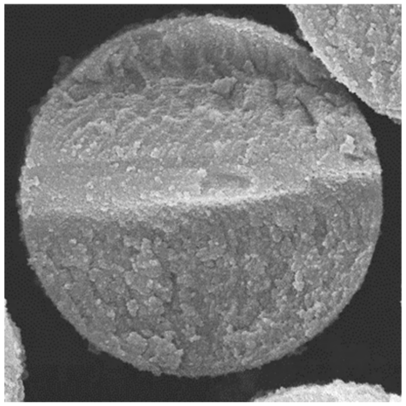
Char removal strategy for fire-forensic analysis of mechanically-failed aerospace carbon/epoxy composites



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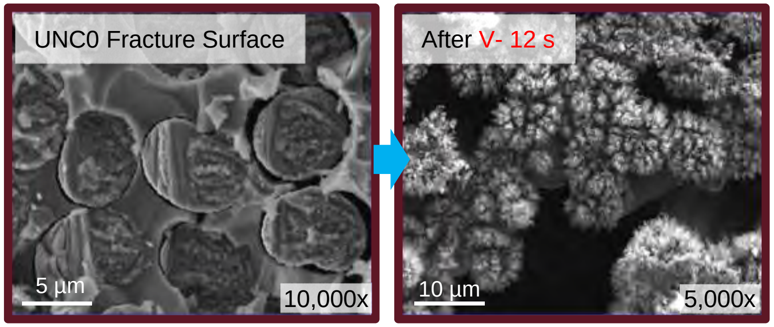
JAMS Project Title:
Post-Crash Fire Forensic Analysis on Aerospace Composites

JAMS Technical Review
April 19, 2023

Background

Motivation

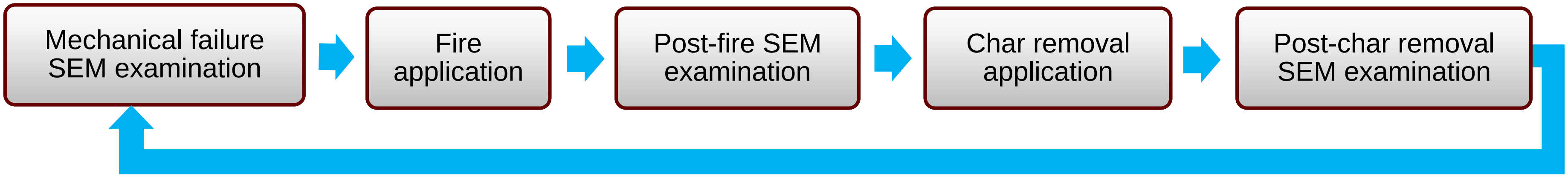
- In-flight aircraft fires may result in severe degradations in composite material performance and in overall flight safety
- Non-fire related aircraft crashes can result in major post-crash fires on the ground
- Char formation due to post-crash fires can mask relevant aspects of the structural damage morphology necessary to identify the underlying failure mechanisms



Objective and Scope

1. Develop method(s) for removing char from fire-damaged surfaces of carbon fiber reinforced epoxy composites
2. Assess the viability of these methods for determining root cause of composite mechanical failure after post-crash fire damage

Approach



Mechanical failure SEM examination → Fire application → Post-fire SEM examination → Char removal application → Post-char removal SEM examination

Char Removal Experiments: Nitric Acid Oxidation

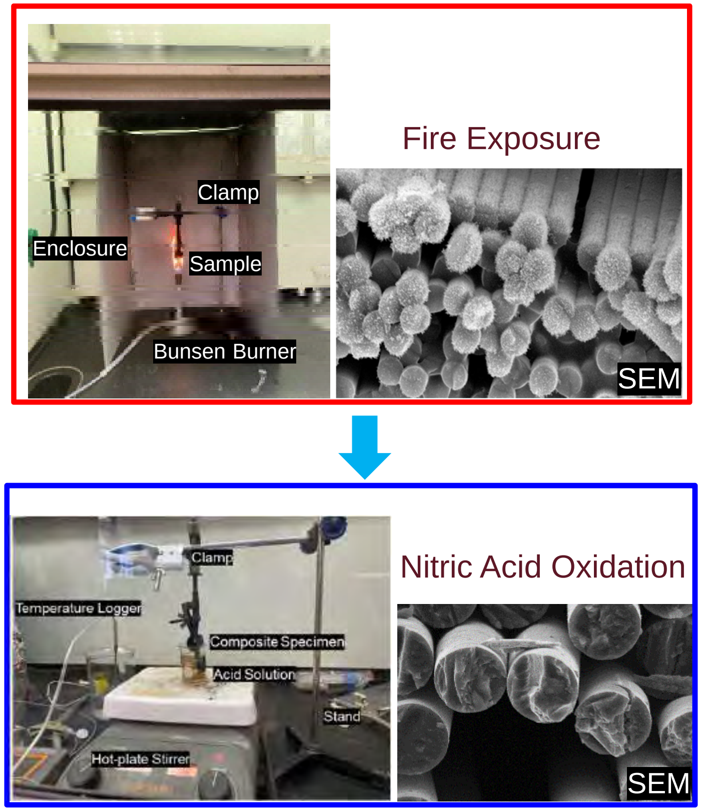
Acid Oxidation**:** Liquid-phase thermo-oxidative char removal experiments were performed on mechanically failed composites ranging from coupon-scale (NCAMP: UNC0, SBS) to structural-scale (open-hole) samples burned in small-scale bunsen burner fires and pool fires

- Solution type**:** Sulfuric/nitric solution
- Composition:
  - Sulfuric acid: [82 – 93] wt.%,
  - Nitric acid: [0.9 – 9.32] wt.%
  - Water: [5.32 – 8.33] wt.%
- Volume: 30 – 75 ml
- Immersion Time: 45 s – 10 min
- Temperature: 90 – 175 °C
- Stirrer: 60 rpm

Experimental Objectives

Select suitable temperature/time/acid compositions to:

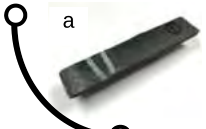
- Oxidize char while preserving fracture surface morphologies
- Maintain solution acidity to improve char oxidation rates
- Minimize immersion times to maintain structural integrity of the samples



Project Experimental Overview

I. Coupon-Level Preliminary Experiments

- Obtain optimal temperature/concentration/time window for char removal
- Evaluate the effect of acid oxidation on fiber cross-sections



- Experiments based on optimal temperature/concentration
- Verify that carbon fiber cross-sections are not adversely affected

II. Pool Fire Experiments

- Use optimal process variables to verify if char removal technique can be applied on failed samples exposed to simulated crash fire conditions (pool-fires)

III. Long Duration Fires

- Demonstrate scalability and effectiveness of nitric acid oxidation by applying the method on failed structural-scale specimens subjected to longer duration fires

Specimen	# of Plies	Layup	Size Scale
Cytec Unnotched Compression[a] (UNC0) (NCAMP from NIAR)	21	$[90/0/90]_7$	Coupon
Cytec Short Beam Strength[b] (SBS) (NCAMP from NIAR)	45	$[0]_{45}$	Coupon
Hexcel UNC0[c]/ Flexure[d]	32	$[0/90]_{8s}$	Coupon
Hexcel Open-Hole[e]	81	$[\pm45/0_2/90/0_2/\mp45]_9$	Part

Specimen Material Systems:

1. Cytec™ T40-800 Cycom® 5215 graphite/epoxy
2. HexForce™ SGP370-8H/HexPly® 8552 carbon/epoxy

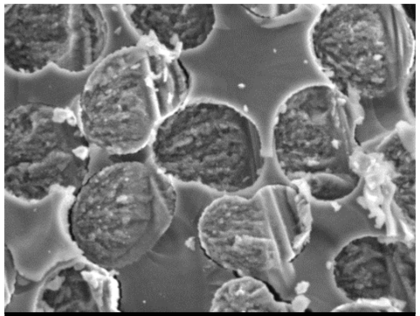
Fractography of Fire-Damaged UNC0 Specimens

Pre-Fire Fractography

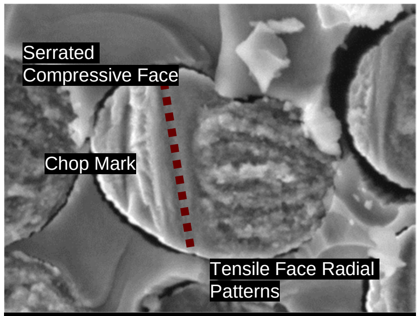
UNC0

[90/0/90]$_7$

- Unburned Cytec Graphite/epoxy [90/0/90]$_7$ sample failed in Compression during Unnotched Compression (UNC0) test



2 µm 10,000x *Microbuckling (Compressive Fracture)*

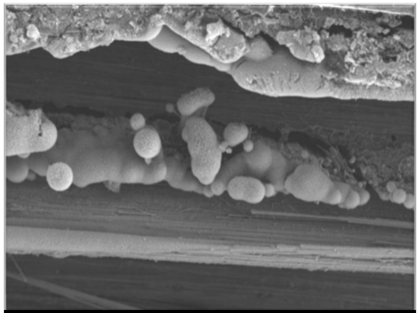


2 µm 20,000x *Microbuckled Fiber Cross-section*

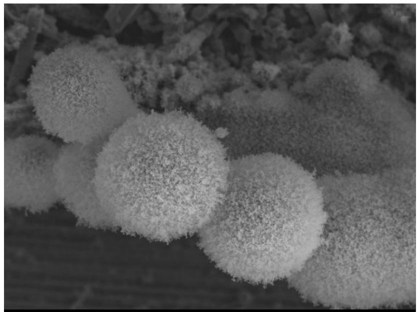
Post-Fire Fractography

UNC0

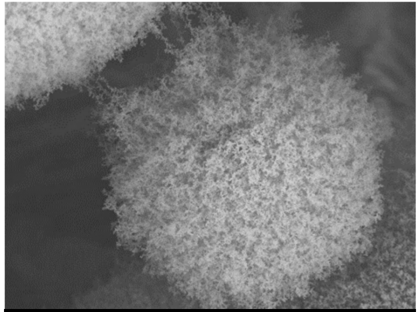
After V-36 s



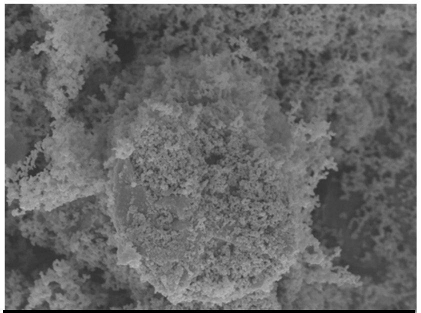
200 µm 70x *Extensive Char Formation (V-36 s)*



10 µm 750x *Fuzzy Char Deposits on Fiber ends*



5 µm 2,000x *Magnified View of Char (Porous)*

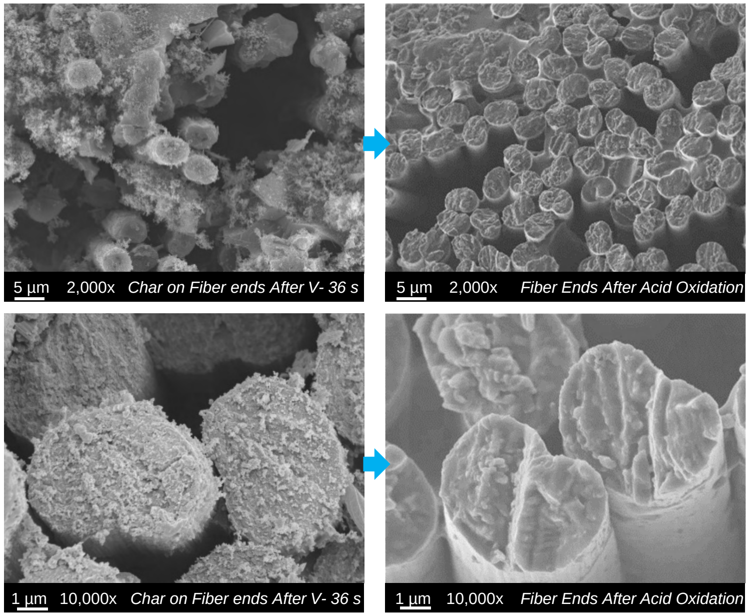


1 µm 15,000x *Char Deposits Covering Fiber Ends*

Temp/Time/Conc Studies on UNC0 Samples

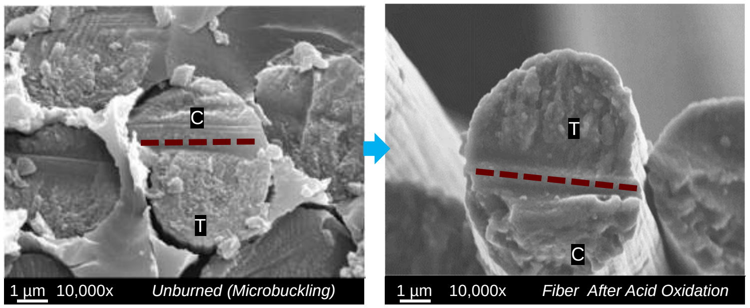
At low temp (100 °C), char oxidation was incomplete and fracture morphologies were still obscured

Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CQDRA213A(5)	0.5	29.5	5.32	1	100



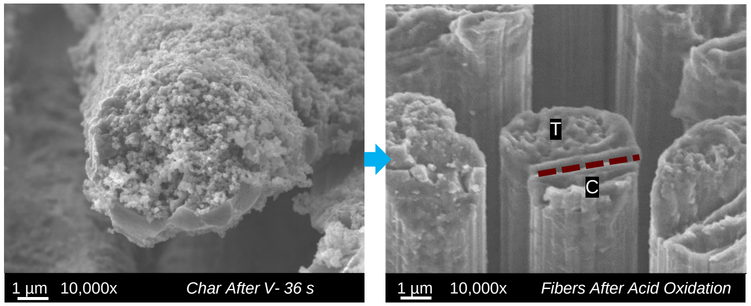
Unburned Specimen

Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CPARA214A(2)	1.75	28.25	6.14	5	125



Fire-damaged Specimen

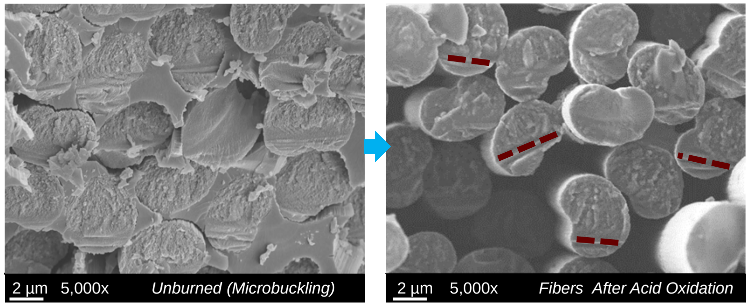
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CPDRA214A(1)	1.75	28.25	6.14	5	125



Temp/Time/Conc Studies on UNC0 Samples

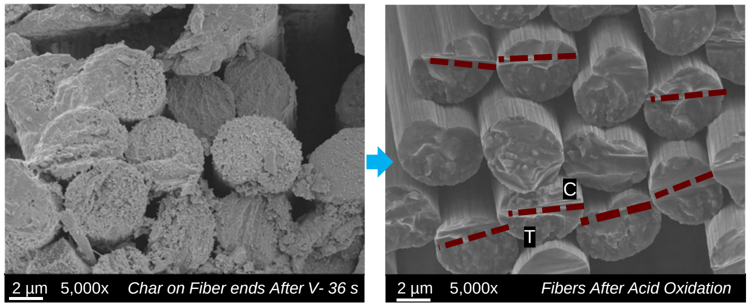
Unburned Specimen

Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CPARA214A(1)	2.5	28	6.6	1.5	125



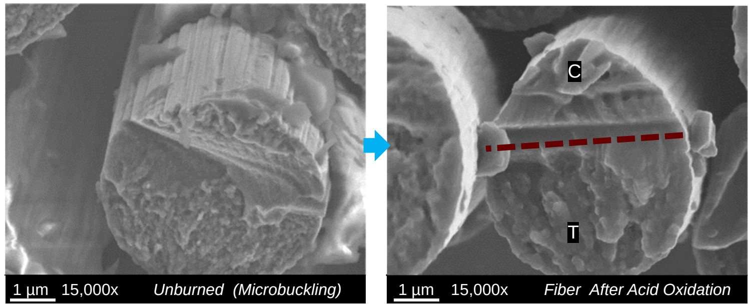
Fire-damaged Specimen

Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CODRB213A(3)	2.5	28	6.6	1.5	125



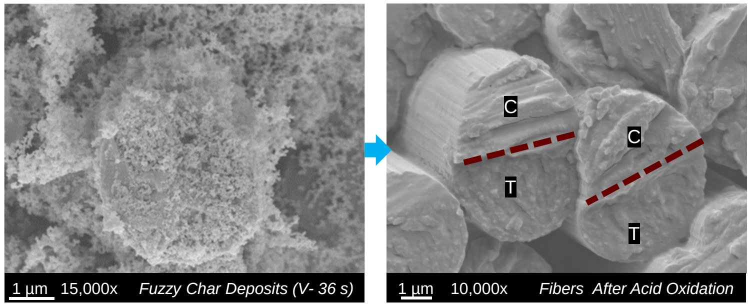
Unburned Specimen

Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CQDRA214A(1)	3	27	7	2	125



Fire-damaged Specimen

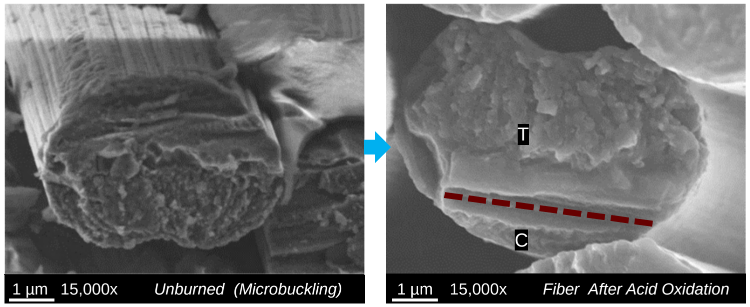
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CODRA212A(3)	3	27	7	2	125



Temp/Time/Conc Studies on UNC0 Samples

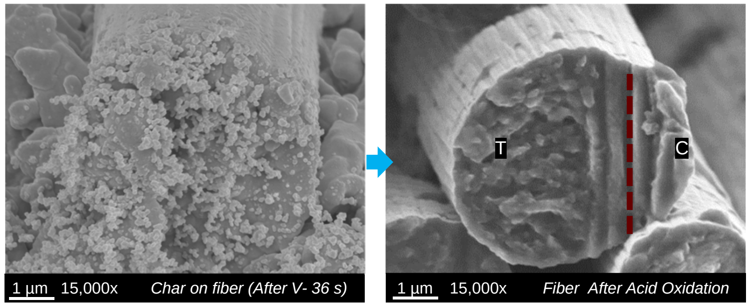
Unburned Specimen

Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CYDRA111A(1)	4.5	26	7.93	2.5	135

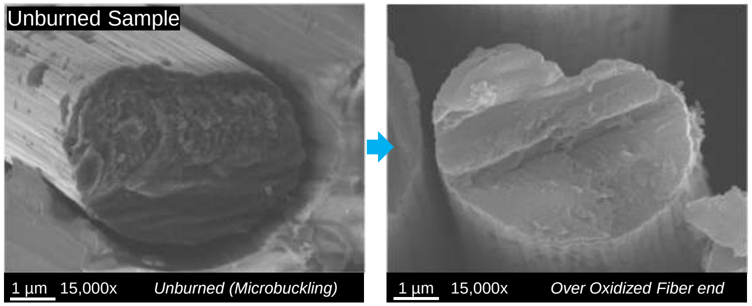


Fire-damaged Specimen

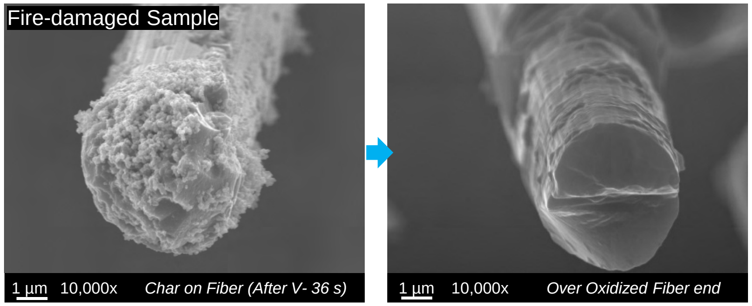
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CODRA212A(4)	4.5	26	7.93	2.5	135



Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CGDRA213A	5	**25**	8.33	**10**	175



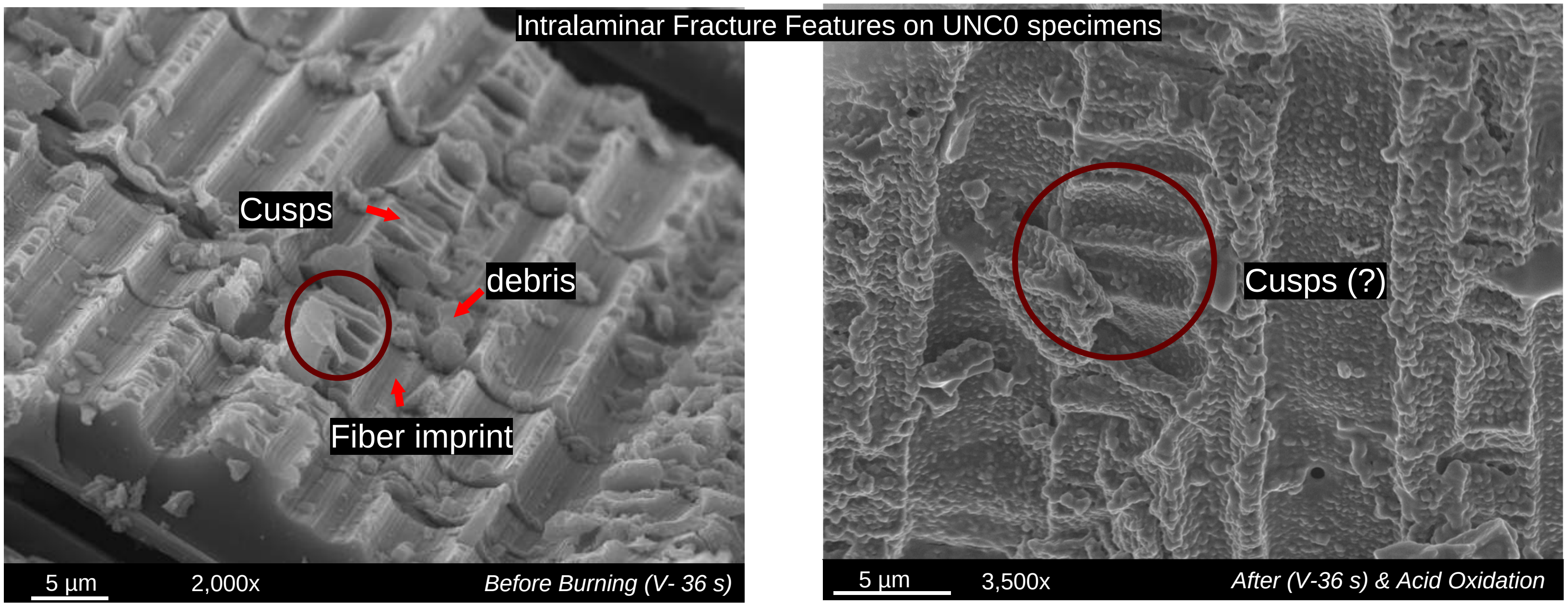
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CODRA211A(1)	5	**25**	8.33	**10**	175



Over Oxidation of fiber cross-sections

Effect of Fire-damage & Acid Oxidation on Matrix Fracture Features

- Remnants of Interlaminar fracture features (examples: fiber imprints and cusps) were partially retained in a fire damaged **UNC0** sample after acid oxidation in ONE test case



Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
CQDRA213A(5)	0.5	29.5	5.32	1	100

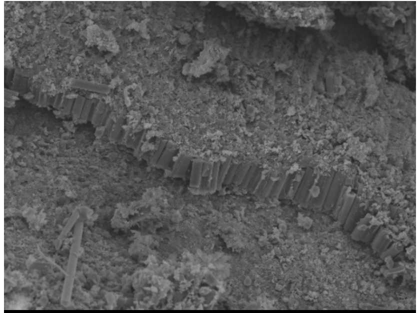
Fractography of Fire-Damaged SBS Specimens

SBS

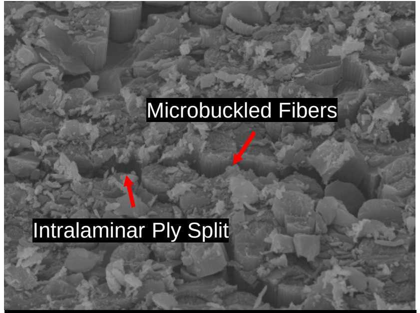
Pre-Fire Fractography

- Unburned Cytec Graphite/epoxy $[0]_{45}$ Sample failed in flexure during Short Beam Strength (SBS) test

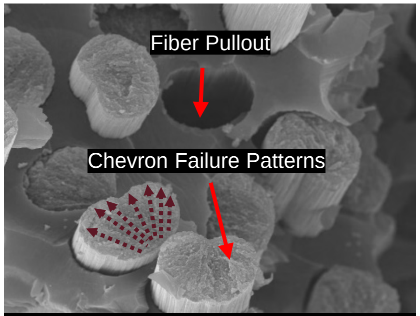
$[0]_{45}$



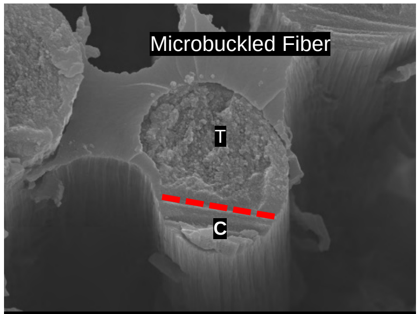
20 µm 500x *Microbuckling Terraces (Comp)*



5 µm 2500x *Ply Splitting from Translaminar Failure*



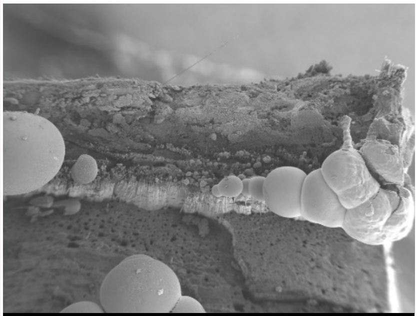
2 µm 5,000x *Tensile Fracture Surface morphology*



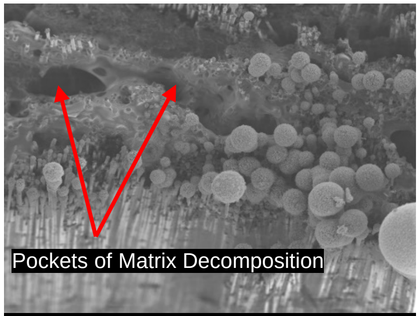
1 µm 10,000x *Compressive Fracture morphology*

Post-Fire Fractography

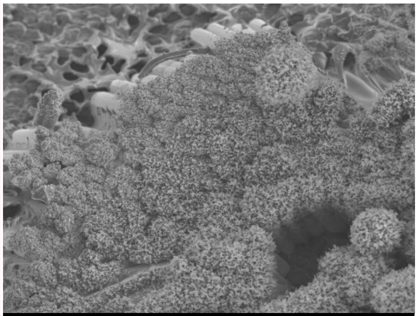
After V- 60 s



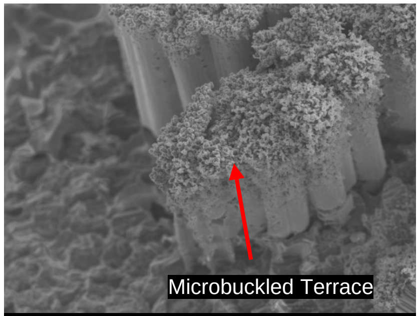
500 µm 25x *Tensile Fibers with Porous Char*



50 µm 150x *Magnified View of Char (Porous)*



10 µm 1,000x *Fuzzy Char on Fiber Cross-Sections*

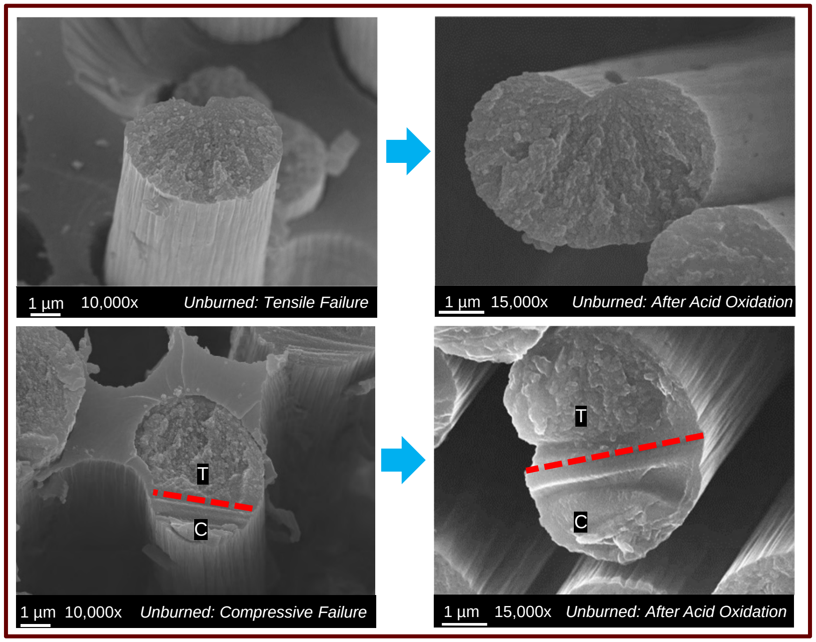


5 µm 2,000x *Magnified View of Char on Fibers*

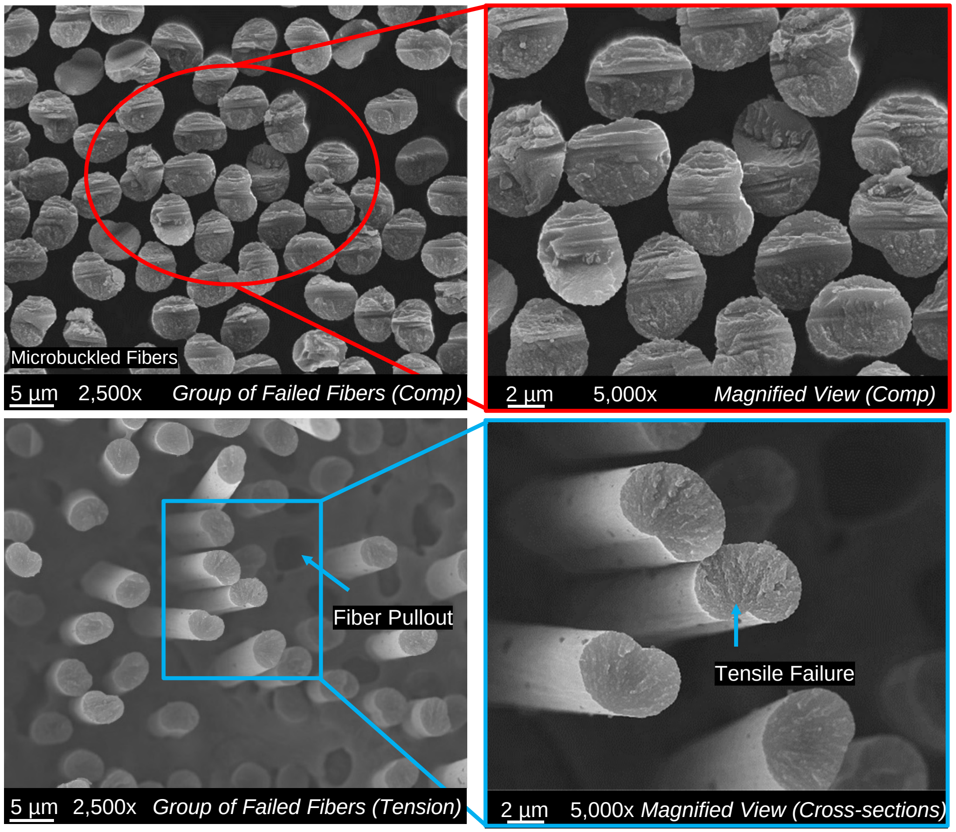
Nitric Acid Oxidation of Unburned SBS Specimens

Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
1	1.75	28.25	6.13	3	135

- Comparison of Fiber Cross-sections Before and After Acid Oxidation



Typical fracture morphologies observed after acid oxidation

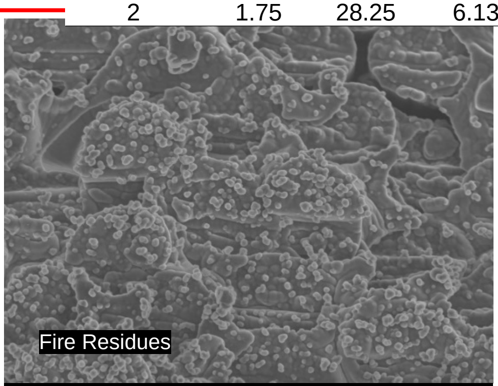


Nitric Acid Oxidation of Fire-Damaged SBS Specimens

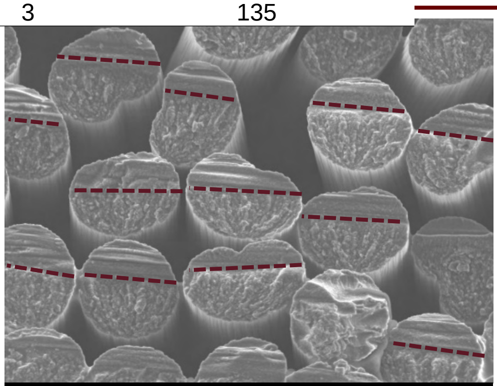
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
2	1.75	28.25	6.13	3	135

V- 60 s

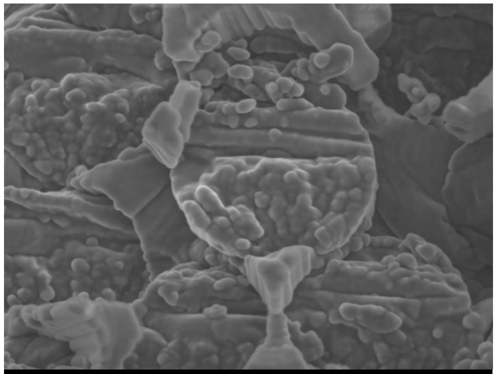
Cytec Graphite/epoxy (SBS)



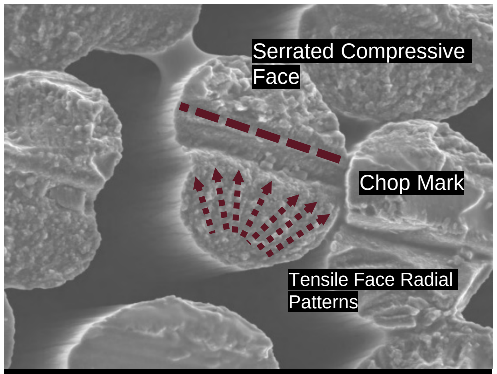
2 µm 5,000x *Microbuckled Fibers After V- 60 s*



2 µm 5,000x *After Acid Oxidation*



1 µm 10,000x *Magnified View Of a Single Fiber*

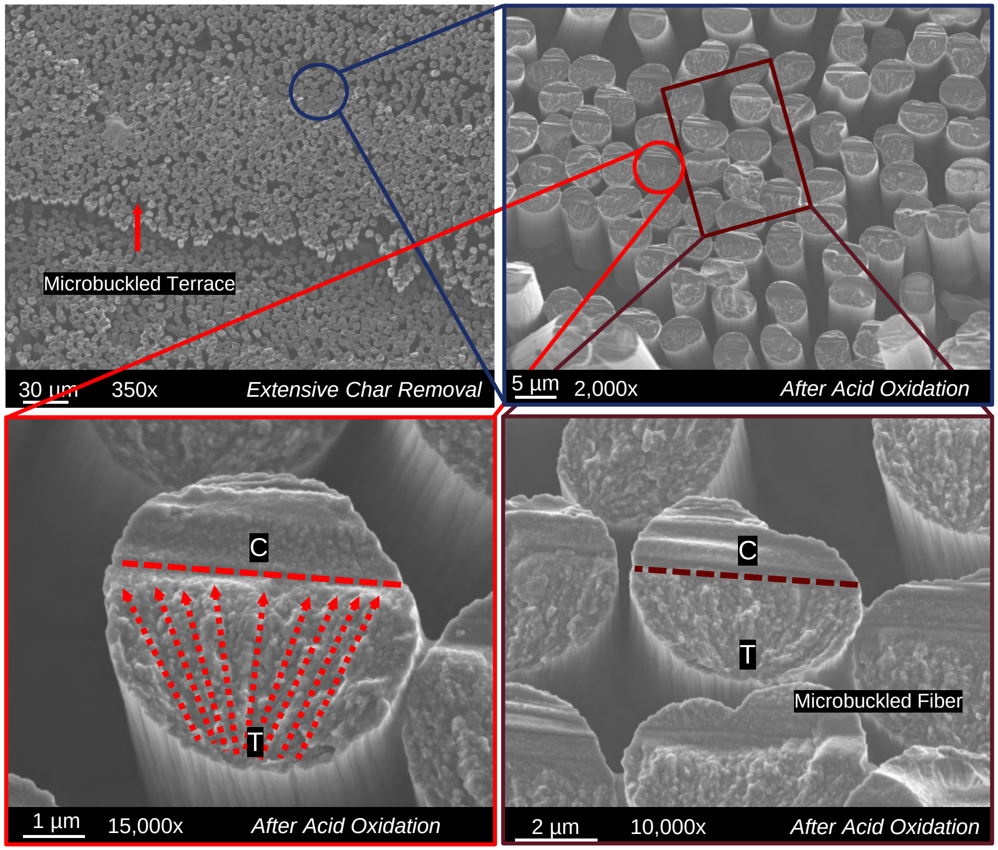


1 µm 10,000x *Cross-section After Acid Oxidation*

N = 3.18 wt.%

Fractography of Fire-Damaged SBS Samples

Cytec Graphite/epoxy SBS Specimens



Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
2	1.75	28.25	6.13	3	135

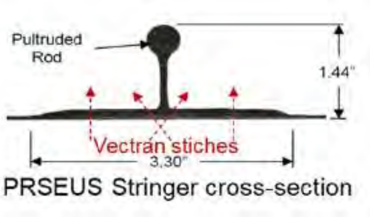
Typical Fracture Morphologies Observed After Nitric Acid Oxidation

Conclusions: Nitric Acid Oxidation Experiments (UNC0 & SBS)

- Char successfully removed from coupon-scale Cytec UNC0 and SBS specimens burned during small scale fire tests without degrading fracture surface morphologies
    - Remnants of matrix-related intralaminar fracture morphologies were retained in UNC0 samples after fire exposure and nitric acid oxidation
- UNC0 char removal experiments: suitable temperature/time/concentration window determined
    - Temperature: 125-135 °C
    - Nitric acid: ~ 3 – 8 wt.%
    - Water: ~ 6 – 8 wt.%
- SBS char removal experiments: temp/conc window for char oxidization
    - Temperature: 135 °C
    - Nitric Acid: 3.18 wt.%
    - *We will see these parameters used in the next set of experiments for open-hole (part-scale) samples burned for large exposure times (up to 10 min)*

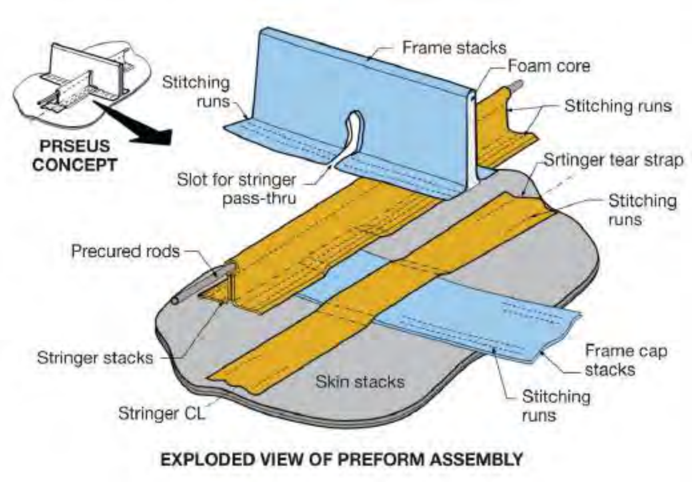
Structural Scale Samples

- Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) assemble dry polyester warp-knit AS4 carbon fabric skin stacks, stringers, and frames with through-thickness Vectran stitching prior to VRM-34 resin infusion and cure

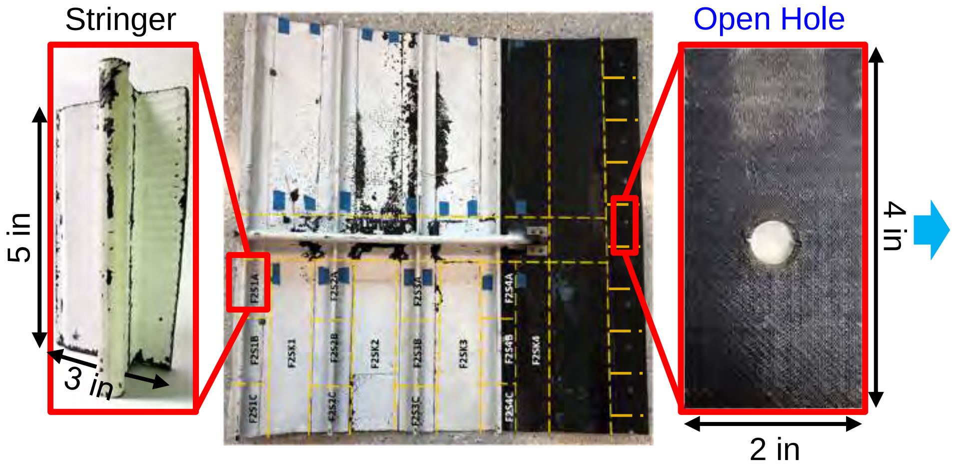


PRSEUS Stringer cross-section

PRSEUS components (Material)	Layup	Thickness (in)
Skin stacks (AS4/VRM-34)	$[\pm45/0_2/90/0_2/\mp45]_2$	0.104
Tear strap (AS4/VRM-34)	$[\pm45/0_2/90/0_2/\mp45]$	0.052
Stringer wrap (AS4/VRM-34)	$[\pm45/0_2/90/0_2/\mp45]$	0.052
Open hole	$[\pm45/0_2/90/0_2/\mp45]_9$	0.47

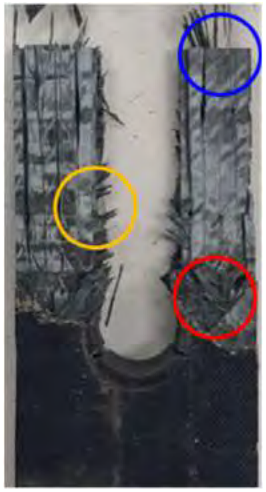


EXPLODED VIEW OF PREFORM ASSEMBLY

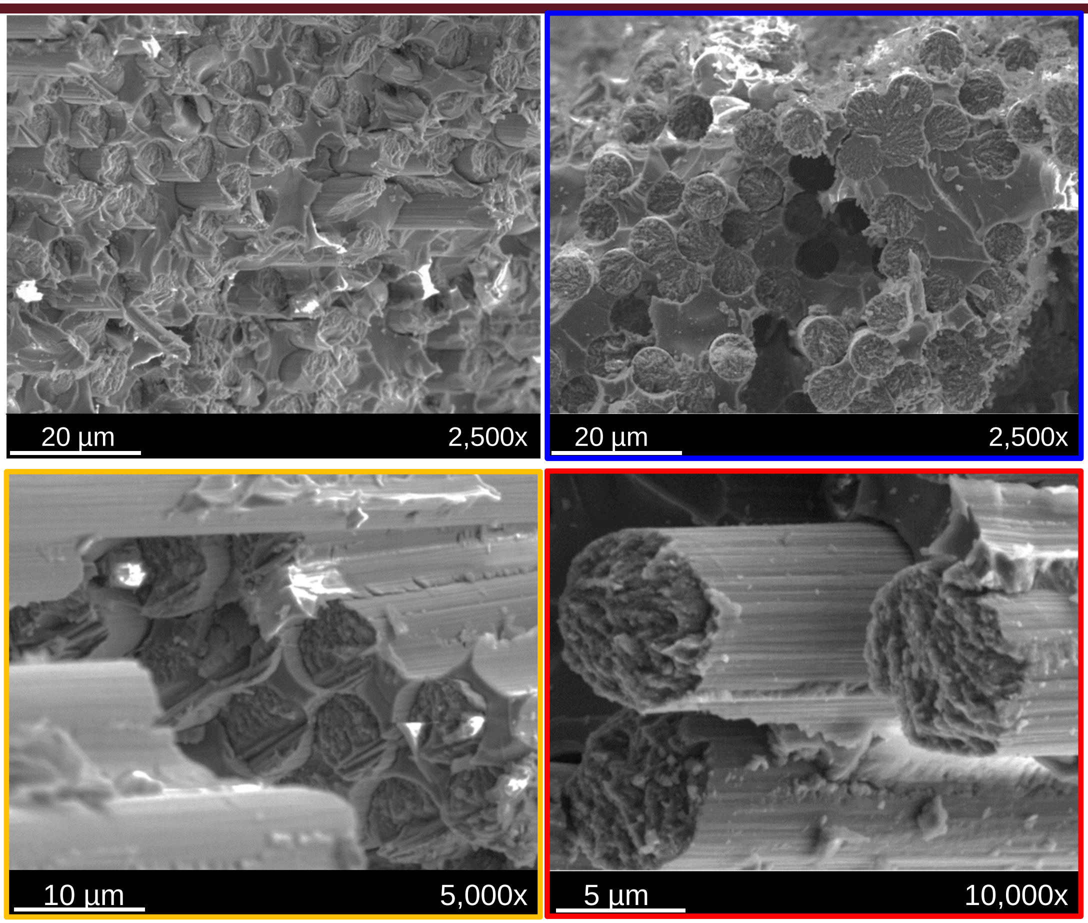


- Pin load tensile testing

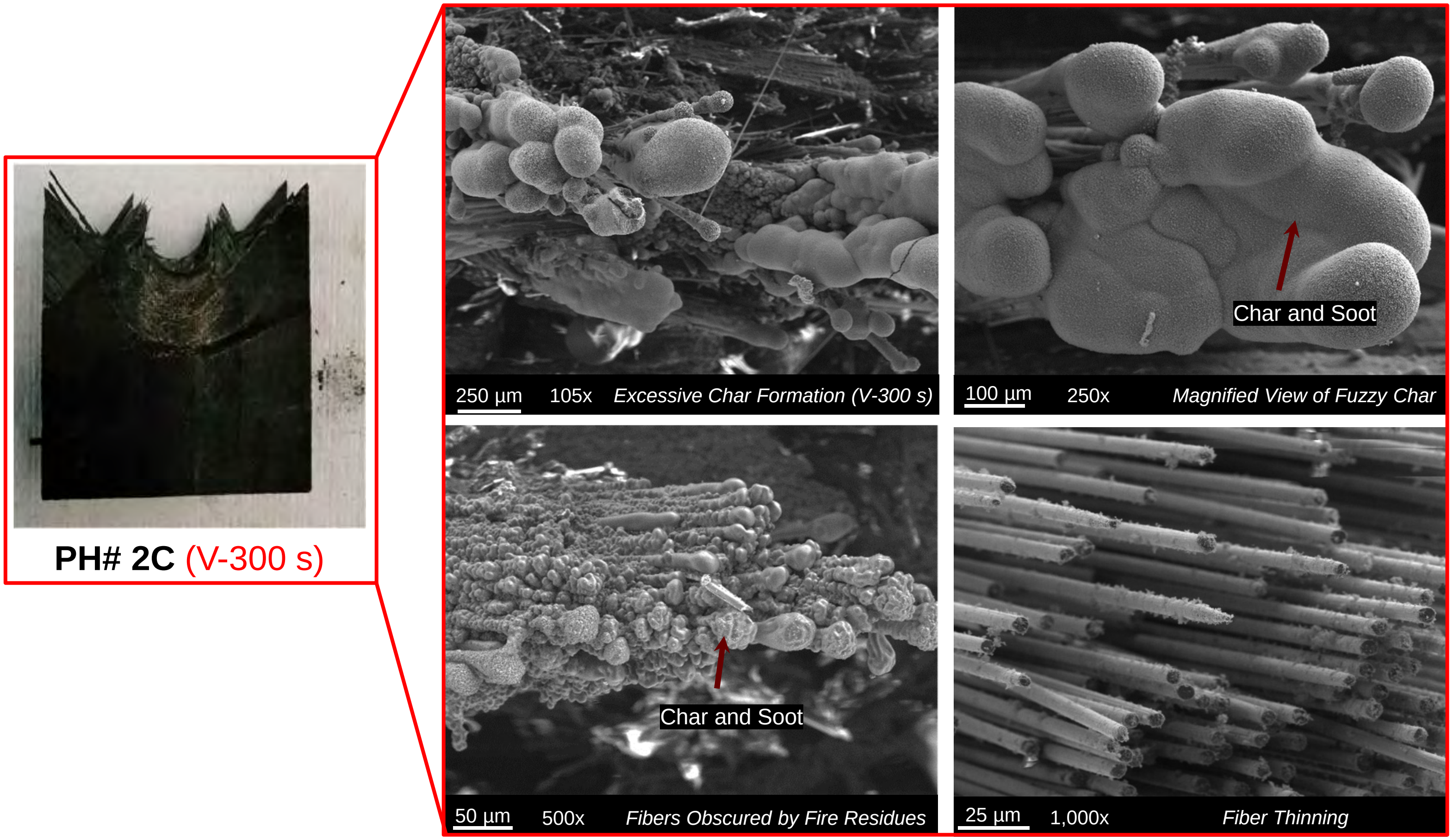
Pre-Fire Fractography of Open-Hole Specimens



Hexcel Carbon/epoxy Open-hole Sample $[\pm 45/0_2/90/0_2/\mp 45]_9$



Post-Fire Fractography of Open-Hole Specimens



PH# 2C (V-300 s)

Excessive Char Formation (V-300 s)

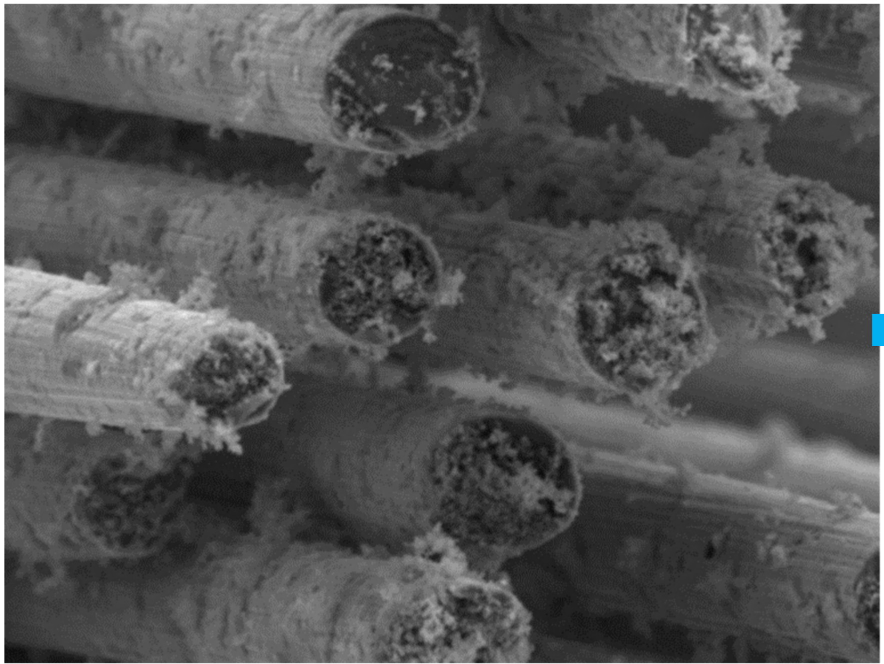
Magnified View of Fuzzy Char

Fibers Obscured by Fire Residues

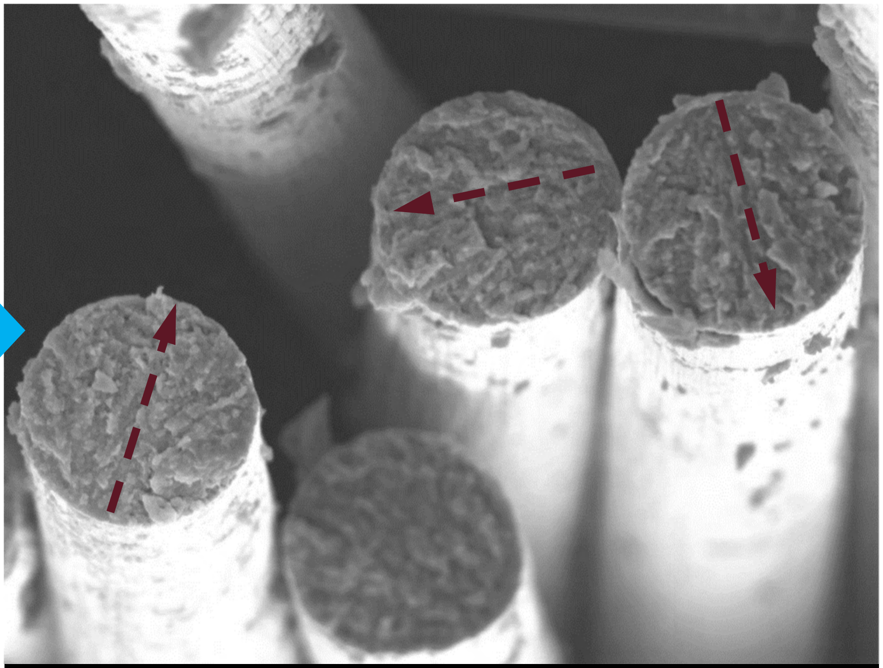
Fiber Thinning

Nitric Acid Oxidation of Fire-Damaged Open-Hole Specimens

Specimen	Burning	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
PH# 2C	V- 300 s	4.5	71.5	6.15	1.25	135



Char Formation on Fiber Ends After V-300 s

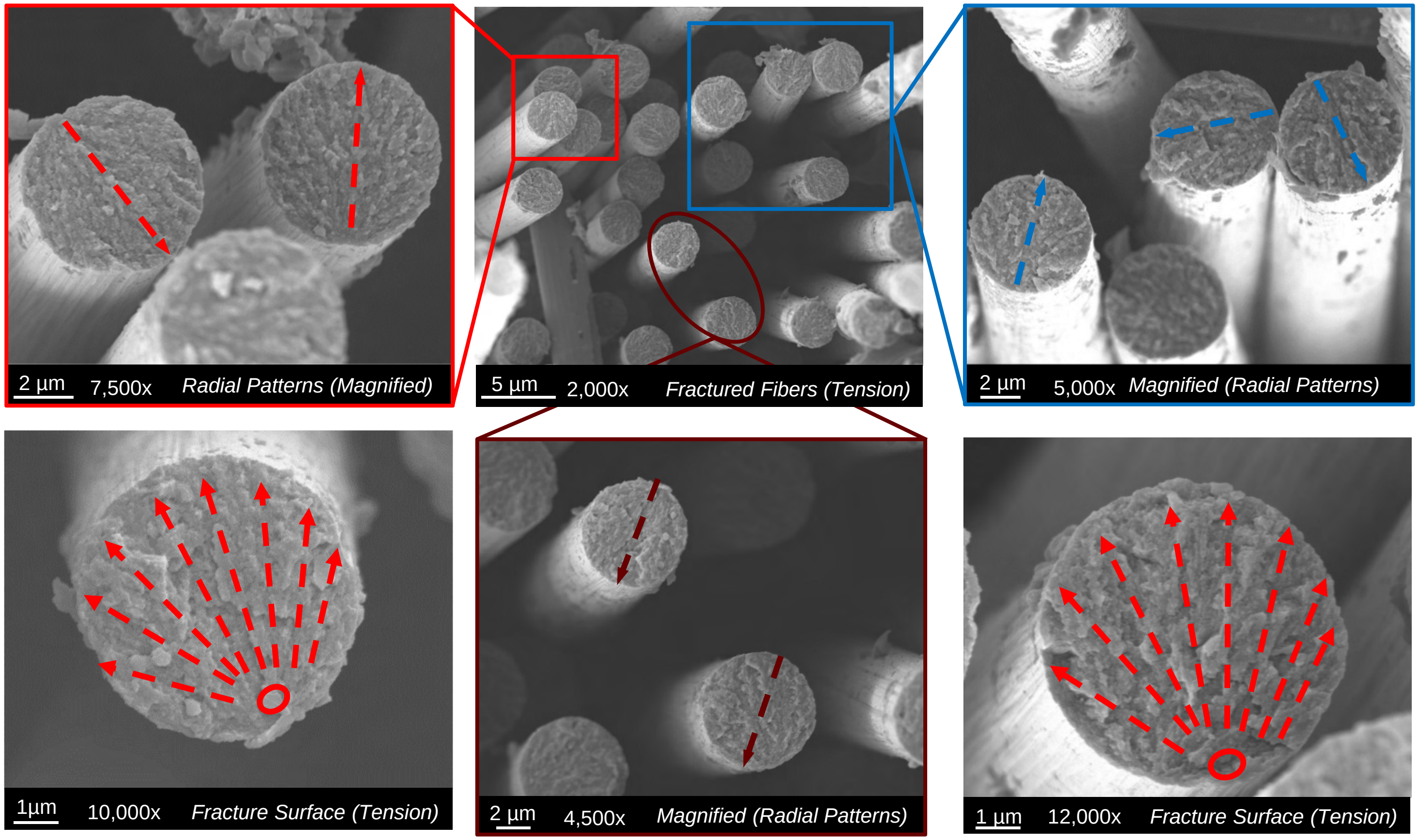


Char Free Fiber Ends After Acid Oxidation

Fractography of Fire-Damaged Open-hole Specimens

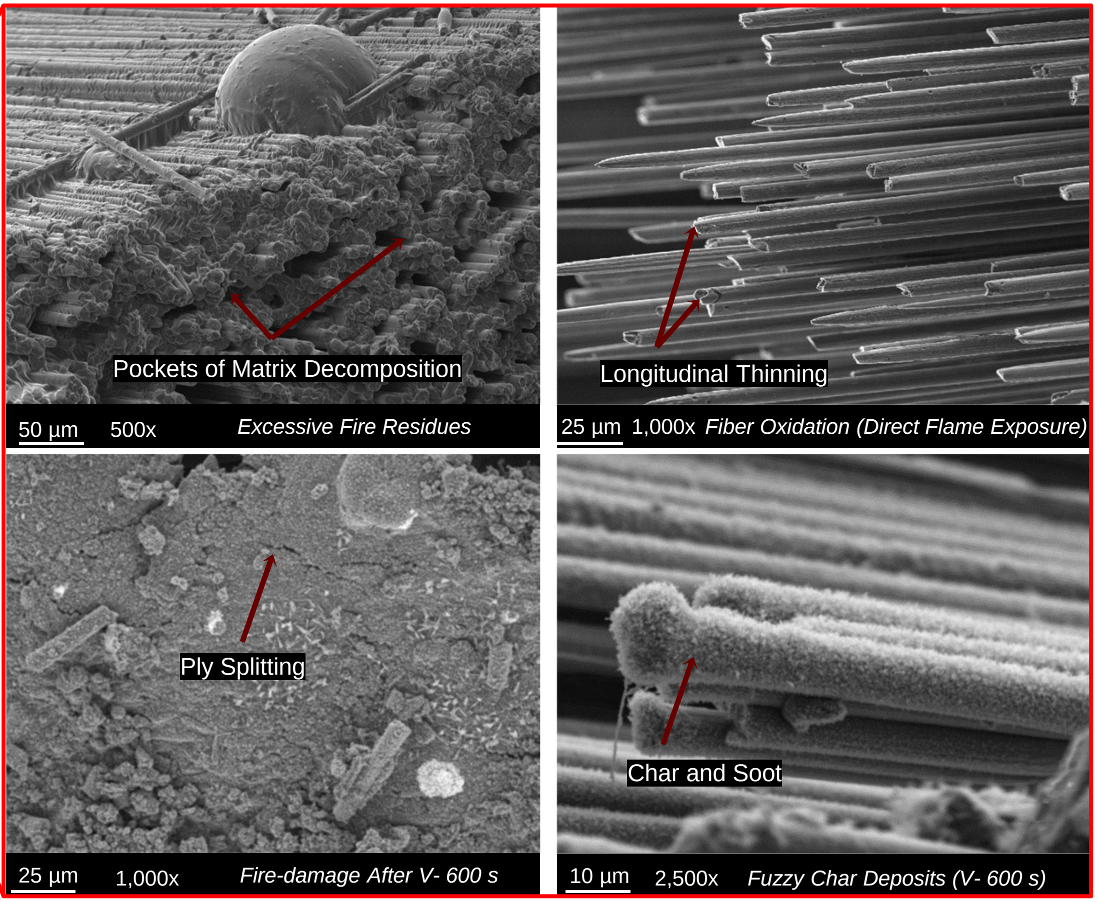
PH# 2C (V-300 s)

Typical Fracture Morphologies Observed after Nitric Acid Oxidation



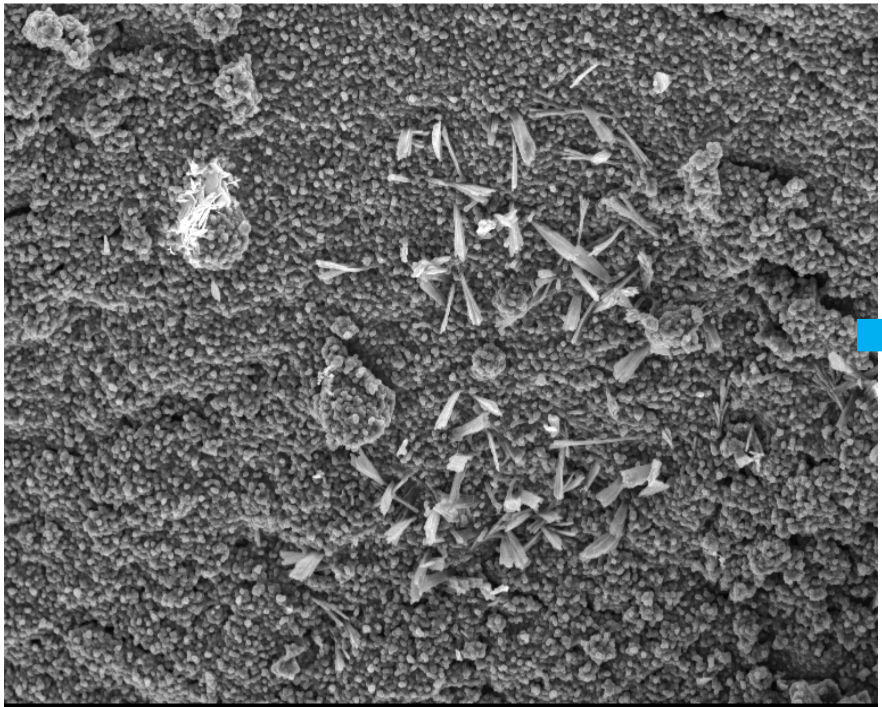
Post-Fire Fractography of Open-Hole Specimens

PH# 5C (V-600 s)

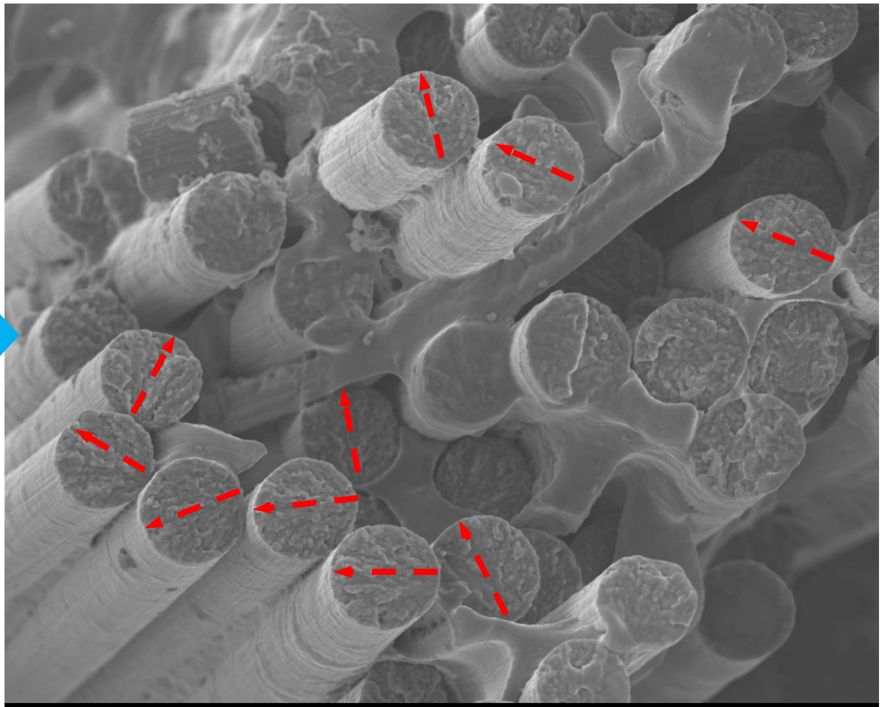


Nitric Acid Oxidation of Fire-Damaged Open-Hole Specimens

Specimen	Burning	N (ml)	S (ml)	W (wt.%)	Time (s)	Immersion Temp (°C)
PH# 5C	V-600 s	4.5	71.5	6.15	0.75	135



10 µm 2,500x *Fire Residues and debris After V- 600 s*

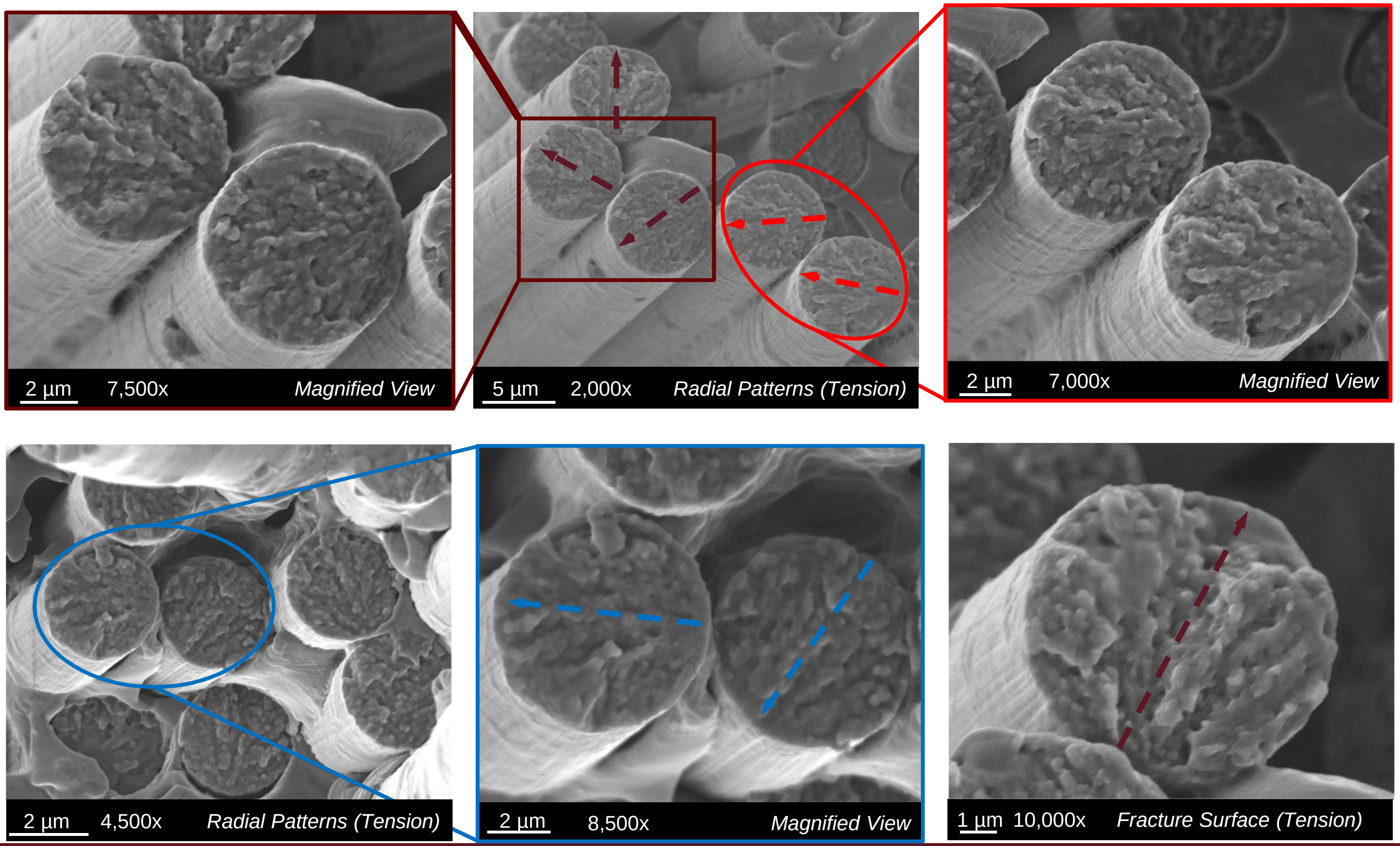


5 µm 2,500x *Char Free Fiber Ends After Acid Oxidation*

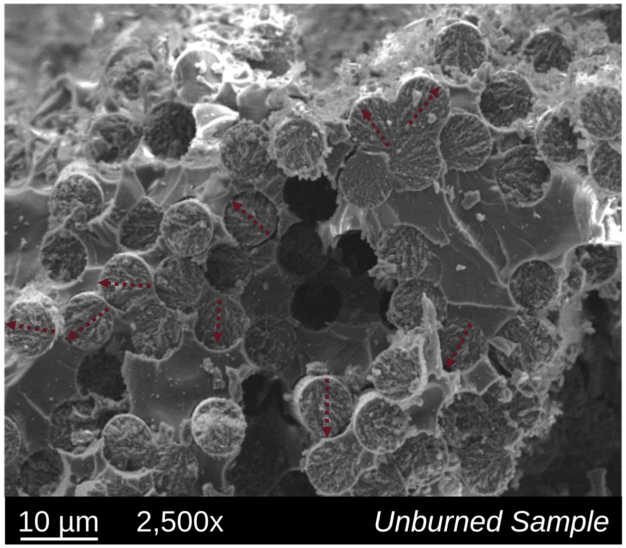
Fractography of Fire-damaged Open-Hole Specimens

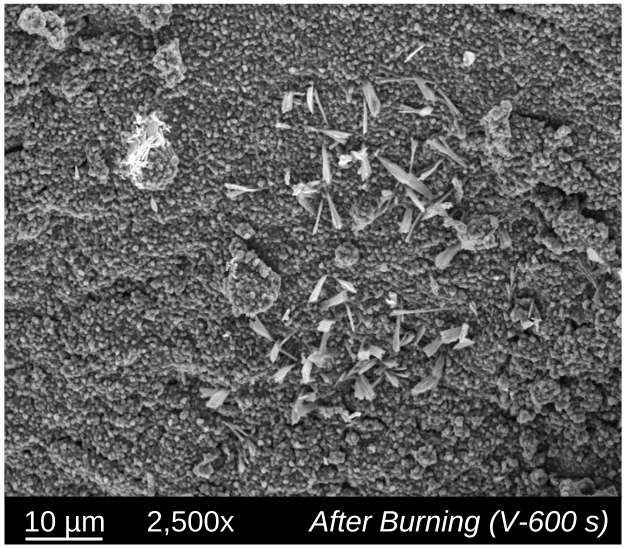
PH# 5C (V-600 s)

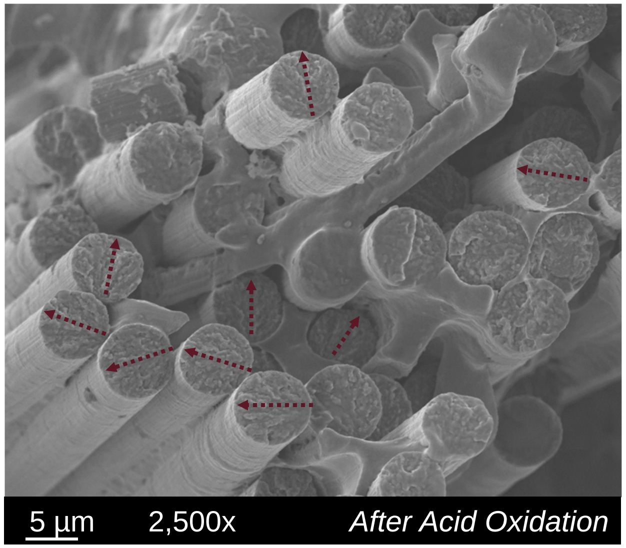
Typical Fracture Morphologies Observed after Nitric Acid Oxidation



Evolution of the Fracture Surface Morphologies Due to Fire Exposure and Nitric Acid Oxidation


10 µm 2,500x *Unburned Sample*


10 µm 2,500x *After Burning (V-600 s)*


5 µm 2,500x *After Acid Oxidation*

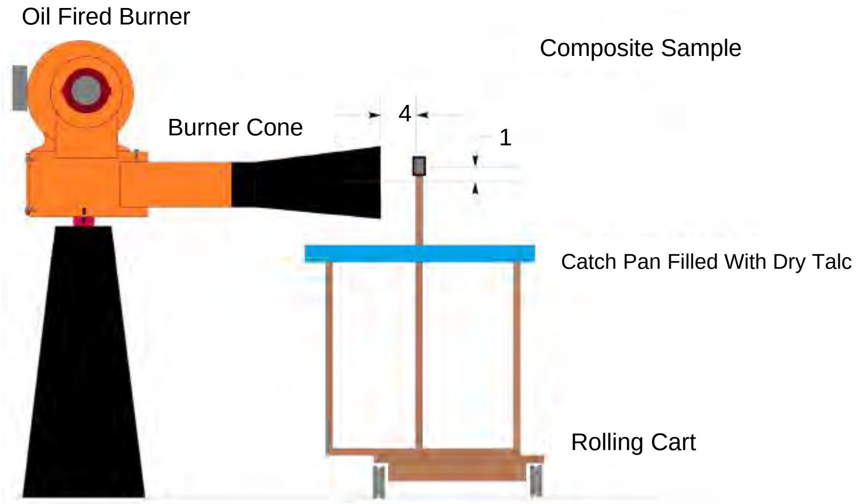
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
PH# 5C	4.5	71.5	6.15	0.75	135

Conclusions: Nitric Acid Oxidation on Open-Hole Specimens

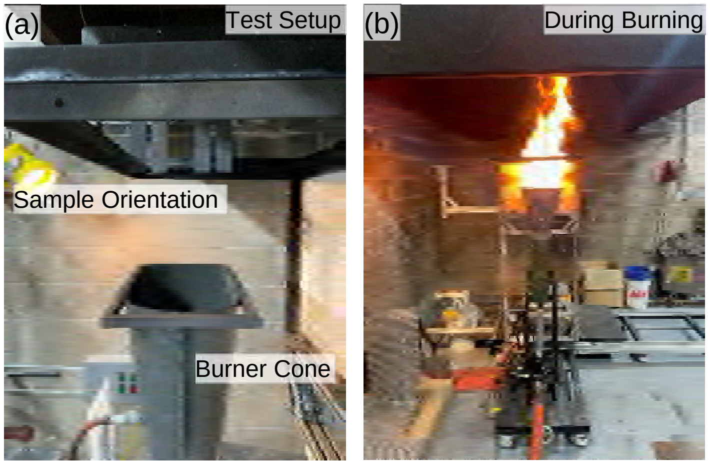
- Vertically oriented structural scale Hexcel open-hole specimens failed in tension were exposed to longer duration Bunsen burner tests (5 and 10 mins)
- Nitric acid oxidation experiments on these samples effectively removed char from fiber ends and exposed the underlying fracture morphologies
- Upon fire exposure, the sample burned for 10 min exhibited:
  - Fiber thinning in plies directly submerged in the flame, but not prevalent over the entire cross-section
  - Char formation was also substantial on fiber ends in plies without fiber thinning

- ***Future work will focus on:***
  - ***Char removal from coupon-scale samples subjected to pool fires at higher exposure durations***
  - ***Char removal from structural-scale samples subjected to pool fires***

Ongoing Work: Pool Fire Applications



Schematic of Next-gen oil burner setup [1]



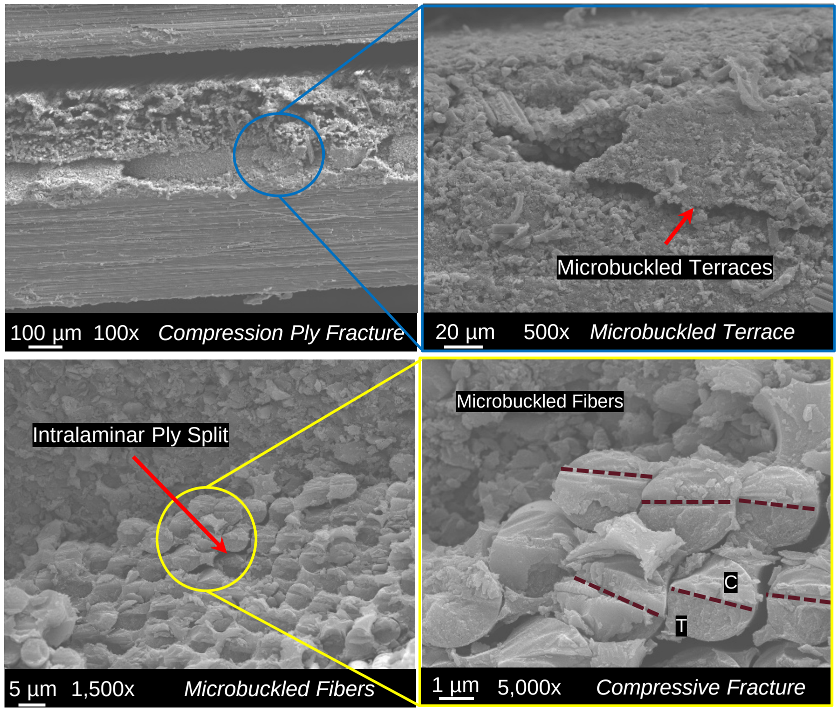
- The oil-fired burner was configured in accordance with Title 14 Code of Federal Aviation Regulations 25.853(c) Appendix F Part II to simulate pool fires.
- Mechanically damaged (Flexure and UNC0) cross-sections of samples were held vertically, 4 inches away from the burner. The flame spread is 11 inches wide. Test durations varied between 12 – 60 s.

Fractography of Pool Fire-Damaged UNC0 Specimens

Pre-fire Fractography

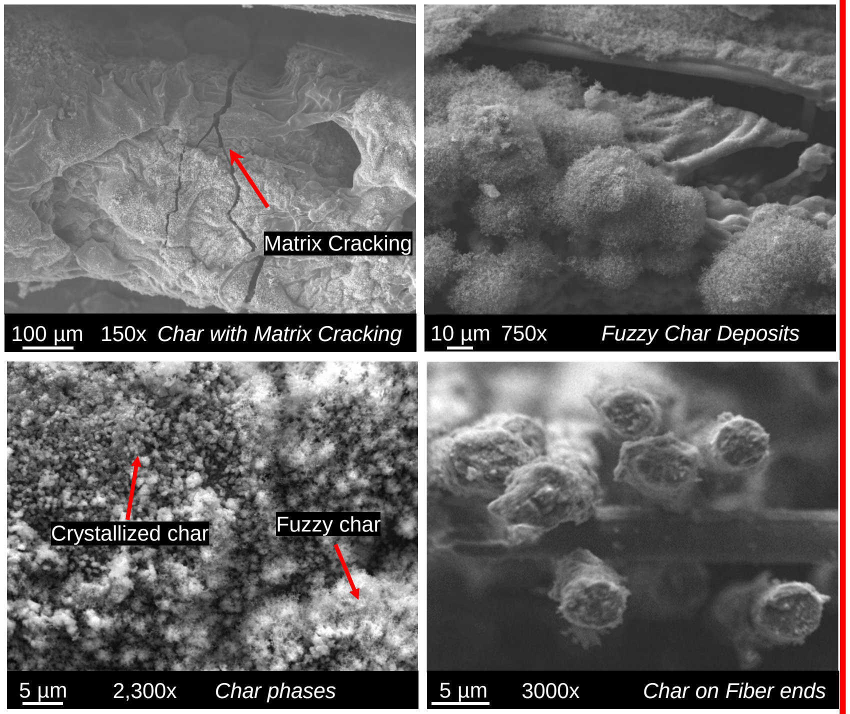
UNC0

- Unburned Hexcel Carbon/epoxy $[0/90]_{8S}$ sample failed in compression during Unnotched Compression (UNC0) test



After V- 60 s

Post-fire Fractography

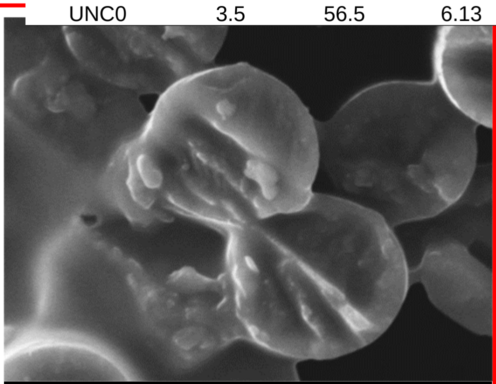


Nitric Acid Oxidation of Pool Fire-Damaged UNC0 Specimens

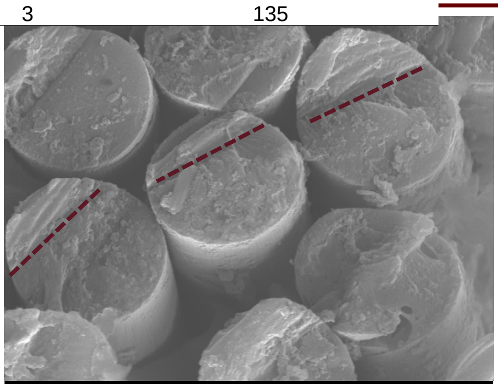
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
UNC0	3.5	56.5	6.13	3	135

V- 60 s

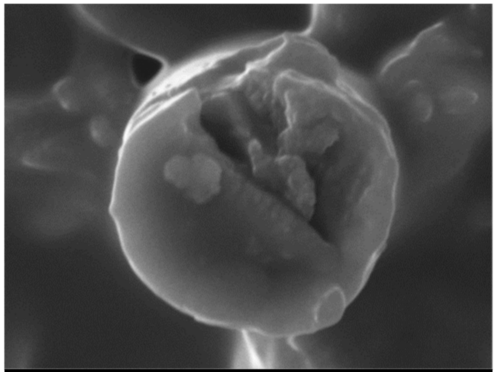
Hexcel
Carbon/epoxy
(UNC0)



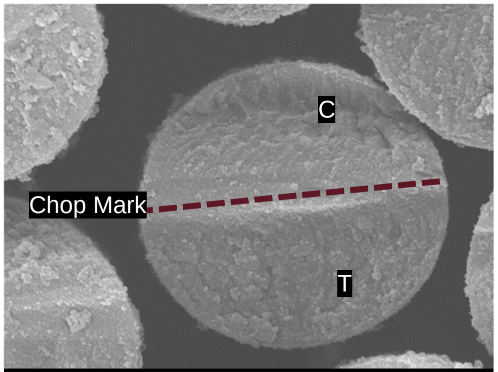
1 µm 7,500x *Microbuckled Fibers (V- 60 s)*



1 µm 7,500x *After Acid Oxidation*



1 µm 15,000x *Residue on Single Fiber*



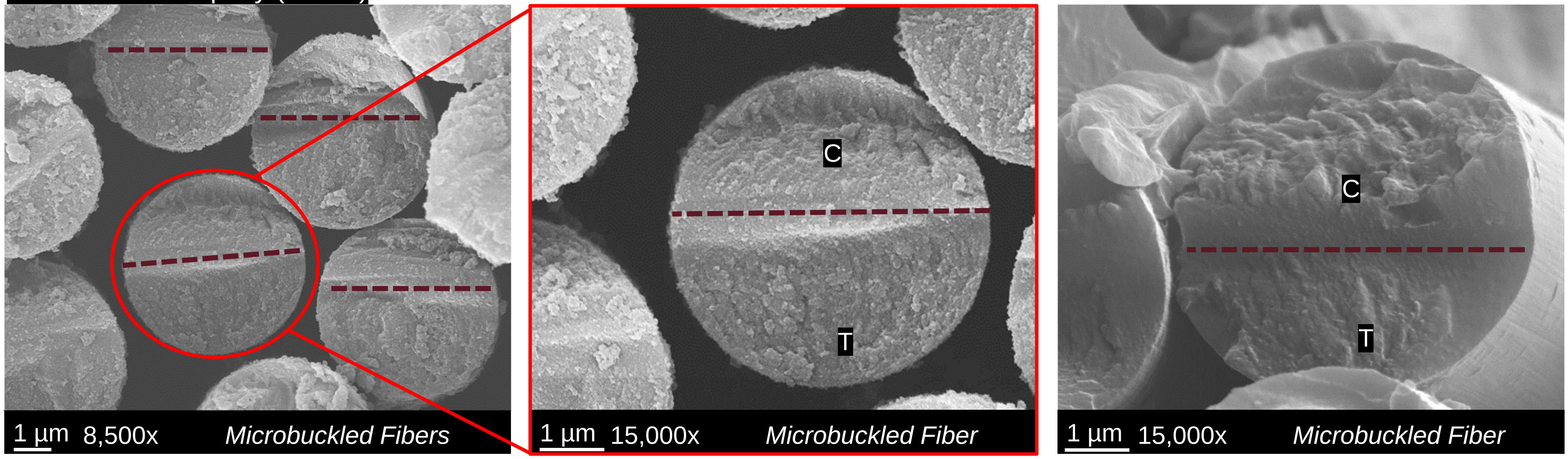
1 µm 15,000x *Fiber end After Acid Oxidation*

N = 3.18 wt.%

Fractography of Pool Fire-Damaged UNC0 Specimens

Specimen	Burning	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
UNC0	V- 60 s	3.5	56.5	6.13	3	135

Hexcel Carbon/epoxy (UNC0)



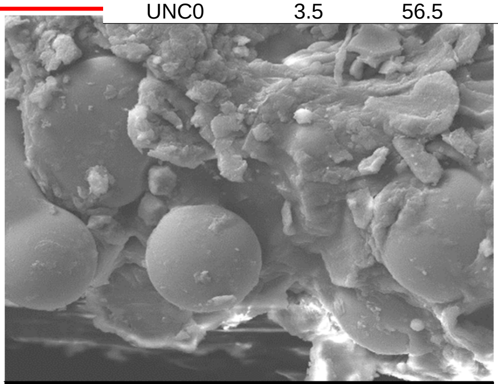
Typical Fracture Morphologies Observed after Nitric Acid Oxidation

Nitric Acid Oxidation of Pool Fire-Damaged UNC0 Specimens

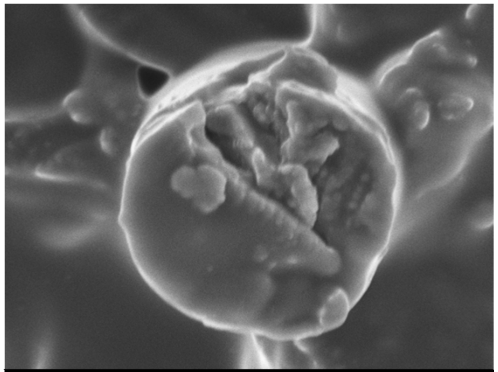
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
UNC0	3.5	56.5	6.13	2.5	135

V- 36 s

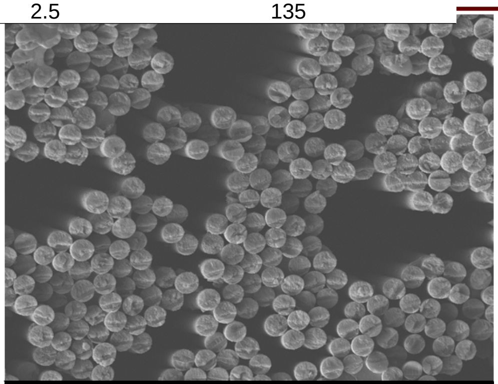
Hexcel
Carbon/epoxy
(UNC0)



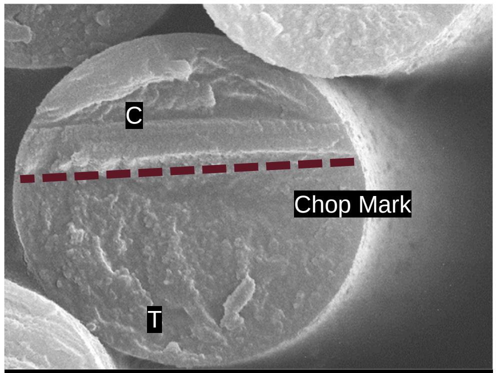
10 µm 1,000x *Microbuckled Fibers (V- 36 s)*



1 µm 13,000x *Magnified View*



10 µm 1,000x *After Acid Oxidation*



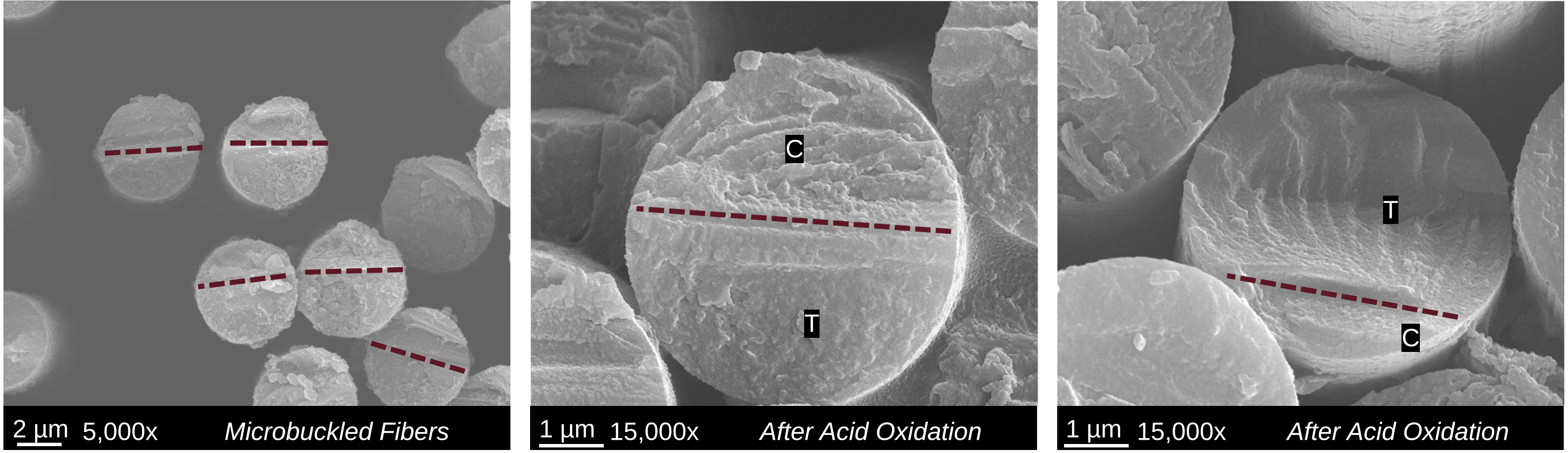
1 µm 15,000x *After Acid Oxidation*

N = 3.18 wt.%

Fractography of Pool Fire-Damaged UNC0 Specimens

Specimen	Burning	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
UNC0	V- 36 s	3.5	56.5	6.13	2.5	135

Hexcel Carbon/epoxy (UNC0)



2 µm 5,000x *Microbuckled Fibers*

1 µm 15,000x *After Acid Oxidation*

1 µm 15,000x *After Acid Oxidation*

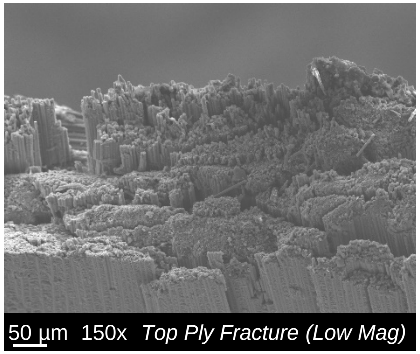
Typical Fracture Morphologies Observed after Nitric Acid Oxidation

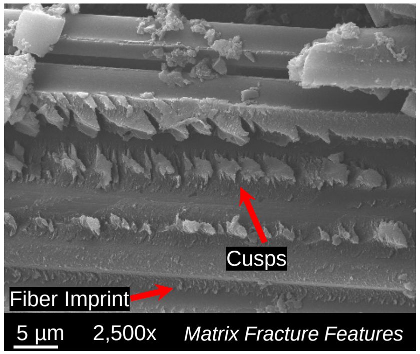
Fractography of Pool Fire-Damaged Flexure Specimens

Pre-fire Fractography

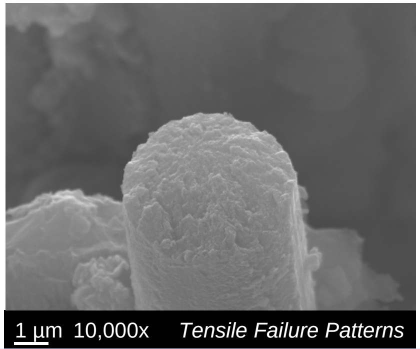
Flexure

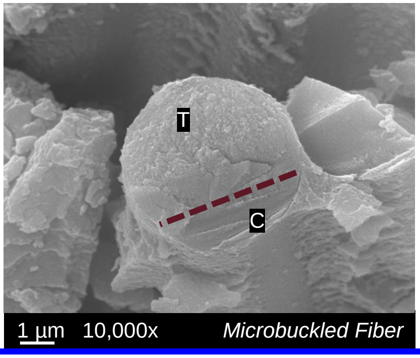
- Unburned Hexcel Carbon/epoxy $[0/90]_{8S}$ sample failed in bending during Flexure test


50 µm 150x *Top Ply Fracture (Low Mag)*



5 µm 2,500x *Matrix Fracture Features*

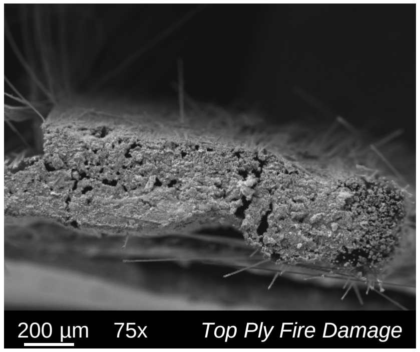

1 µm 10,000x *Tensile Failure Patterns*

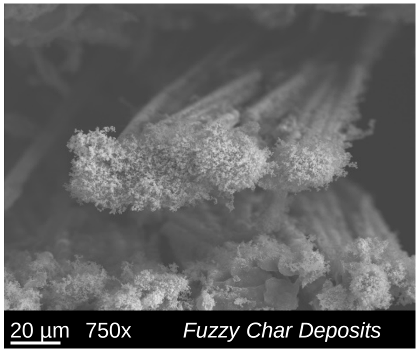


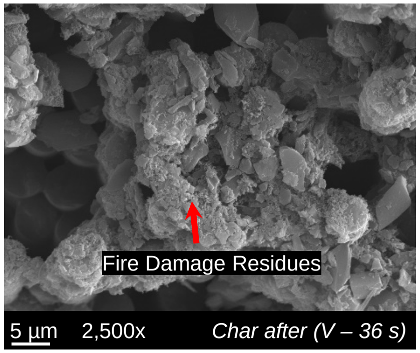
1 µm 10,000x *Microbuckled Fiber*


After V- 36 s

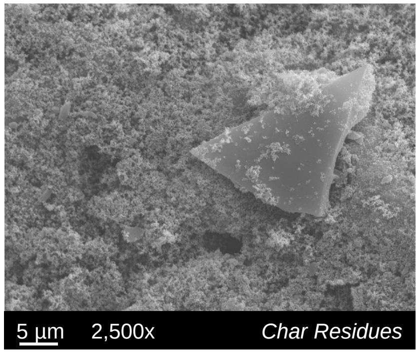
Post-fire Fractography


200 µm 75x *Top Ply Fire Damage*


20 µm 750x *Fuzzy Char Deposits*



5 µm 2,500x *Char after (V – 36 s)*

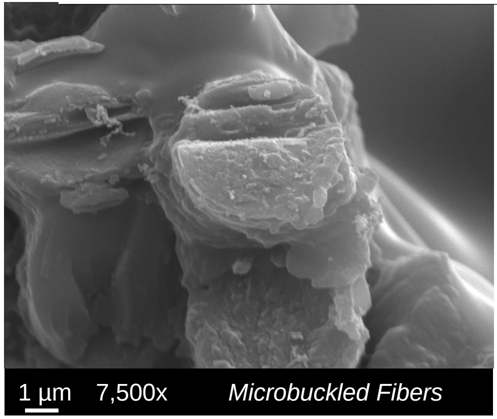

5 µm 2,500x *Char Residues*

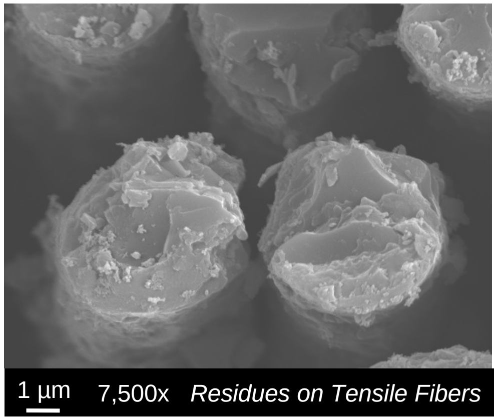
Nitric Acid Oxidation of Pool Fire-Damaged Flexure Specimens

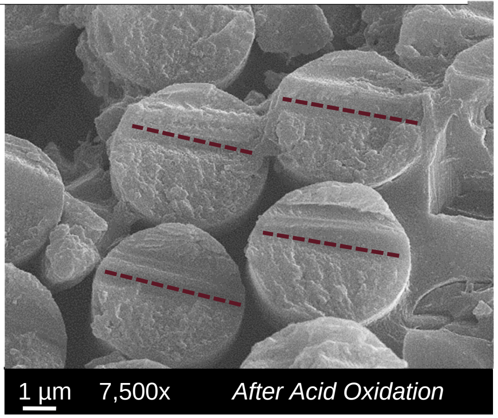
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
Flexure	3.5	56.5	6.13	2.5	135

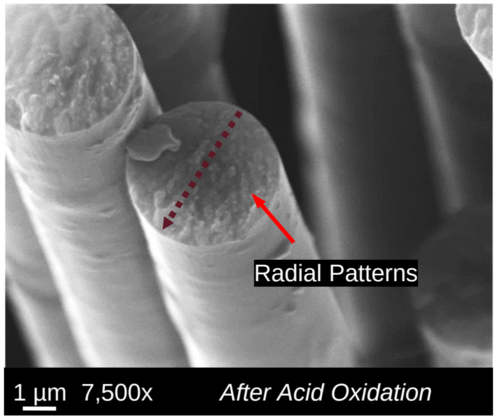
V- 36 s

Hexcel
Carbon/epoxy
(Flexure)







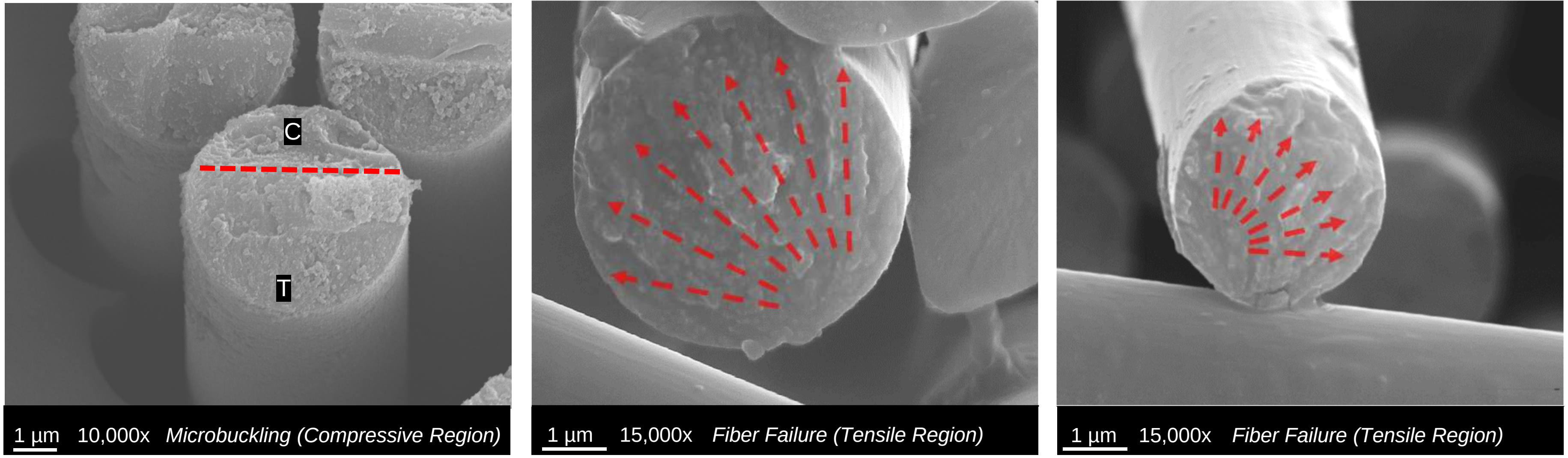


N = 3.18 wt.%

Fractography of Pool Fire-Damaged Flexure Specimens

Specimen	Burning	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
Flexure	V- 36 s	3.5	56.5	6.13	2.5	135

Hexcel Carbon/epoxy (Flexure)



1 µm 10,000x *Microbuckling (Compressive Region)*

1 µm 15,000x *Fiber Failure (Tensile Region)*

1 µm 15,000x *Fiber Failure (Tensile Region)*

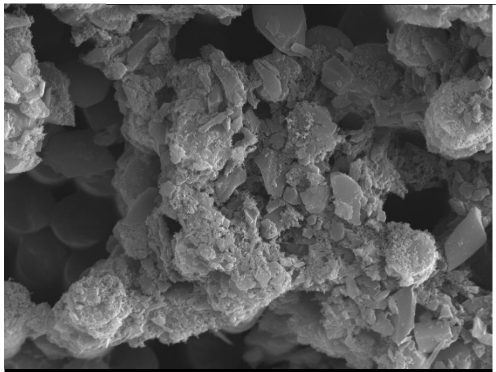
Typical Fracture Morphologies Observed after Nitric Acid Oxidation

Nitric Acid Oxidation of Pool Fire-Damaged Flexure Specimens

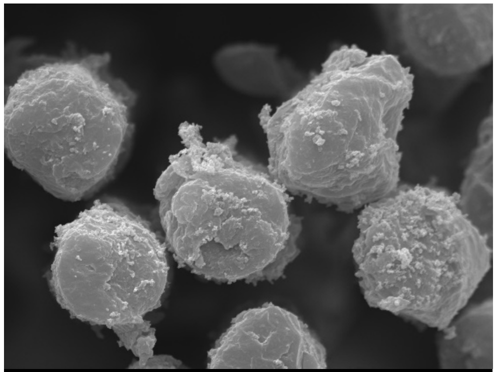
Specimen	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
Flexure	3.5	56.5	6.13	3	135

V- 12 s

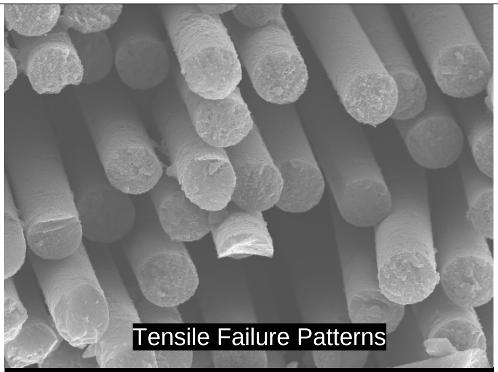
Hexcel Carbon/epoxy (Flexure)



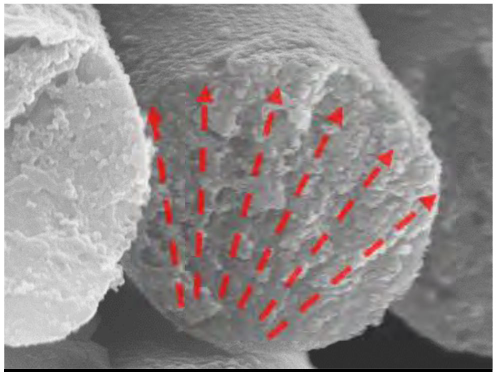
5 µm 2,500x *Char Formation (V- 12 s)*



2 µm 5,000x *Residues on Tensile Fibers*



5 µm 2,500x *After Acid Oxidation*



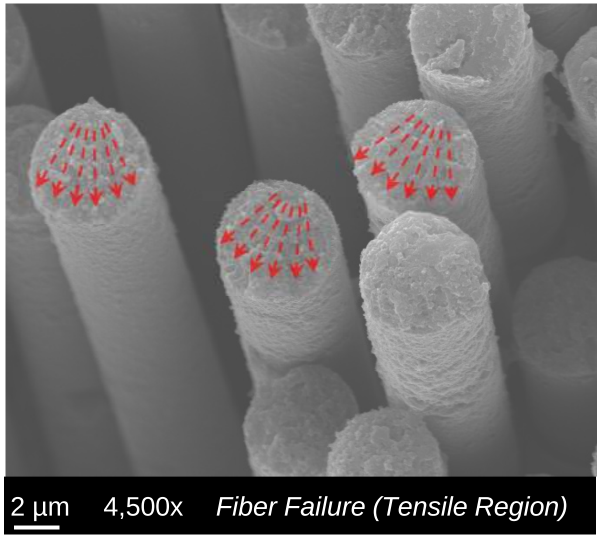
1 µm 15,000x *After Acid Oxidation*

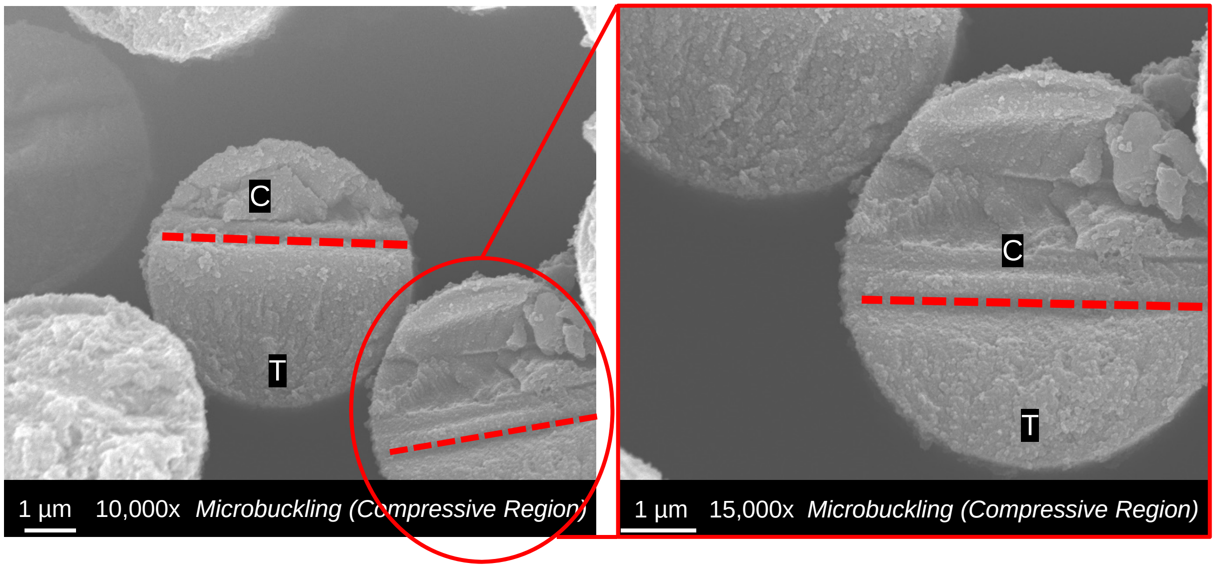
N = 3.18 wt.%

Fractography of Pool Fire-Damaged Flexure Specimens

Specimen	Burning	N (ml)	S (ml)	W (wt.%)	Time (min)	Immersion Temp (°C)
Flexure	V -12 s	3.5	56.5	6.13	3	135

Hexcel Carbon/epoxy (Flexure)





Typical Fracture Morphologies Observed after Nitric Acid Oxidation

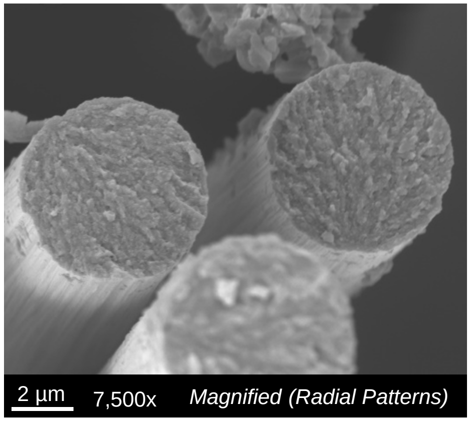
Conclusions: Nitric Acid Oxidation on Pool Fire Specimens

- Vertically oriented Hexcel UNC0 and Flexure specimens (coupon-scale) were exposed to shorter duration pool fires (36 and 60 s)
- Fire-damaged samples still retained char residues on sample cross-sections and fiber ends, obscuring salient fracture surface morphologies
- Fiber thinning was not observed for lower duration tests even at high heat fluxes (> 75 kW/m^2)
- Nitric acid oxidation experiments on these samples effectively removed char from fiber ends and exposed the underlying fracture morphologies

- ***Future work will focus on:***
    - ***Char removal from coupon-scale samples subjected to pool fires at higher exposure durations***
    - ***Char removal from structural-scale samples subjected to pool fires***

Overall Conclusions

- Char removal methodology with a **broad temp/time/conc window** to treat fire-damaged composite samples was developed as part of this work
- Nitric acid oxidation effectively removed char and exposed underlying fracture surface morphologies (as shown with fractography):
  - Compression samples: evidence for microbuckling and the direction of crack propagation were preserved after char removal
  - SBS and Flexure samples: compressive and tensile failure features were preserved after char removal
  - Open-Hole samples: Burned for longer exposure durations (5 and 10 min) at very low treatment times (45 to 75 s)



Fire-damaged fiber cross-sections of an Open-hole sample after char removal

- ***Future work will focus on fire damage characterization and char removal of structural scale samples exposed to higher duration pool fires***

Thank You!

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Mechanical Engineering

Affiliated Faculty
Advanced Composites Institute

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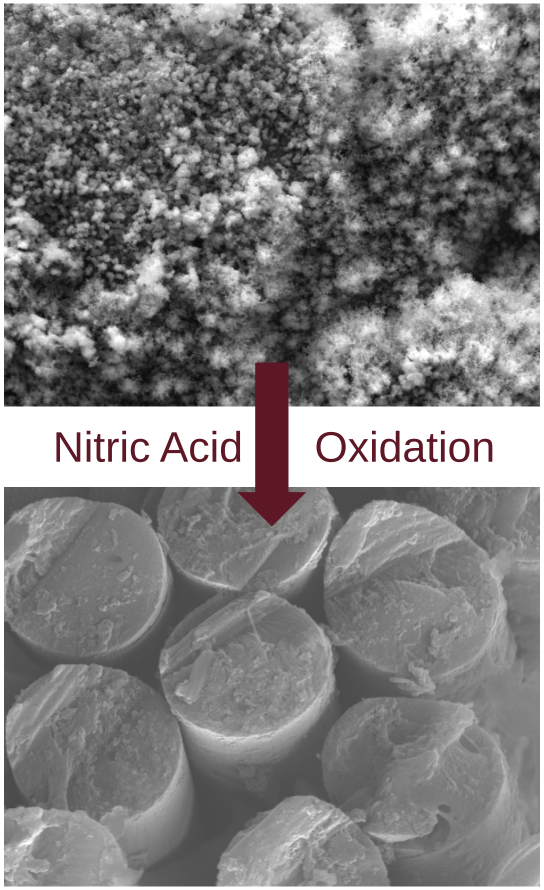

Publications

Technical reports

Lacy Jr., T. E., Kundu, S., Pittman Jr., C. U., Priddy, M., Boushab, D., Ouidadi, H., Righi, H., Madabhushi, A. (2021). Post-Crash Fire Forensic Analysis of Aerospace Composites-Phase I. Technical Report for Federal Aviation Administration. Mississippi State University, Starkville, MS. (Submitted to the FAA)

Righi, H., Madabhushi, A., Ouidadi, H., Boushab, D., Lacy Jr., T. E., Kundu, S., Pittman Jr., C. U. & Priddy, M. (2020). Post-Crash Fire Forensic Analysis on Aerospace Composites – Literature Review (DOT/FAA/TC-20/21). Federal Aviation Administration. Mississippi State University, Starkville, MS. (Published)

Conference paper

Mote, A., Ouidadi, H., Boushab, D., Priddy, M., Kundu, S., Pittman Jr., C. U., Grunlan, J., Wang, Q., Lacy Jr., T. E. (2021). Post mechanical failure fire damage characterization of graphite/epoxy composites. Proceedings of the American Society for Composites 36th Technical Conference. (Published)

Journal

Boushab, D., Ouidadi, H., Mote, A., Priddy, M., Kundu, S., Pittman Jr., C. U., Grunlan, J., Wang, Q., Lacy Jr., T. E. (2022). Fire impact on mechanically failed graphite/epoxy composites. **(polymer composites)**

Boushab, D., Madabhushi, A., Mote, A., Pittman Jr., Priddy, M., Kundu, S., C. U., Grunlan, J., Lacy Jr., T. E. Influence of direct flame exposure on PRSEUS. **(In preparation)**

Madabhushi, A., Priddy, M., Lacy Jr., T. E., Kundu, S., and Pittman Jr., C. U., The removal of epoxy-based char from carbon-fiber cross-sections of aerospace composites subjected to fire. **(In preparation)**

Madabhushi, A., Boushab, D., Priddy, M., Lacy Jr., T. E., Kundu, S., and Pittman Jr., C. U., Post-fire forensic examination of fire-damaged and mechanically failed carbon/epoxy composites. **(In preparation)**

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- Lacy Jr., T. E., Kundu, S., Pittman Jr., C. U., Priddy, M., Boushab, D., Ouidadi, H., Righi, H., & Madabhushi, A., (2021). Post-Crash Fire Forensic Analysis of Aerospace Composites-Phase I. Technical Report for Federal Aviation Administration. Mississippi State University, Starkville, MS.
- Horner, "Aircraft materials fire test handbook," Federal Aviation Administration., New Jersey, Final Report DOT/FAA/AR-00/12, 2000.
- https://smartsiteconstruction.com/wet-ice-blasting/