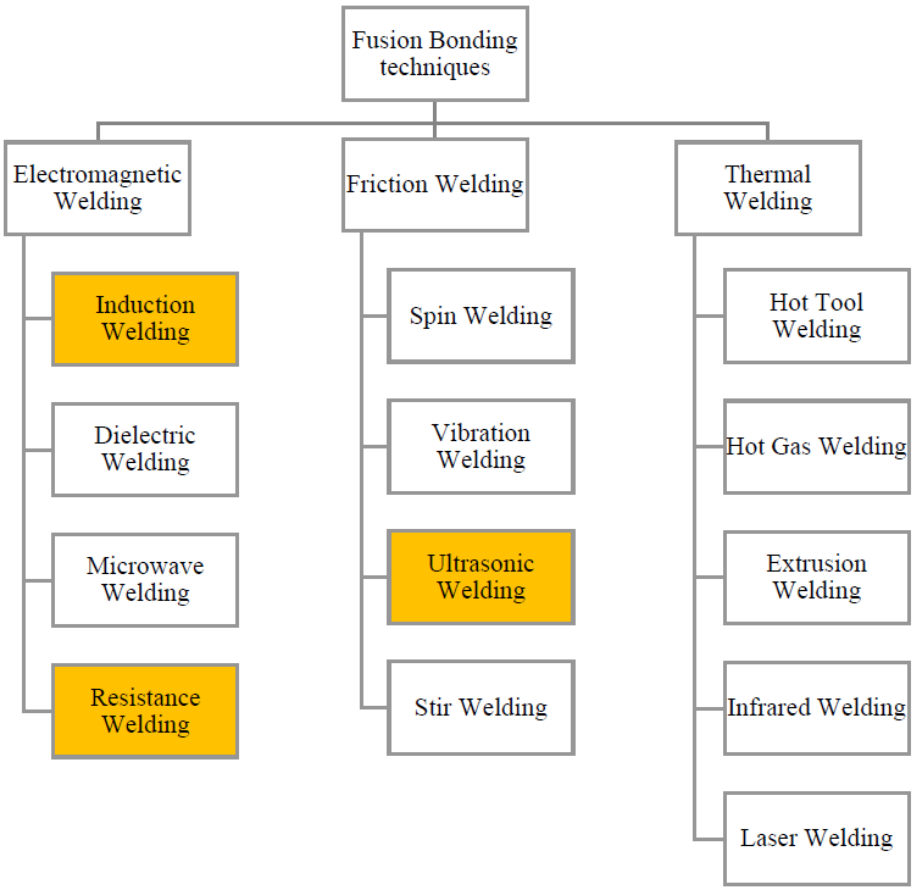


Figure 6. Fusion bonding methods.

Surfaces to be joined under heat and pressure must be heated to temperatures above the glass transition temperature (T_g) and melting temperature (T_m) of the thermoplastic material. To prevent degradation of the polymer structure, this temperature value should generally not exceed 1.75 times the glass transition temperature for amorphous plastics and the melting temperature for semi-crystalline structures. Table 3 shows the melting and glass transition temperatures of some thermoplastic materials (Suresh et al., 2007).

Table 3. Thermal properties of thermoplastic materials (Yousefpour et al., 2004).

Material	**Glass transition temperature (T_g) ℃**	**Melting temperature (T_m) ℃**
Polyetheretherketone (PEEK)	145	340
Polytermid (PEI)	230	-
Nylon 6.6	49	250
Polypropylene (PP)	-25	70

B. 1. Ultrasonic Welding

In ultrasonic welding, the surfaces to be welded are subjected to pressure and simultaneously vibrate at a frequency between 20 and 50 kHz. In ultrasonic welding, the strength of the weld interface is related to the heat generated by friction (Barroeta Robles et al., 2022; Chen et al., 2020). Yousefpour et al. (2004) investigated the effects of ultrasonic welding on delamination and damage tolerance in carbon fiber-reinforced thermoplastics (CFRTP). They reported that strength increased due to fiber reorientation in the weld zone, but overheating could lead to degradation of the polymer matrix. Köhler et al. (2021) Examined how fiber orientation influences heat generation, heat transfer, and defect formation during the ultrasonic welding of unidirectional carbon fiber–reinforced PEKK composites. Their results show that the orientation of the fibers has a clear impact on both the type and the location of edge defects forming in the weld region. In samples where the fibers were aligned parallel to the welding direction (0°), defects such as fiber squeeze-out and voids were observed. In contrast, samples with a 90° fiber orientation exhibited a more uniform heat distribution

and showed almost no edge defects. Despite this, the mechanical tests revealed that the 0° specimens reached a higher average maximum shear strength of 37.4 MPa, whereas the 90° specimens showed a lower average strength of 25.2 MPa. Sarasini et al. (2017) investigated the effectiveness of ultrasonic welding in multilayer thermoplastic composites using experimental and simulation methods. It was emphasized that weld depth and temperature distribution directly affect joint quality, and sonication time is a critical parameter. Zhao et al. (2022) modeled the thermal behavior during ultrasonic welding using FEM (Finite Element Method) and validated it with experimental data. They explained that the temperature distribution in the weld zone is affected by the viscoelastic properties of the polymer, and that welding should be carried out 5-10 °C above the melting temperature for optimal weld quality. The process parameters are pressure, application time and vibration amplitude. Figure 7 shows a schematic representation of the ultrasonic welding method. Semi-crystalline thermoplastics, which have a high energy absorption capacity, are more difficult to weld than amorphous thermoplastics. Villegas et al. (2013) reported that semi-crystalline and amorphous thermoplastics can be welded when pressure up to 3 MPa is applied, but that the weld interface strength of semi-crystalline materials is weak. Benatar et al. (1989) investigated the ultrasonic welding of amorphous and semi-crystalline thermoplastics and stated that changes in welding pressure had little effect on weld strength, while vibration amplitude and application time had a greater effect. Sacchetti et al. (Sacchetti et al., 2018) investigated the effect of resin content at the interface in ultrasonic welding of carbon/PEEK composites and concluded that fracture toughness increases with increasing matrix content at the weld interface.

The most important advantage of ultrasonic welding is that it has a very short application time of between 1 and 5 seconds. However, the heavy weight of ultrasonic welding equipment poses difficulties for on-site repair of aircraft.

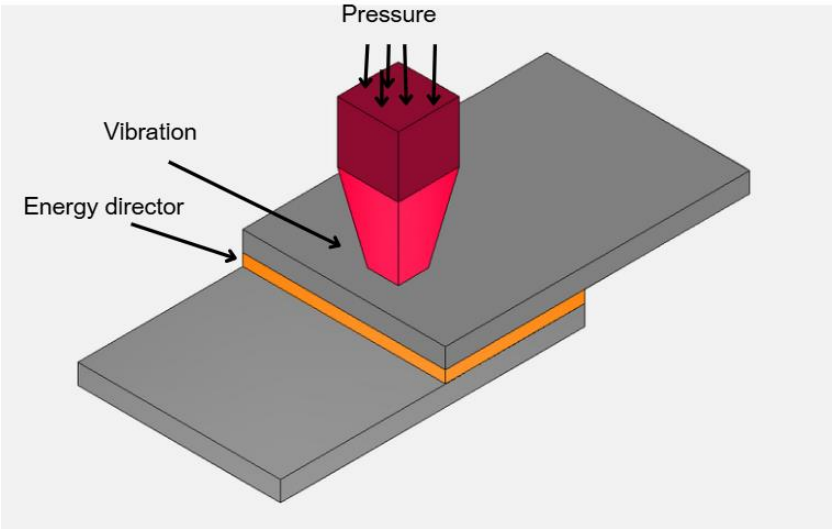


Figure 7. Schematic representation of ultrasonic welding.

B. 2. Induction Welding

In induction welding, an alternating current is passed through a conductive coil to create a magnetic field, and a receiver material that is electrically conductive and heats up faster than the base material is placed on the surface to be welded. The magnetic field created by the induction coil causes eddy currents in the receiver material, and the resistance of the material to these eddy currents generates the heat required for welding. Figure 8 shows a schematic representation of the induction welding method. The basic parameters in induction welding are frequency, power, pressure and welding time (Choi et al., 2023). Villegas et al. (2013) reported that the appropriate pressure range for induction welding is 0.2–1.2 MPa and the application time is between 10 and 360 seconds. In their study, Gouin O'Shaughnessey et al. (2016) used stainless steel as a heating element in the induction furnace of a carbon/polyphenylene sulphide composite and concluded from their experimental and numerical studies that the size of the heating element had no effect on the mechanical performance of the furnace. Becker & Mitschang (2022) tested the reassembly of multilayer composite structures using induction welding in advanced repair techniques. They reported that microcracks in damaged areas were closed, thermal damage was minimized, and this repair technique has high potential for automation. Rodríguez-Vidal et al. (2016) investigated the effectiveness of induction welding on polypropylene (PP) and carbon fiber-reinforced thermoplastic composites. They found that the highest weld strength was achieved at a frequency of 3 kHz and a power of 2 kW. They emphasized the importance of temperature control, as overheating can cause matrix degradation. Sacchetti et al. (2015) concluded that applying pressure during induction welding prevents delamination and improves weld quality in polyetheretherketone (PEEK) matrix composites. They found that under pressure of 0.5-1 MPa, the porosity of the weld zone was lower than 5%. Ahmed et al. (2006) reported that in mechanical tests performed after induction welding of carbon/PEEK and glass/PLA composites, the repaired parts reached 85-90% of the strength of the original material. It was concluded that this technique is suitable for use in aircraft structures. Korycki et al. (2022) They found

that induction welding consumes lower energy compared to resistance welding and that the temperature range of 280-300°C gives the best welding performance in PEKK matrix composites. Modi et al. (2023) Investigated the repairability of impact damage in carbon fiber–reinforced PEEK and PEKK composites using induction welding. Their results showed that, following repair, the damaged area decreased by approximately 5% in PEEK composites and by about 3% in PEKK composites. In terms of post-impact compressive strength, PEEK specimens recovered around 17% of their strength, while PEKK specimens regained approximately 13%. These findings suggest that both thermoplastic matrices respond positively to induction welding-based repair, allowing for a partial restoration of their mechanical performance.

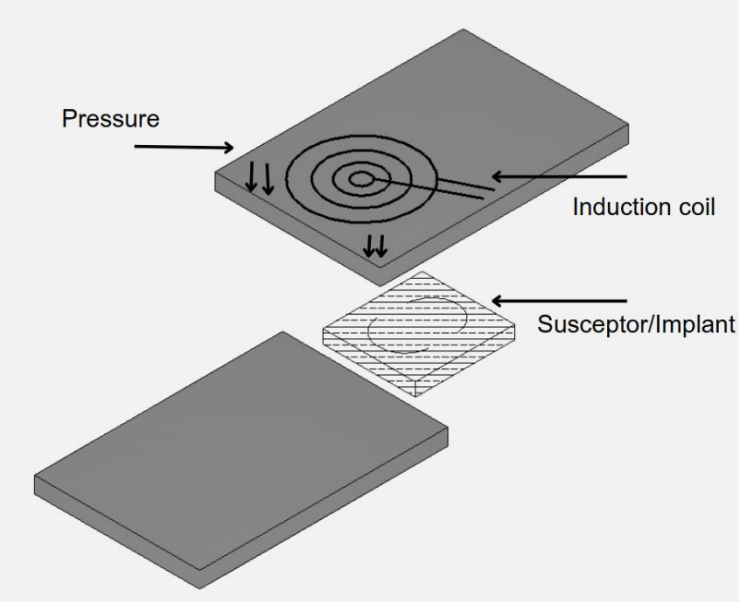


Figure 8. Schematic representation of induction welding.

B. 3. Resistance Welding

In resistance welding, heat is generated by passing an electric current through a heating element placed between the surfaces to be welded. The resulting heat softens the thermoplastic matrix, and the welding process is carried out by applying pressure until it solidifies. A metallic material or carbon fiber fabric can be used as the heating element. Figure 9 shows a schematic representation of the resistance welding method. Resistance welding has been successfully employed in the joining of structural components in aircraft such as the Airbus A320, A340/A380, and the Fokker 50. This technique is particularly favored in large-scale thermoplastic fuselage structures due to its compatibility with automation and its potential to reduce manufacturing costs (Stankiewicz et al., 2024; Voleppe et al., 2021). In their study, Brassard et al. (2019) used carbon nano tubes as an intermediate heating layer in resistance welding of carbon fibre/PEEK composites to increase the conductivity of polyetherimide (PEI). They reported that carbon nano tubes were effective in homogenizing the temperature distribution in the welding area. In their study, Shi et al. (2015b) used stainless steel as a heating element in the resistance welding of thermoplastics and developed a numerical model to predict heat distribution. They reported that the numerical model was consistent with the experimental results. They concluded that welding power and speed were the two most effective parameters in welding temperature.

The efficiency of resistance welding and the quality of the final joint fundamentally hinge on two interconnected decisions: choosing the right heating element and fine-tuning the process parameters. For the heating element, engineers typically choose between metal meshes and carbon fiber templates. Metal meshes offer excellent heat distribution but come with an inherent risk of corrosion. Carbon fiber templates, on the other hand, are compatible with the composite substrate and benefit from a mono-material design, simplifying the structure. While advanced nano-composite heaters based on materials like Multi-Walled Carbon Nanotubes (MWCNT) or Graphene Oxide (GO) promise even higher interfacial strength, their widespread industrial adoption is currently limited by the technical challenges of large-scale, consistent manufacturing. Regardless of the heater type, achieving a high-quality weld ultimately comes down to the precise control of three critical parameters: temperature, pressure, and time. This control is especially crucial when joining aerospace-grade polymer composites. In practice, optimal mechanical performance and consistent joint quality are generally achieved within specific windows: a pressure range of 0.2–1.5 MPa, a welding time of 30–150 seconds, and a tightly controlled heating profile that carefully stays within the melting or degradation temperature range of the base polymer matrix. Therefore, a systematic understanding of the relationship between material, mechanism, and process forms the cornerstone of reliable resistance welding for critical aerospace structures. The process, however, is not without its challenges. The primary issue often lies in achieving uniform heat distribution across the weld interface. Other significant hurdles include the relatively long cycle times required and the need for high consolidation pressure.

Addressing these limitations is key to broadening the application and improving the efficiency of the technique (Ageorges et al., 2001; Koutras et al., 2018; Nagatsuka et al., 2018; Stankiewicz et al., 2024; Xie et al., 2016; Yousefpour et al., 2004). Studies on resistance welding of thermoplastic composites are summarized in Table 4.

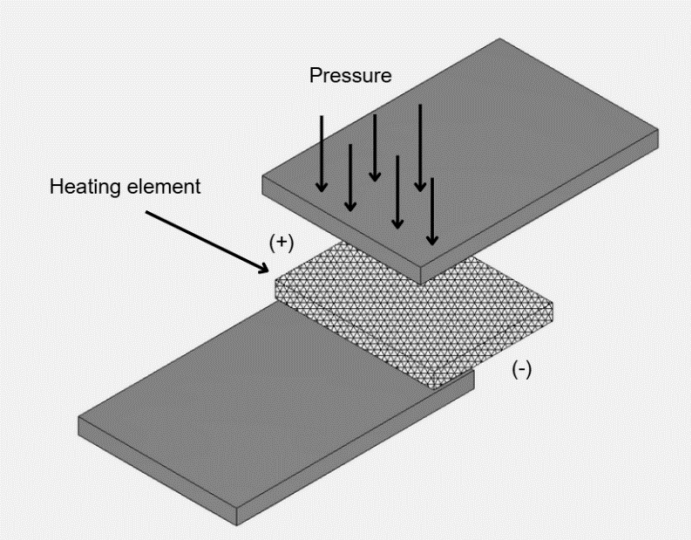


Figure 9. Schematic representation of resistance welding.

Table 4. Methods and findings of studies on resistance welding of thermoplastic composites.

Author	Material	Method	Findings	Citation
Eveno & Gillespie, 1988	Graphite/PEEK	-Nickel-plated carbon fiber mesh was used - 5-10 bar pressure at 300-400°C -30-60 seconds welding time	- Optimum temperature for 0.5 mm thickness: 380°C - 85% of the base material strength was recovered	(Eveno & Gillespie, 1988)
Ageorges & Ye, 2001	CF/PP	- Stainless steel mesh (50 µm pore) - 0.5-1.0 MPa pressure - Direct current (DC) heating	- Matrix deformation was observed upon overheating. - Best result: 0.7 MPa, 30 seconds	(Ageorges & Ye, 2001)
Talbot et al., 2013	PEEK	-2D and 3D finite element models were used to simulate the resistance weld. -Heating element: Stainless steel mesh	- It was concluded that the heat distribution was more homogeneous by controlling the clamping distance.	(Talbot et al., 2013)
Shi et al., 2015a	GF/PEI	- The pores formed during resistance welding were examined	- It has been stated that welding temperature and pressure are critical in cavity formation.	(Shi, Villegas, & Bersee, 2015a)
Koutras et al., 2018	GF/PPS	- The shear strength of the weld joint was examined between -50°C and 150°C.	It has been observed that the shear strength remains constant between - 50°C and 90°C.	(Koutras et al., 2018)
Rohart et al., 2020	CF/PPS	- The shear strength of the resistance weld was investigated between 21°C and 150°C	- Shear strength decreased by up to 61%. - Humidity was found to have a limited effect on shear strength.	(Rohart et al., 2020)
Du et al., 2020	GF/PP	- The effects of time, current and pressure on flexural strength were investigated.	- Resistance welding has been shown to improve the material's flexural strength by 31% compared to hot pressing.	(DU et al., 2020)

Among thermoplastic matrix materials exhibiting superior mechanical, thermal, and chemical properties, PEEK (Polyether Ether Ketone) is widely preferred in aerospace structures due to its high strength and temperature resistance. Studies investigating the joining performance of carbon- and graphite-reinforced PEEK matrix composites summarize the lap shear strength values obtained using different joining techniques in figure 10. Evaluating studies related to PEEK matrix repair, it is observed that carbon fiber-reinforced composites exhibit higher lap shear strength compared to graphite-reinforced ones. Moreover, for both carbon/PEEK and graphite/PEEK composites, the highest lap shear strength values in welded joints were achieved using the induction welding technique (Benatar et al., 1989; Gouin O'Shaughnessey et al., 2016; Reis et al., 2020; Tao et al., 2019; Villegas et al., 2013).

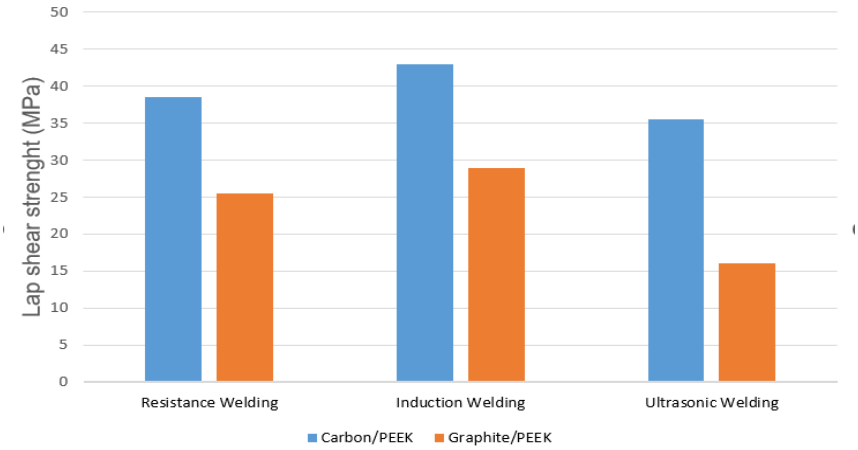


Figure 10. Lap shear strengths of Carbon/PEEK and Graphite/PEEK composites in different welding techniques

IV. CONCLUSION

Thermoplastic composites are increasingly being used in aerospace structures due to their properties such as high strength-to-weight ratio, superior impact resistance, and improved fatigue strength compared to thermoset-based materials. Their reformable nature enables the development of repair methods that require no surface preparation, can be applied quickly, and can be performed on-site; furthermore, their recyclability aligns with sustainable manufacturing goals.

Among the welding-based repair methods applied to thermoplastic composites, ultrasonic, resistance, and induction welding stand out. While the ultrasonic welding method offers the advantage of high processing speed, its applicability for on-site repairs is limited due to the large equipment volume. In resistance welding, non-uniform temperature distribution at the interface can adversely affect joint strength, whereas induction welding provides high energy efficiency, controlled heat distribution, and application flexibility, especially in conductive matrix systems.

Comparative experimental studies show that for repairing carbon/PEEK material, commonly used in aircraft structural sections, the highest lap shear strength is achieved with the induction welding technique, while in graphite/PEEK systems, the highest shear strength is provided by the resistance welding method. These findings reveal that the interaction between the material type and the heating method is one of the fundamental factors determining joint performance.

However, it is observed in the literature that quantitative data concerning the fatigue behavior of repaired regions, fracture toughness, long-term environmental durability, and the effects of permanently embedded heating elements on mechanical performance are quite limited. These gaps constitute the primary issues that future research should focus on. Particularly, a comprehensive investigation of the effects of different thermal cycles on microstructural integrity, residual stresses, and interface bond quality, through both experimental and numerical analyses, stands out as a critical research area to enhance the reliability and standardization of thermoplastic composite repairs in aerospace applications.

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