

JOINING, DISASSEMBLY, AND RECONFIGURATION OF THERMOPLASTIC COMPOSITES FOR SPACE APPLICATIONS

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ABSTRACT

Thermoplastic composites are increasingly being investigated for aerospace applications because of their relatively short processing time, good chemical and radiation resistance, and potential for reforming and reuse via melting. The manufacturing, reforming, and reuse of thermoplastic composites can be leveraged to advance joining, disassembly, and on-site reassembly of structures for space exploration activities. Potential applications include, but are not limited to, habitats and on-orbit assembly and reassembly of large-scale truss structures.

This work focuses on demonstrating the feasibility of joining, disassembly, and reassembly of a thermoplastic bond using heat and pressure. Polyether ether ketone (PEEK) composite adherends were joined using low-melt polyaryl ether ketone (LM-PAEK) thermoplastic films at the bonding interface. The single lap shear specimens with LM-PAEK film were tested and had a maximum shear strength between 5 and 8 MPa and consistently failed adhesively at the bondline.

Reassembly of disassembled specimens was successfully demonstrated using additional thermoplastic interlayers. Thus, the reassembly of thermoplastic composite joints was found to be feasible. However, additional work is required to reduce film flowout and optimize consolidation parameters for an in space environment.

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1. INTRODUCTION

Composites are attractive for aeronautics and space applications due to their high strength-to-weight ratio and geometric tailorability (Ref. 1). Historically, thermoset composites (TSCs) have dominated composite use in aerospace because of their lower raw material cost, better defined

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manufacturing and repair processes, and lower processing temperature and pressure compared to those of thermoplastics (Ref. 2). However, thermoplastic composites (TPCs) offer many advantages, including reduced cycle time and increased production rate, reformability and reusability, high fracture toughness and durability, and good chemical, ultraviolet, and radiation resistance (Refs. 3 and 4). The manufacturing benefits of TPCs can be leveraged for space applications such as habitats and on-orbit assembly and reassembly of large-scale truss structures. The objective of this work was to assess the feasibility of disassembly and reassembly of thermoplastic composite joints and understand its effects on mechanical performance.

Fusion bonding and disassembly of dissimilar materials (TPCs, TSCs, and metals) can be achieved either by coprocessing a thermoplastic film to the adherend or by using a hybrid interlayer (Ref. 5). De Weert investigated the disassembly of fusion bonded TPC joints using induction heating, finding that induction heating to 130 °C caused a 37-percent reduction in force required to separate the single-lap shear (SLS) specimens with minimal edge defects (Ref. 6). Larger reductions in force were achieved at higher temperatures but at the cost of thermal damage to the specimen. This finding is of interest because a reduction in strength with targeted heating could be beneficial to an application such as in-orbit disassembly and reassembly.

Some researchers have investigated disjoining thermoplastic composites but rely on additives such as electrically conductive multiwall carbon nanotube (MWCNT) films (Ref. 7), graphene nanoplate (GnP) sheets (Ref. 8), or stainless-steel heating elements (Ref. 9). The work presented in this paper differs in that there are no additives in the thermoplastic film used to join thermoplastic composites, simplifying the assembly and reassembly process. Another method to join thermoplastic composites is the use of ultrasonic welding. Palardy et al. investigated (1) the processing parameters necessary for ultrasonic consolidation of thermoplastic composites using experimental and finite element modeling, (2) heat generation effects at joint interface, and (3) the effect of energy director thickness on heat dissipation to the adherend (Refs. 10 to 13). This technology has promising potential but has not been thoroughly investigated for space application.

The purpose of this report is to evaluate the feasibility of the joining, disjoining, and reassembly of carbon fiber/polyether ether ketone (PEEK) thermoplastic composites using low-melt polyaryl ether ketone (LM-PAEK) interlayer film. These materials were chosen because they are high-performance, space-application-relevant thermoplastics. Performance was characterized using SLS tests. Interlayer thickness and failure mode were recorded as well. Finally, rejoining of SLS joints was attempted and mechanical properties were characterized to better understand the transferability of this process to future space applications such as on-orbit reassembly.

2. METHODS

2.1 Materials and Specimen Preparation

2.1.1 Carbon-Fiber-Reinforced Panels

Prepreg plies of AS4 carbon fiber with the semicrystalline thermoplastic PEEK Cetex® TC1200 unidirectional tape was obtained from Toray Advanced Composites. Likewise, prepreg plies of

T700 carbon fiber with semicrystalline thermoplastic LM-PAEK Cetex® TC1225 was obtained from Toray Advanced Composites. LM-PAEK powder from Victrex (AE™ 250 FFPD25) was used to fabricate the film to be used at the bondline.

AS4/PEEK quasi-isotropic adherends were compression molded using a $[45/0/-45/90]_{2s}$ ply configuration for the lap shear specimen. AS4/PEEK prepreg was laid up in a picture frame tool and compression molded at 393 °C (740 °F) and 335 kPa (48.6 psi) for 1 h. The cool-down rate was maintained between 10 and 20 °C/min to ensure crystallization within the matrix. The panels were then cut to size with a diamond saw cutter. A similar process was repeated for the hybrid composite panel in a $[45/0/-45/90]_{2s}$ configuration except that the bottom and top layers were substituted to be T700/LM-PAEK prepreg plies before compression molding. The hybrid panel was pressed at 382 °C (720 °F), 335 kPa, for 1 h.

2.1.2 Thermoplastic Film Interlayer

LM-PAEK film was fabricated by pressing 20 g of LM-PAEK powder between sheets of polyimide tape coated in mold release in a hot press at 329 °C for 10 min with approximate applied pressure ranging from 0.10 to 0.51 MPa. This created a flat sheet that still had slight variations in thickness due to processing. Therefore, only sections that varied in thickness from 0.08 to 0.15 mm were used. To create thicker films, more powder was used and pressed for shorter amounts of time.

2.1.3 Single Lap Shear Specimen Preparation

Lap shear test coupons were assembled in a steel frame and aligned with balancing shims and spacers. The lap shear joint with LM-PAEK film interlayer was formed by compression molding at 329 °C and 0.14 MPa for 1 h. The joining process for the SLS panel is pictured in Figure 1.

Nominal dimensions for the SLS coupons were 25.3 mm wide by 229 mm long with a 25.4 mm overlap in the center joint. All adherends were AS4/PEEK, with the exception of a single hybrid joint design where the top and bottom plies of the AS4/PEEK $[45/0/-45/90]_{2s}$ panel were substituted with a ply of T700/LM-PAEK prepreg. This panel was used to investigate whether having a similar material layer could help transition the entanglement and consolidation using LM-PAEK film in a gradient to the remaining PEEK adherend.

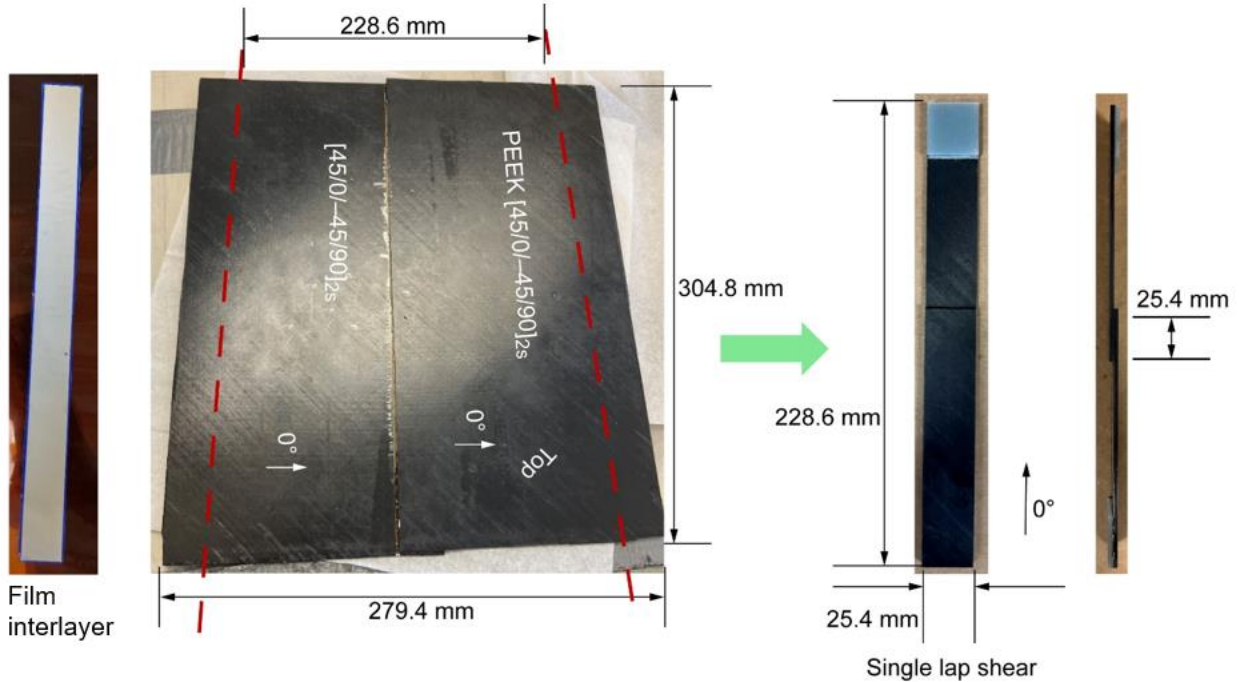


Figure 1. Manufacturing and joining process of PEEK adherends with film interlayer for composite single lap shear joint specimens.

2.2 Single Lap Shear Test

To quantify the shear strength of thermoplastic joints, SLS tests were performed according to ASTM Standard D5868 (Ref. 14). Modifications to the standard test method included holding the displacement rate to 1.3 mm/min, rather than the suggested 13 mm/min, and increasing the PEEK adherend length from 102 to 127 mm long, making the final specimen 229 mm long. The length extension was required so the specimen would fit fully inside the furnace for ET tests. Each SLS specimen was tabbed on both ends for a more symmetric loading profile. The top grip fixture was an adjustable grip head, which allowed for realignment upon loading to ensure the specimen was being pulled in pure shear without twisting or contortion.

The full Instron® 68TM–50 diagram without the furnace configuration is pictured in Figure 2.

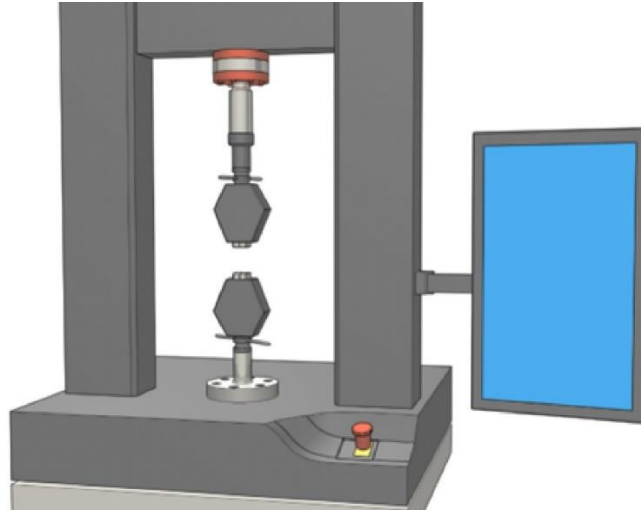


Figure 2. SLS test setup on Instron[®] system (sample and furnace not shown).

2.3 Thermal Screening

Thermal screening was necessary to ensure accurate temperature profiles of the specimen within the heating chamber. For the tests, the desired ET at the joint was 121 °C. This ET was selected because originally the film interlayer material was varied to include polyphenylene sulfide (PPS) which has a glass transition of 90 °C. A more detailed version of this work exists as a NASA Technical Memorandum which includes LM-PAEK and PPS film interlayers. For this paper, the scope was narrowed to LM-PAEK for its success and demonstration of reassembly. Temperature screening was conducted for the SLS specimen test setup using an Applied Test Systems Series 3210 furnace (900 W, 7.8 A, maximum temperature 900 °C). High-temperature Type K thermocouples were wired to the practice specimen as shown in Figure 3. Steady-state temperature measurements revealed a ± 4 °C offset between desired temperature at the center joint and the ambient readout, which could be accessed during ET testing.

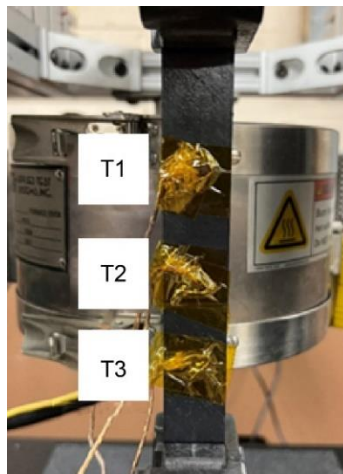


Figure 3. Practice SLS specimen for thermal testing showing placement of thermocouples T1, T2, and T3; furnace open for photographing but closed during testing.

3. RESULTS

3.1 Mechanical Testing

SLS specimens bonded with LM-PAEK film were loaded and tested at RT and ET, five specimens each. The average maximum strength at RT was 6.6 MPa and displacement to failure at RT was 1.1 mm. There was not a significant difference (average values within one standard deviation of each other) between maximum stress and displacement at failure in RT as compared to ET. The similarity of properties was expected, as the ET of 121 °C was below the T_g of the LM-PAEK (147 °C) film, meaning the material remained in the glassy state for both RT and ET tests. Tests above this T_g could not be completed because the T_g of PEEK is 143 °C, and therefore both the film and adherend would be rubbery, rendering SLS testing ineffective. Results are summarized in Table 1 and Figure 4.

TABLE 1. AVERAGE MAXIMUM STRESS AND DISPLACEMENT AT FAILURE FOR SLS SPECIMENS OF PEEK ADHERENDS WITH LM-PAEK FILM INTERLAYER.

[Elevated temperature is within ± 3 °C; values are ± 1 standard deviation.]

Property	Test temperature	
	RT, ~23 °C	ET, ~121 °C
Maximum stress, MPa	6.56 $\pm$ 1.07	8.47 $\pm$ 1.19
Displacement at failure, mm	1.09 $\pm$ 0.21	1.4 $\pm$ 0.18

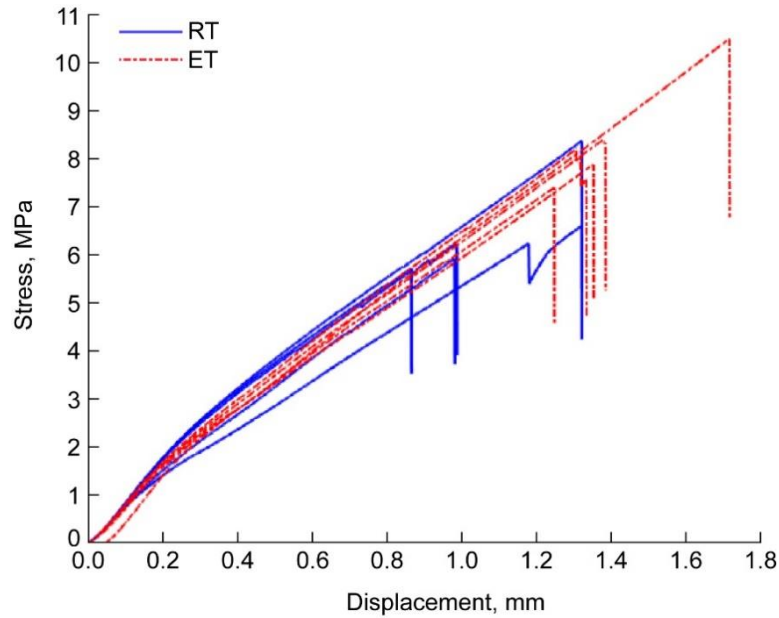


Figure 4. Stress versus displacement for SLS specimens of PEEK adherends with LM-PAEK film interlayer at RT and ET.

Furthermore, the hybrid PEEK/LM-PAEK adherends bonded with LM-PAEK film were tested in the SLS configuration, five specimens each for RT and ET. The outer plies of the adherend were LM-PAEK prepreg to increase the bonded strength of thermoplastic joint assembly. The results show that the specimens handled a much higher shear stress to failure, 34.6 MPa at RT, with similar behavior at ET. As noted previously, the ET of 121 °C was still below the T_g of both PEEK and LM-PAEK. There was a similar displacement to failure as well at RT and ET. Utilizing LM-PAEK as outer plies on the adherend reduced the film interface as a separate entity and increased entanglement between the two adherends. The weakest point of the composite matrix was no longer isolated to the film interface but was instead a few plies above or below. Results are recorded in Table 2 and Figure 5. The failure mode is discussed in Section 3.2 of this report.

TABLE 2. AVERAGE MAXIMUM STRESS AND DISPLACEMENT AT FAILURE FOR SLS SPECIMENS OF HYBRID PEEK/LM-PAEK ADHERENDS WITH LM-PAEK FILM INTERLAYER.

[Elevated temperature is within ± 3 °C; values are ± 1 standard deviation.]

Property	Test temperature	
	RT, ~23 °C	ET, (~121 °C)
Maximum stress, MPa	34.6 $\pm$ 2.48	32.7 $\pm$ 1.28
Displacement at failure, mm	5.38 $\pm$ 0.39	5.14 $\pm$ 0.2

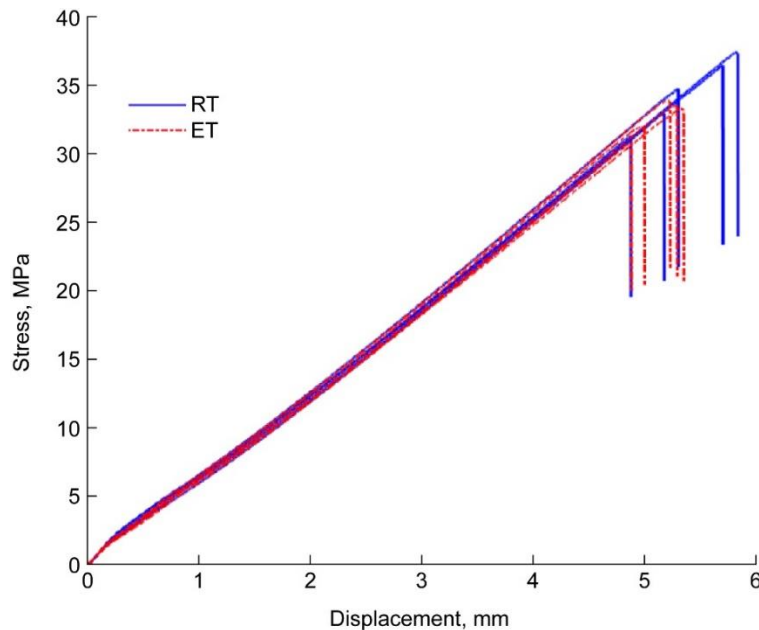


Figure 5. Stress versus displacement plot for single-lap shear specimens of hybrid PEEK/LM-PAEK adherends with LM-PAEK film interlayer at RT and ET.

The data demonstrate that joining PEEK with a dissimilar film, such as LM-PAEK, limits the maximum stress to a range of 5 to 8 MPa with a 1.1 mm displacement before failure at RT. Co-consolidating LM-PAEK prepreg with the PEEK adherend drove the maximum stress to 34.6 MPa and displacement to 5.38 mm before failing at RT.

Fracture surfaces of the SLS coupons were evaluated to gain a better understanding of the advantages and disadvantages of each material system.

3.2 Failure Mode

The SLS specimens were tested until failure. As seen in Figure 6, the LM-PAEK film failed adhesively at the film/adherend interface. This is desired for reassembly in that the adherend remained undamaged. However, the residual LM-PAEK film did not fully cover the bond area of the adherend. Greater coverage is required for reassembly, so an additional layer of film was deemed necessary prior to reassembly.

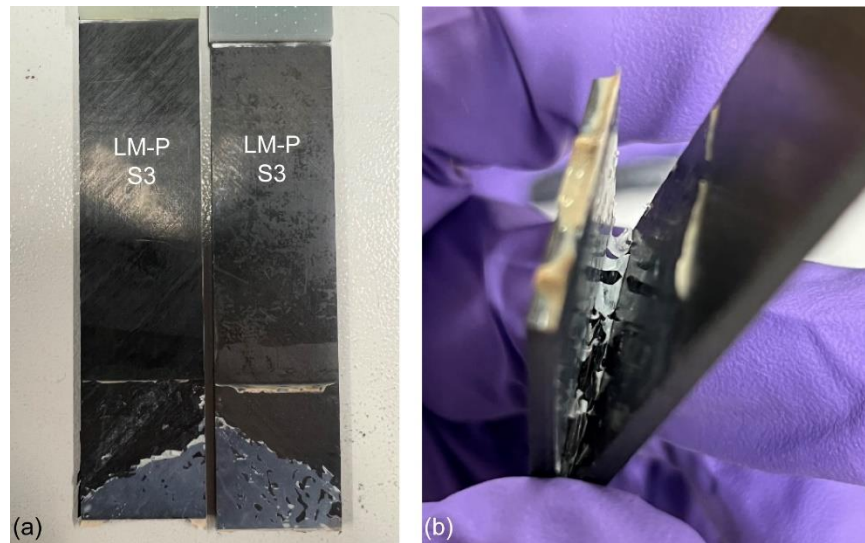


Figure 6. Adhesive failure of broken SLS joints of PEEK adherends with LM-PAEK interlayer.
(a) At RT. (b) At ET.

In addition, the specimens with a hybrid PEEK/LM-PAEK adherend and LM-PAEK film were tested to failure. Fracture surfaces are shown in Figure 7. Note that ET was still below the T_g of LM-PAEK. Failure was more random and occurred within the adherend rather than at the joint interlayer surface.



Figure 7. Broken SLS joints using LM-PAEK interlayer with hybrid PEEK/LM-PAEK adherend. (a) At RT. (b) At ET.

This hybrid adherend provided opportunity for polymer chain entanglement between the LM-PAEK film and the adherend. As a result, the failure mode was much more catastrophic, unpredictable, and damaging to the adherend with the fracture surface composed of exposed carbon fiber rather than LM-PAEK film. Although this approach yielded a stronger bond, it is not amenable yet for reliable disassembly and reassembly of thermoplastic composite applications because of the high amount of damage inflicted on the adherends.

4. REASSEMBLY

After SLS testing, the coupons were preserved for reassembly purposes. A custom frame was built to hold the specimens in place and apply heat and pressure in the press. An additional layer of fresh LM-PAEK film with the same thickness was added in the 25- by 25-mm overlap to improve joint fidelity prior to reassembly. This approach was taken for both the PEEK and hybrid PEEK/LM-PAEK adherends and is outlined in Figure 8. Steel bars were overlaid to allow for even pressure distribution and heat conduction. The reassembled coupons were pressed at 1.15 MPa, 329 °C, for 30 min.

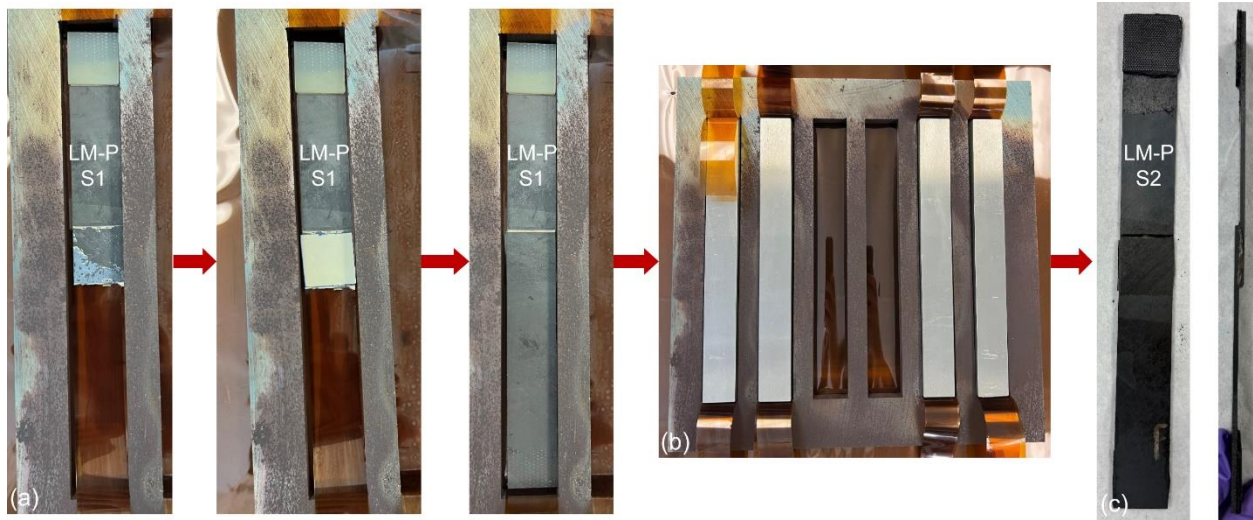


Figure 8. Reassembly of SLS specimens. (a) Addition of new LM-PAEK film interlayer. (b) Addition of platens for pressing. (c) Reformed joint after pressing.

The glass fiber tabs and glue melted as expected due to high temperature exposure, but the joint was reformed. The pressure used during reassembly could be optimized in future work as it was high, resulting in film flowout which should be minimized. Once rejoined, two coupons were tested again in the SLS configuration. Mechanical results of the specimens of PEEK adherends with LM-PAEK film are shown in Figure 9, and the data for specimens of hybrid PEEK/LM-PAEK adherend with LM-PAEK film are shown in Figure 10.

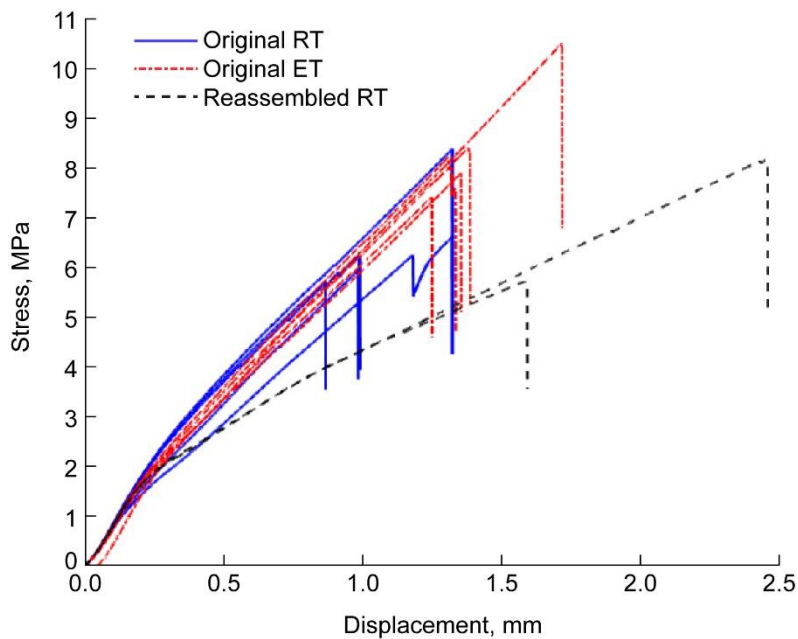


Figure 9. Stress versus displacement for reassembled PEEK adherends with LM-PAEK film interlayer SLS specimens at RT compared to original SLS specimens at RT and ET.

There was not a significant difference in average maximum stress values for the rejoined PEEK adherends with LM-PAEK film (6.9 MPa) as compared to the original average maximum stress values at RT (6.6 MPa). This was because the joint adhesively failed and carried the load, so it behaved similarly. However, a different trend was observed with the reassembled specimens having the hybrid PEEK/LM-PAEK adherend.

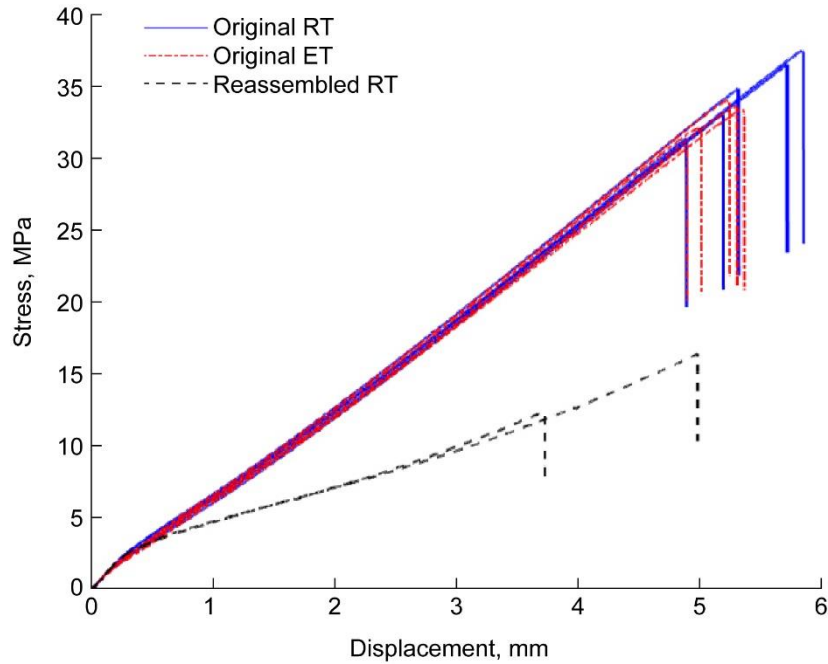


Figure 10. Stress versus displacement for reassembled hybrid PEEK/LM-PAEK adherends with LM-PAEK film interlayer SLS specimens at RT compared to original SLS specimens at RT and ET.

The reassembled hybrid PEEK/LM-PAEK coupons were significantly weaker (14.3 MPa) than the pristine coupons at RT (34.6 MPa). This was due to the damage inflicted during disassembly, as previously detailed. The broken specimens are shown in Figure 11.



Figure 11. Broken SLS joints using LM-PAEK interlayer at RT. (a) PEEK adherends with LM-PAEK interlayer. (b) Hybrid PEEK/LM-PAEK adherends with LM-PAEK interlayer.

As with the disassembly of the as-manufactured test coupons, the fracture surfaces of the reassembled coupons indicate adhesive failure of the LM-PAEK film bonded to PEEK adherends, whereas fiber breakage was observed with the hybrid PEEK/LM-PAEK adherends. Flowout of the film from the bondline was an issue, as very little residual LM-PAEK film remained at the interface, highlighting the need for optimization of press parameters to create a thermoplastic joint with high fidelity. It is important to note that in each case the reassembled coupons had a lower slope than the original. This was most likely due to slippage in the grips during testing because the tabs were charred and damaged during the reassembly process. It may be plausible that thermal degradation of the materials occurred during the reassembly process, but further investigation is needed to support or reject this claim.

5. CONCLUSIONS

This work demonstrated the feasibility of joining, disassembly, and reassembly of thermoplastic composite bonds in a hot press using low-melt polyaryl ether ketone (LM-PAEK) film interlayer. The film interlayer contained no additives, energy directors, or mesh design. Necessary balancing shims, a reassembly frame, adjustable grip heads, and furnaces were set up and developed to complete this work. Single-lap shear specimens were tested at room temperature (RT) (23 °C) and elevated temperature (ET) (121 °C) to understand how mechanical behavior changes with temperature. For this paper, there was not a significant performance difference in average strength and displacement between RT and ET because the ET was still well below the glass transition of LM-PAEK. PEEK adherends joined with LM-PAEK film interlayer had an average shear strength of 6.6 MPa with an adhesive failure mode at the film interface. The hybrid PEEK/LM-PAEK adherends joined with the same LM-PAEK film interlayer had a much higher strength of 34.6 MPa at the cost of a more catastrophic and random failure mode which damaged the adherends.

Reassembly of the bonded joint was demonstrated. Reassembled specimens with PEEK adherends had a similar strength to the original SLS specimens at RT, whereas the reassembled hybrid PEEK/LM-PAEK adherends exhibited much weaker strength compared to the pristine SLS specimens at RT. Additional film interlayers will likely be required with each subsequent reassembly to maintain joint fidelity. Future work will focus on reducing the loss of film at the interlayer and investigating alternative joining methods to enable manufacturing methods in a space environment.

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