Furkan Karaboğa
Eray Koştur
Zelal Yavuz
Merve Özkutlu Demirel
Mahide Betül Öztürkmen
Yahya Öz
Turkish Aerospace
Ankara

Serkan Toros
Nigde Omer Halisdemir University
Nigde

Fahrettin Öztürk
İstanbul Technical University
İstanbul

Makale Bilgisi:
Araştırma Makalesi
Gönderilme: 29 Ağustos 2024
Kabul: 12 Aralık 2024

*Sorumlu yazar
E-mail: furkan.karaboga@tai.com.tr

Development of Joining Methods of Thermoplastic Composites for Aerospace Applications

Fiber-reinforced thermoplastic matrix composite laminates pose great potential for current and future aircraft components. Thermoplastic composites' recyclability, long shelf life, resistance to environmental conditions, and high toughness properties are rapidly increasing their application areas. In addition, its environmental hazardous is much lower compared to thermosets. Thermoplastic composites have gained an important position in aviation due to these properties. In this study, some joining methods that can be used for a thermoplastic matrix composite aircraft structure have been experimentally examined. The methods were compared by performing a single lap shear test (ASTM D5868) at the coupon level. In addition, details about a novel ultrasonic welding machine that performs the welded joining method are also given. Results show that the joint strength of thermoplastic composites can be tailored by the chosen method and corresponding parameters.

Keywords: Composites, Thermoplastic composites, Joining methods, Adhesive bonding, Ultrasonic welding, Consolidation

1. INTRODUCTION

Composite materials are widely used in structural applications and aerospace technology, serving as components in a variety of vehicles such as passenger and fighter aircrafts, space shuttles, and helicopters [1]. These materials are often combined with other substances in the aerospace industry. In the Boeing 787, for instance, a mix of 50 % composite materials and 50 % other materials like aluminum, titanium, and steel is incorporated. Joining techniques are employed to combine composite materials with other substances, including metals, wood, and plastics, as illustrated in Figure 1 showcasing applications in modern aircraft structures [2,3].

Conventional joining of composite materials presents a significant drawback for composites. This is because it results in undesirable stress concentrations when composites are drilled for mechanical joining, potential corrosion between carbon fiber reinforced polymer (CFRP) laminate and fasteners, as well as deformations like delamination and fiber pull-out within the composite material [4-7]. To prevent these deformations, composite parts at the joints need to be designed thicker than the rest of the structure, which contradicts the goal of lightweight design driven by fuel consumption and emission requirements [8,9]. Therefore, the aerospace sector is highly interested in alternative joining techniques in addition to mechanical joining [10]. Correspondingly, it is a known fact that joining is critical in terms of weight reduction and structural stability.

In the past, high-performance structural applications relied on thermosetting resins like epoxies, which were reinforced with short and continuous fibers. However, with the advent of thermoplastic resins, a wider range of weldable composite materials can now be produced to meet demands of high-performance applications. There has been a focus on localized welding of thermoplastic composites [11]. On the other hand, adhesive bonding is often preferred over mechanical methods due to the ability to achieve a uniform joint offering continuous load transmission and desirable fatigue properties. Also the joining of different materials such as composites, metals, wood, or ceramics is available [12]. The process involves solidifying the adhesive between materials to create a strong bond [13]. Adhesives can form durable bonds that maintain their strength across various temperatures [14]. There are different types of adhesives available, from low strength for filling gaps to high strength for structural purposes [10]. The most significant advantage of thermoplastic composites (TPC) is their ability to melt. This characteristic allows TPCs to be "reprocessable," making them fully recyclable and highly suitable for joining and repairing through local melting and re-consolidation processes which are methods for joining thermoplastic matrix composites by re-melting and fusing to create strong and integrated bonds [15,16].

In this study, different joining methods including adhesive bonding, re-consolidation and ultrasonic welding were investigated experimentally. Carbon fiber (CF) reinforced polyetherketoneketone (PEKK) laminates were utilized in these experimental studies. Different types of adhesive films and commercial adhesives were experienced for bonding purposes. The effects of ultrasonic welding with and without polymer films at the welding interface were investigated. Methods were compared by conducting single lap shear tests to different types of specimens according to ASTM 5868 standards.

2. MATERIALS AND METHODS

2.1. Materials

In this study, various joining techniques were applied to CF/PEKK (Toray Cetex® TC1320) composite laminates sourced from Toray, Japan. Due to the reinforcement of CFs into neat PEKK resin, the strength of the materials was enhanced dramatically enabling a wide range of use in aerospace applications.

Important features of aforementioned PEKK thermoplastic are:

- Qualified and certified according to aerospace specifications
- Excellent toughness and impact resistance
- Excellent mechanical performance even at elevated temperatures
- Low moisture uptake for good hot/wet strength retention
- Inherently flame retardant
- Outstanding chemical and solvent resistance
- Indefinite shelf life at ambient temperature storage

The laminates were chosen in terms of neat resin properties presented in Table 1.

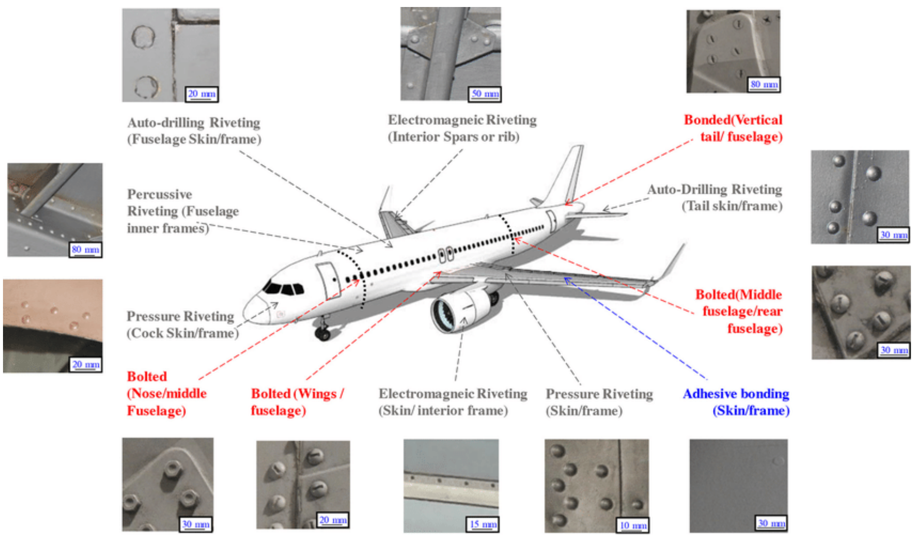

Figure 1. Commonly used joining applications in an aircraft [3].

Table 1. Significant properties of CF/PEKK laminate.

Property	Value
Density (specific gravity)	1.30 g/cm³ (80.5 lb/ft³)
T_g (glass transition)	160 °C (320 °F)
T_m (melt)	337 °C (639 °F)
T_c (crystallinity)	265 °C (509°F)
T_p (processing)	370 – 400 °C (700 – 750 °F)

Typical applications of CF/PEKK laminates involve primary and secondary aircraft structures, high load aircraft interiors applications, access panels, rib stiffeners, brackets, conduits and flooring. In addition, adhesive films were used in order to join two composite parts prepared according to the sampling specified in the ASTM D5868 standard for the single lap shear (SLS) test. 20.800, 22.100 and A21.4500 adhesive films were obtained from Pontacol, Switzerland, while the FM 300K was obtained from the Solvay, USA. Product characteristics of the used adhesive films are listed in Table 2. Experimental parameters were determined by considering these properties.

2.2. Methods

In this study, different joining methods including adhesive bonding, re-consolidation, and ultrasonic welding were investigated experimentally on CF /PEKK laminates. These laminates were produced via autoclave consolidation. Methods were compared by conducting single lap shear tests to different types of specimens according to the ASTM D5868 standard.

First of all, in preparation of specimens, composite laminates were cut according to the SLS test method (i.e. ASTM D5868) as seen in Figure 4. Surfaces of laminates were treated with mechanical abrasion via sandpaper such that the joint strength could be enhanced. Since the surface roughness was increased by abrasion, mechanical interlocking of two laminates was facilitated throughout the joining process. After abrasion was performed, surfaces of both laminates and adhesive films were cleaned by application of isopropyl alcohol (IPA) to get rid of impurities that may hinder effective adhesion.

In the second step, prepared composite laminates were joined by using 4 different adhesive films whose specifications were noted above. Laminates were grouped separately and joining treatments were applied for them analogously.

In the third step, the joint thermoplastic composite laminates were cured with adhesive films, alternatively. The curing was completed in an autoclave according to the parameters presented in the following section. Curing parameters were determined according to the properties of adhesive films such as T_g and T_m as summarized in Table 3.

Table 2. Types and properties of adhesive films used for joining.

Property	20.800	22.100	A21.4500	FM 300K
Base	Modified Polyolefin	Modified Polyolefin	Polypropylene	Epoxy Resin
Density	0.9 g/cm^3	0.9 g/cm^3	0.9 g/cm^3	0.88 g/cm^3
Melting Temperature	80 – 90 °C	120 – 130 °C	140 – 155 °C	-
Glass Transition Temperature (Tg)	5075 °C	110 58 °C	40140 °C	148 °C
Service Temperature	-30 to +70 °C	-40 to +80 °C	-40 to +120 °C	-55 to +149 °C

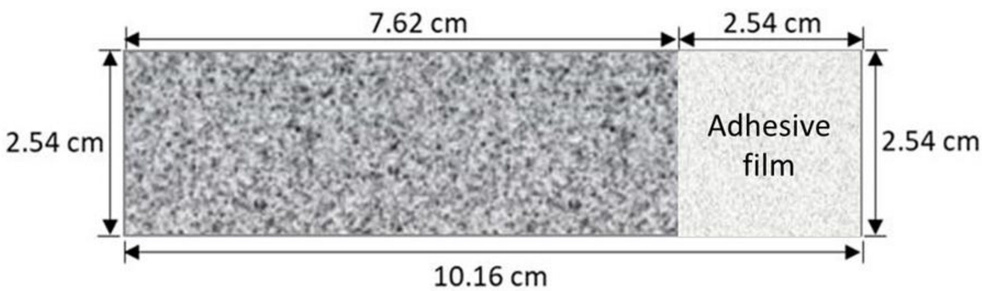

Figure 4. Schematic depiction of test specimens.

Table 3. Curing parameters of adhesive films with CF/PEKK laminates.

Curing parameter	20.800	22.100	A21.4500	FM 300K
Temperature	120 °C	160 °C	185 °C	180 °C
Pressure	3 bar	3 bar	3 bar	3 bar
Time	2 h	2 h	2 h	1 h

The second method applied onto PEKK composite laminates was re-consolidation. Two consolidated laminates were fixed onto each other without adhesive film in a shape determined by the SLS test standard which was noted previously. Then, joined laminates were cured in an autoclave with parameters summarized in Table 4.

Table 4. Consolidation parameters of re-consolidated PEKK laminates.

Parameter	Nominal value
Temperature	375 °C
Pressure	6 bar
Time	2 h

In addition, an ultrasonic welding device has been designed to investigate the performance of ultrasonic joining methods. The welding device is depicted in Figure 3. The equipment has been meticulously engineered with a fixture design that accommodates single point, multi-point, and continuous welding methodologies. It boasts adjustable horn height and pressure values, allowing for precise customization according to specific welding requirements. Operating at a frequency of 12 GHz, this system is optimized to deliver exceptional performance across a range of welding applications, ensuring superior weld quality and efficiency.

Transducer, booster, horn, anvil, power supply, controller, and safety features are essential parts of ultrasonic welding equipment. Ultrasonic vibrations are produced by the transducer from electrical energy, and the booster amplifies as well as focuses these vibrations onto the workpiece using the horn. The workpiece is given a surface by the anvil, which also aids in vibration transmission. The transducer is powered by the power supply, while welding settings are adjusted by the controller. Safe operation is ensured by safety features. Together, these elements generate frictional heat at the interface between the workpieces, enabling them to be joined without the need of adhesives or other materials.

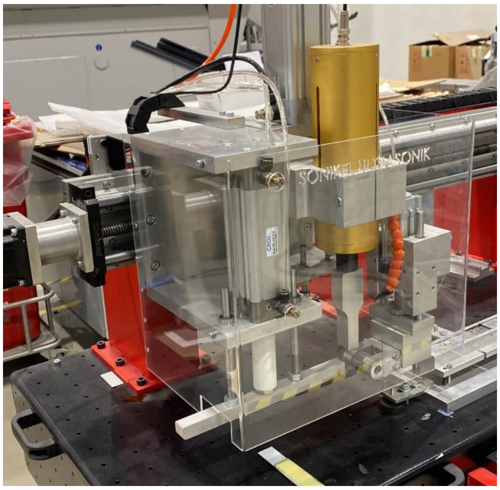

Figure 3. Sonikel ultrasonic welding machine

In the experiments, two types of ultrasonic welding techniques which include single and three-point welding zones were performed. In single-point experiments, the center of the horn was positioned at the center of the welding area, corresponding to the 12.5 mm point within the 25 mm x 25 mm square weld zone. In three-point experiments, welding was performed in three stages. First, the center of the welding zone (12.5 mm) was welded, followed by welding at 17.5 mm and then 7.5 mm, in sequence. Additionally, in some experiments, PEEK films were placed between two samples to generate a region with higher resin content for welding.

In single-point experiments, the welding time was 1.7 sec., while for three-point experiments, durations of 1, 1.2, and 1 sec. were conducted. The shorter welding time caused insufficient melting of the PEKK matrix, thus a smaller welding area. On the other hand, longer welding times result in the decomposition of the PEEK films without melting. Therefore, the welding times were kept the same as in the experiments without films.

Mechanical Tests

Single lap shear tests were performed according to the ASTM D5868 for all samples. Before the test, 25 x 25 mm^2 plates were cut from the same laminates and stacked to the ends of the lap shear specimens using Loctite 496 to correct the alignment. Tests were performed with 5 specimens for each case at room temperature and relative humidity of 50 %. The apparent lap shear strength (LSS) of the joints was calculated as the maximum load divided by the total overlap area.

3. RESULT AND DISCUSSIONS

Within the scope of this study, five samples for each joining method which were adhesive bonding, re-consolidation and ultrasonic welding methods were tested via single lap shear tests. The maximum amount of force that samples can withstand and shear strength were compared.

From Table 5, results of the adhesive bonding method of CF/PEKK laminates with the 20.800, 22.100, 21.450 and FM 300K respectively, were represented. For the adhesive bonding process, due to the low surface free energies of thermoplastic composites, insufficient shear force values were obtained [17]. Among four film adhesives, the best results were observed as 8.06 MPa for the FM 300K adhesive film.

Table 5. Adhesive bonding results

Laminate Material	Bonding Material	Lap Shear Strength (MPa)
CF/PEKK	Pontacol 20.800	2.66 ± 0.40
CF/PEKK	Pontacol 22.100	2.90 ± 0.16
CF/PEKK	Pontacol 21.450	5.29 ± 0.26
CF/PEKK	FM 300K	8.06 ± 1.63

Table 6 shows that the re-consolidation method provides reasonable results with a shear strength of 28.91 MPa. Since thermoplastic laminates melt and consolidate together, proper adhesion was achieved inherently within this method.

Table 6. Re-consolidation result

Laminate Material	Lap Shear Strength (MPa)
CF/PEKK	28.91 ± 4.25

The lap shear strength of PEKK composites which were welded via ultrasonic welder at different conditions were given in Table 7. According to the results, the welding performance using the three-point welding method surpassed that of single-point welding, regardless of whether a PEEK film was used. Interestingly, the application of the PEEK film led to a decrease in lap shear strength. This decrease could be attributed to the inadequate compatibility between the PEEK film and the PEKK matrix. Another factor might be insufficient melting of the polymer matrix in the presence of the PEEK film, as the vibrational energy primarily melted the PEEK film. Notably, extending the welding time did not alleviate this problem, likely due to the degradation of the PEEK films.

4. CONCLUSION

The study provides a comprehensive comparison of three joining methods—adhesive bonding, re-consolidation, and ultrasonic welding—for carbon fiber-reinforced polyetherketoneketone (CF/PEKK) laminates in aerospace applications.
Results indicate that re-consolidation, achieving a lap shear strength exceeding 20 MPa, demonstrates the highest bond strength among the methods tested, meeting critical aerospace thresholds [17]. This approach combines efficiency, strength, and design flexibility, making it particularly suited for complex geometries.

Interestingly, the application of a PEEK film for PEKK laminates led to a decrease in the lap shear strength during the ultrasonic welding approach. Also, this approach allows the manufacturing of complex geometries while it includes further advantages like process efficiency, environmental benefits, design flexibility and repairability.

Table 7. Welding results

Laminate Material	Welding Methodology	Film	Lap Shear Strength (MPa)
CF/PEKK	Single point	Applied	6.5 ± 1.2
CF/PEKK	3 points	Applied	8.8 ± 1.6
CF/PEKK	Single point	Not Applied	7.0 ± 1.5
CF/PEKK	3 points	Not Applied	9.3 ± 1.1

In aerospace applications, adhesive bonding, re-consolidation, and ultrasonic welding each offer distinct advantages and limitations, making them suitable for different joining needs. Adhesive bonding provides flexibility for bonding diverse materials with minimal heat and good stress distribution, but it has longer cure times, requires special surface preparation for thermoplastic composites to obtain higher strength, and can be limited by high temperature applications. Re-consolidation, on the other hand, creates high strength which can be understood from test results, thermally compatible joints by re-melting and consolidating the bond, producing a structure similar to the bulk material and allowing for repairability. However, it requires high process temperature and pressure, a complex tool setup, and can risk thermal deformation. Lastly, ultrasonic welding offers rapid processing with localized heating, which avoids thermal distortion and eliminates the need for adhesives, although it's typically limited to small, flat surfaces and requires precise selection of many process parameters. This method is best suited for smaller components or sub-assemblies, particularly in high-speed production.

In conclusion, each method brings unique advantages and trade-offs in structural integrity, process complexity, and thermal requirements, enabling selective application based on aerospace manufacturing needs.

In future works, some chemical surface treatments will be investigated to increase surface free energy and results will be compared to mechanical treatments. Parameters of chemical treatments that affect lap shear strength of composites will also be examined. Moreover, welding parameters like temperature, pressure and welding time will be optimized to maximize lap shear strength.

HAVACILIK UYGULAMALARI İÇİN TERMOPLASTİK KOMPOZİTLERİN BİRLEŞTİRME YÖNTEMLERİNİN GELİŞTİRİLMESİ

Fiber takviyeli termoplastik matrisli kompozit laminatlar, mevcut ve gelecekteki uçak bileşenleri için büyük bir potansiyel oluşturmaktadır. Termoplastik kompozitlerin, geri dönüştürülebilir olması, raf ömürlerinin uzunluğu, çevresel koşullara dayanımı, yüksek tokluk özellikleri uygulama alanlarını hızla arttırmaktadır. Ayrıca termosetlere göre çevreye verdiği zarar oldukça düşüktür. Termoplastik kompozitler bu özelliklerinden dolayı havacılıkta önemli bir konuma gelmiştir. Bu çalışmada, termoplastik matrisli kompozit bir hava aracı yapısalı için kullanılabilecek bazı birleştirme yöntemleri deneysel olarak incelenmiştir. Yöntemler, kupon seviyesinde tek bindirmeli kayma testi (ASTM D5868) yapılarak karşılaştırılmıştır. Ayrıca kaynaklı birleştirme yöntemini gerçekleştiren ultrasonik kaynak makinesine ilişkin detaylar da verilmiştir. Sonuçlar, termoplastik kompozitlerin bağlantı mukavemetinin seçilen yönteme ve karşılık gelen parametrelere göre ayarlanabileceğini göstermektedir.

Anahtar Kelimeler: Kompozitler, Termoplastik kompozitler, Birleştirme yöntemleri, Yapışkan bağlama, Ultrasonik kaynak, Konsolidasyon

REFERENCES

1. Siddique, A., Iqbal, Z., Nawab, Y., & Shaker, K. (2022). A review of joining techniques for thermoplastic composite materials. Journal of Thermoplastic Composite Materials, 36(8), 3417–3454.
2. Toozandehjani, M. (2018). Conventional and Advanced composites in Aerospace industry: Technologies revisited. American Journal of Aerospace Engineering, 5(1), 9.
3. Zhao, H., Xi, J., Zheng, K., Shi, Z., Lin, J., Nikbin, K., Duan, S., & Wang, B. (2020). A review on solid riveting techniques in aircraft assembling. Manufacturing Review, 7, 40.
4. Kim, K., Yoo, J., Yi, Y., & Kim, C. (2006). Failure mode and strength of uni-directional composite single lap bonded joints with different bonding methods. Composite Structures, 72(4), 477–485.
5. Teti, R. (2002). Machining of composite materials. CIRP Annals, 51(2), 611–634.
6. Liu, D., Tang, Y., & Cong, W. (2012). A review of mechanical drilling for composite laminates. Composite Structures, 94(4), 1265–1279.
7. Bolat, Ç., Karakılınç, U., Yalçın, B., Öz, Y., Yavaş, Ç., Ergene, B., Ercetin, A., & Akkoyun, F. (2023). Effect of Drilling Parameters and Tool Geometry on the Thrust Force and Surface Roughness of Aerospace Grade Laminate Composites. Micromachines, 14(7), 1427.
8. Knoop H. (2016). Numerical Simulation of failure of adhesively bonded composite parts using the cohesive zone method. Hamburg: Hamburg University of Applied Sciences;
9. Fernández-Cañadas, L. M., Ivañez, I., Sanchez-Saez, S., & Barbero, E. J. (2019). Effect of adhesive thickness and overlap on the behavior of composite single-lap joints. Mechanics of Advanced Materials and Structures, 28(11), 1111–1120.

10. Karaboğa, F., Göleç, F., Yunus, D. E., Toros, S., & Öz, Y. (2024). Mechanical response of carbon fiber reinforced epoxy composite parts joined with varying bonding techniques for aerospace applications. Composite Structures, 331, 117920.
11. Nishida, H., Carvelli, V., Fujii, T., & Okubo, K. (2018). Thermoplastic vs. thermoset epoxy carbon textile composites. IOP Conference Series. Materials Science and Engineering, 406, 012043.
12. Nasreen, A., Shaker, K., & Nawab, Y. (2021). Effect of surface treatments on metal–composite adhesive bonding for high-performance structures: an overview. Composite Interfaces, 28(12), 1221–1256.
13. Lathabai, S. (2011). Joining of aluminium and its alloys. In Elsevier eBooks (pp. 607–654).
14. Campilho, R. D. S. G., Da Silva, L. F. M., & Banea, M. D. (2017). Adhesive Bonding of Polymer Composites to Lightweight Metals. Joining of Polymer-Metal Hybrid Structures: Principles and Applications, 29–59.
15. Ye, L., Chen, Z., Lu, M., & Hou, M. (2005). De-consolidation and re-consolidation in CF/PPS thermoplastic matrix composites. Composites. Part a, Applied Science and Manufacturing, 36(7), 915–922.
16. Reis, J. P., De Moura, M., & Samborski, S. (2020). Thermoplastic composites and their promising applications in joining and repair composites structures: a review. Materials, 13(24), 5832.
17. 17. Khan, M. A., Aglietti, G.S., Crocombe, A.D., Viquerat, A.D. & Hamar, C.O. (2018). Development of design allowables for the design of composite bonded double-lap joints in aerospace applications. International Journal of Adhesion and Adhesives, 82, 221-232.