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Selim Gürgen

Joining Operations for Aerospace Materials

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Preface

The book *Joining Operations for Aerospace Materials* provides a deep knowledge on the specialized world of aerospace material joining, focusing on the methods, techniques, and strategies essential for creating resilient and high-performance structures in aeronautics and space applications. From the precision demands of metallurgical joining methods to the mechanical joining techniques, this book provides an exclusive roadmap to mastering the intricacies of joining processes tailored for aerospace materials. Uncover the latest advancements and emerging technologies that define the future of aerospace manufacturing. For the engineers, researchers, and technical staff, this book equips with the expertise to navigate the challenges of working with cutting-edge materials in the most demanding of environments.

Eskişehir, Türkiye
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About the Editor

Selim Gürgen, Ph.D., is an Associate Professor with the Department of Aeronautical Engineering at Eskişehir Osmangazi University and the Director of Eskişehir Vocational School. He is an Executive Board Member of the ESOGU Aerospace Technologies Research Center. He was a visiting researcher at the University of Wollongong for a project on smart materials. He was at the University of Aveiro on natural composites, and worked as a researcher with the School of Transportation at Anadolu University for four years. Before his academic life, he worked as a manufacturing engineer in a joint venture of KMWE-Dutch Aero. Dr. Gürgen has contributed to several industrial and research projects in collaboration with major organizations such as Fiat Automobiles, Turkish Aerospace Industries (TAI), and the Turkish Air Force. His projects were funded by the Scientific and Technological Research Council of Turkey (TÜBİTAK) and the European Union (EU). He has many publications in refereed international journals and conferences. He serves as an editorial member for several international journals. Dr. Gürgen is the co-editor of the book Materials, Structures, and Manufacturing for Aircraft (Springer, 2022) and editor of the books Shear Thickening Fluid: Theory and Applications (Springer, 2023) and Shear Thickening Fluid: Case Studies in Engineering (Springer, 2023). His primary area of research is material science.

Chapter 1
Adhesive Bonding Operations for Aeronautical Materials

Fermin Bañon, Carolina Bermudo, Francisco Javier Trujillo, Sergio Martin-Béjar, Manuel Herrera, and Lorenzo Sevilla

1.1 Materials for Aircraft Structural Components

The aeronautical industry is presently focused on achieving sustainability and energy efficiency as primary objectives. Among these goals, the industry aims to decrease the release of harmful gases, including CO_2 and NO_x, by 75–95% compared to the emissions recorded in 2000 [1, 2]. Additionally, aircraft must be designed and manufactured with recyclability in mind. To meet these objectives, new innovative materials, design techniques, and manufacturing processes are being developed to enhance efficiency and reduce consumption to meet current and future demands [3, 4]. This goal can be approached in various ways, including the advancement of more effective combustion engines or engines utilizing novel technologies, as well as the reduction of aircraft weight through the development of new materials or the creation of structures with optimized mass-to-mechanical strength ratios.

The materials used in aircraft manufacturing play a significant role in achieving sustainability and energy efficiency goals. Aircraft and aerospace materials are generally classified into four distinct categories: metallic, polymeric, composite, and ceramic materials. For structural components, light alloys—primarily aluminum and titanium alloys—and polymeric matrix composites are the most prevalent choices [5].

Wrought and cast aluminum alloys are used in the manufacturing of a wide range of parts in an aircraft. Cast alloys are typically more cost-effective and occasionally the sole method to manufacture intricately shaped products. However, this group shows lower mechanical properties than wrought alloys due to the lack of deformation processing. Therefore, they are used to manufacture noncritical components,

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such as pulleys, ducts, waveguides, or hydraulic valve bodies, among others. On the other hand, wrought aluminum alloys are preferred for manufacturing structural components of the airframe. Their excellent mechanical properties to weight ratio, durability, and damage tolerance make these alloys suitable for the manufacture of wing tension members, shear webs, and ribs, which involve critical requirements such as high tensile and compressive strength, or extended fatigue life [6, 7]. In this regard, the 2xxx and 7xxx series are the usual choice for these applications. The 2xxx series (Al-Cu alloys) presents excellent fracture toughness and fatigue behavior, as well as low crack growth rates, which make it appropriate for the lower wing and body skin. The 7xxx series (Al-Zn alloys) shows improved mechanical properties. Cu is added to these alloys to enhance resistance to stress corrosion cracking. They are used in wing skins and stringers in the upper wing structures and structures that require compressive loading. Aluminum-lithium (Al-Li) alloys also provide good opportunities for weight reduction. Li addition reduces the alloy density by about 3% and increases modulus by around 6%. However, these alloys pose certain unresolved challenges, including low thermal stability, high anisotropy of properties, or significant scattering of fracture toughness values, which hinder their widespread adoption in the aircraft industry [8, 9].

Although composite materials are increasingly replacing aluminum alloys, the latter still offer competitive advantages in terms of manufacturing. Additionally, most commercial aircraft aeronautical projects typically have a lifetime of about 15–20 years [10]. Therefore, these alloys continue to be utilized in the manufacturing of structural parts. In fact, some new airframe developments in modern aircraft consist of approximately 80% aluminum by weight. A notable example is the Boeing 737 MAX, the fourth generation of the Boeing 737. Its fuselage is a semi-monocoque structure primarily composed of various aluminum alloys. This model consumes 20% less fuel than the previous generation (737 NG) and is considered to be as efficient as a hybrid electric car [11].

Titanium alloys possess exceptional properties that render them highly suitable for aeronautical applications. With low density, an exceptionally high strength-to-weight ratio (even surpassing that of wrought aluminum alloys), and outstanding corrosion resistance at high temperatures, they prove ideal for aircraft structural parts and components that operate in extreme environmental conditions such as turbine blades and combustion chambers [12]. These alloys are generally categorized into two major groups based on their crystalline structure: (i) corrosion-resistant alloys (α alloys) and (ii) structural alloys (close α, $\alpha + \beta$, and β alloys) [13]. Specifically, the Ti-6Al-4V alloy, which falls into the latter category, constitutes 60% of the titanium utilized in the aerospace industry. It finds primary application in fabricating components for engines and structures, either independently or in conjunction with composites to form fiber metal laminate (FML) structures. β-Ti alloys (notably Ti-10V-2Fe-3Al and Ti-15V-3Cr-3Al-3Sn) are employed in scenarios requiring high strength coupled with fracture resistance, such as in springs, fasteners, or landing gears [5].

Globally, the integration of composites into aircraft design is widely acknowledged as a crucial technology in achieving emission reduction objectives.

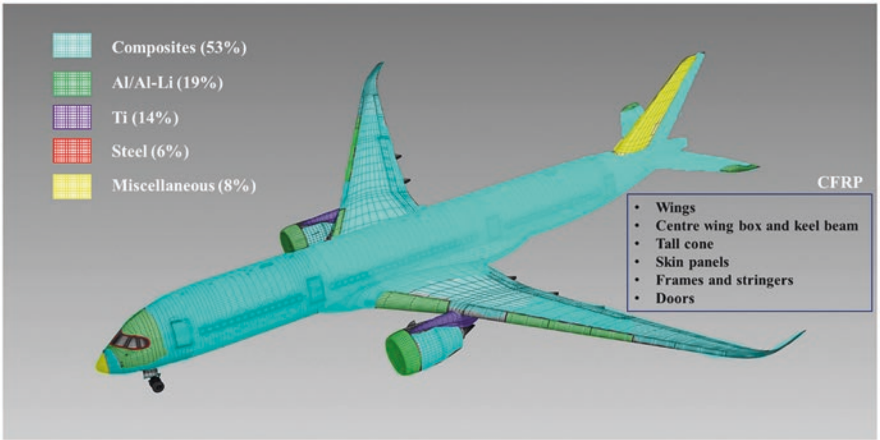

Fig. 1.1 Materials used in the Airbus A350 XWB [16]

Composites offer material characteristics that surpass those of lightweight alloys, enabling the creation of lighter structural designs, ultimately resulting in reduced fuel consumption and emissions [14]. In this context, Airbus has successfully developed and produced the A350 XWB series, utilizing 53% advanced lightweight fiber-reinforced polymer (FRP) composites, as shown in Fig. 1.1. This innovation has led to a 25% enhancement in fuel efficiency compared to its predecessors, the A330 [15, 16]. Another notable example is the A220 model, which incorporates Al-Li parts in its fuselage and titanium and FRP components in its wings. As a result, it is widely recognized as the most fuel-efficient aircraft family in its class [4].

In this context, carbon fiber-reinforced polymers (CFRP) are among the most commonly used composites for structural purposes in aircraft. These composite materials possess a set of properties that render them an excellent alternative to lightweight alloys for airframe manufacturing: high strength-to-weight and stiffness-to-weight ratios, excellent fatigue behavior, high corrosion resistance, and low thermal expansion. Additionally, CFRP allows for the creation of complex geometries due to their good formability [17]. CFRP consists of two different components. On the one hand, the carbon fiber acts as a reinforcement, providing strength and rigidity, while the matrix offers protection to the reinforcements against impacts and transmits the load. Thermosetting and thermoplastic materials are often used as matrix materials, each with its own advantages and disadvantages, with thermosetting being the most commonly used in aircraft applications. Thermosetting materials have low viscosity resin, allowing for easy impregnation. However, they are not recyclable, and their manufacturing processes consume a significant amount of time and energy, resulting in a low level of automation. On the other hand, the use of thermoplastics as composite matrix (carbon fiber-reinforced thermoplastic (CFRTP)) offers greater impact resistance (up to ten times higher), higher recyclability and repairability, and shorter processing times (eliminating the need for curing stages). However, the main challenge with thermoplastics is the lower compatibility between the resin and the fiber, which requires the use of special techniques and tools for manufacturing, usually at a higher cost than CFRP [14].

The use of light alloys and FRP, separately, still presents disadvantages in their application to structural components when compared to each other. Light alloys exhibit lower fatigue behavior, whereas CFRP demonstrates lower impact and residual strength. These disadvantages can be mitigated by the hybrid use of both materials. A hybrid structure typically involves the combination of FRP with a metal alloy, which can be joined by adhesive bonding or thermal joining. Typical examples of hybrid structures include FML and sandwich panels [18].

Sandwich panels consist of a high-thickness core (honeycomb, foam, folded, or lattice) made of low-density material covered by a thin layer (skin) of high-stiffness material, usually aluminum alloys or FRP, as shown in Fig. 1.2. These hybrid structures significantly improve the strength-to-weight ratio and stiffness. Combining aluminum skins with aluminum honeycomb cores is typical in critical structures subject to higher loads, while polymer foam or Nomex honeycomb cores, along with FRP skins (carbon or glass fiber), are common in less critical structures such as wing flaps or internal bulkheads [19].

FMLs are hybrid composite structures composed of alternating thin sheets of light alloys (aluminum, titanium, or magnesium) and plies of FRP prepregs. This structure enhances the properties of both FRP and bulk light alloy, offering lower density, superior mechanical properties (including fatigue resistance, strength, fracture toughness, impact resistance, and energy-absorbing capacity), and higher durability (including excellent moisture and corrosion resistance, reduced material degradation, and increased fire resistance). However, FMLs also present certain disadvantages. Firstly, it is crucial to ensure good insulation between the layers, as bonding different electrochemical potential materials may lead to corrosion in certain environments. Additionally, the manufacturing process involves higher labor costs and is time-consuming, resulting in lower productivity [20].

The most commonly used FMLs in aircraft structural components consist of layers of aluminum alloys and polymer matrix reinforced with fibers of aramid, glass, or carbon, as shown in Fig. 1.3. Aramid-reinforced fiber-aluminum laminates (ARALL) are composed of alternating layers of aluminum alloy (0.3 mm thick) and high-strength aramid fibers embedded in epoxy (0.22 mm thick, 50% fiber to resin

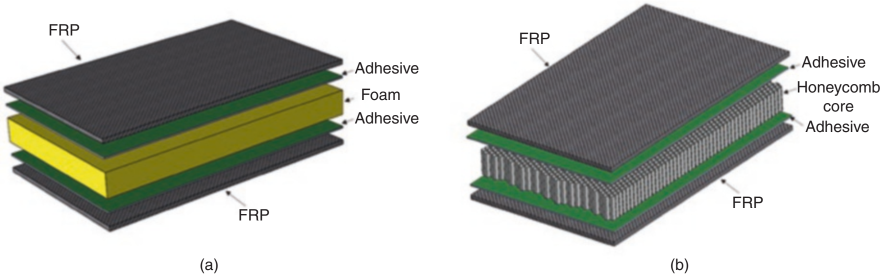

Fig. 1.2 Sandwich panels with (**a**) foam and (**b**) honeycomb cores [18]

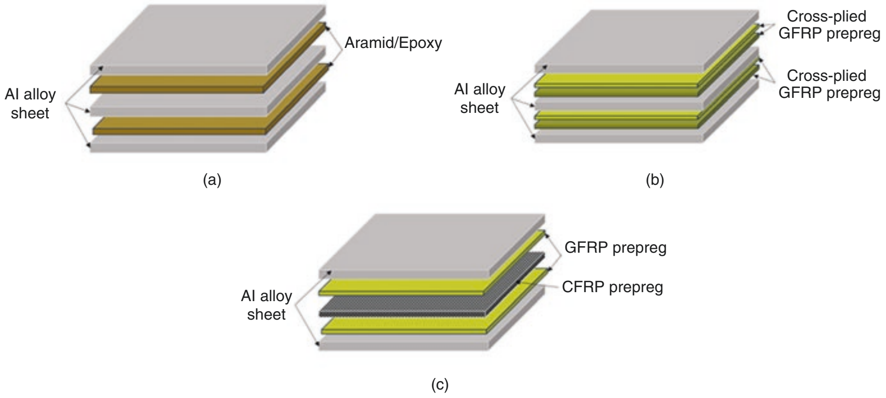

Fig. 1.3 Typical FML-based hybrid structures used in aircraft: (**a**) ARALL, (**b**) GLARE, and (**c**) CARALL [21]

weight ratio). The composite layers are unidirectional fiber prepreg, oriented in the main load direction and parallel to the aluminum sheet rolling direction (Fig. 1.3a). Their main properties include high strength and excellent fatigue behavior, while their major disadvantage lies in low compressive strength. ARALLs find applications in the fuselage, lower wing skin panels, and cargo doors of aircraft. Special attention is required during manufacturing to ensure proper bonding between layers due to potential moisture ingress problems into the aramid-epoxy layers, which may compromise material integrity. Glass-reinforced fiber-aluminum laminates (GLARE) comprise thin sheets of aeronautical aluminum alloy bonded to thin layers of high-strength glass-epoxy prepreg composite. GLARE allows fiber placement in two different directions (0° and 90°) due to its better adhesion between the matrix and the reinforcing phase (Fig. 1.3b), making it suitable for parts under biaxial stresses. Additionally, GLARE exhibits superior behavior compared to ARALL in terms of tensile and compressive strength and impact resistance. It is commonly used in the vertical fin, horizontal stabilizers, upper fuselage, and cargo doors of aircraft. Carbon-reinforced fiber-aluminum laminates (CARALL) consist of alternating layers of carbon fiber epoxy and glass fiber epoxy, along with sheets of structural aluminum alloy (top and bottom layers) (Fig. 1.3c). Developed as an improvement over ARALL laminates, CARALLs offer higher stiffness and very low crack growth rates. Applications of CARALL in aircraft include wing sheathing, flaps, vertical and horizontal stabilizers, and the fuselage [21].

Despite the significant advantages of using composites and hybrid materials in the aeronautical industry, there remain several unsolved issues that hinder their 100% applicability as substitutes for light alloys. Firstly, the manufacturing of composite components still relies on a low level of automation, requiring highly qualified labor and significant time consumption. Consequently, the manufacturing costs are higher compared to those of light alloys. Additionally, ensuring repeatability and meeting high-quality standards pose challenges in producing defect-free parts.

These challenges extend to maintenance and repair technologies [14]. In this context, the development of efficient joints for manufacturing hybrid structures stands out as a crucial aspect to address.

1.2 Adhesive Bonding

The fuselage of an aircraft consists of numerous parts that must be joined during the assembly process. These components vary in geometry, dimensions, and materials. Special attention must be paid to the in-service behavior of the joints, as they are often considered one of the weakest parts of the structures in terms of mechanical resistance, crack growth, and fatigue behavior [22]. These concerns become especially critical when joining dissimilar materials, such as in the case of using hybrid structures (metal-to-composite joints). Joining dissimilar materials requires considering additional factors, including differences in expansion coefficients, which can affect behavior under thermal loads, and differences in galvanic properties, which can impact corrosion behavior at the material interface, among others. Therefore, proper design, manufacturing, and maintenance are crucial to ensure the durability, integrity, and reliability of these joints [23].

There are three types of technologies that can be used to join structural components: welding joints, mechanical fastening, and adhesive bonding, as shown in Fig. 1.4 [24]. Conventional welding technologies are typically not applied in

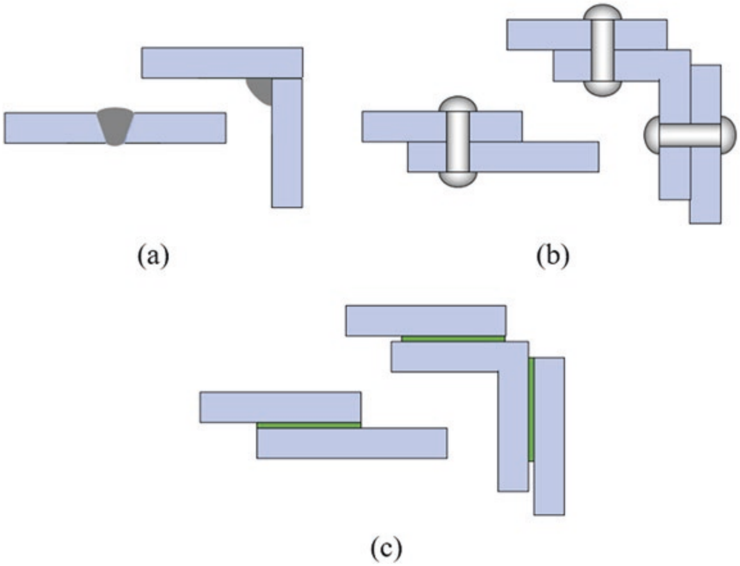

Fig. 1.4 Joining technologies for structural components: (**a**) welding, (**b**) mechanical fastening, and (**c**) adhesive bonding [25]

aeronautical assemblies for several reasons. Firstly, the high energy used in these processes leads to residual stresses and deformation around the joining area, increasing the likelihood of defects in light alloy structures. Such defects are incompatible with the stringent requirements for the in-service properties of airframe joints. Additionally, conventional welding methods are unsuitable for hybrid structures due to the presence of polymer matrix composites, and they pose challenges in inspection, maintenance, and disassembly. New innovative approaches, such as friction stir welding, are emerging for joining structural components in aircraft. However, the stringent regulatory environment combined with a conservative market results in lengthy validation and implementation processes for new joining technologies, thereby slowing down their application [22].

Mechanical fastening, including riveting and bolted joints, is the predominant technology in this field. Mechanical joints offer ease of design, maintenance, and disassembly. However, they come with a set of disadvantages for the aircraft structures. First, fasteners provide an additional weight to the structure, negatively impacting final fuel consumption and emissions. Moreover, they may lead to difficulties in achieving load transfer from one part to another. Another drawback is stress concentration, an undesirable effect in structural designs, due to machining holes in the material, where most fatigue cracks initiate. Furthermore, the drilling process can cut the fibers of FRP, potentially reducing structural integrity. Another risk with fasteners is corrosion between bolts/rivets and sheets.

Adhesive bonding is a joining technology that involves placing an adhesive between two or more surfaces, which then solidifies to create a bonded component, as shown in Fig. 1.5. It is widely used, especially when one of the materials to be joined is nonmetallic or when joining dissimilar materials. Adhesive bonding offers several advantages over mechanical joints: lower weight, resulting in a better strength-to-weight ratio; better distribution of loads from one part to another; reduction of residual stresses; improved fatigue behavior and resistance to cracks; reduced corrosion; vibration damping; and greater design flexibility [17, 21, 26]. Due to these properties, adhesives are increasingly used as an alternative to mechanical joints in a wide variety of industries and engineering applications, including electronics, automotive, construction, sports, aerospace, aeronautics, etc. [27]. This is evidenced by the increase in research in this field over the last 10 years, as shown in Fig. 1.6.

Although adhesives were initially used in noncritical or secondary structural components in aircraft, their current level of safety and reliability now enables their use in primary structural components as well. Examples include the joining of stringers and straps to the fuselage and core-skin bonding in metallic honeycomb structures such as wing skins, ailerons, and spoilers. Despite their many advantages, adhesive joints are not without drawbacks, some of which remain unresolved.

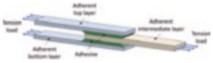

Fig. 1.5 Adhesive bonding (double lap joint under tension load) [25]

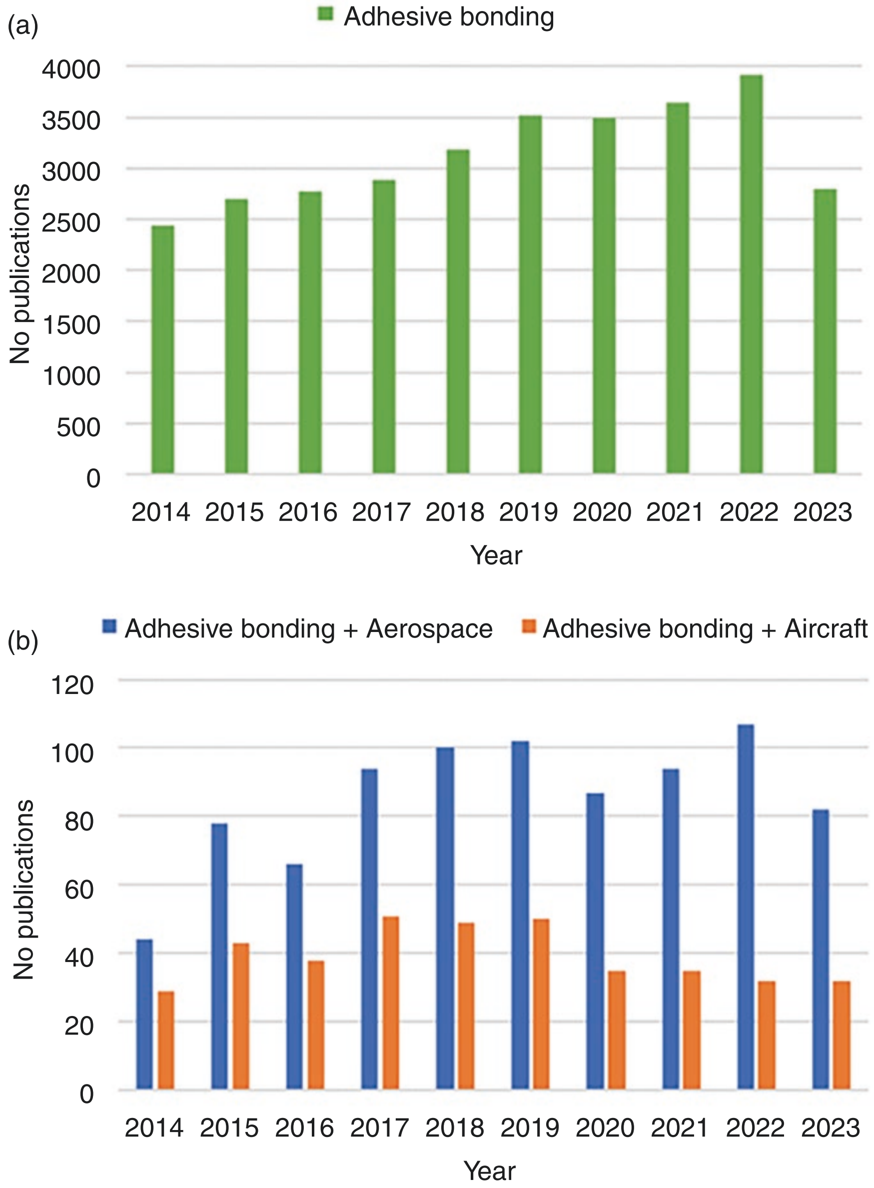

Fig. 1.6 Number of publications in the Web of Science database having the main topic of (**a**) adhesive bonding and (**b**) adhesive bonding + aerospace and adhesive bonding + aircraft

Improving tear strength and reducing peeling and cleavage stresses are necessary to enhance the mechanical strength and reliability of these joints. Additionally, issues such as the aging of adhesives and environmental degradation and poor performance under high temperature and humidity conditions pose challenges. Moreover, the