Enabling Assembly and Repair of Dissimilar Thermoplastic Composites for Space Applications via Ultrasonic Welding

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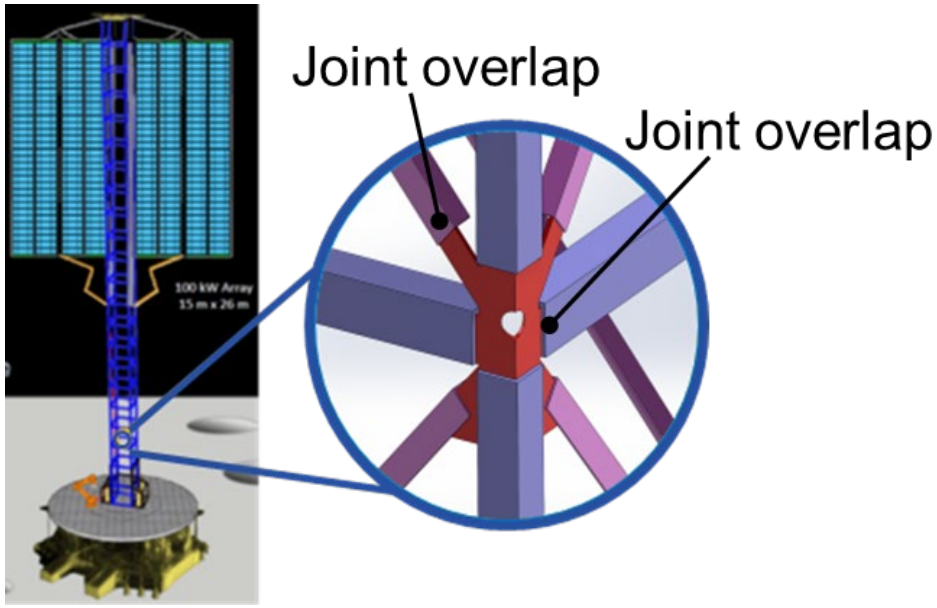
Background

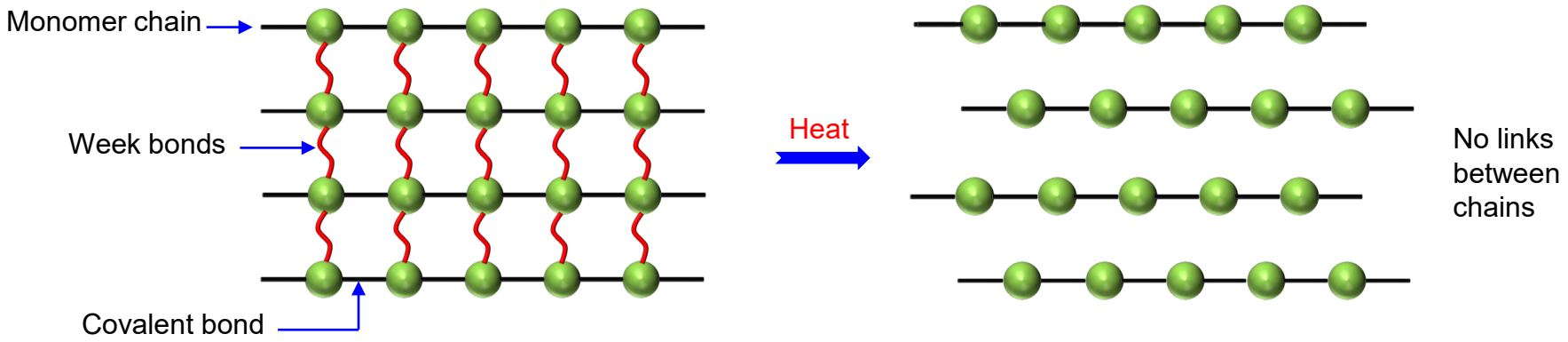
- Sustained human presence for space exploration needs structures
- Fiber-reinforced composites makes for a lightweight building material
  - Thermoplastics (TPCs) allow for assembly/disassembly/reassembly



Lunar tower

Image: NASA

Thermoplastic Composites

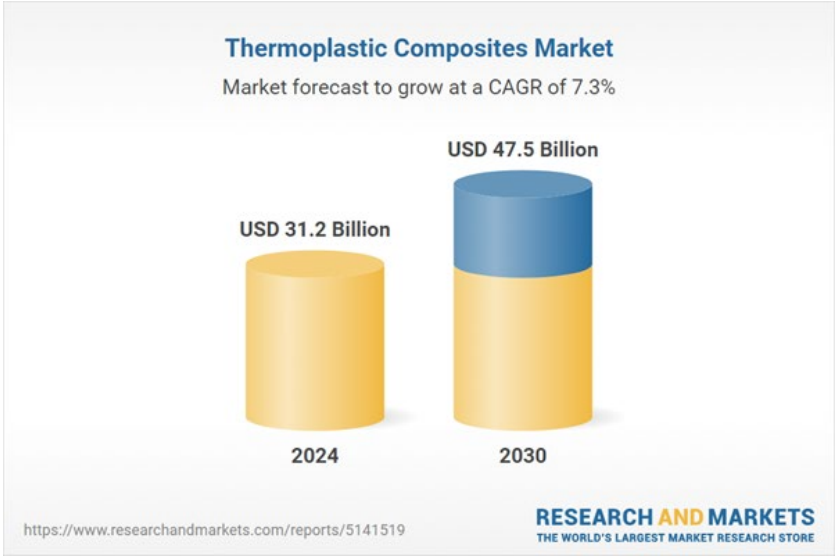


Thermoplastic polymer

Thermoplastic softened state

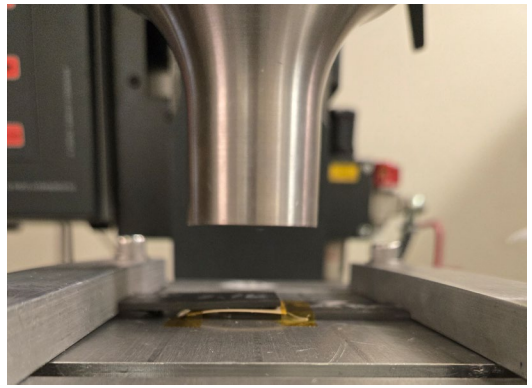
- Soften or melt when heated
- Solidify with cooling
- Molecules do not cross-link

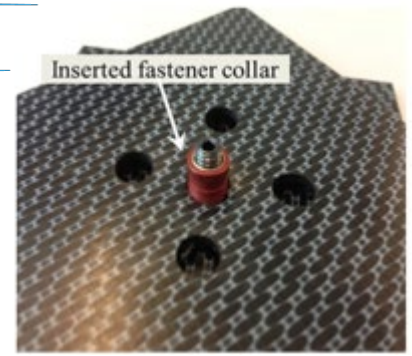
- Recyclable: can be reshaped or remolded
- High-impact resistance and toughness
- Suitable for welding (fusion bonding)
- Reduced manufacturing time and cost

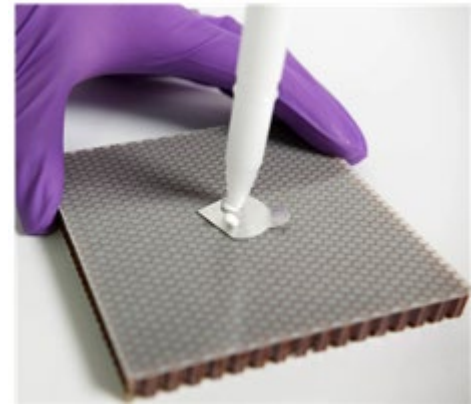


Li and Palardy, Presented at SAMPE Seattle, WA, 2023.

Joining Methods







Joining technique

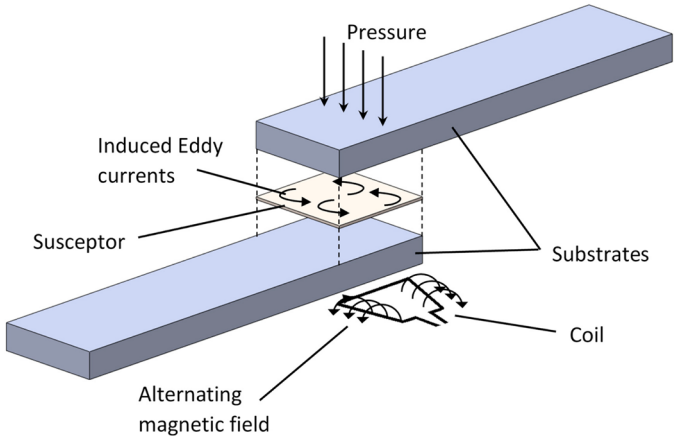
- Mechanical fastening
  - Pros
    - Easy to install
    - Easy to disassemble
    - No thickness limitations
  - Cons
    - Stress Concentration
    - Prone to corrosion
    - Higher weight
- Fusion bonding (welding)
  - Pros
    - Short processing time
    - Repairable
  - Cons
    - Nonuniform heat distribution
    - Limited joint complexity
- Adhesive bonding
  - Pros
    - More uniform stress distribution
    - Smooth appearance
    - Corrosion resistance
  - Cons
    - Long curing time
    - Rigorous surface preparation
    - Difficult to repair

Zhao et al. Compos Part B, 122, 2017.

Images: L&L Products, Europe Technologies

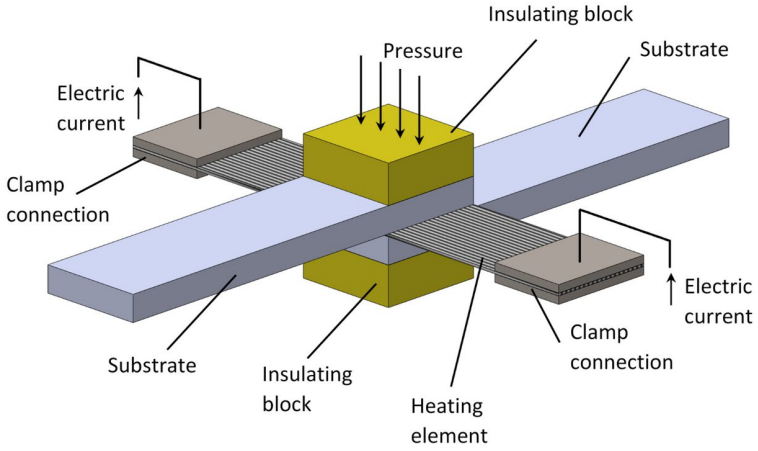
Fusion Bonding Methods

Induction welding



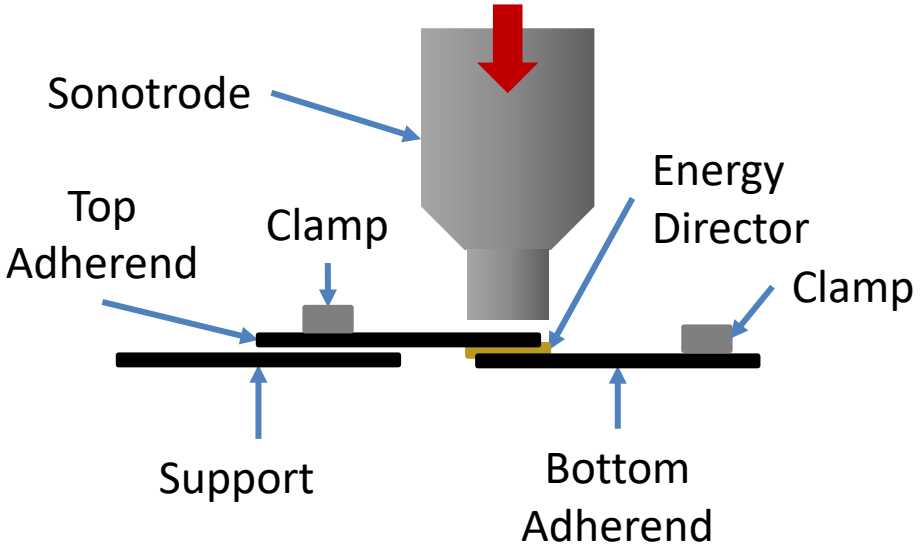
85 s
(23 kJ)*

Resistance welding



90 s
(1.8 kJ)*

Ultrasonic welding

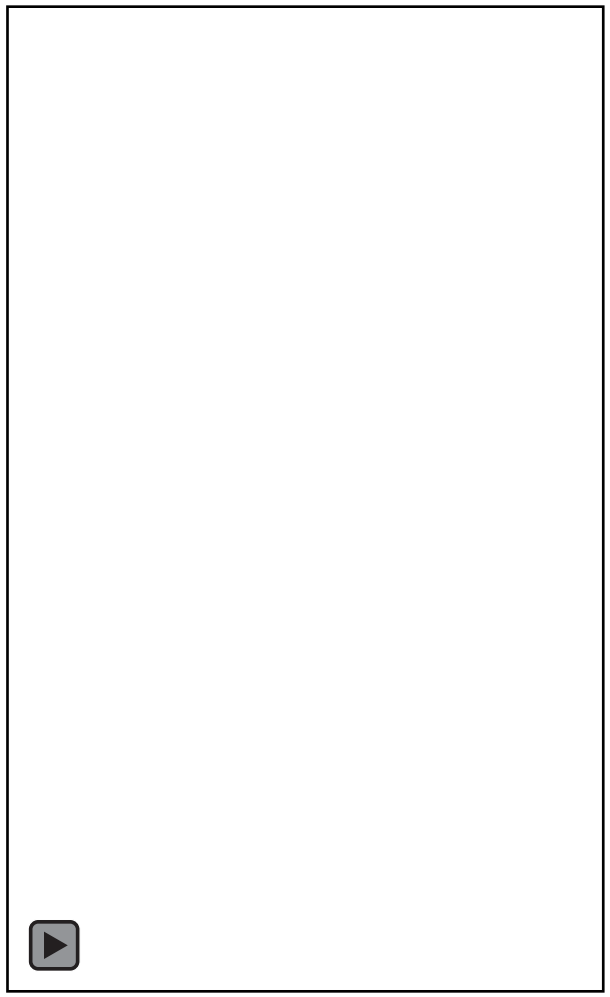


4.5 s
(0.7 kJ)*

Reis et al. Materials, 13(24), 2020.
Villegas et al. Journal of Thermoplastic Compos Matls, 26(8), 2012.

*for CF/PPS

Ultrasonic Welding



Video:
Li and Palardy, Presented at SAMPE Seattle, WA, 2023.

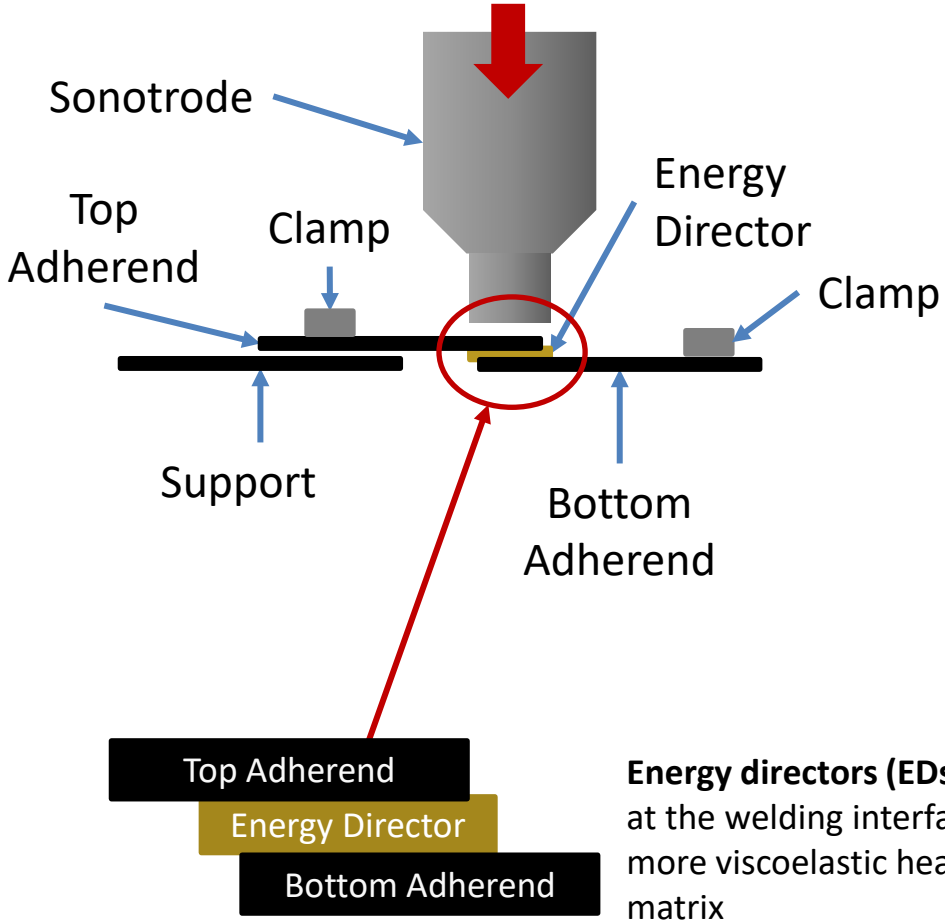


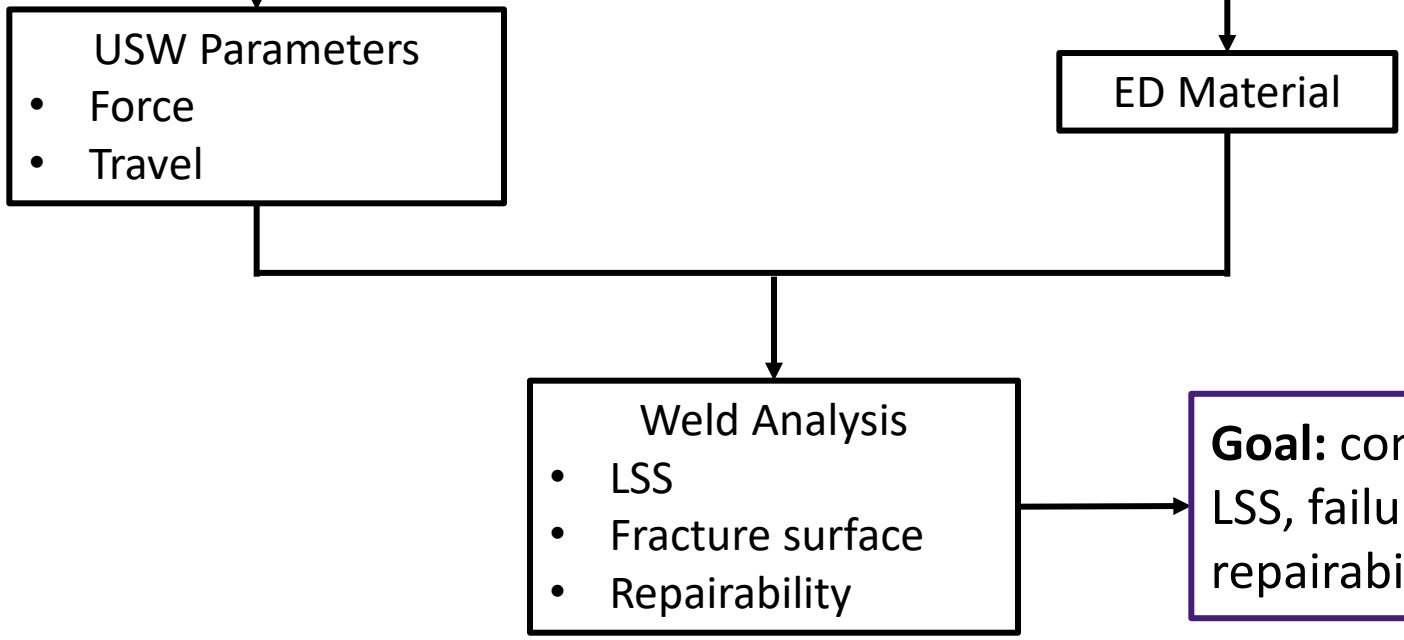
Diagram for USW setup of a SLJ

Ultrasonic welding (USW) applies vibrations to generate heat and applies pressure that bonds the adherends

Energy directors (EDs) concentrate energy at the welding interface by generating more viscoelastic heating than the TPC matrix

Objective

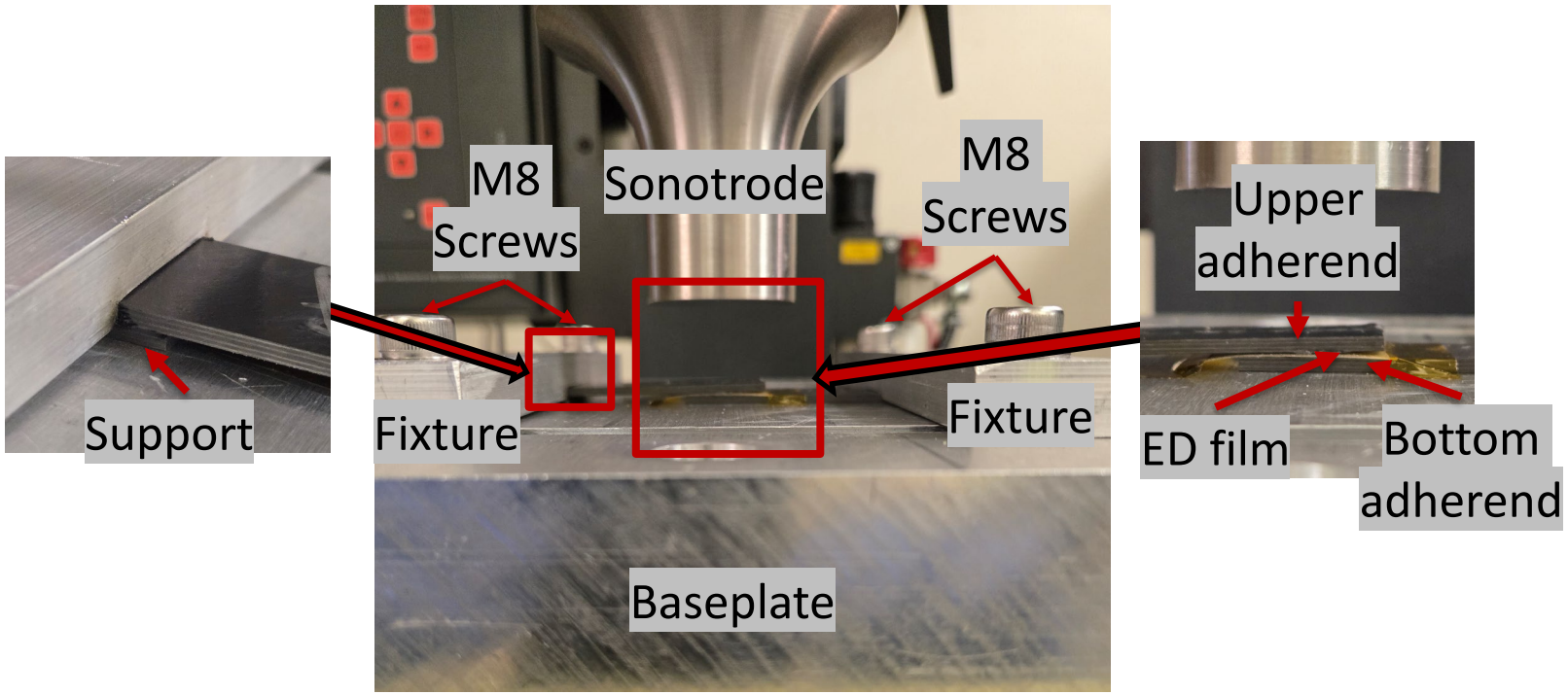
Customizability: use ED compatibility to tailor the properties of welds for specific applications



Materials

- Carbon Fiber (CF)/PEEK adherends
  - Compression molded
  - $[45/0/-45/90]_{2s}$
  - Provided by NASA
- Energy Directors
  - Polyether ether ketone (PEEK)
  - Polyetherimide (PEI)
  - Polyphenylene sulfide (PPS)

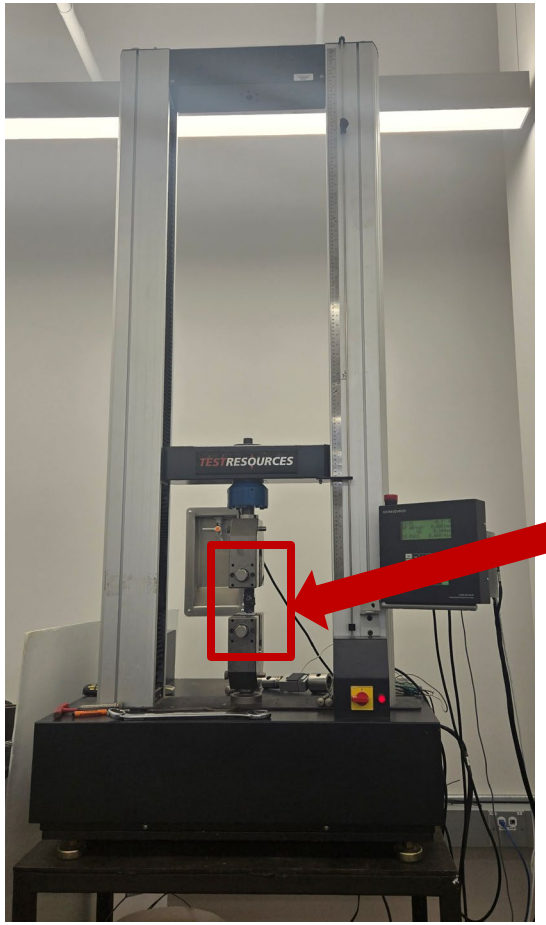
USW Setup

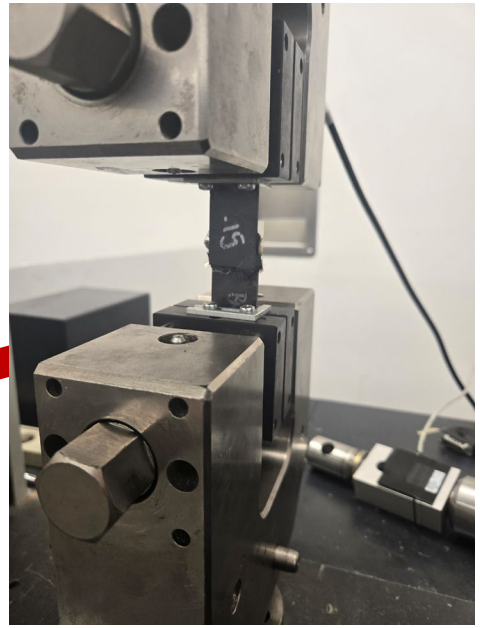


Regular Welding Parameters	
Energy Director	
PEEK	0.20 mm
PPS	0.06 mm (3x)
PEI	0.25 mm
Welding & Solidification Force	
PEEK	1000 N
PPS	500 N
PEI	1000 & 500 N
Holding Time	4000 ms
Vibration Amplitude	38.1 µm
Frequency	20 kHz
Travel	
Initial Weld	40%
Repair Welds	60-90%

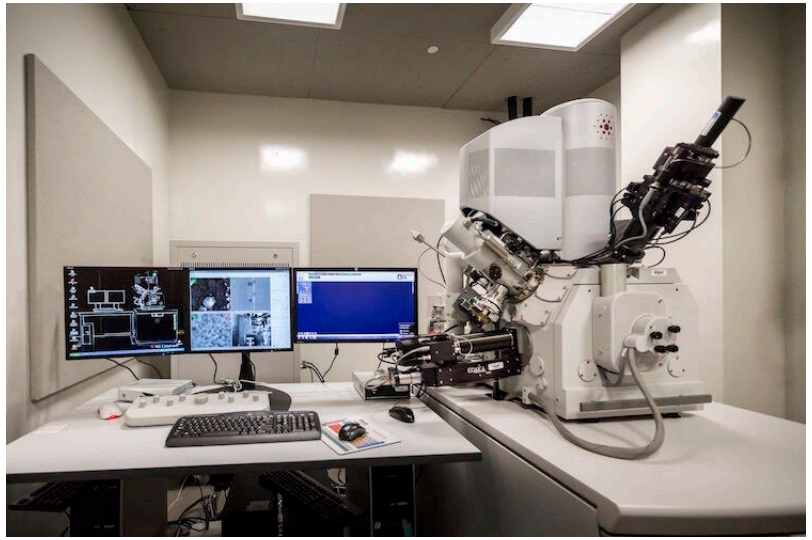
Mechanical Testing & Analysis

Tensile Test



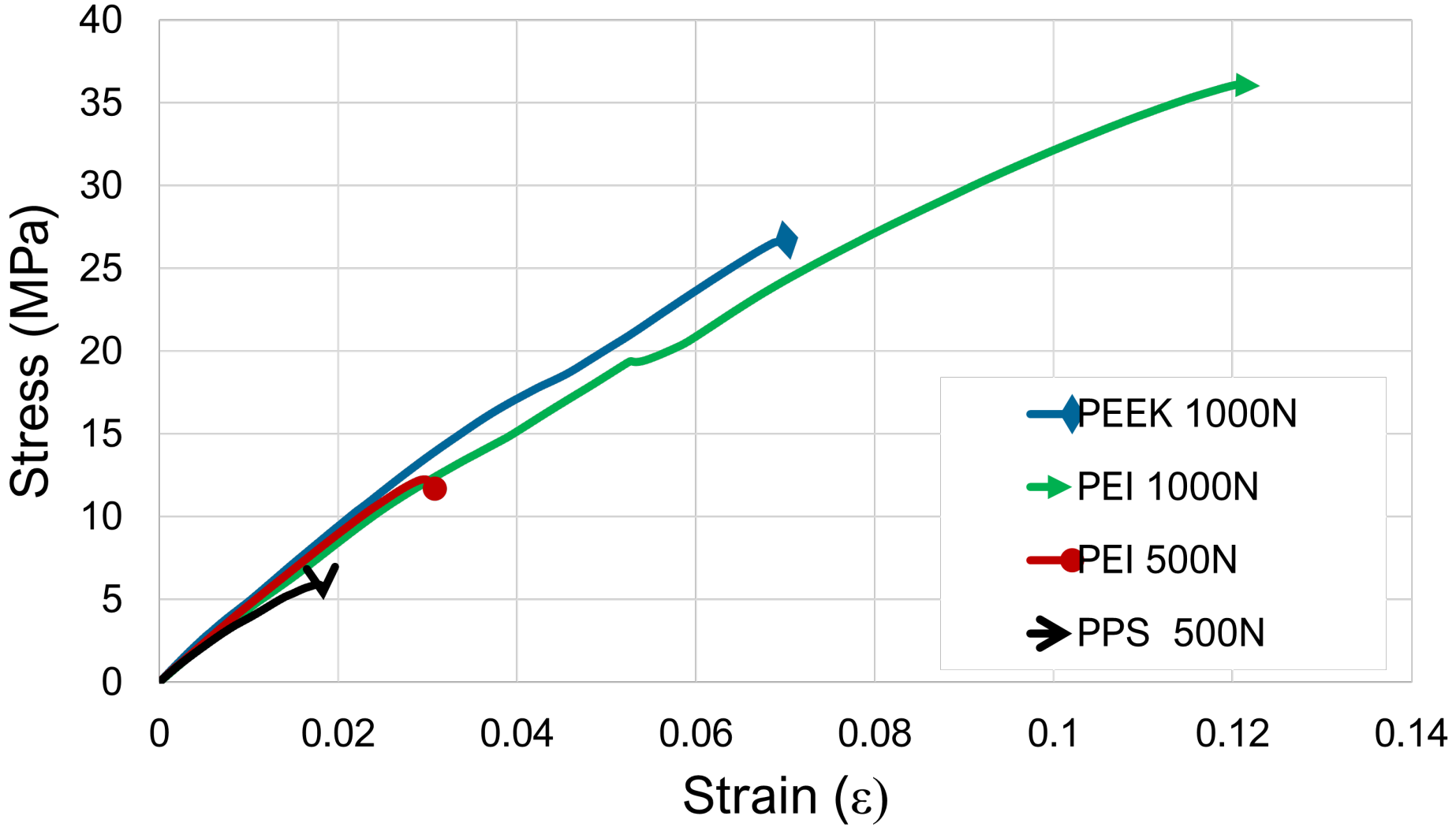


Analysis



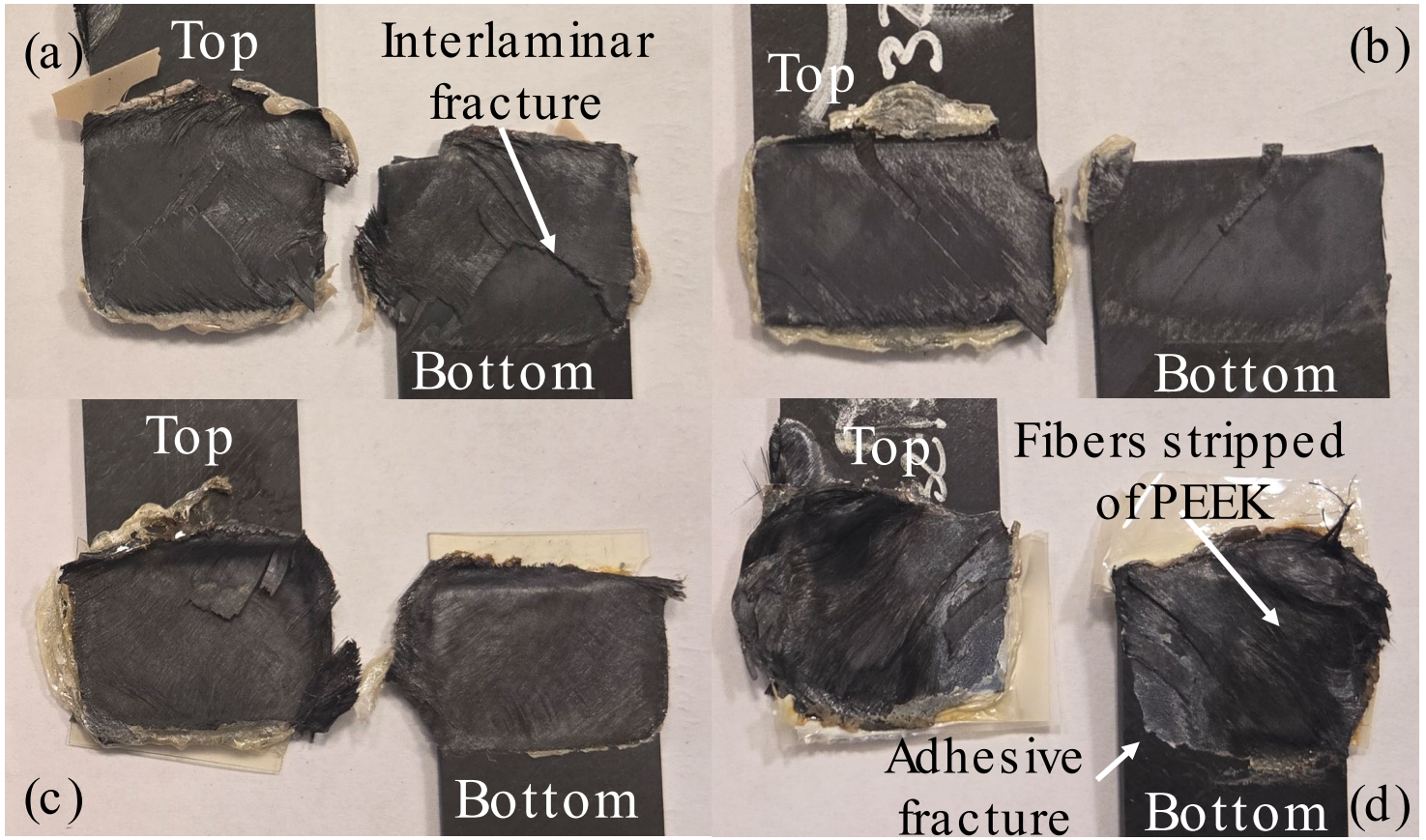
Images: LSU SIF, ImageJ

Initial Regular Weld Behavior



Initial Regular Weld Fracture Surfaces

(a) CF/PEEK-PEEK 1000 N



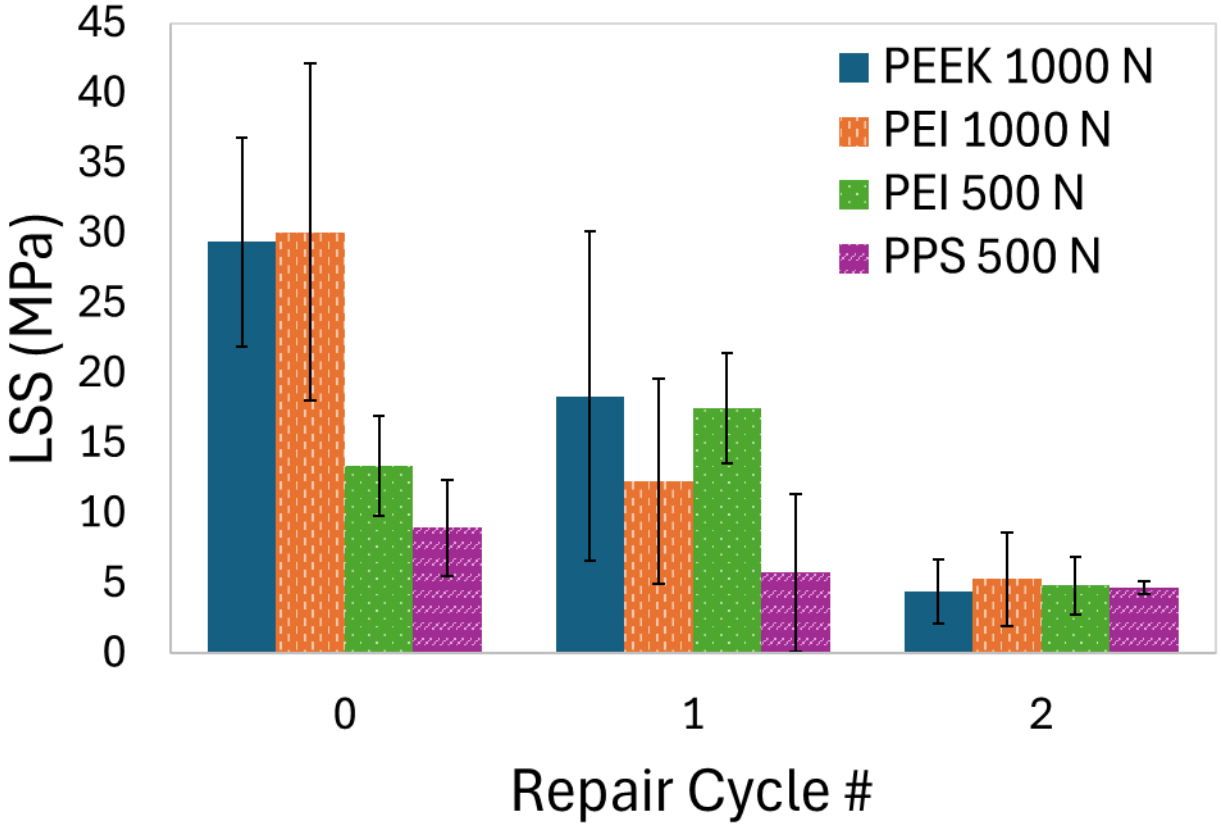
(b) CF/PEEK-PEI 1000 N

(c) CF/PEEK-PEI 500 N

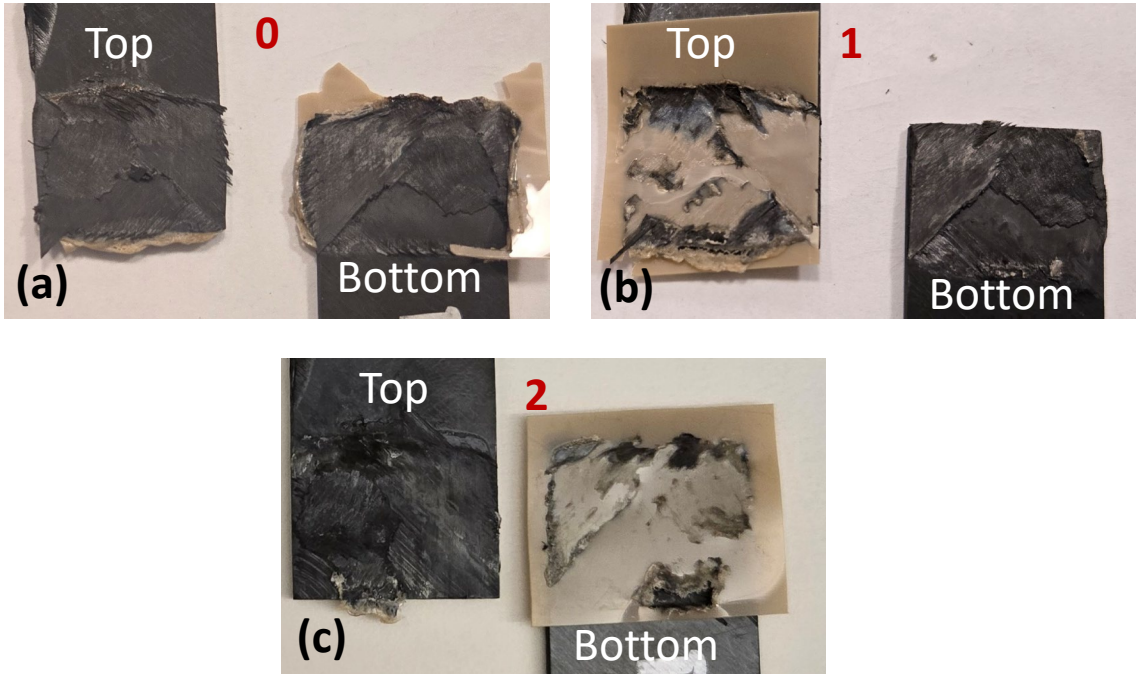
(d) CF/PEEK-PPS 500 N

Fracture surfaces after the initial welds

Repaired Regular Weld Behavior

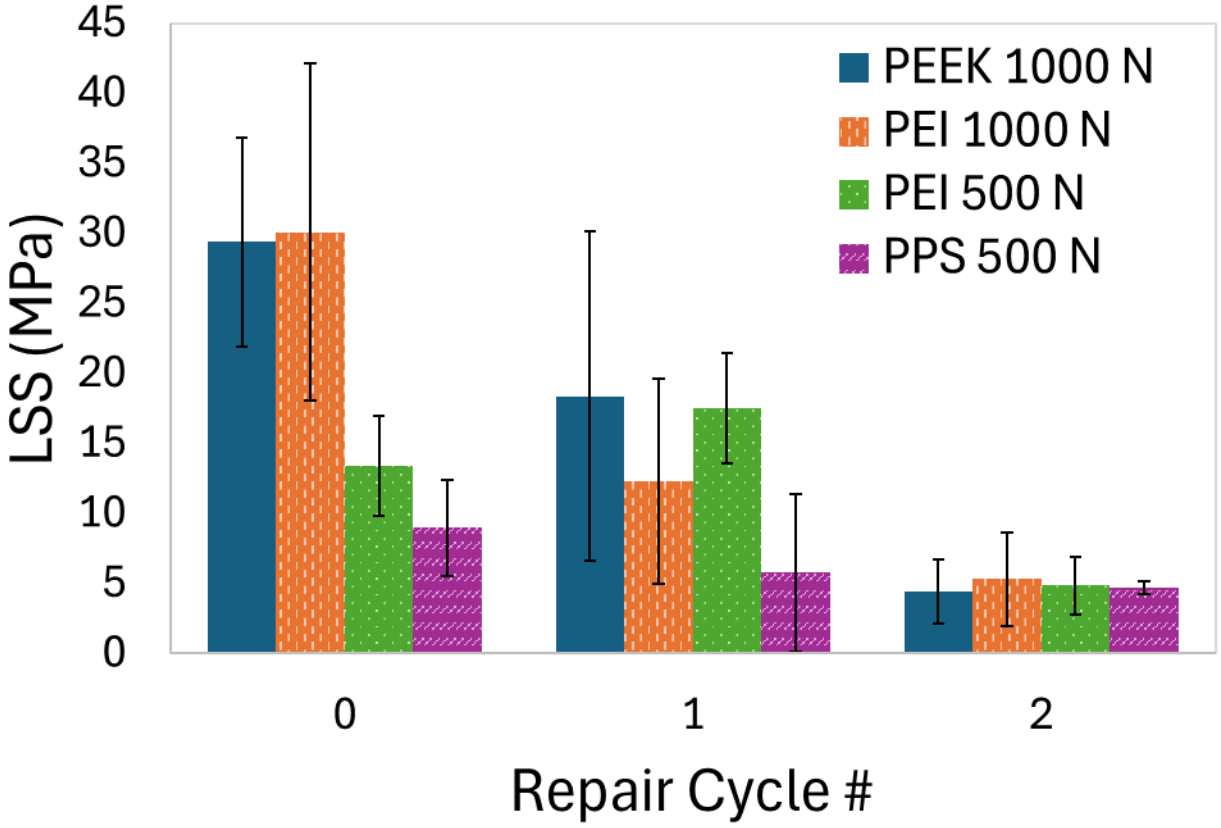


Effect of repair cycles on LSS



Fracture surface of CF/PEEK-PEEK 1000 N over 2 repair cycles

Repaired Regular Weld Behavior



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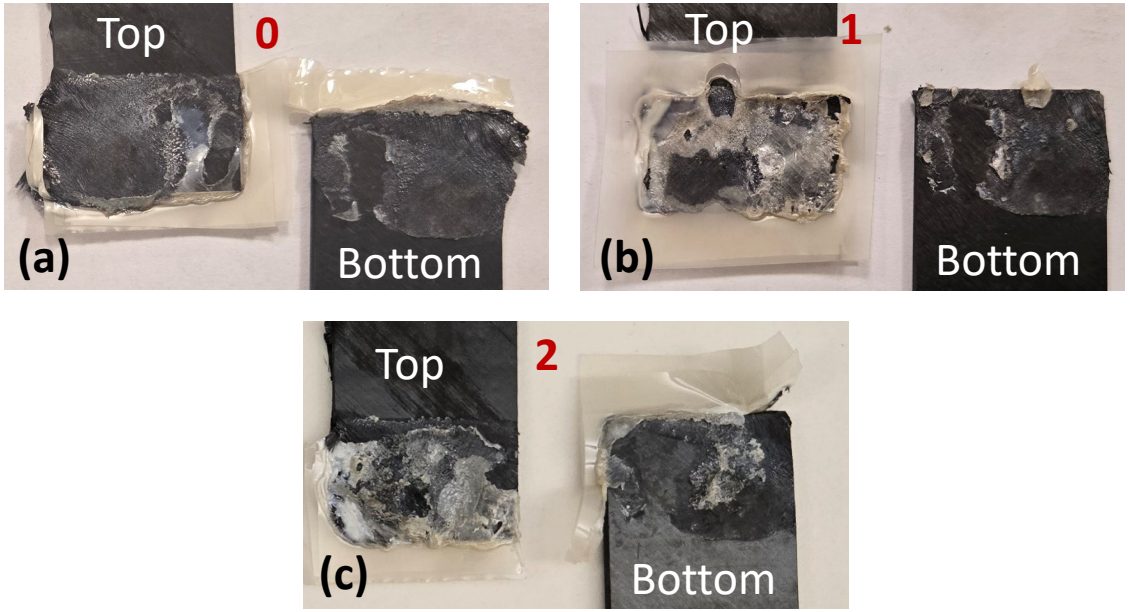
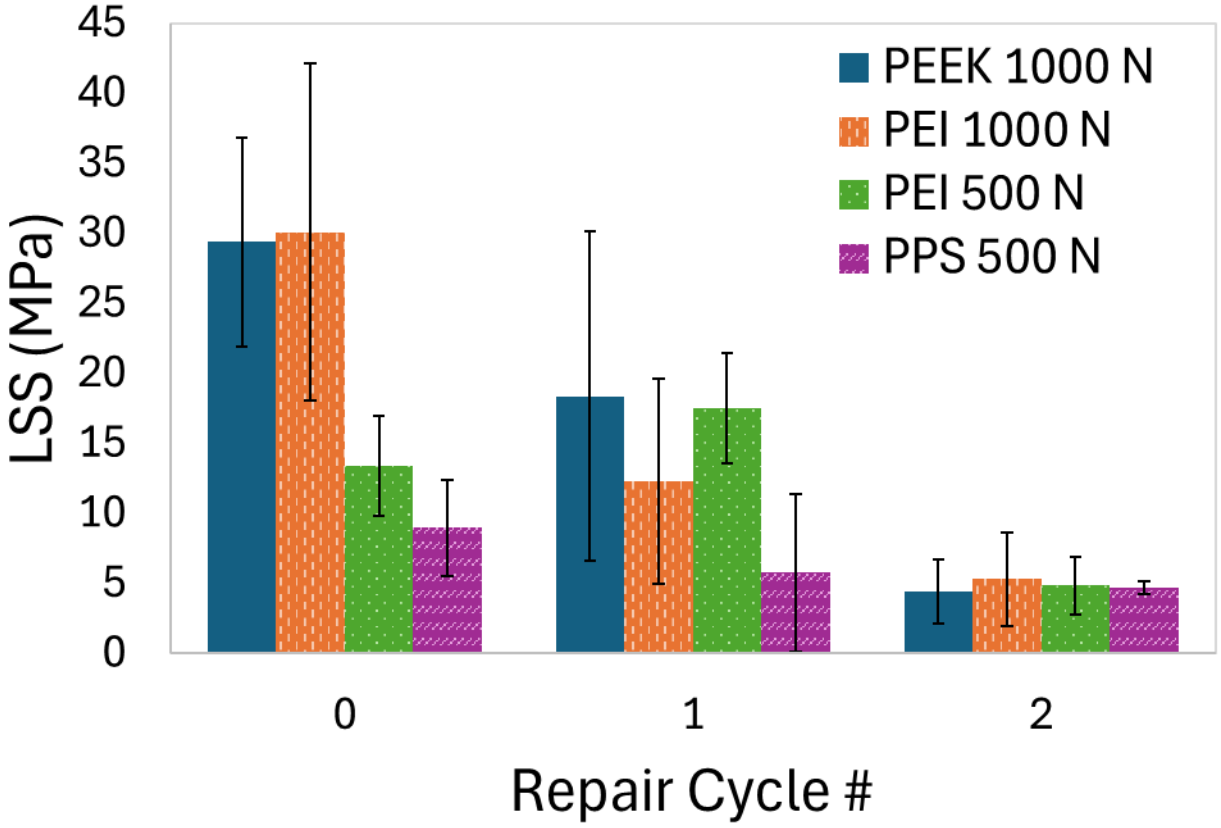
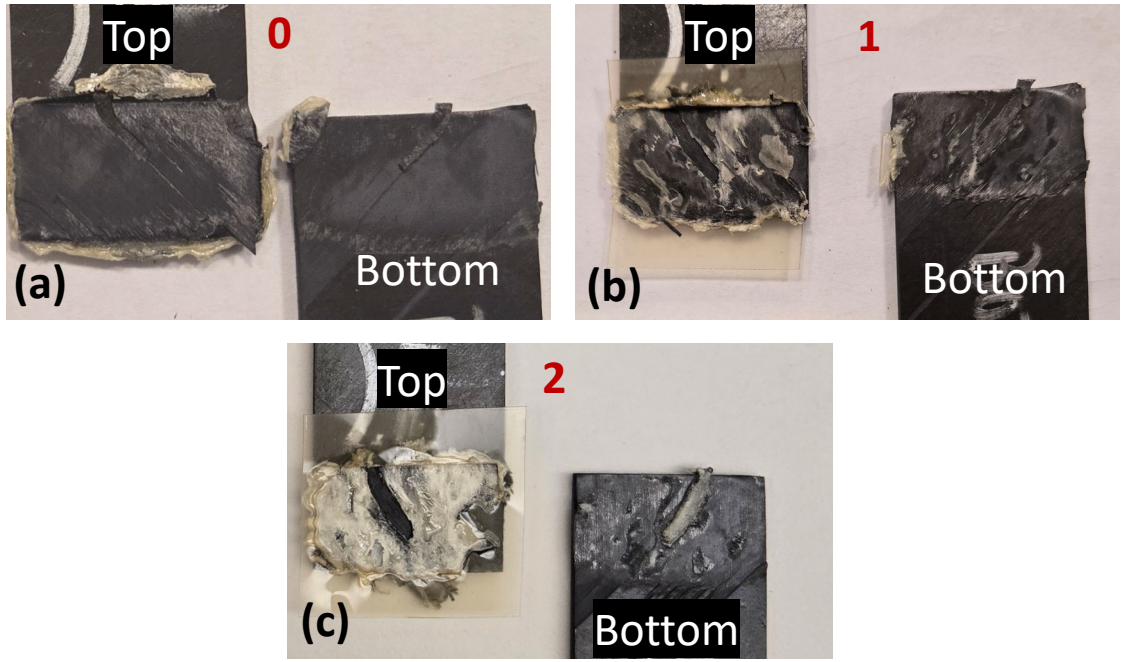


Fracture surface of CF/PEEK-PPS 500 N over 2 repair cycles

Repaired Regular Weld Behavior

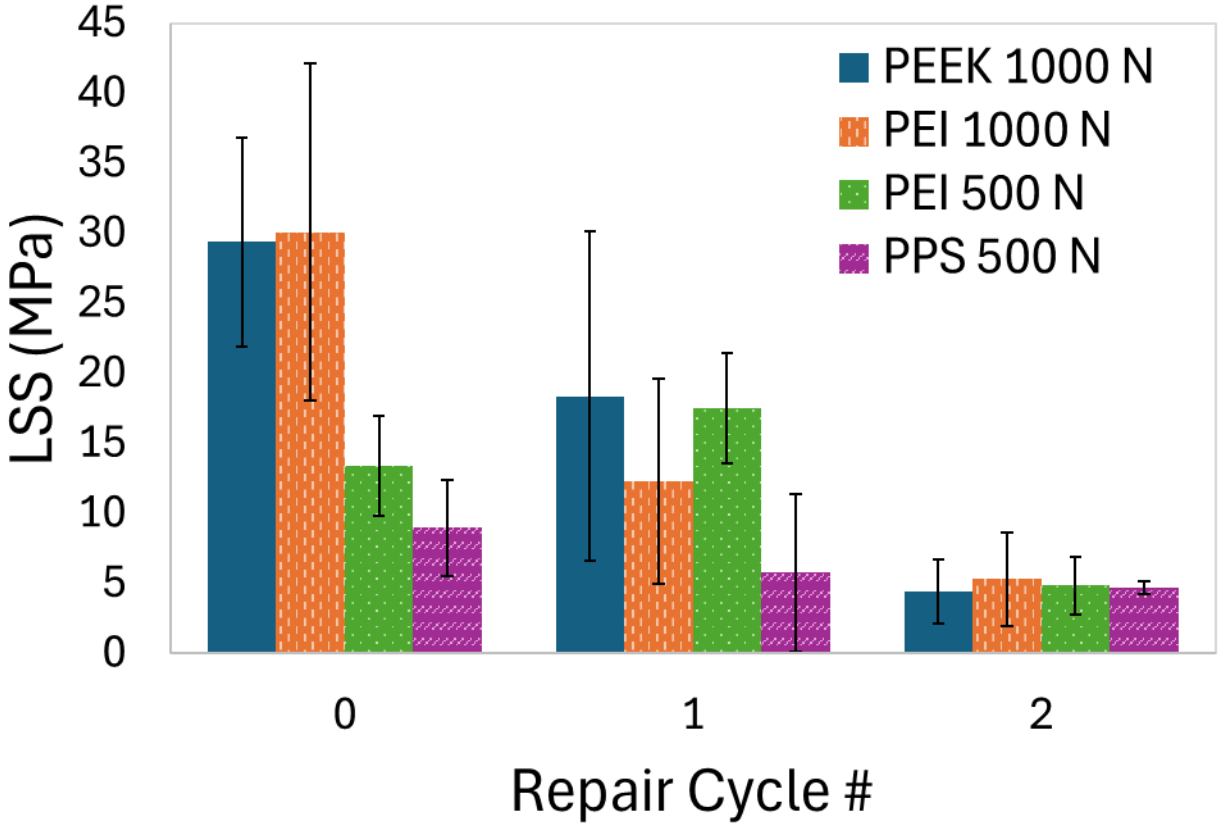


Effect of repair cycles on LSS

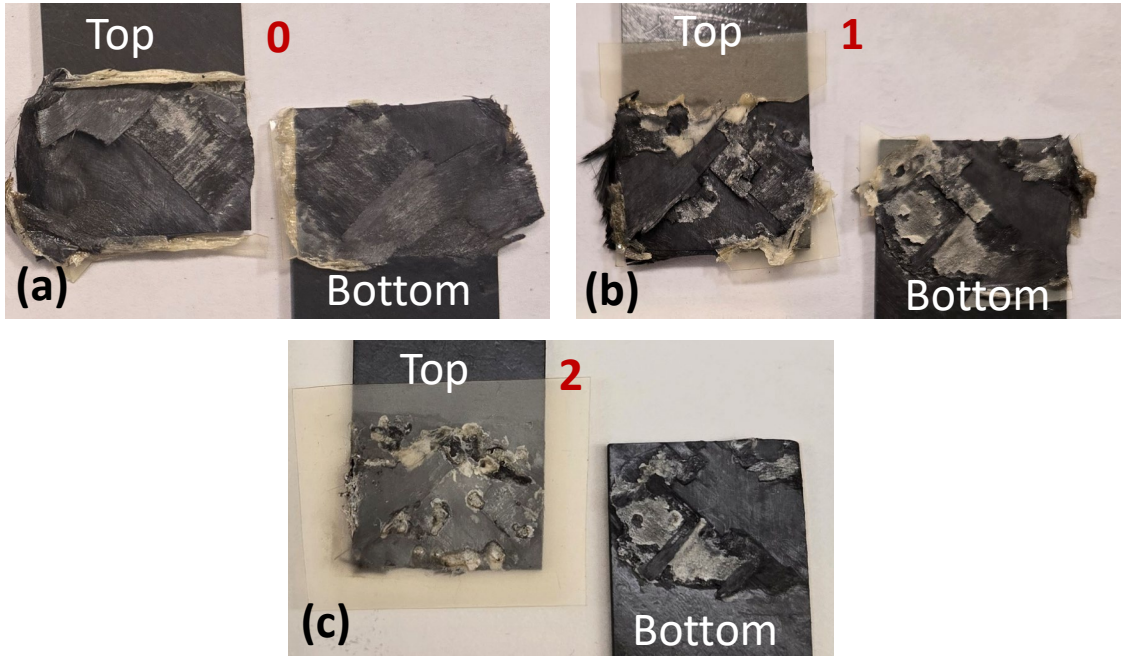


Fracture surface of CF/PEEK-PEI 1000 N over 2 repair cycles

Repaired Regular Weld Behavior

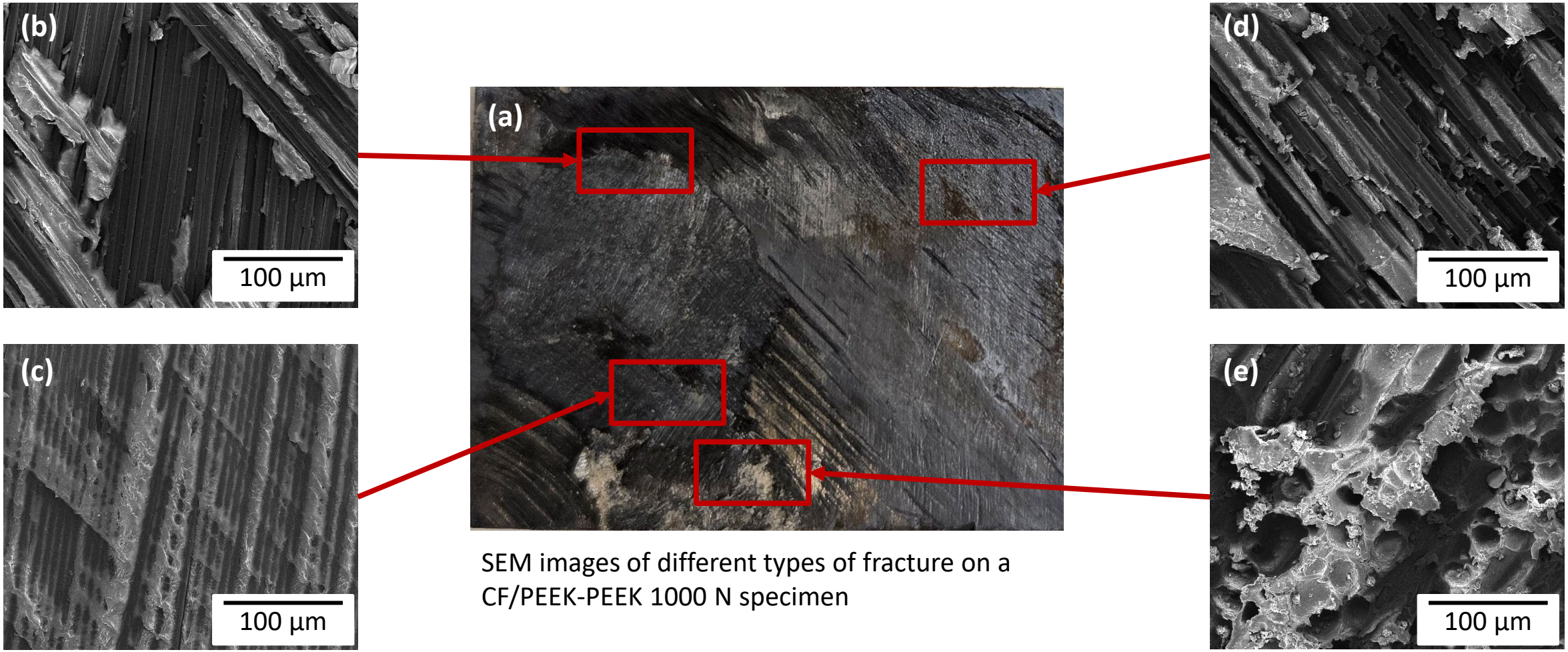


Effect of repair cycles on LSS



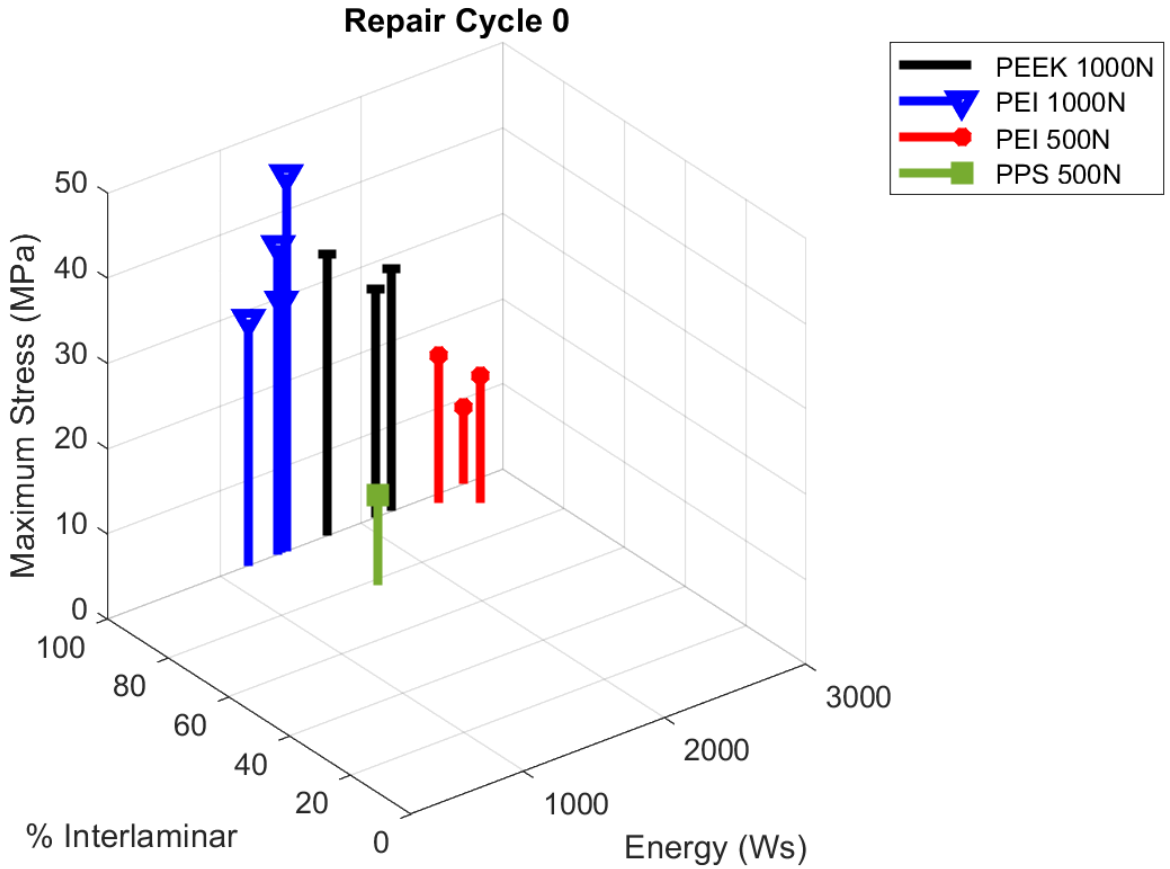
Fracture surface of CF/PEEK-PEI 500 N over 2 repair cycles

Repaired Regular Weld Fracture Surface Analysis



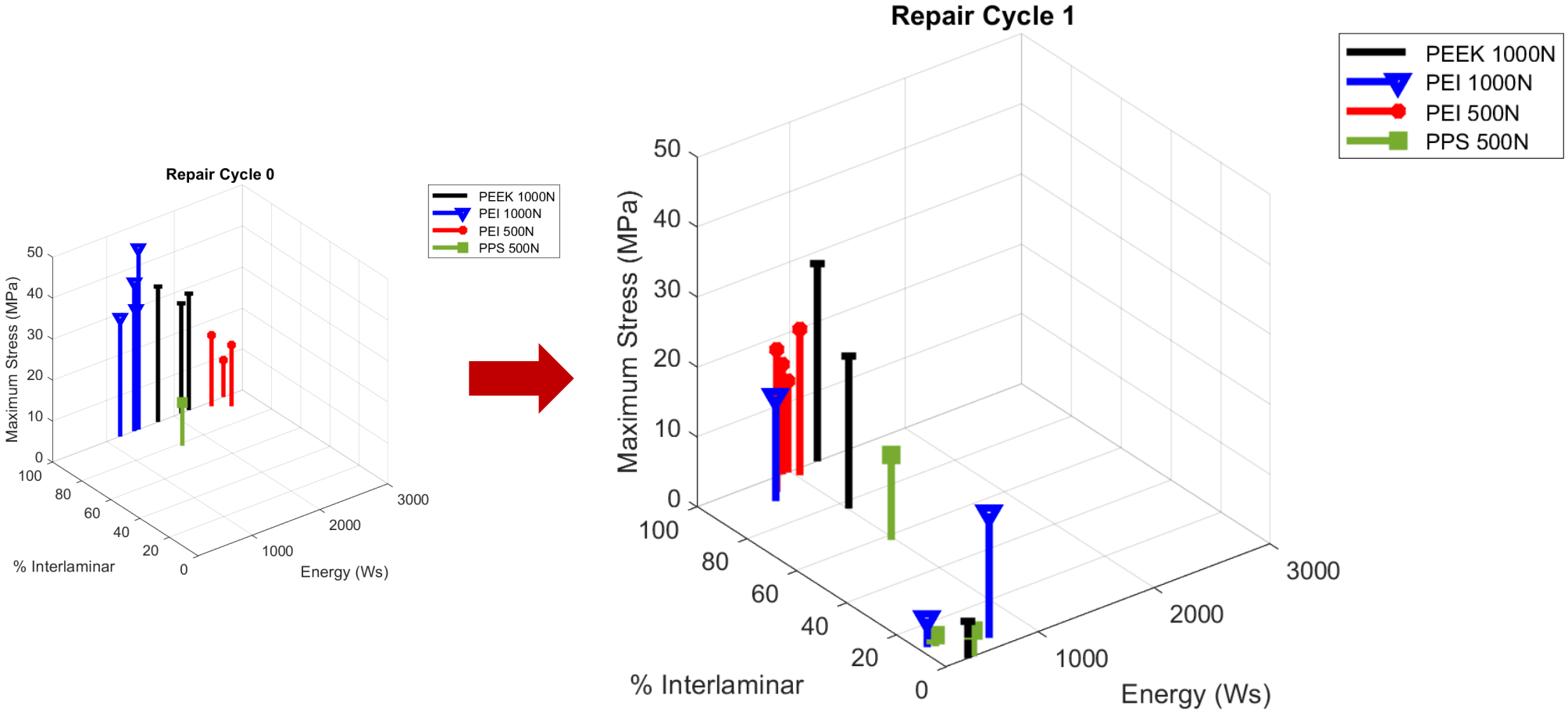
SEM images of different types of fracture on a CF/PEEK-PEEK 1000 N specimen

Regular Weld Comparison



Comparison of LSS, % interlaminar fracture, and energy consumed during USW over 2 repair cycles

Regular Weld Comparison



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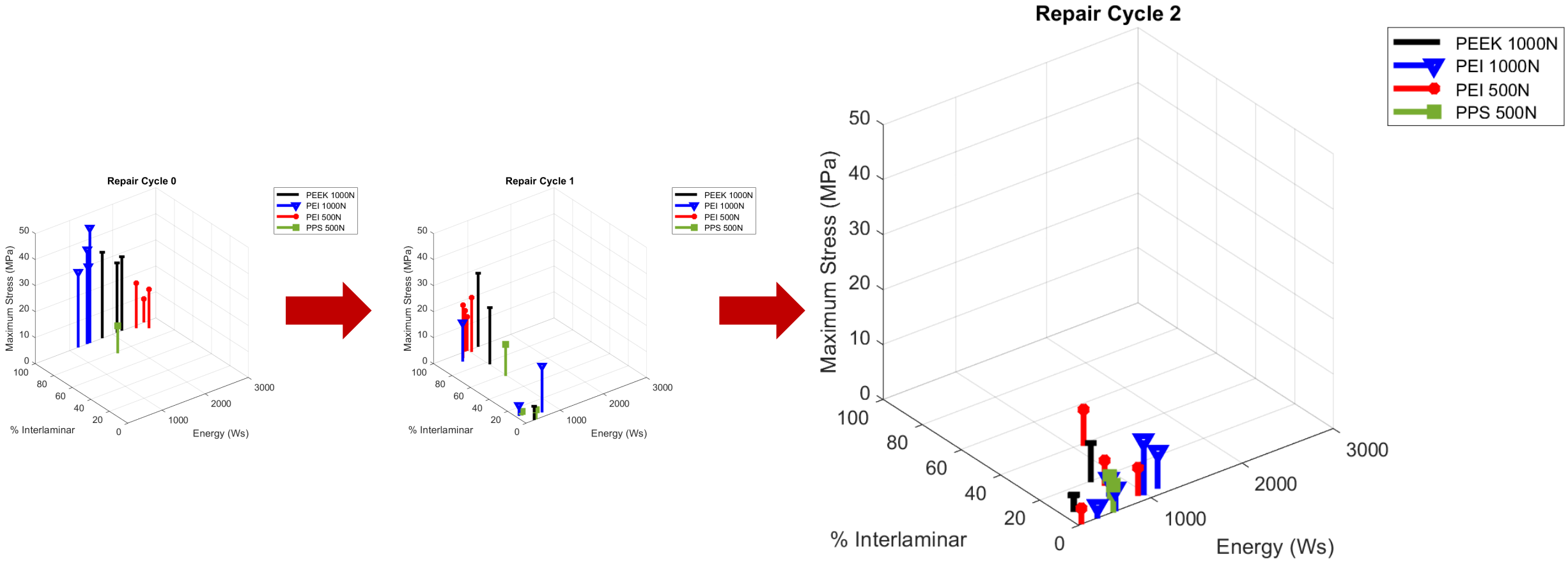
Regular Weld Comparison



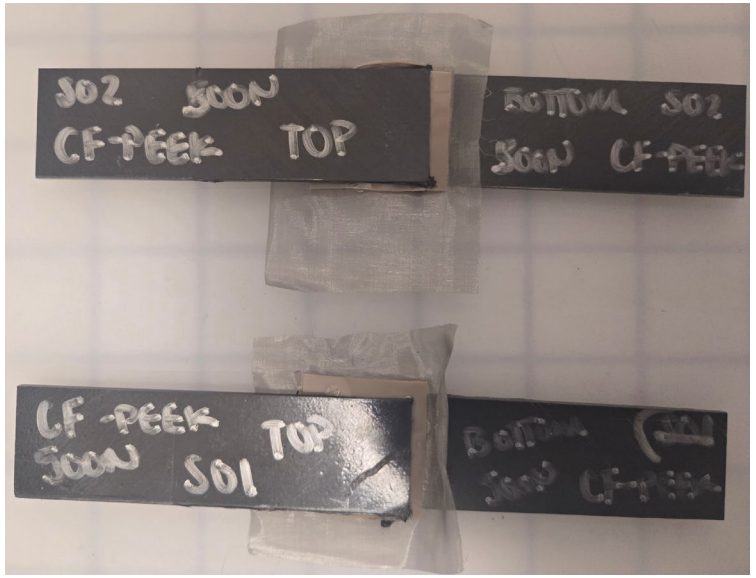
Comparison of LSS, % interlaminar fracture, and energy consumed during USW over 2 repair cycles

Conclusions

- PEEK is most compatible with PEEK and PEI
- PEEK and PEI films welded with higher forces (750-1000 N) and any travel are recommended for more permanent structures
- PEI and PPS films welded with lower forces (500 N) are recommended for temporary structures

Future Work

- Further evaluate material bonding
- Varying adherend thickness
- Examining the effect of dissimilar woven energy directors
- Perform FTIR tests
- Analyzing the effect of a steel mesh at the interface to be used for resistance heating upon disassembly



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Thank you to

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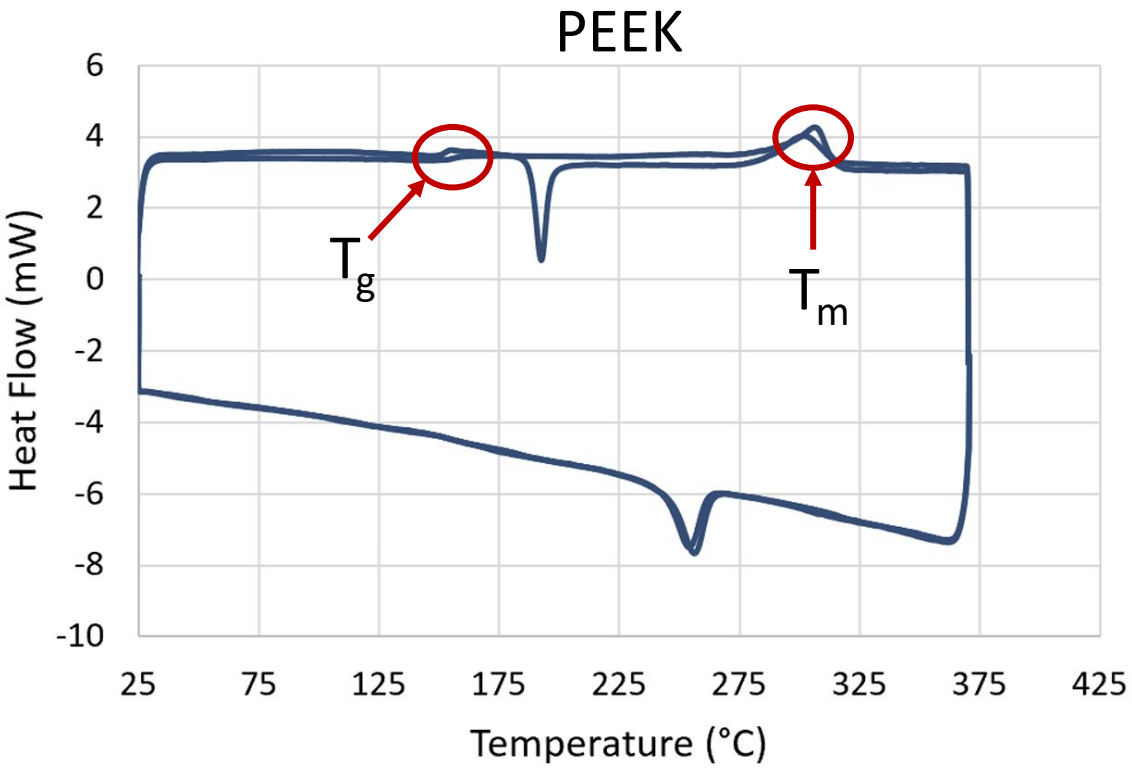
- Dr. Yang Mu (Shared Instrument Facility, LSU) and Mark Brennan (Mechanical Engineering, LSU)

Questions?

Appendix

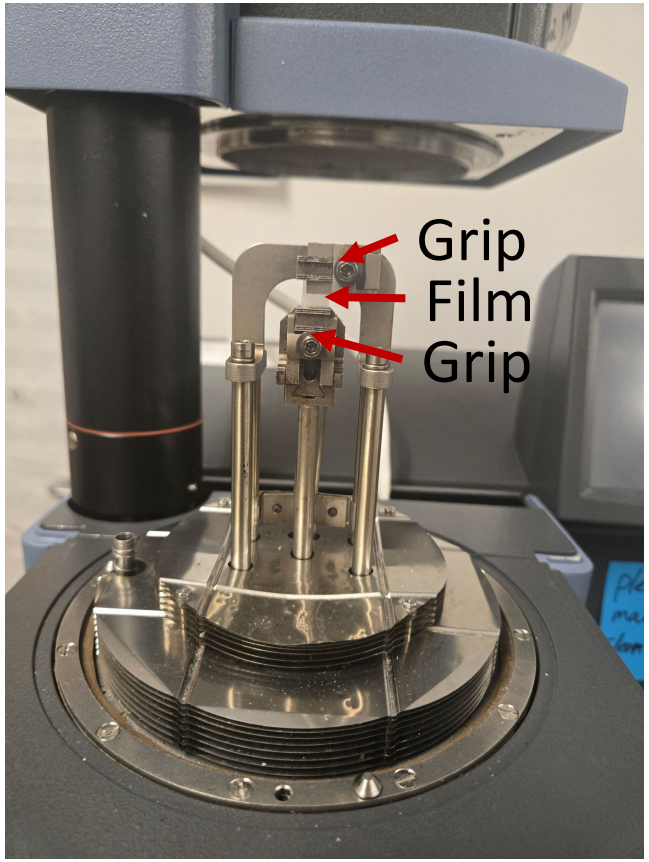
Differential Scanning Calorimetry

- Heating Rate: 10°C/min
- 5-10 mg of film



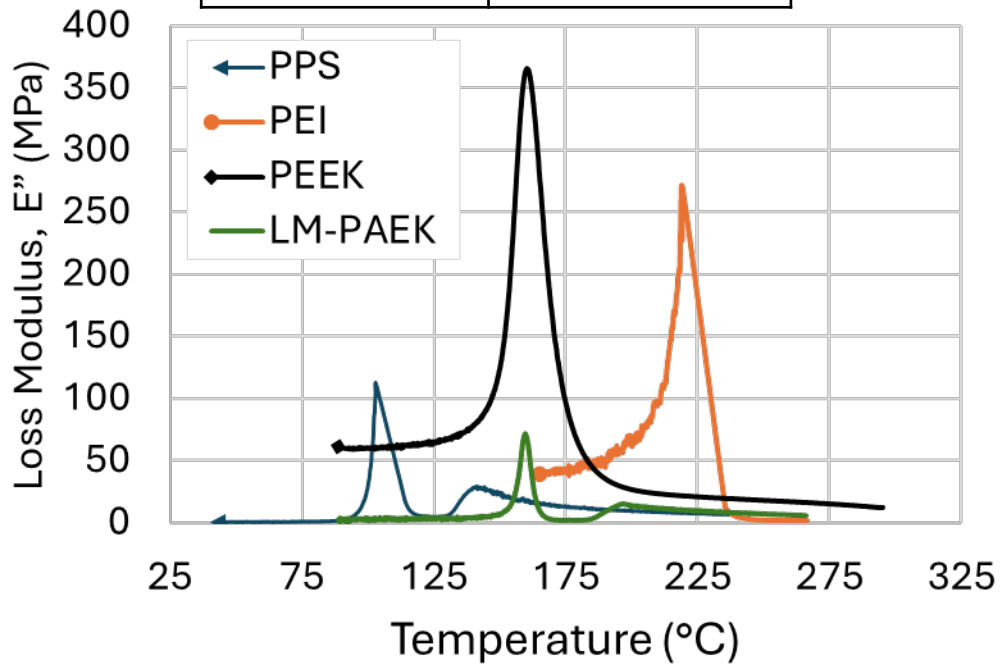
Perkin Elmer DSC 4000, 2025.

Dynamic Mechanical Analysis

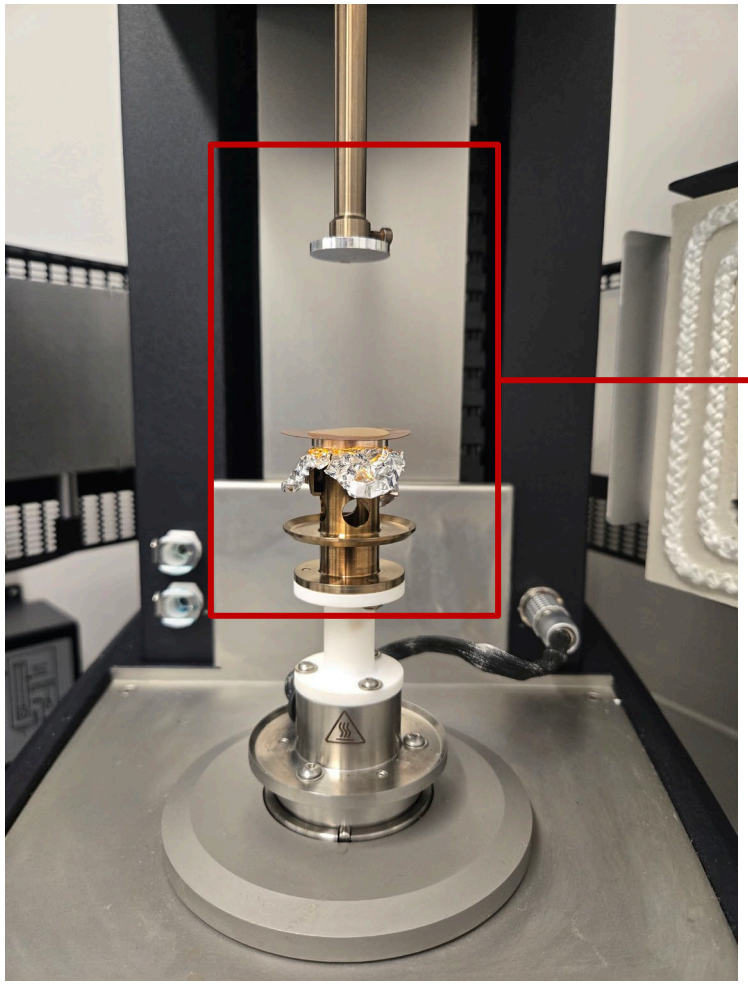


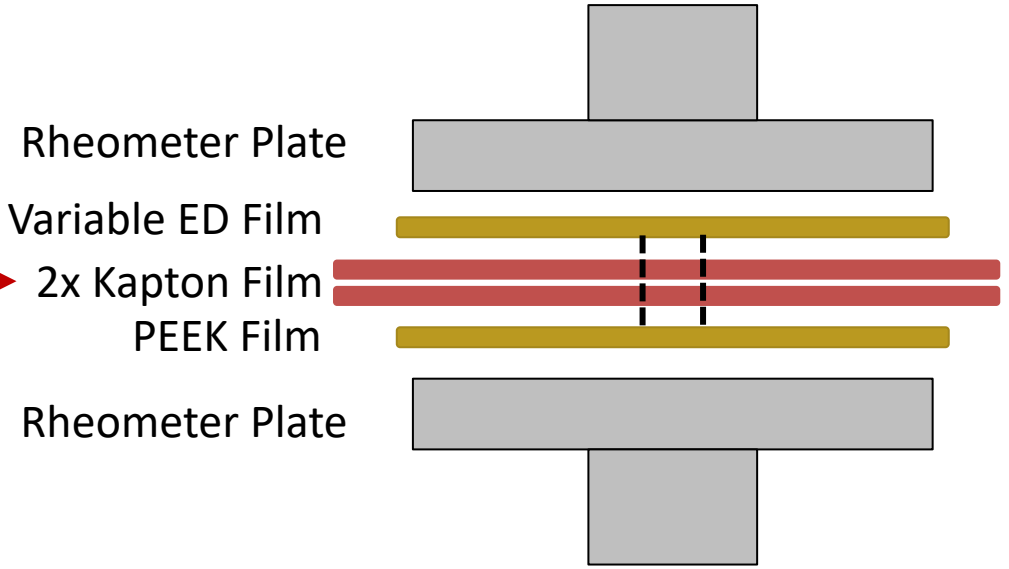
- Heating Rate: 3°C/min
- Frequency: 1 Hz
- Force Oscillation: 0.01 N
- 18 × 8 mm film

Material	T_g (°C)
PEEK	160.8
PEI	218.5
PPS	104.6
LM-PAEK	160.0



Degree of Healing





Degree of Healing (D_H)

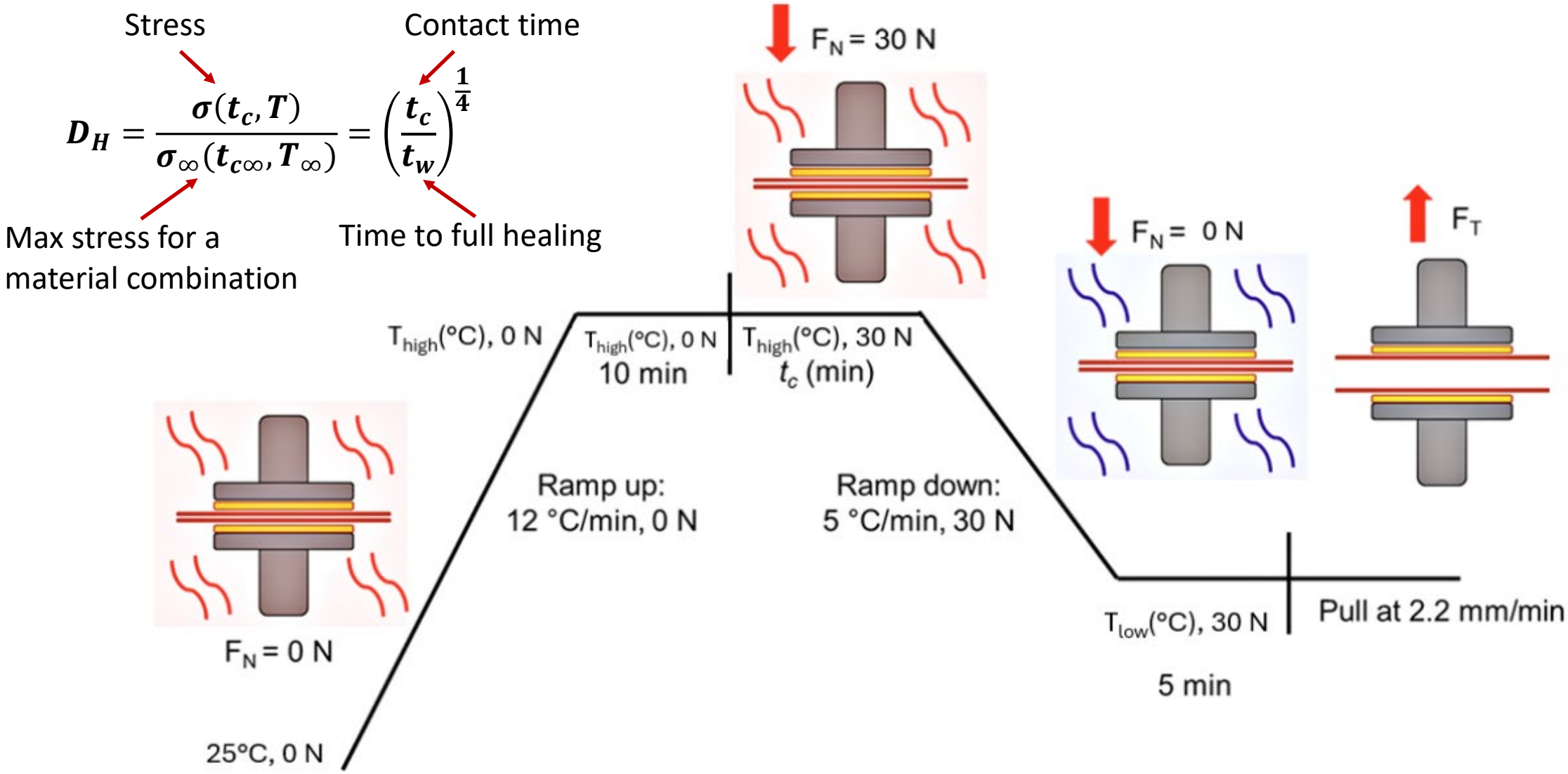
Stress

Contact time

$$D_H = \frac{\sigma(t_c, T)}{\sigma_\infty(t_{c\infty}, T_\infty)} = \left(\frac{t_c}{t_w}\right)^{\frac{1}{4}}$$

Max stress for a material combination

Time to full healing



Modified from Baroetta et al., The International Journal of Adv. Mfg. Tech., 132(3-4), 2024.

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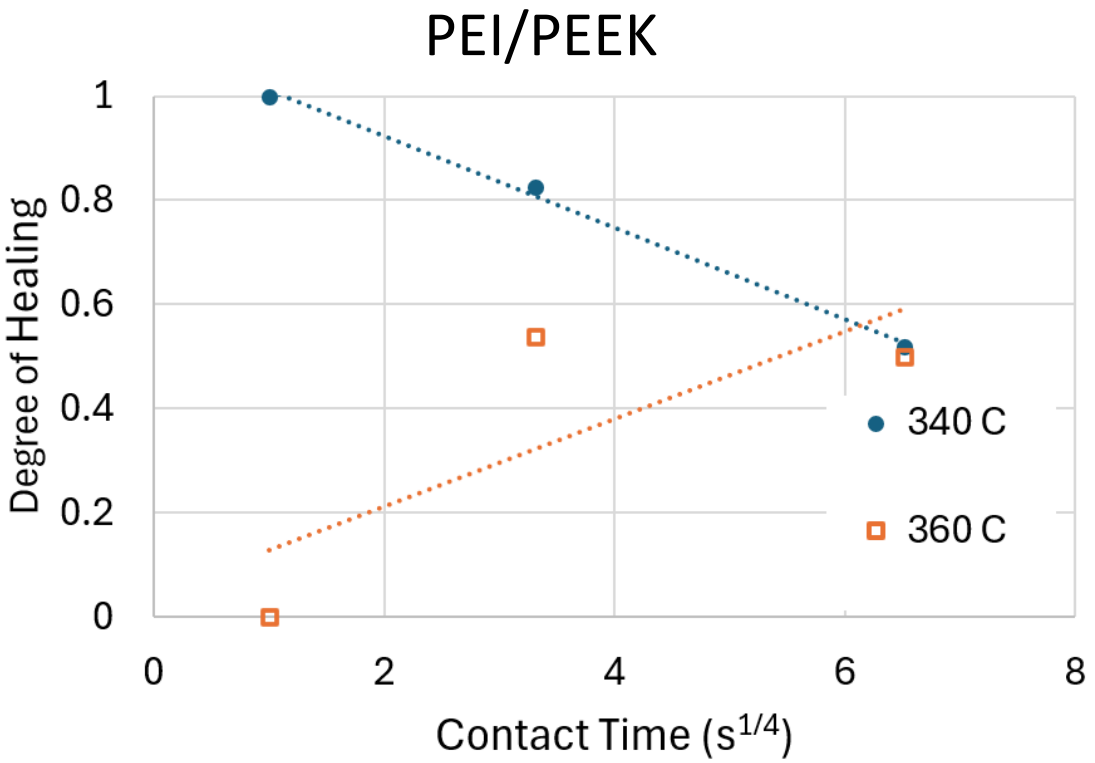

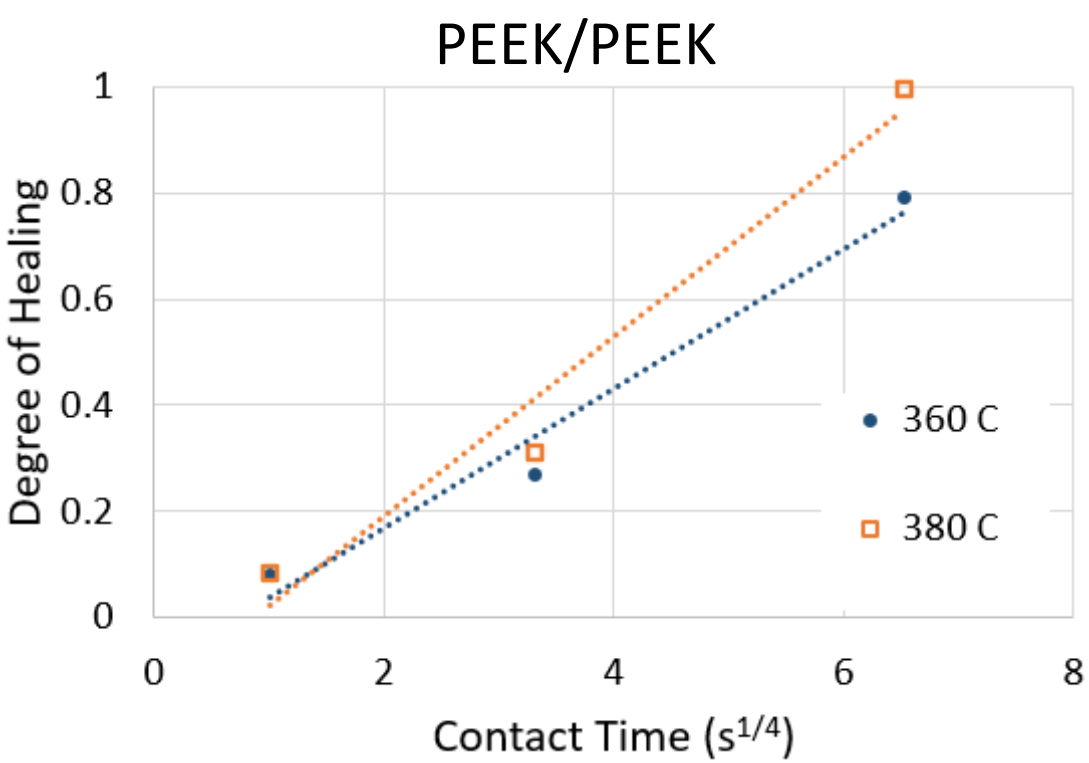

- PPS/PEEK burned
- Bonding between LM-PAEK and the rheometer plate at elevated temperatures was insufficient

Differential Scanning Calorimetry

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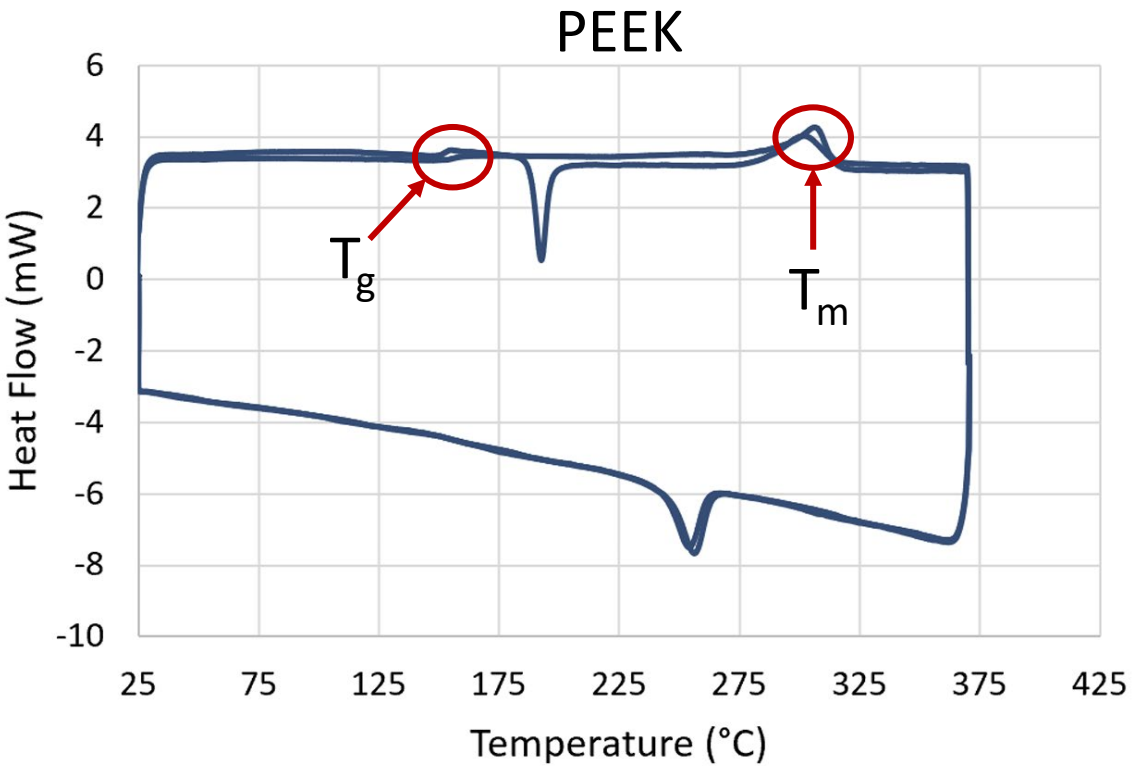

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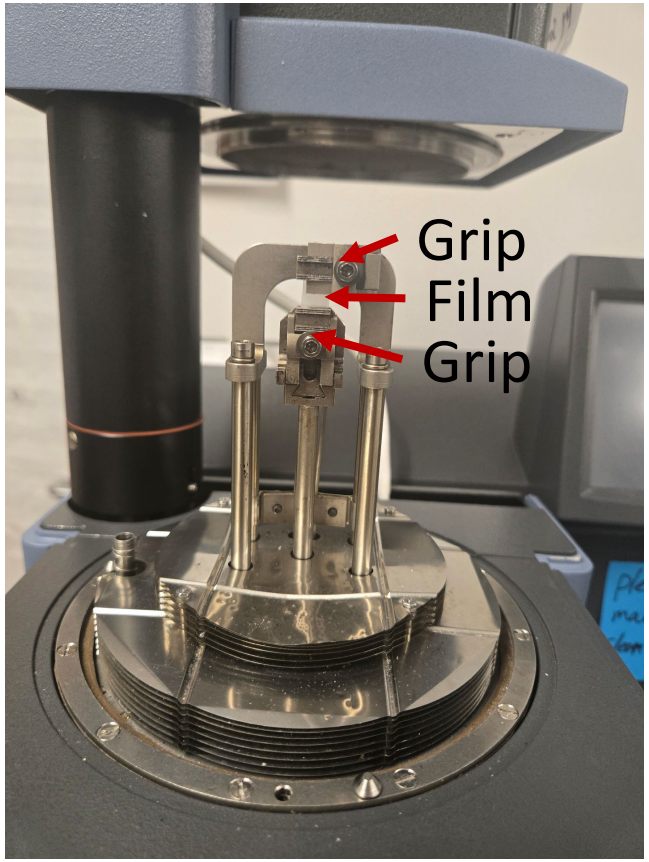

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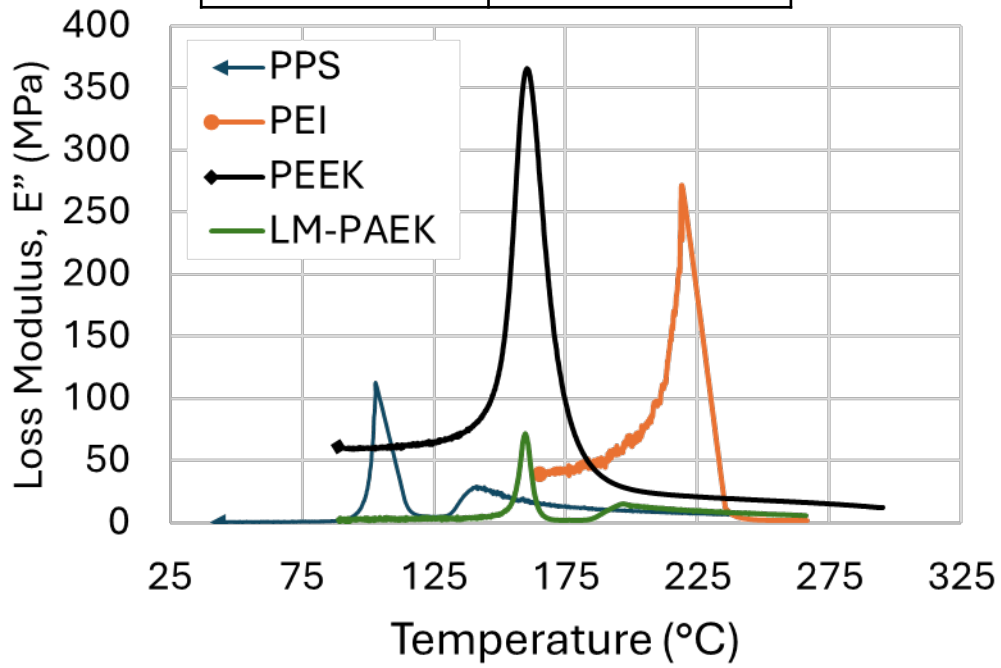

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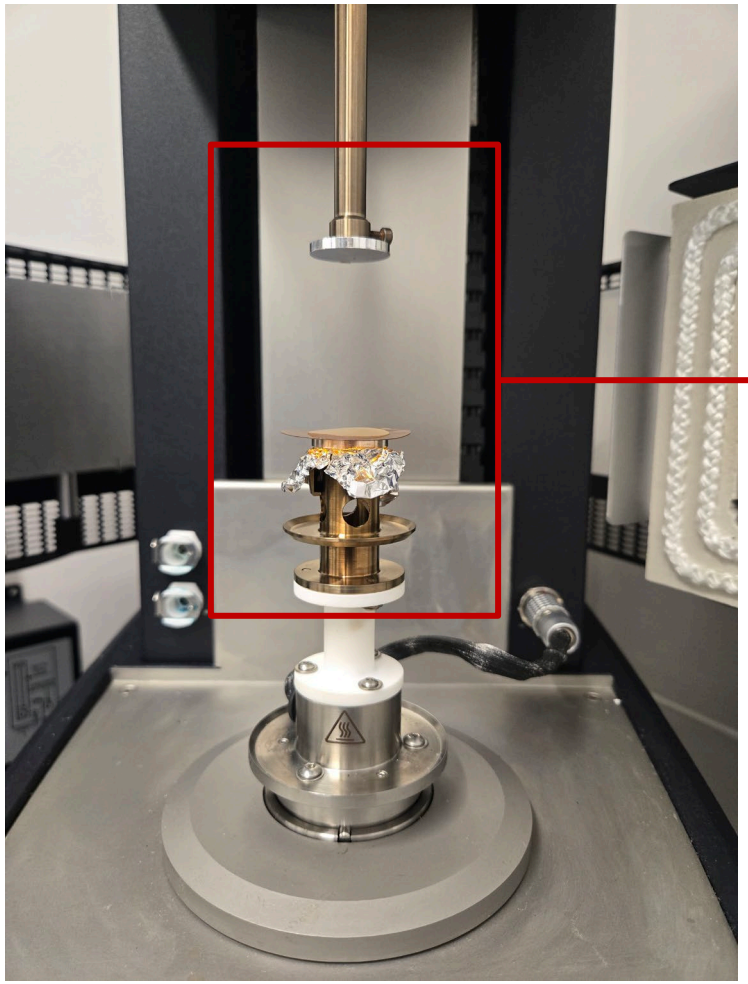

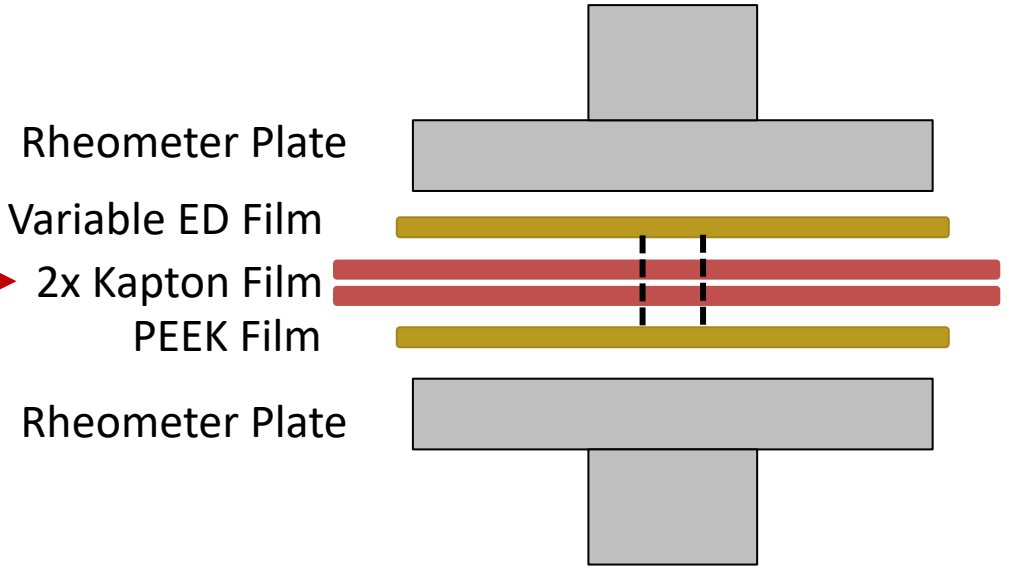

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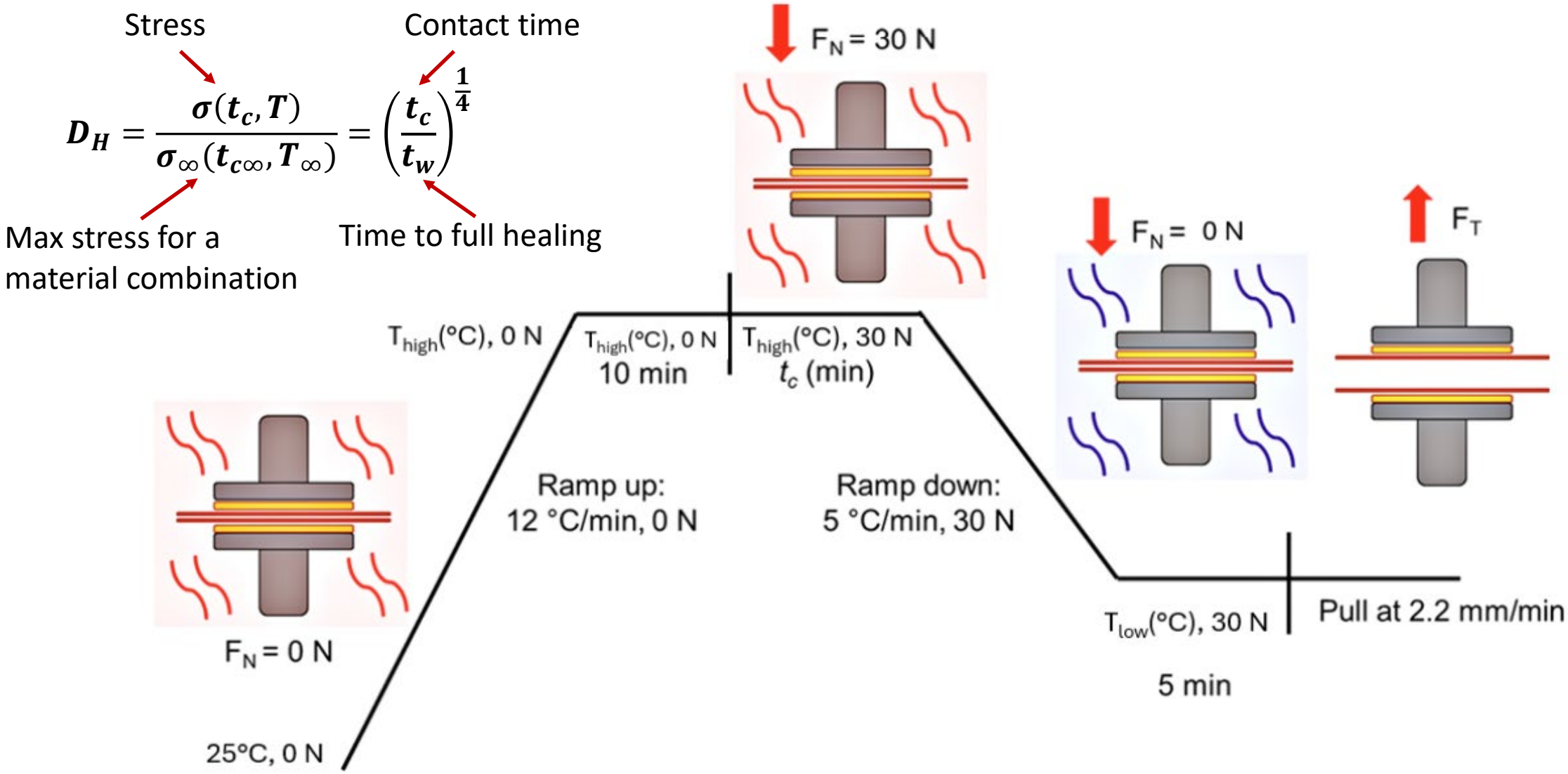

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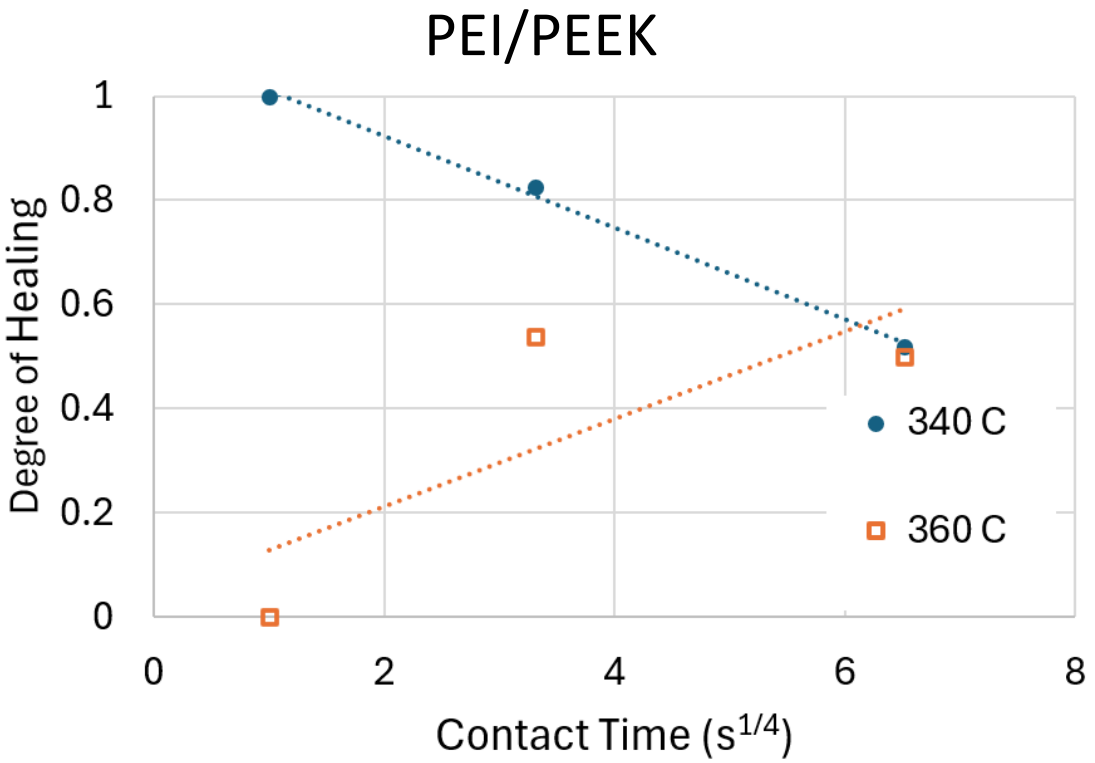
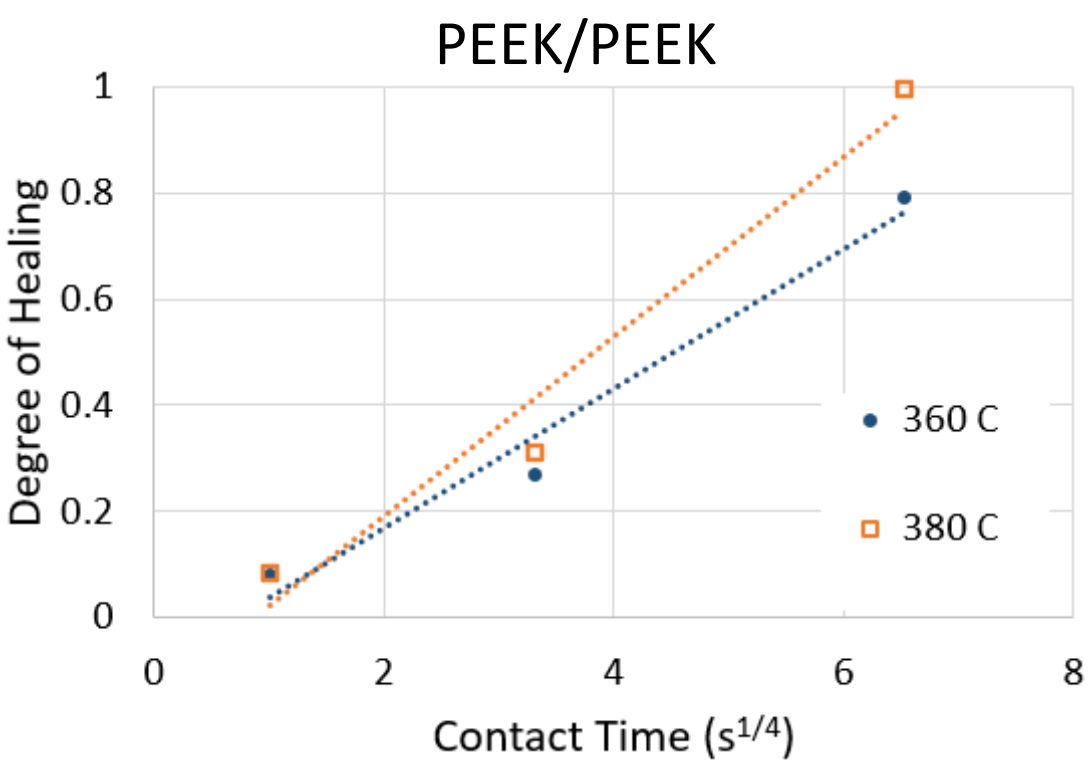
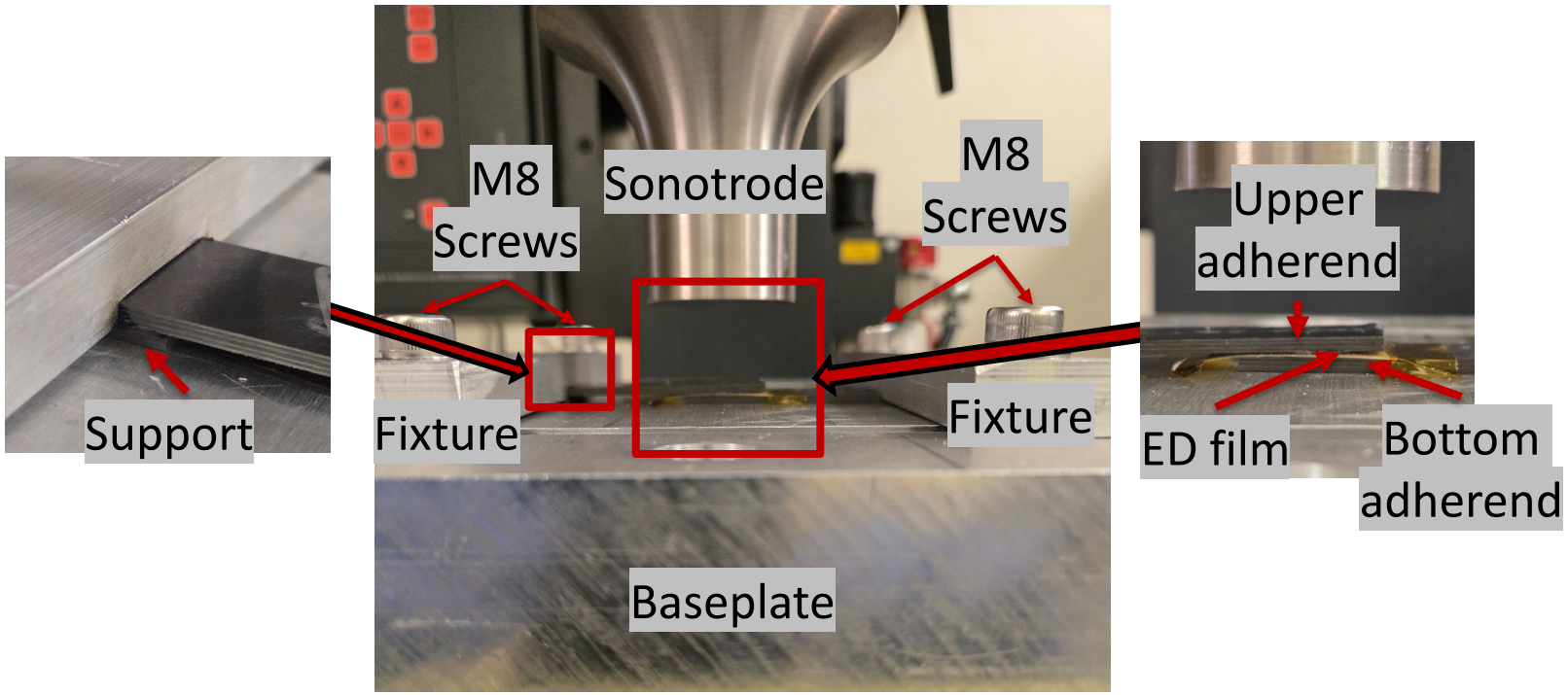




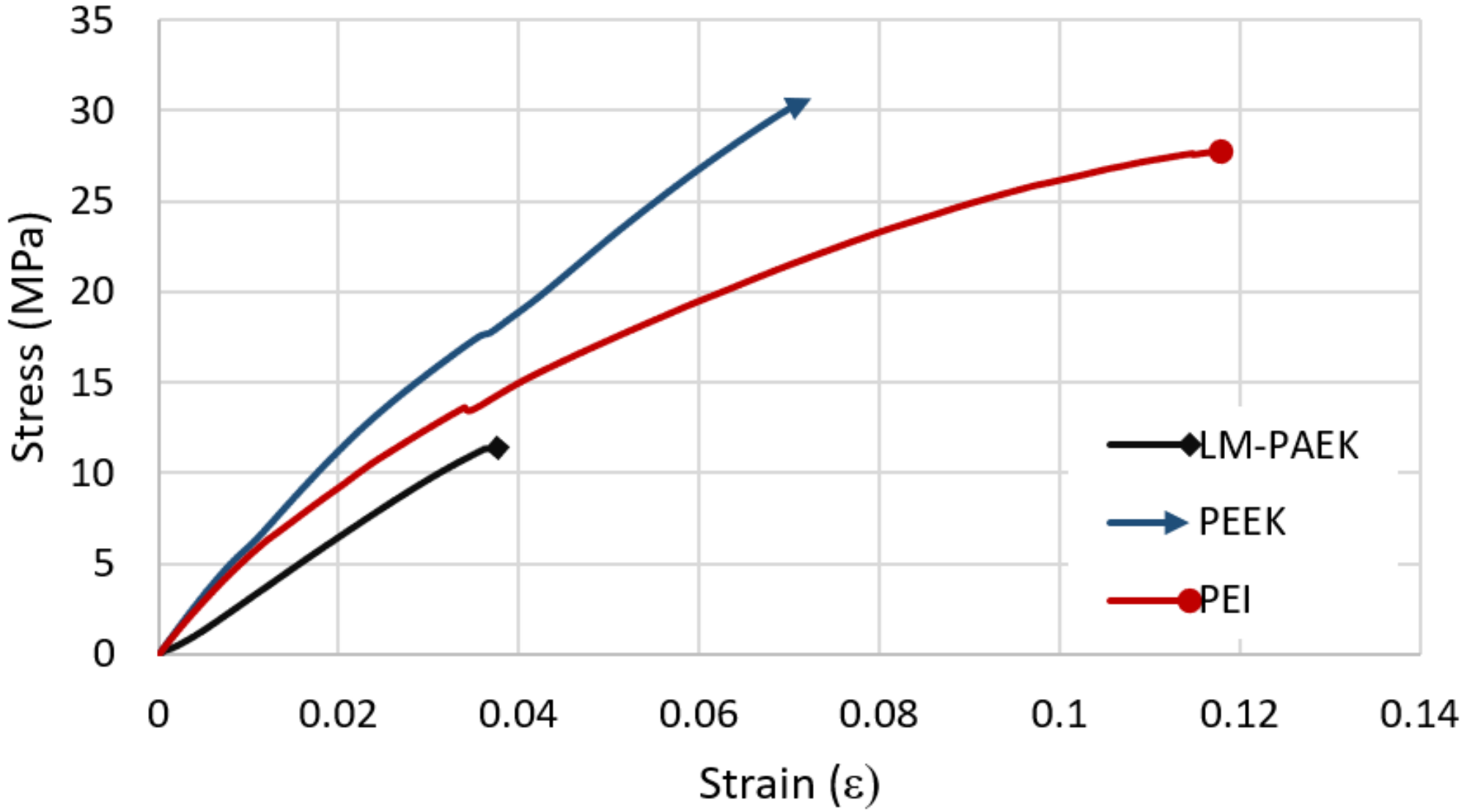
- PPS/PEEK burned
- Bonding between LM-PAEK and the rheometer plate at elevated temperatures was insufficient

USW Setup



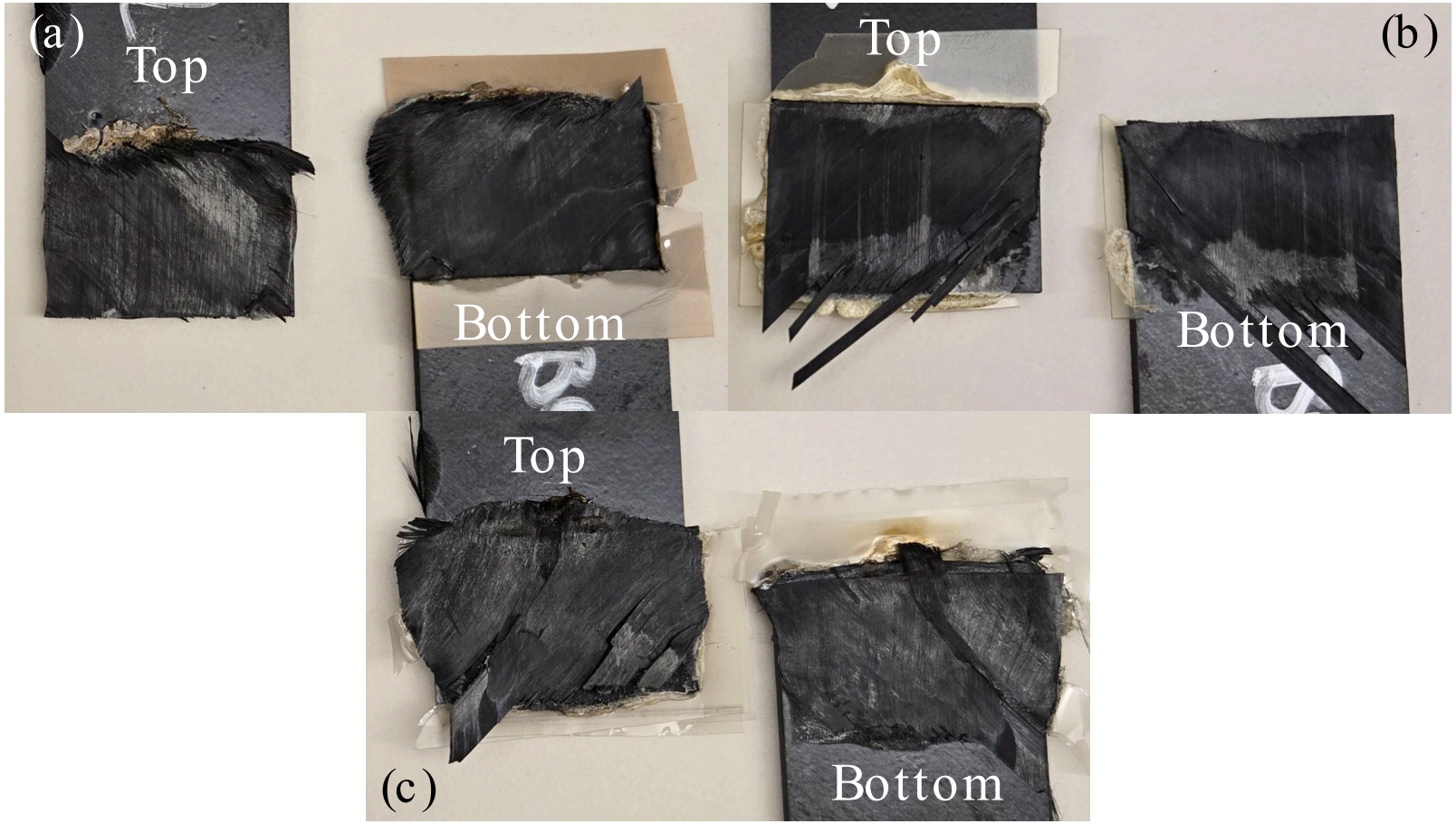
Low Travel Welding Parameters	
Energy Director	
PEEK	0.20 mm
PEI	0.25 mm
LM-PAEK	0.06 mm (3x)
Initial Welding & Solidification Force	
PEEK	750 N
PEI	750 N
LM-PAEK	800 N
Repair Welding & Solidification Force	1500 & 2500 N
Holding Time	4000 ms
Vibration Amplitude	
Initial	38.1 µm
Repair	41.3 µm
Frequency	20 kHz
Travel	20%

Initial Low Travel Weld Behavior



Initial Low Travel Weld Fracture Surfaces

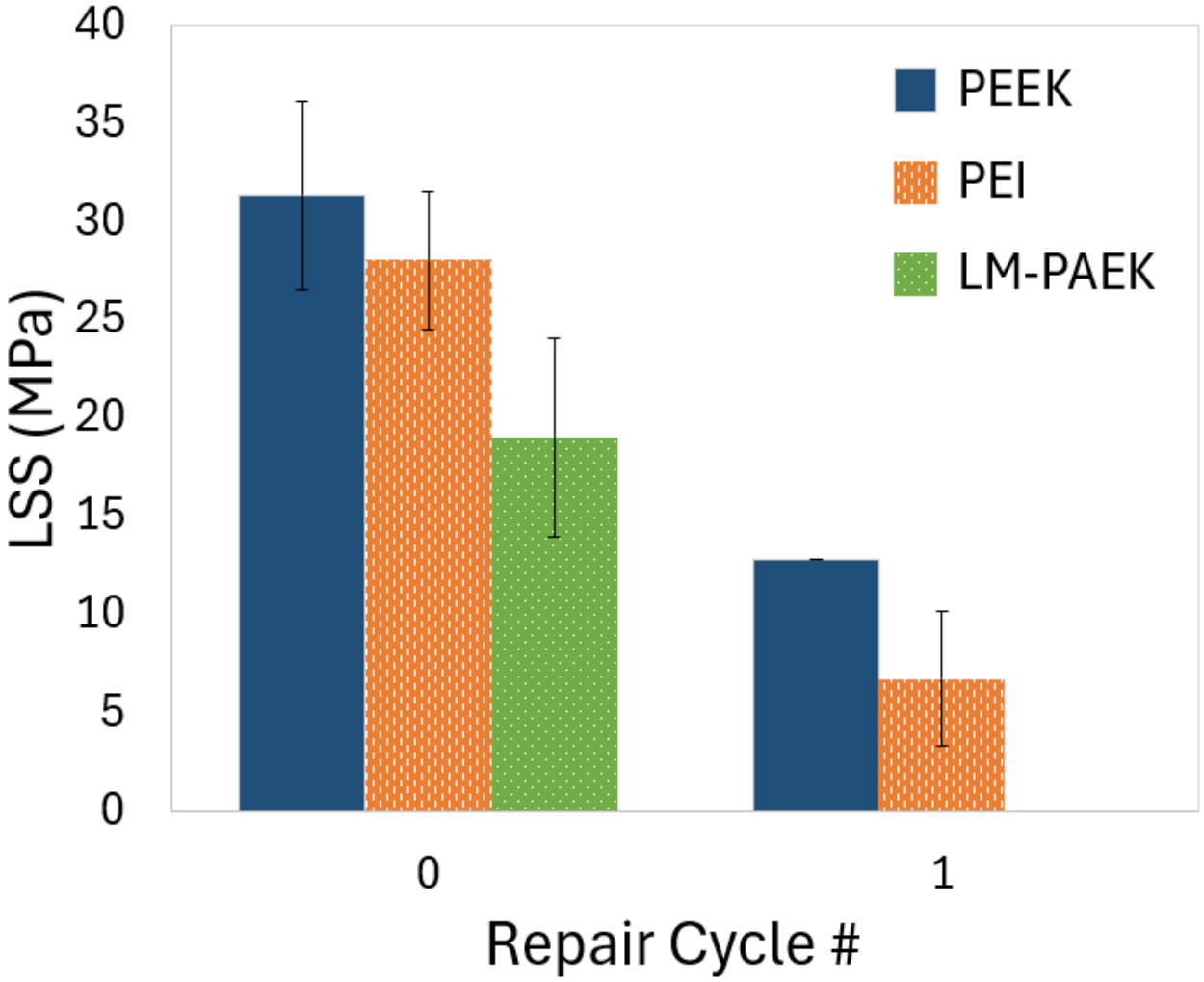
(a) CF/PEEK-PEEK
750 N



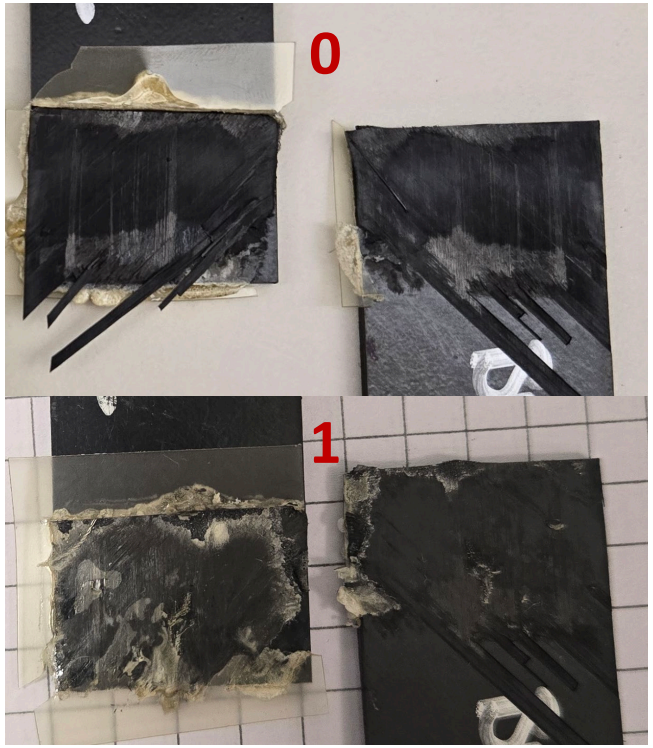
(b) CF/PEEK-PEI
750 N

(c) CF/PEEK-LMPAEK
800 N

Repaired Low Travel Weld Behavior

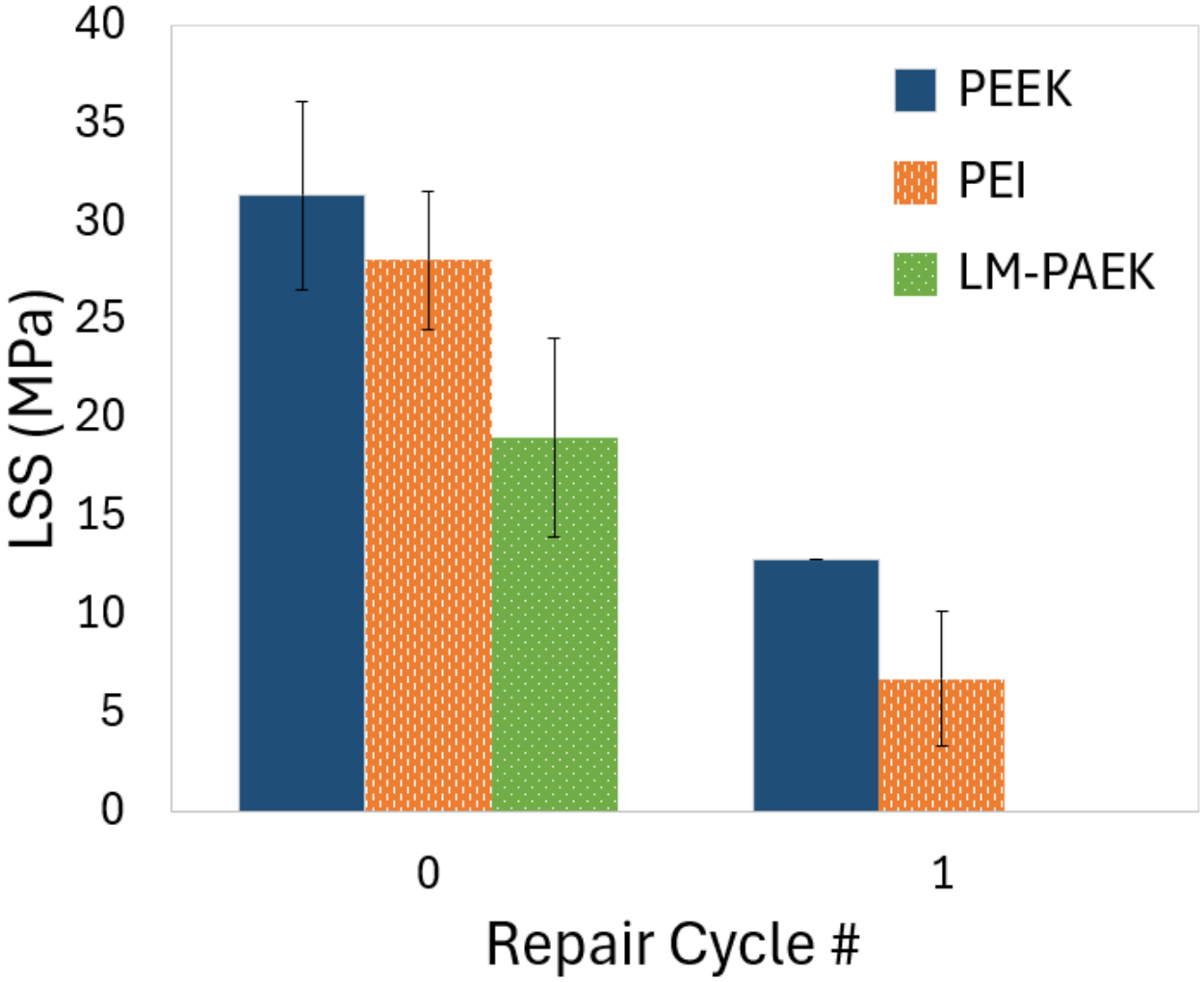


Effect of repair cycles on LSS

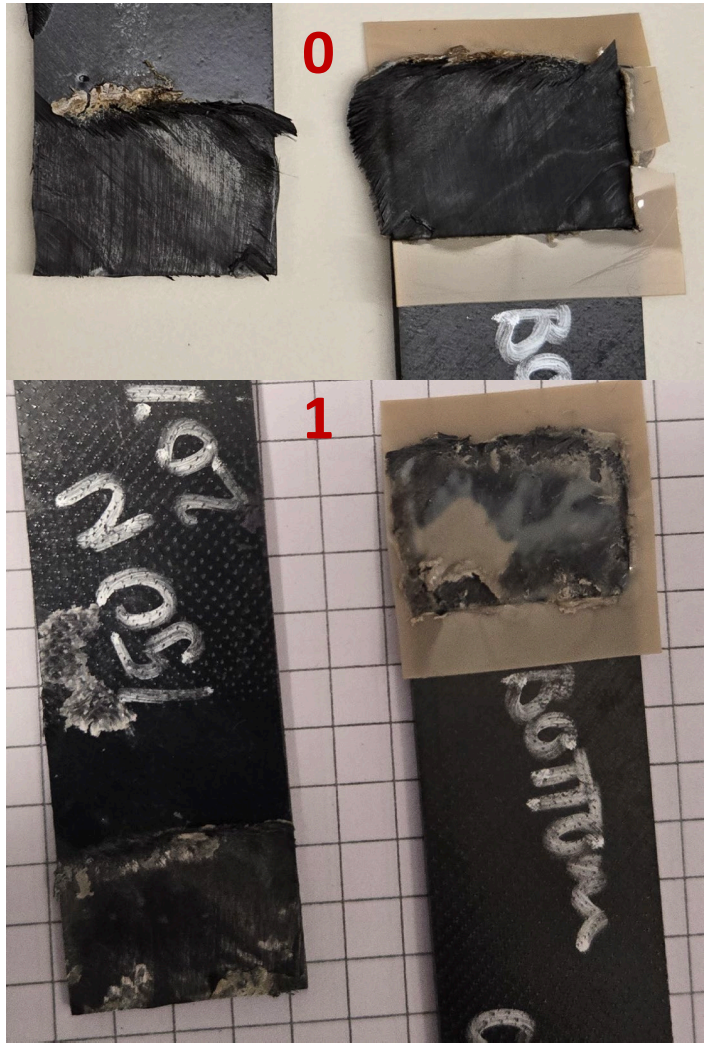


Fracture surface of CF/PEEK-PEI low travel over 1 repair cycle

Repaired Low Travel Weld Behavior

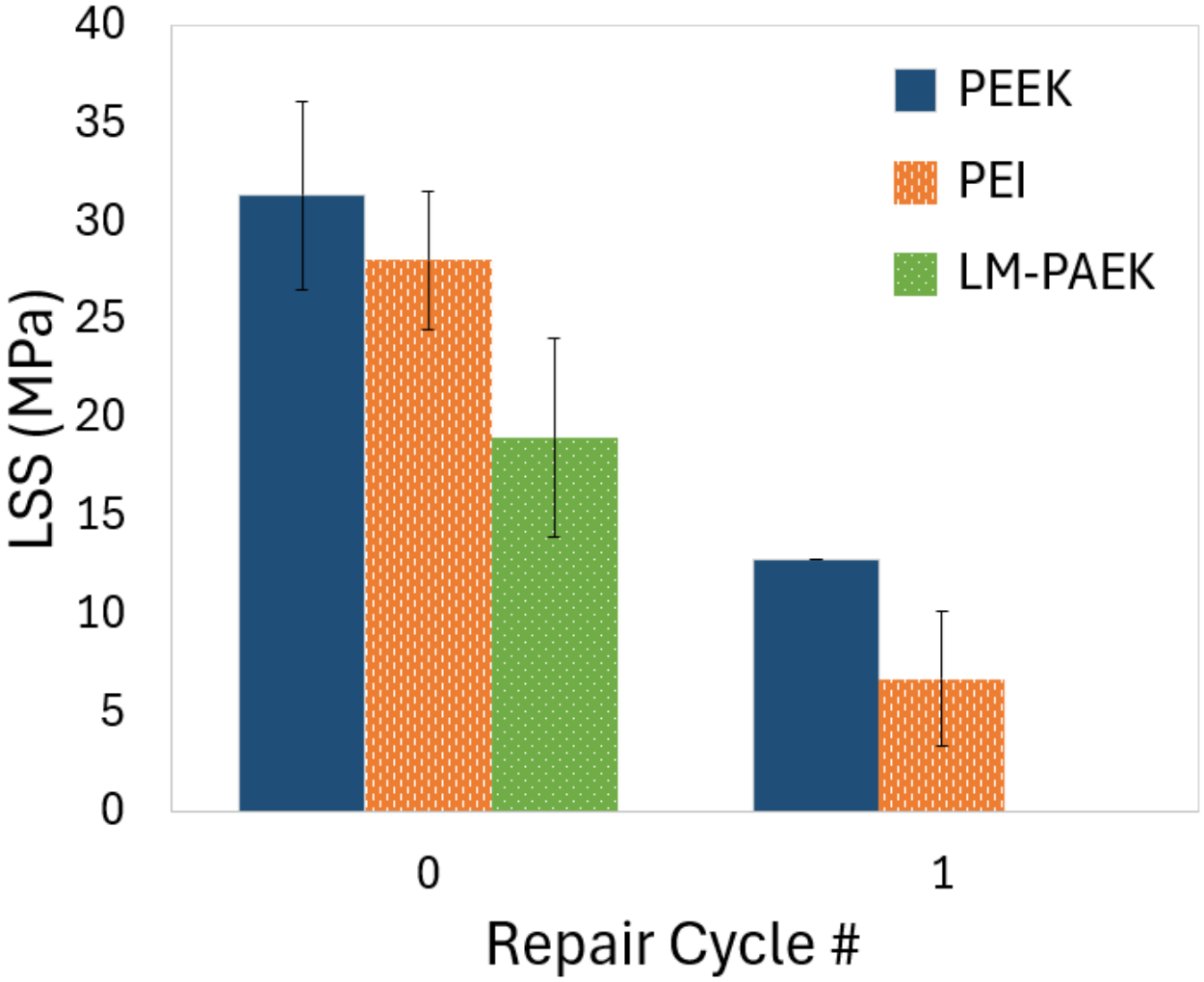


Effect of repair cycles on LSS

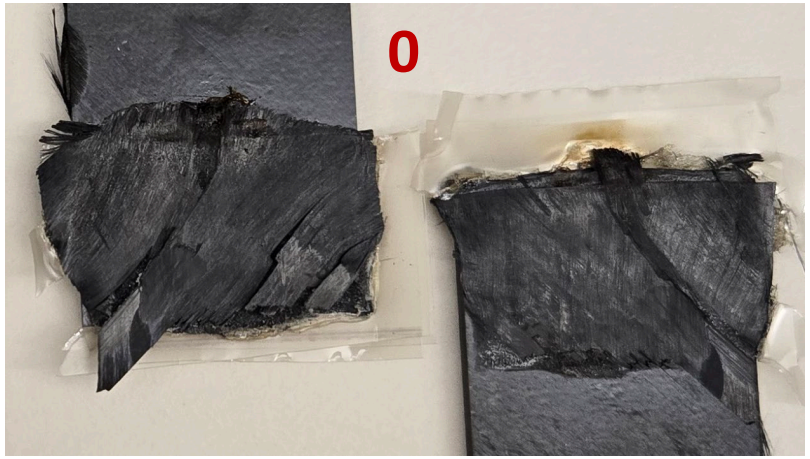


Fracture surface of CF/PEEK-PEEK low travel over 1 repair cycle

Repaired Low Travel Weld Behavior

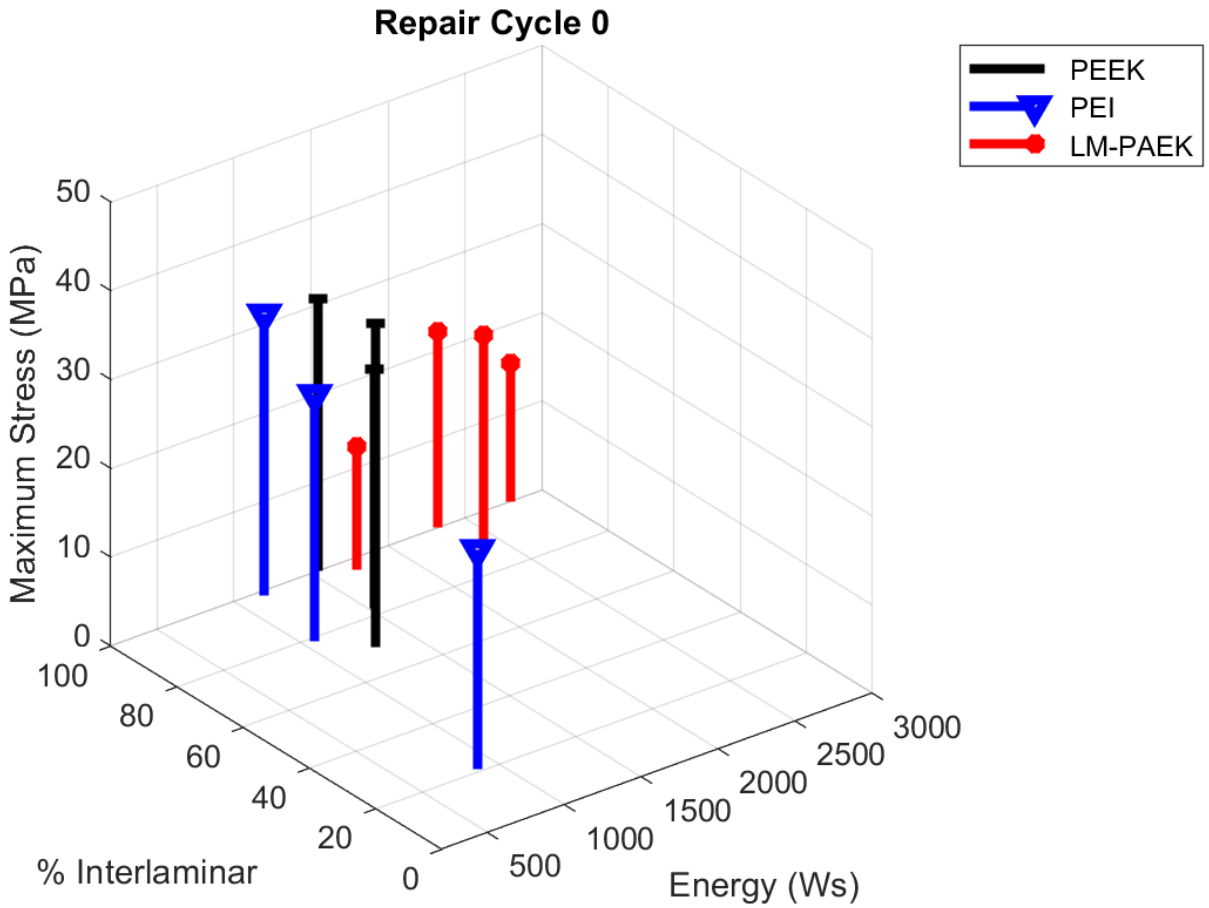


Effect of repair cycles on LSS



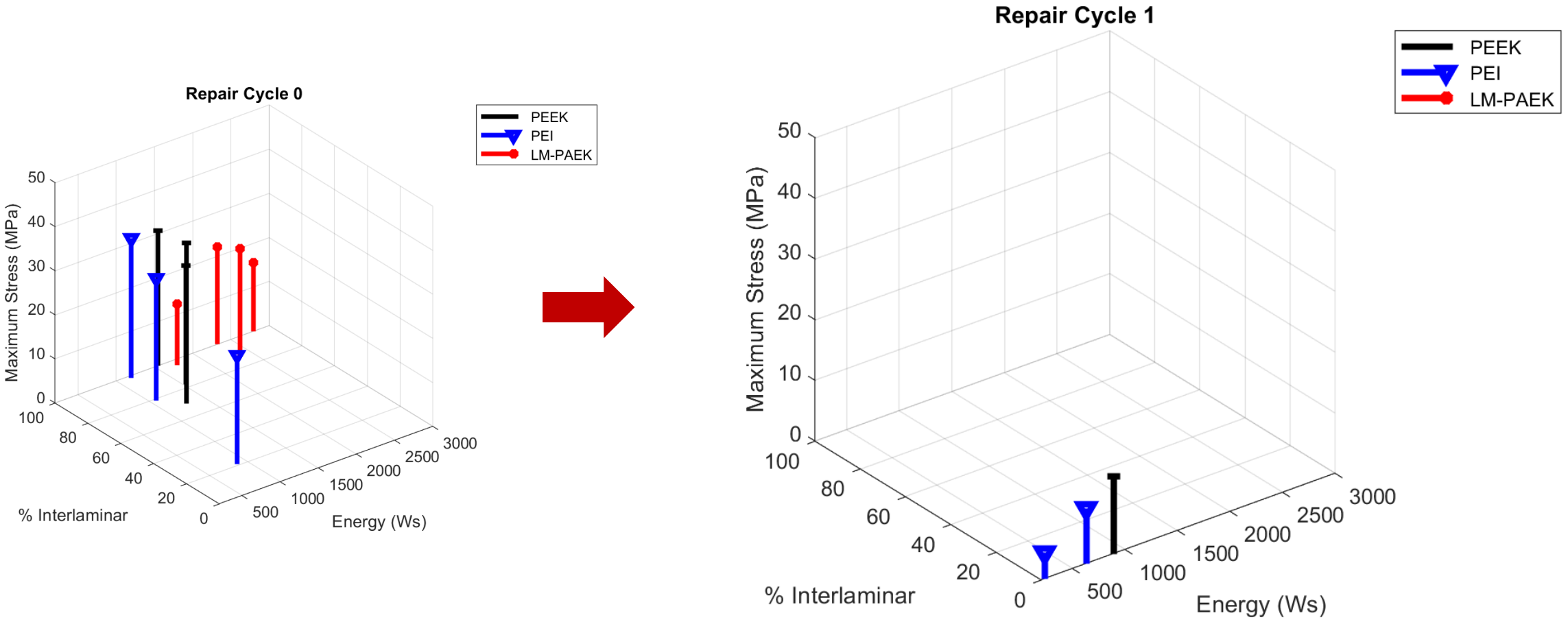
Fracture surface of CF/PEEK-LMPAEK low travel

Low Travel Weld Comparison



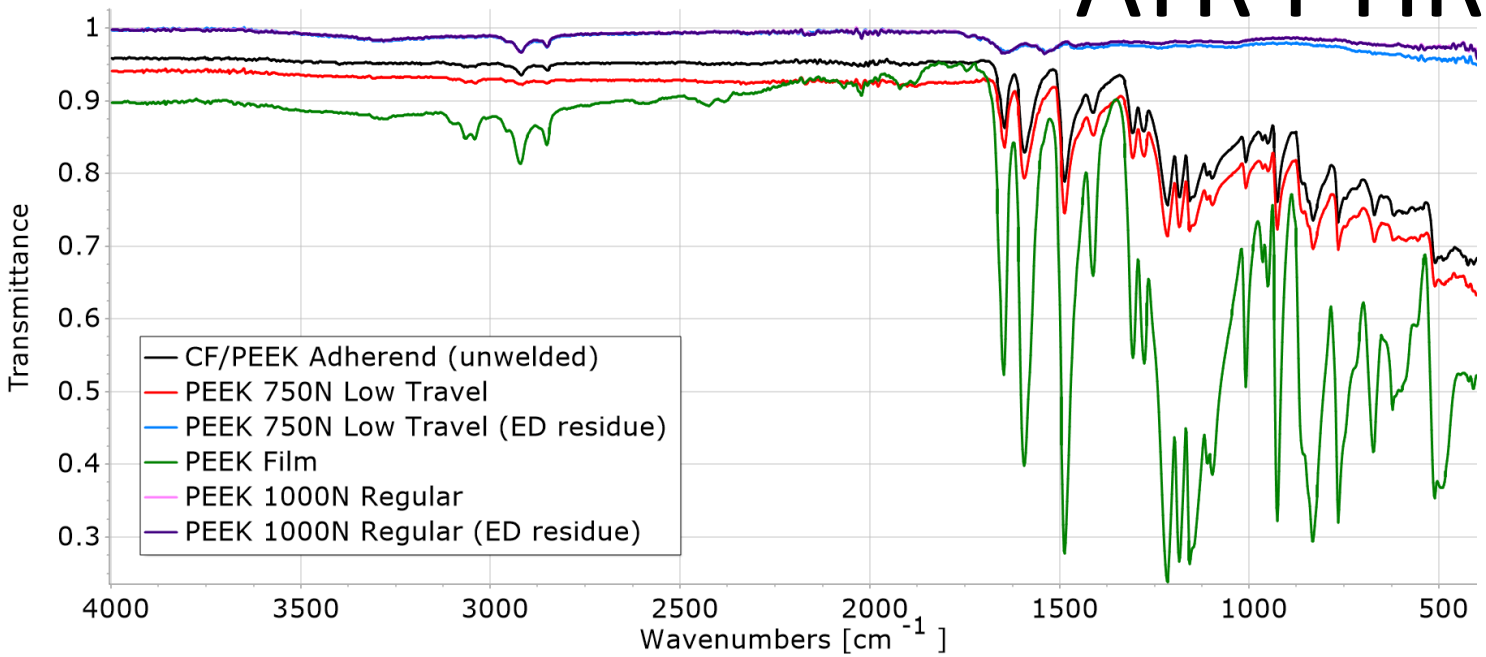
Comparison of LSS, % interlaminar fracture, and energy consumed during USW over 1 repair cycle

Low Travel Weld Comparison

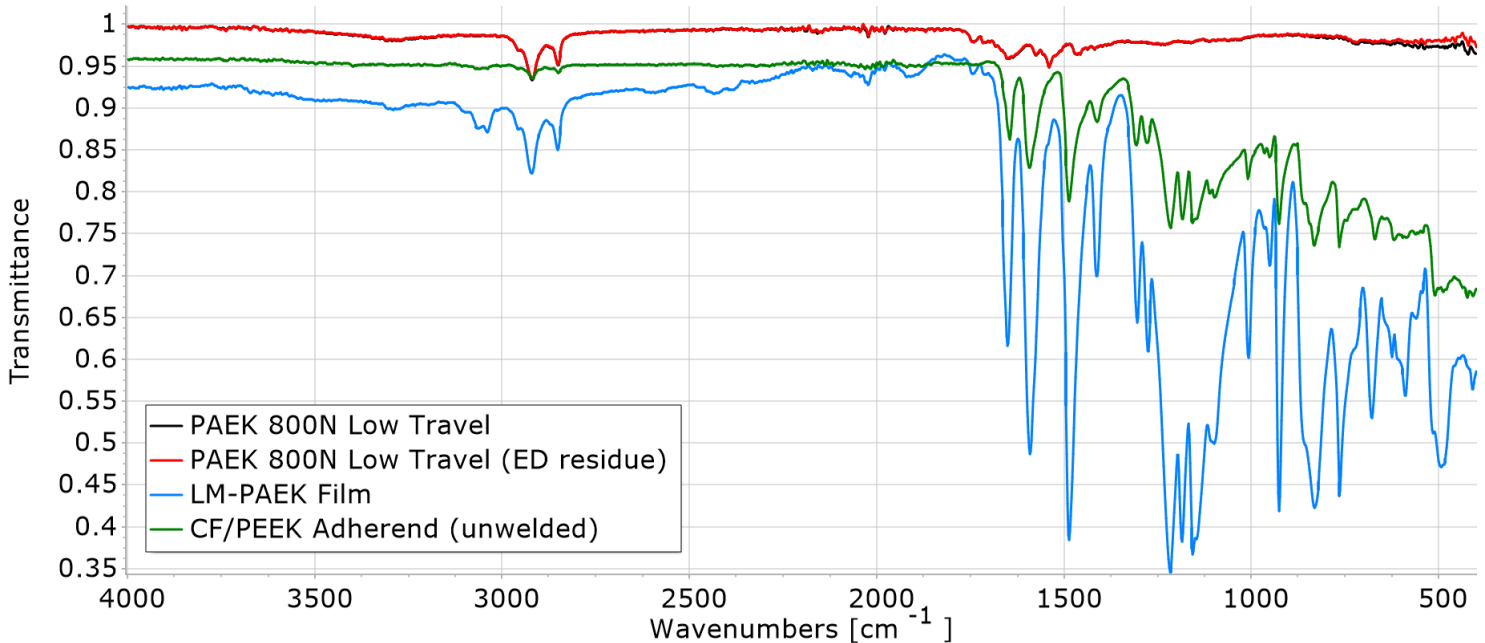


Comparison of LSS, % interlaminar fracture, and energy consumed during USW over 1 repair cycle

ATR FTIR



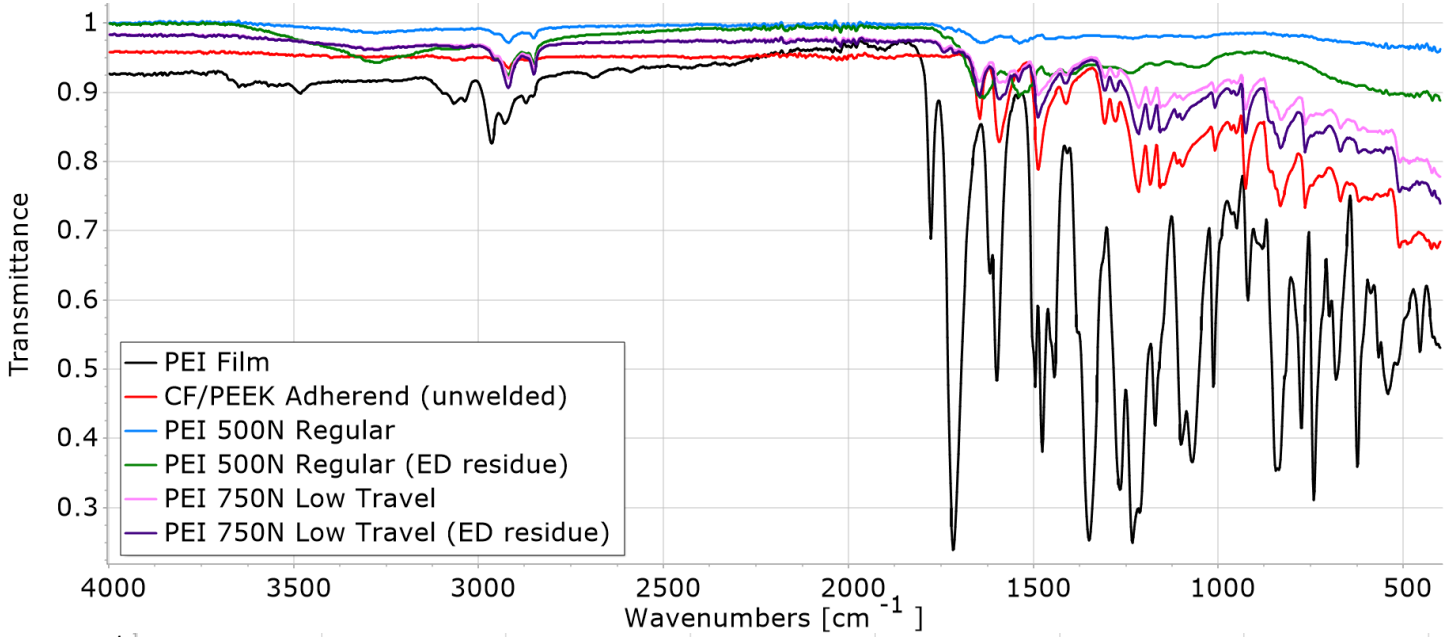
CF/PEEK-PEEK



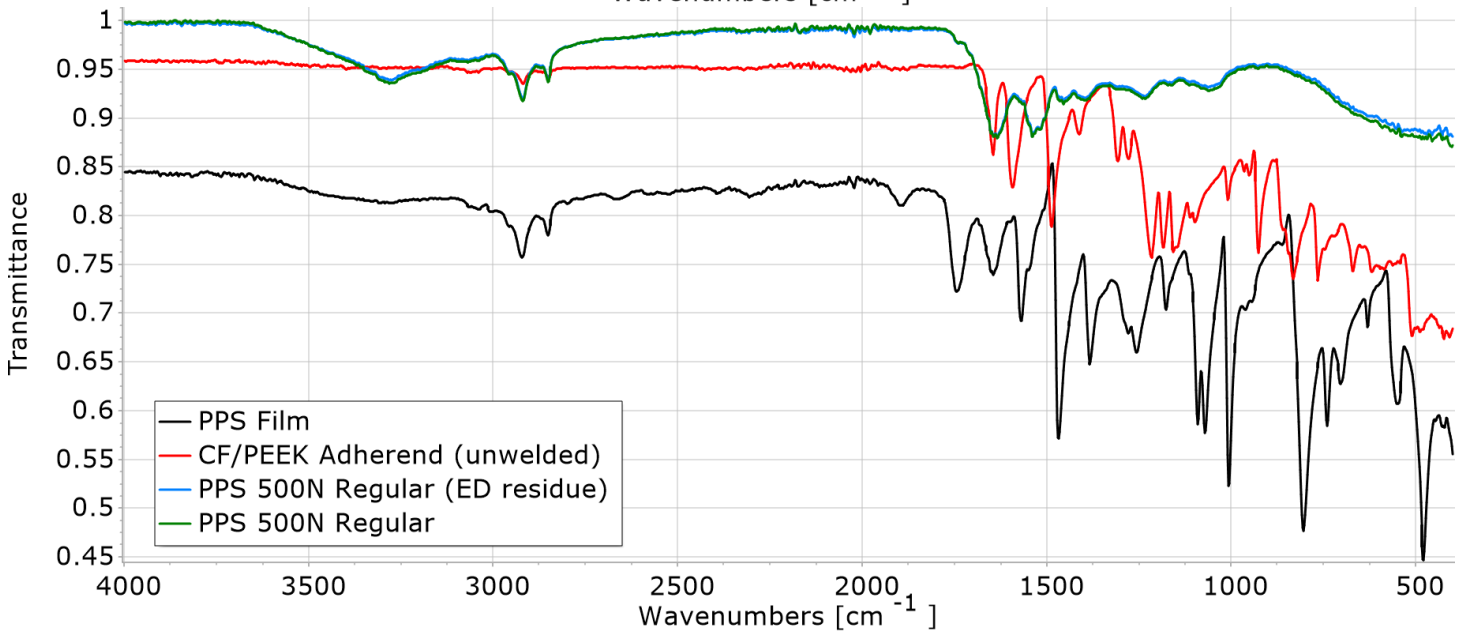
CF/PEEK-LMPAEK

ATR FTIR

CF/PEEK-PEI

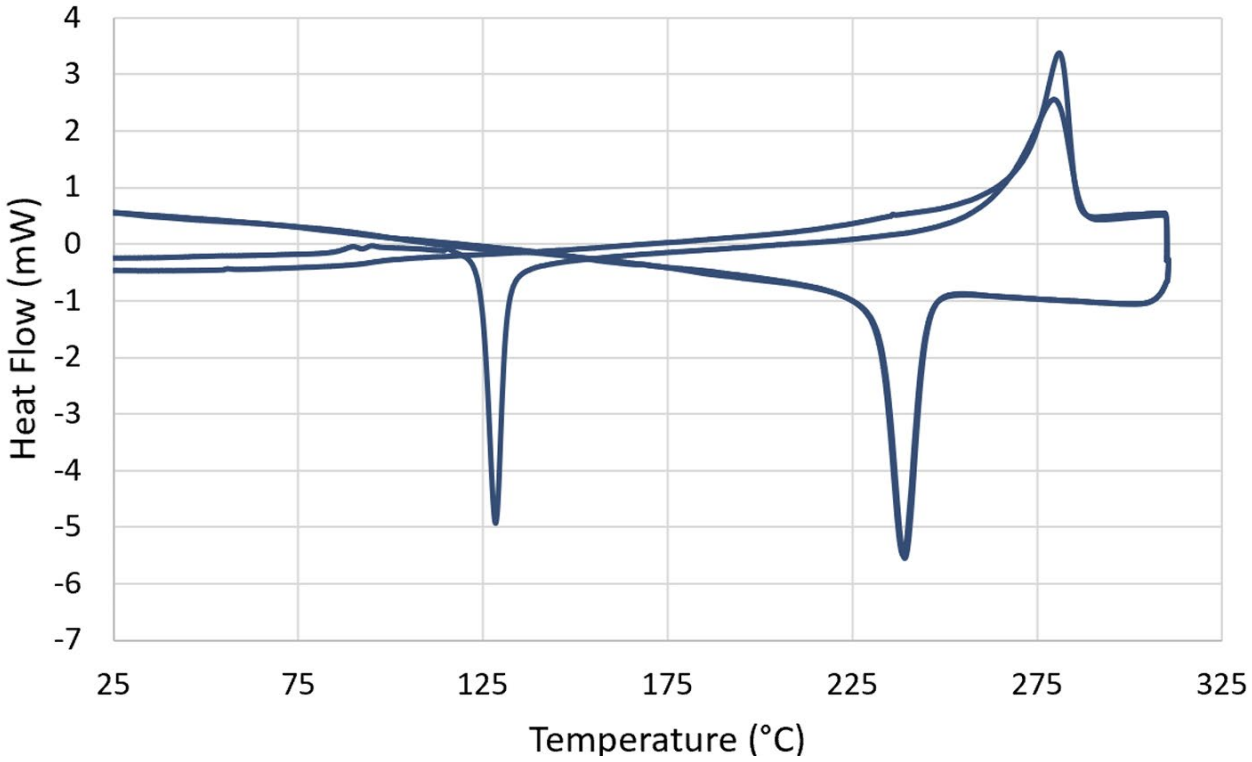


CF/PEEK-PPS

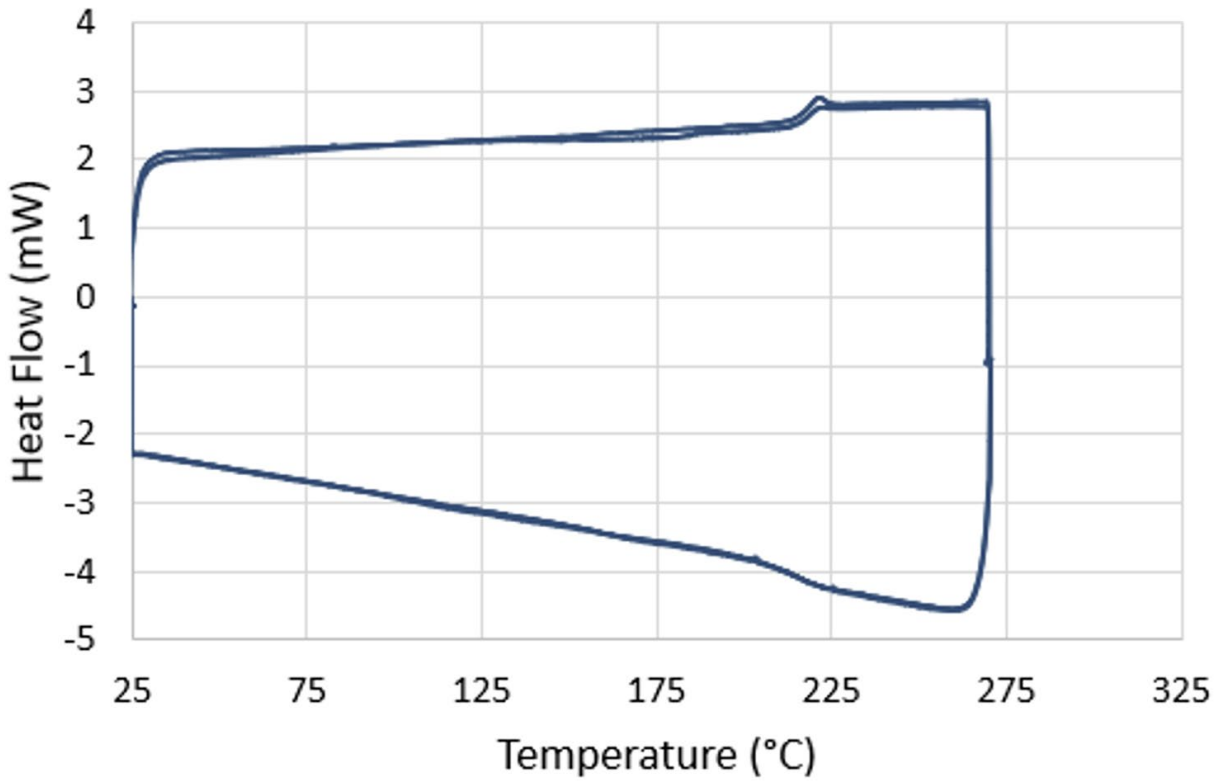


DSC

PPS

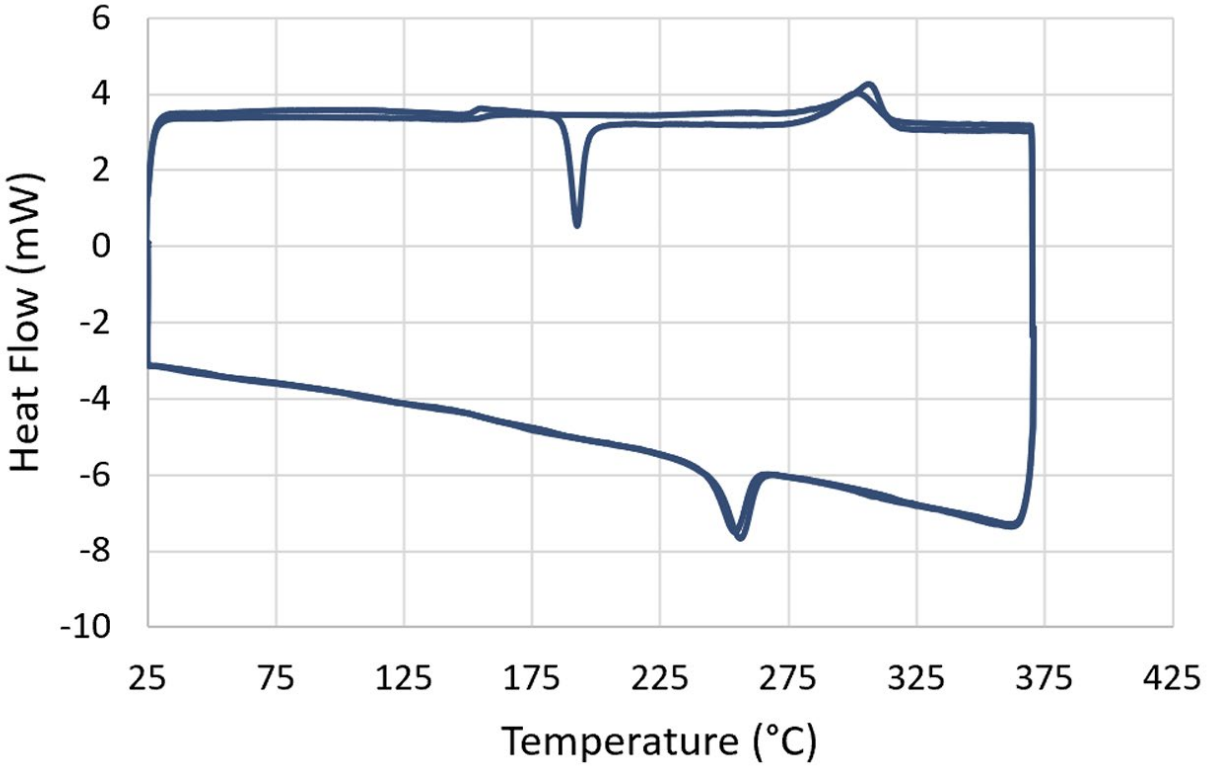

4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
Heat Flow (mW)
25
75
125
175
225
275
325
Temperature (°C)

PEI

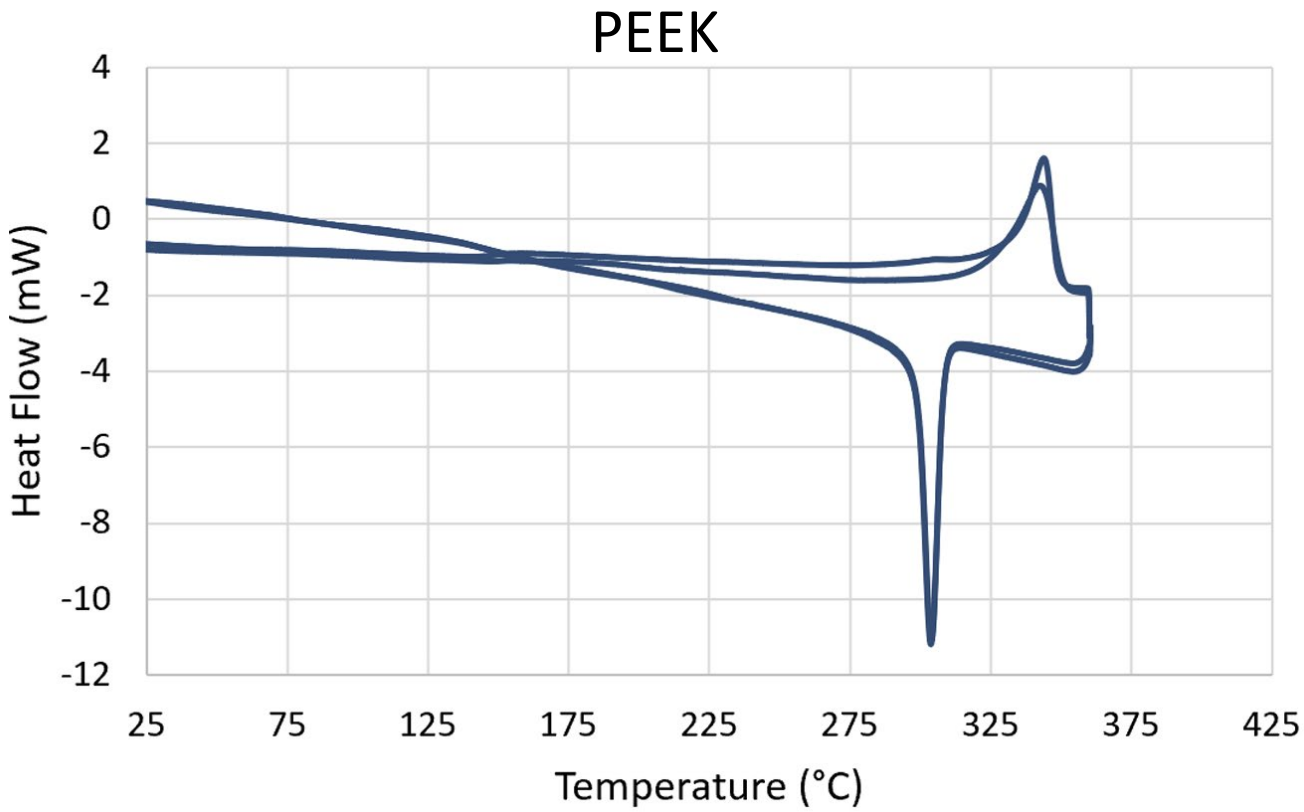

4
3
2
1
0
-1
-2
-3
-4
-5
Heat Flow (mW)
25
75
125
175
225
275
325
Temperature (°C)

DSC

LM-PAEK

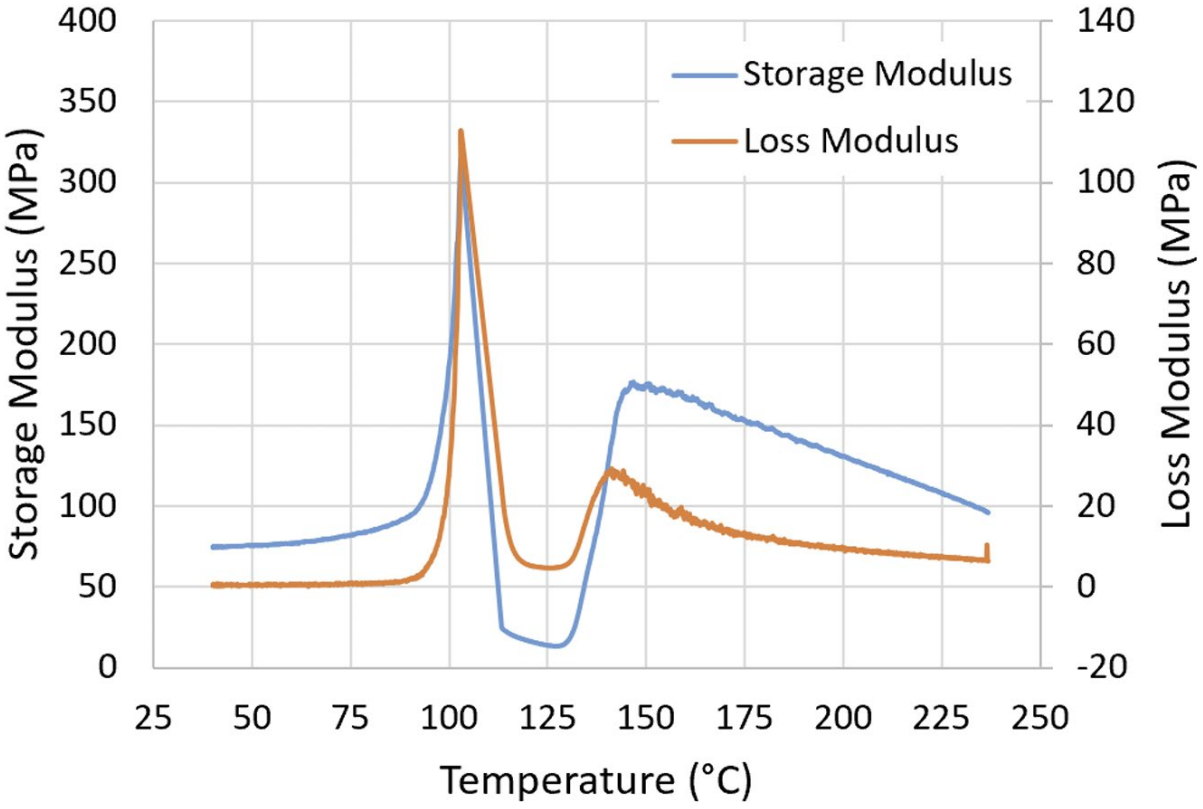


PEEK

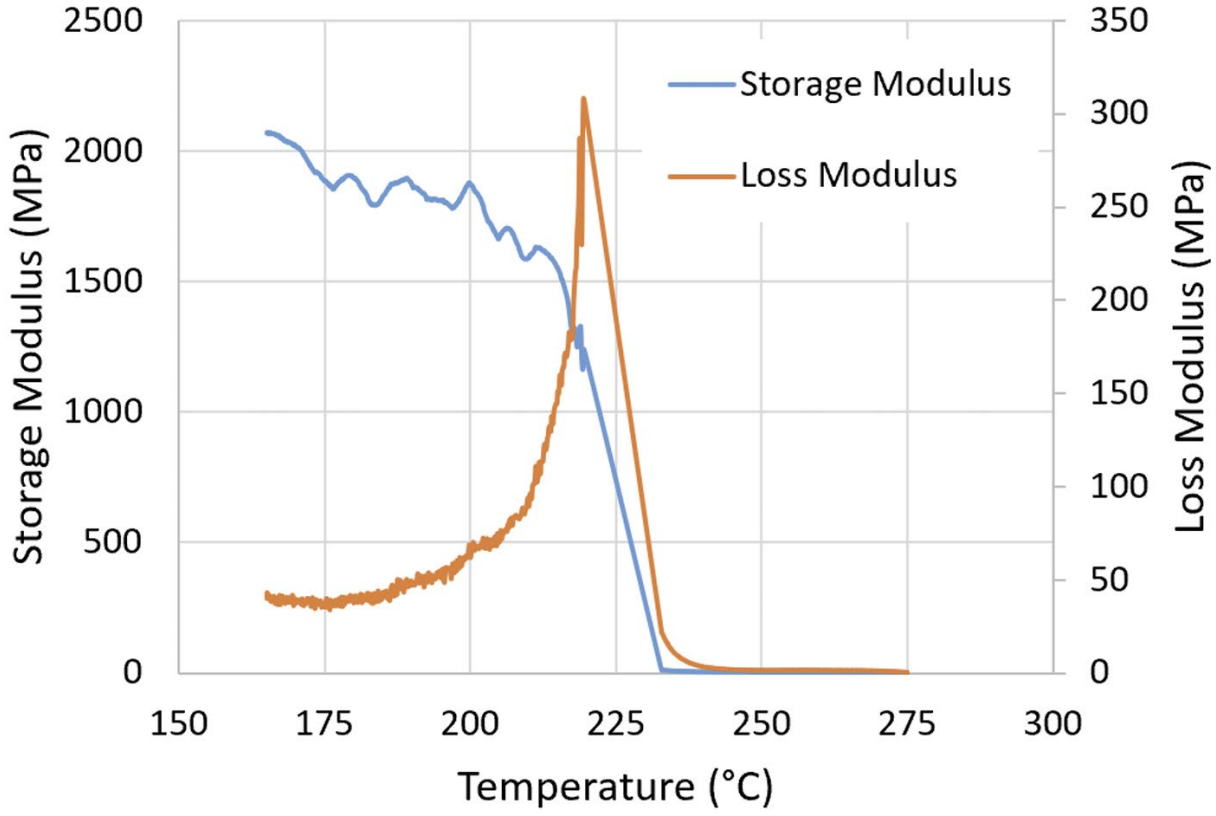


DMA

PPS

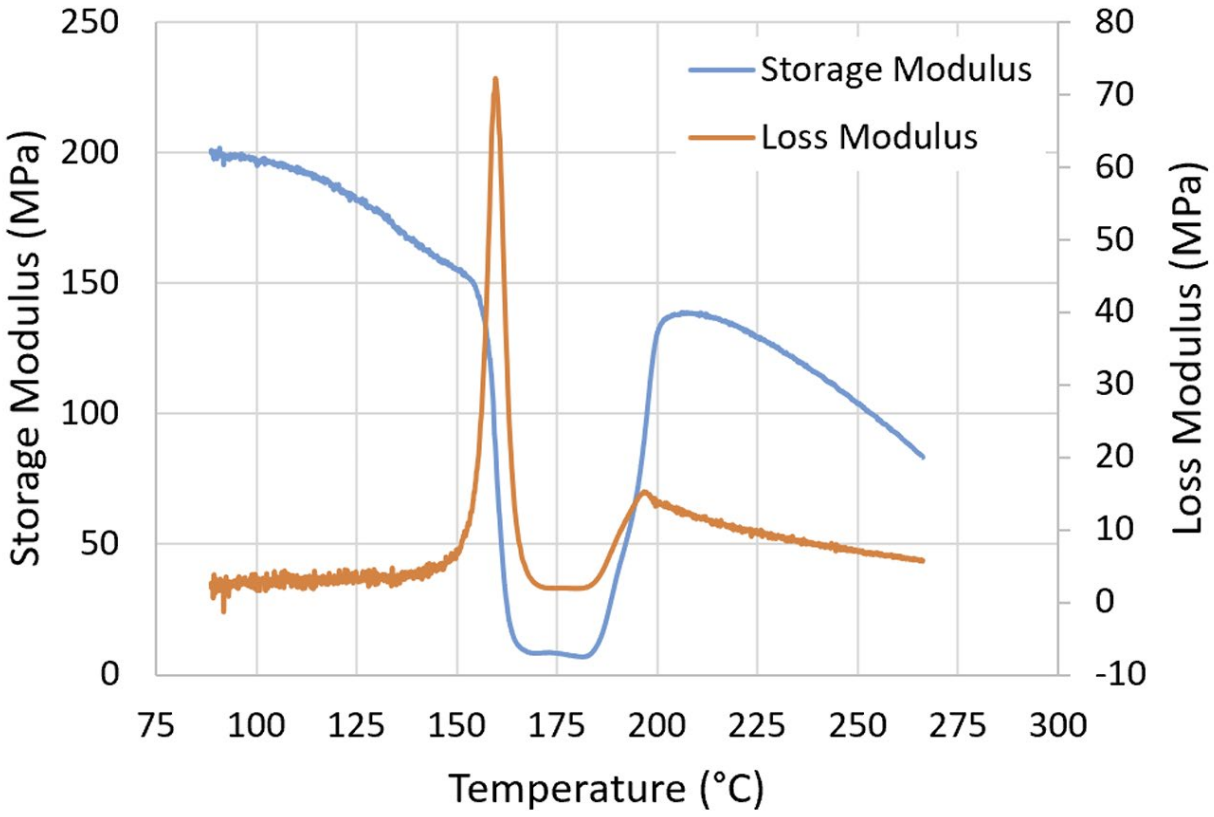

Storage Modulus
Loss Modulus
Storage Modulus (MPa)
Loss Modulus (MPa)
Temperature (°C)
400
350
300
250
200
150
100
50
0
140
120
100
80
60
40
20
0
-20
25
50
75
100
125
150
175
200
225
250

PEI

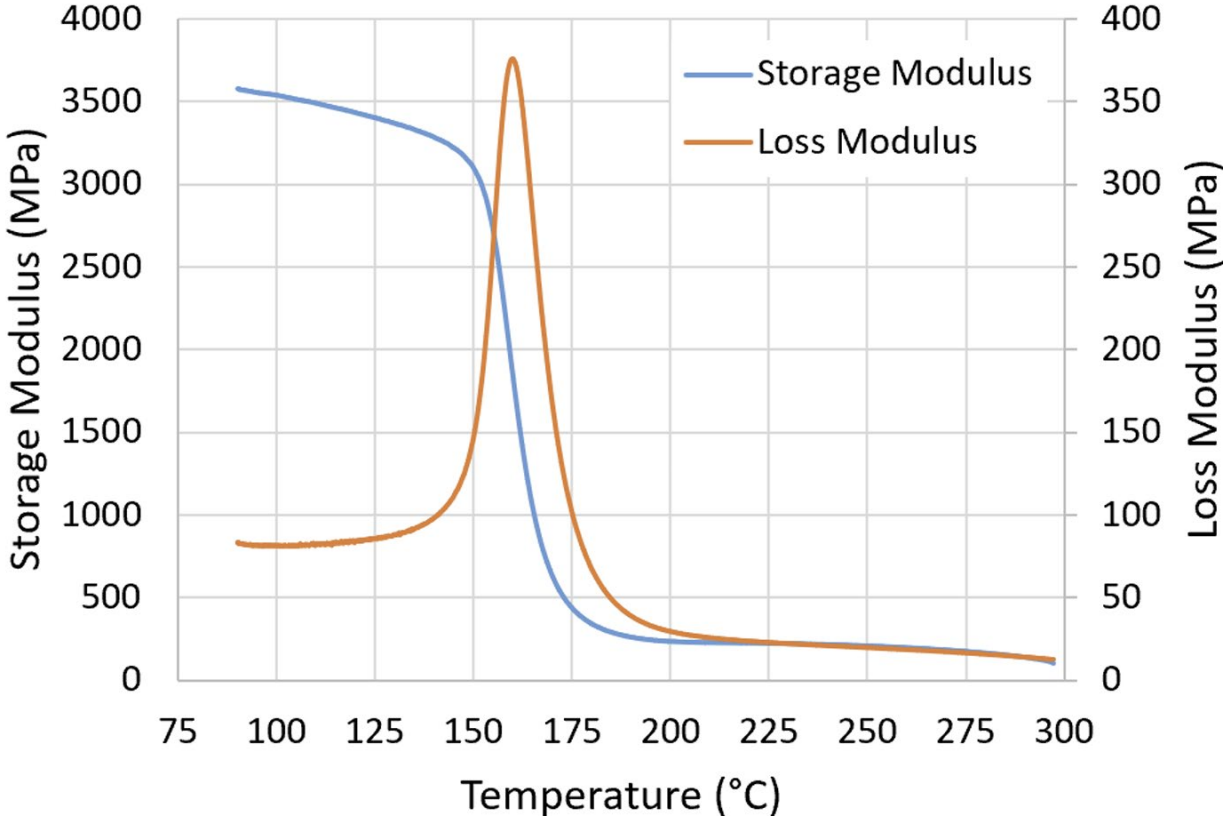

Storage Modulus
Loss Modulus
Storage Modulus (MPa)
Loss Modulus (MPa)
Temperature (°C)
2500
2000
1500
1000
500
0
350
300
250
200
150
100
50
0
150
175
200
225
250
275
300

DMA

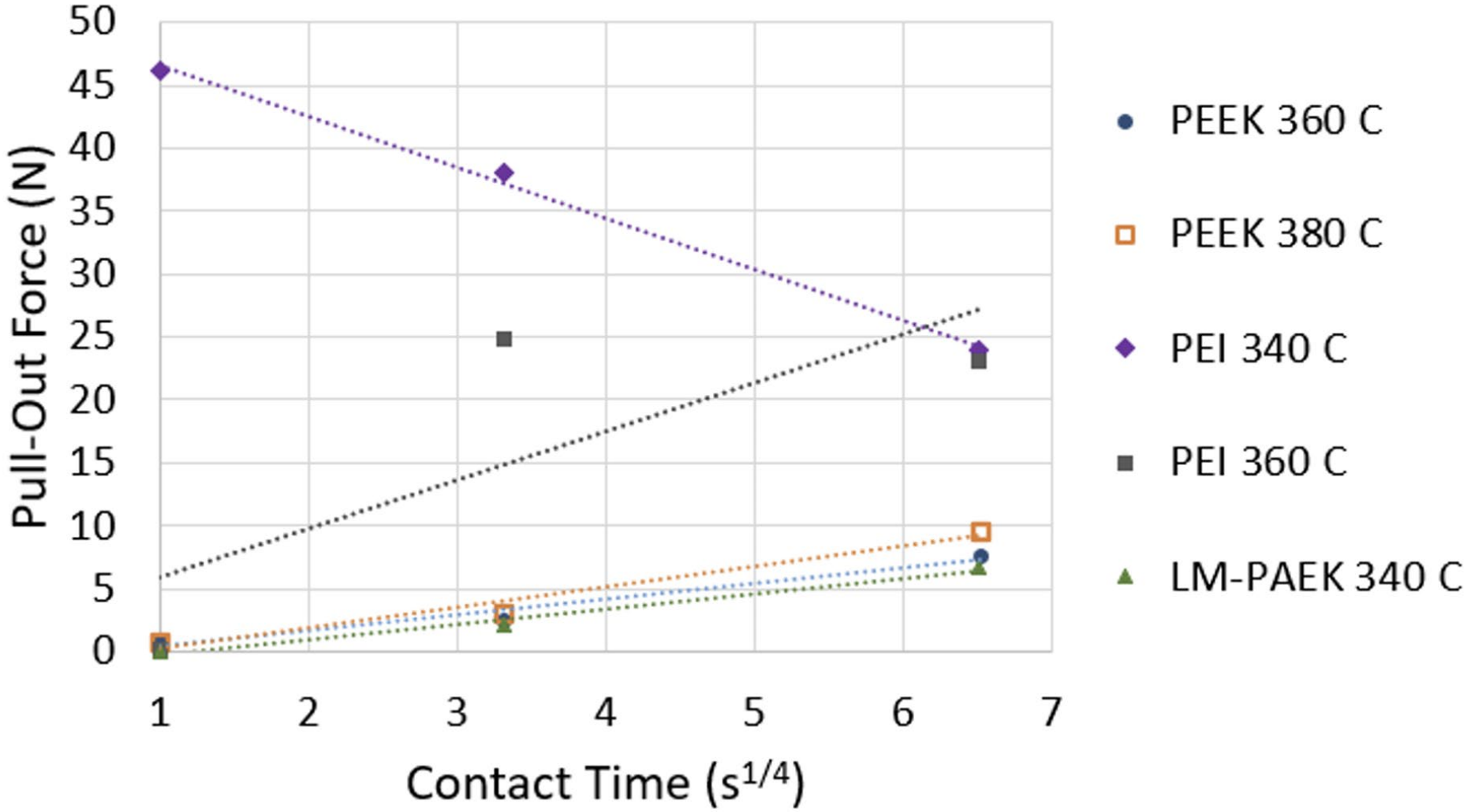
LM-PAEK



PEEK

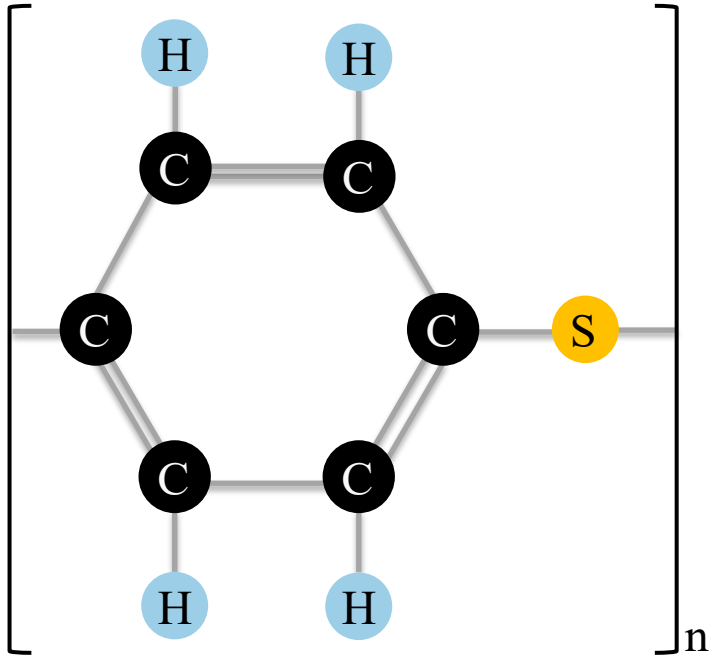


Degree of Healing Force Curves



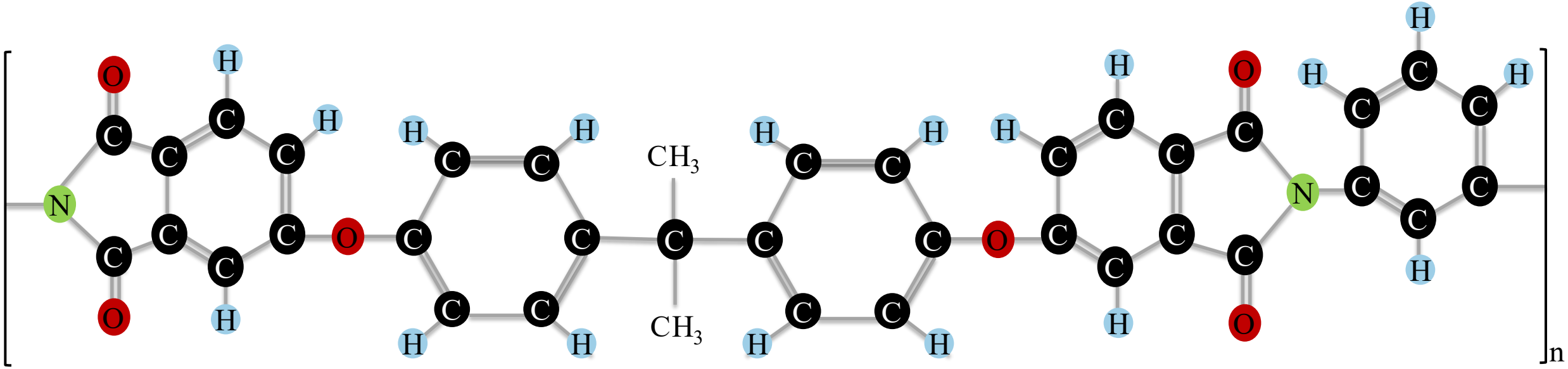
PPS

- Chemical formula: $[C_6H_4S]_n$
- Structure: semi-crystalline
- T_m = ~280℃
- T_g = ~90 ℃
- T_p = 300~330 ℃
- Tensile strength = ~90 MPa
- Higher cost plastic
- Potentially compatible with PEEK



PEI

- Chemical formula: $[C_{37}H_{24}O_6N_2]_n$
- Structure: amorphous
- T_g = ~217 ℃
- T_p = 320~350 ℃
- Tensile strength = ~100 MPa
- Higher cost plastic
- Good compatibility with PEEK

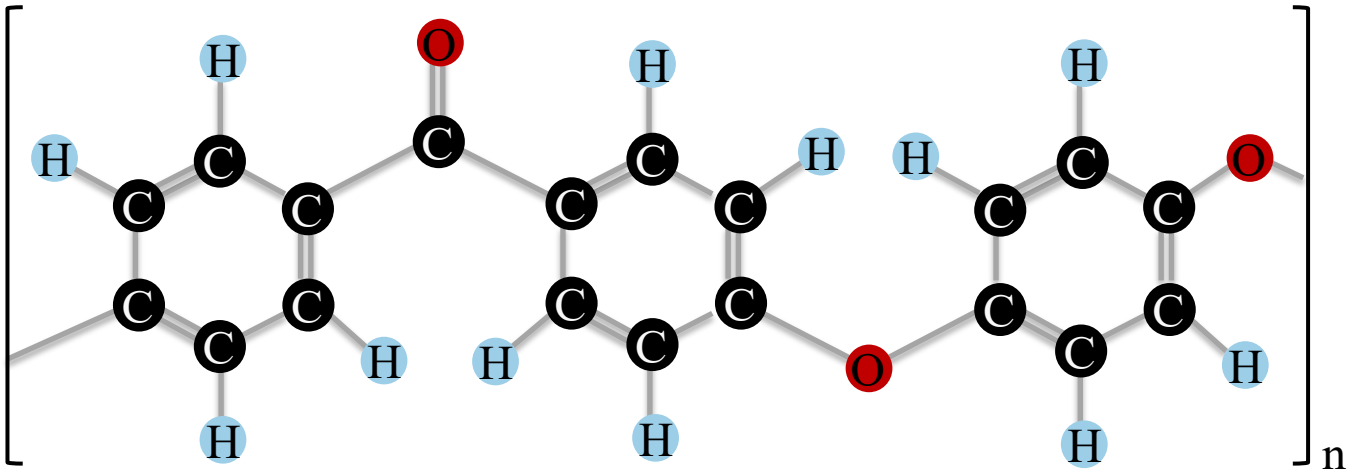


LM-PAEK

- Chemical formula: proprietary
- Structure: semi-crystalline
- T_m = ~303℃
- T_g = ~156 ℃
- T_p = 340~380℃
- Tensile strength = ~91 MPa
- Higher cost plastic
- Compatible with PEEK

PEEK

- Chemical formula: $[C_{19}H_{14}O_3]_n$
- Structure: semi-crystalline
- T_m = ~343℃
- T_g = ~143 ℃
- T_p = 370~400℃
- Tensile strength = ~100 MPa
- Higher cost plastic
- Perfect compatibility with PEEK



CF/PEEK

- Tensile strength: ~800 MPa
- Typical LSS values of fusion bonded joints:
  - Induction Welding: 20-30 MPa
  - Resistance Welding: 35-45 MPa
  - Ultrasonic Welding: 30-50 MPa

Miller et al. NASA STI, 2023.
Choi et al. Materials, 16(11), 2023.
Li et al. Journal of Matl Research and Tech 12, 2025.
Bonmatin et al. Compos Part A Appl Sci Manuf, 162, 2022.