Laser-Assisted Joining Process of Aluminum and Carbon Fiber Components

Project ID: LM097

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2016 DOE Vehicle Technologies Annual Merit Review and Peer Evaluation Meeting

June 07, 2016

Overview

Timeline

- Project start date: 10/1/2013
- Project end date: 12/30/2015
- Percent complete: 100%

Budget

- Total project funding $600,000
  - DOE share: $600,000
  - Not required cost-share: $30,000
- Funding received in FY14: $300,000
- Funding for FY15: $300,000

What's Next

- Proposals have been submitted for commercial scale-up of these technologies

Barriers Addressed

- Dissimilar Material Joining
- Rapid/Consistent Joining of Multi-Material Structures
- Manufacturability
- Corrosion Prevention

Partners

- Magna
- 3M Company
- Plasan Carbon Composites

Subcontractors

- Clearwater Composites, Inc.
- University of Tennessee Knoxville

Relevance to VT Goals

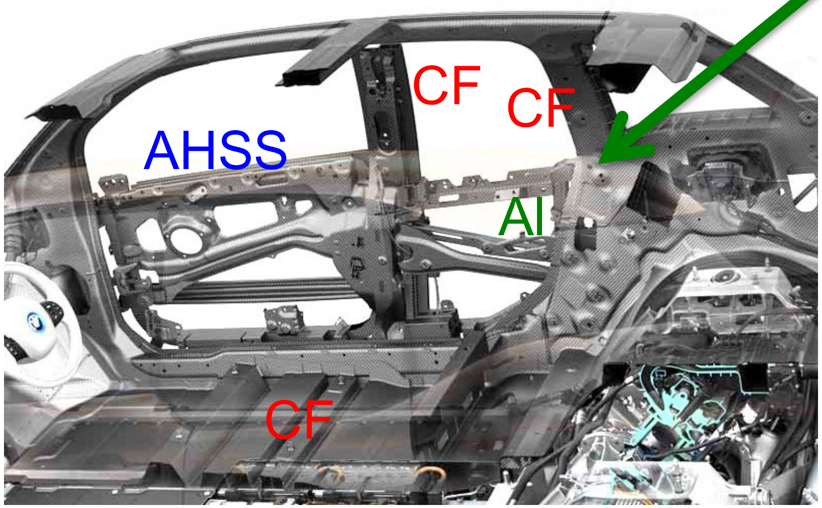
- Future Automotive Designs will Likely Be Multi-Material

- Lightweighting, Joining and Assembly
  - High Volume, High-Yielding Technologies for dissimilar materials
  - Joining methods must be rapid, affordable, repeatable and reliable.
  - Galvanic Corrosion Potential must be mitigated
  - Safety and Functionality must be maintained.
  - Adhesive Technology does provide an insulating layer

- Current Adhesive Joining Methods are:
  - Labor Intensive
  - Variable depending up the person doing the Surface Preparation
  - Not High Volume Friendly
  - Not Eco-Friendly (Involve Solvent Cleaning)

Successful Al-CF joining in this project will enable an increase in Multi-Material use in automotive and consequently lead to significant weight reduction thereby reducing greenhouse gas emissions and dependency on foreign oil (Reference: VT Program, Multi-Year Program Plan 2011-2015, Dec 2010, pp. 1.0-2, 2.5-3, 2.5-4.)

Objective: Develop a Breakthrough Joining Technology for Joining Carbon Fiber Polymer Composites (CFPC) and Aluminum (Al) Components



http://www.extremetech.com/extreme/162582-bmw-i3-will-bmws-new-ev-finally-be-the-breakthrough-for-carbon-fiber-cars

<u>Goals:</u> Surface preparation of Al and CFPC via laser structuring will:

- Increase joint strength,
- Reduce variability in surface preparation,
- Elimination of empirical, labor-intensive surface preparation
- Eliminate the use of solvents.
- Provide an electrically insulating layer for corrosion prevention.

<u>Specific Advantages of laser-structured CFPC and Al</u>:

- Eliminates sanding
- Eliminates solvent cleaning
- Removes resin rich surface layer
- Provides a greater, non-planar contact area
- Yields a fiber reinforced adhesive/composite interface
- Increases Joint ductility by 2X (Crash Energy Absorbance)

Project Status: Milestones/Deliverables

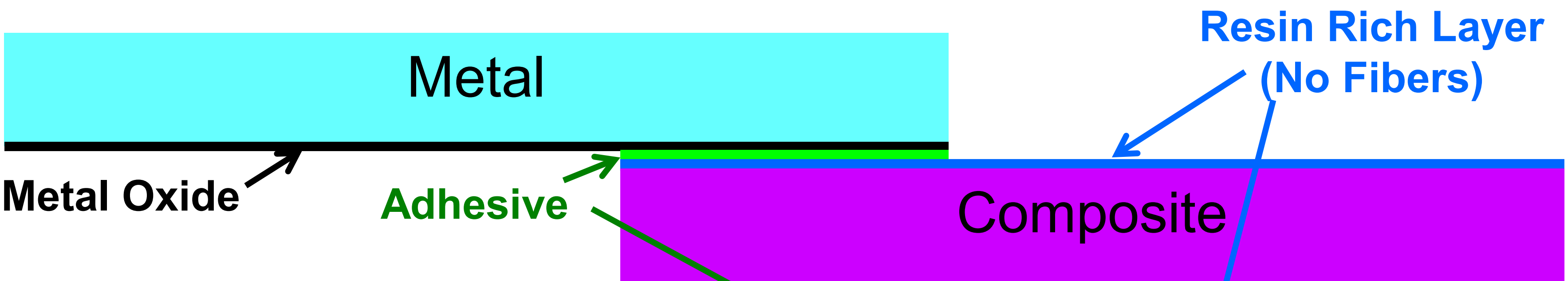
Date	FY14 Milestones/Deliverables	Status
12/31/2013	Identified and/or obtained, the Al alloy, composite material system, and the laser ablation wavelengths	Complete
3/31/2014	Identified appropriate adhesives and obtained baseline adhesive joint properties (i.e., without laser structuring)	Complete
6/30/2014	Demonstrated laser-structuring for CFPC and the aluminum	Complete
9/30/14	Demonstrated 20% improvement in the lap shear strength of a single-lap joint produced by using Al and CFPC	Go-no-go Complete
12/31/2014	Identified optimum operating parameters for the laser-structuring of Al and laser ablation for CFPC.	Complete
3/31/2015	Identified optimum adhesive.	Complete
6/30/2015	Demonstrate 20% improvement in lap shear strength of a double lap shear joint produced by using Al and CFPC	Complete
9/30/2015	Demonstrate a 40% improvement in the lap shear strength of a lap shear joint produced by bonding aluminum to composites as compared to baseline samples without laser structuring.	Complete

All milestones were successfully completed.

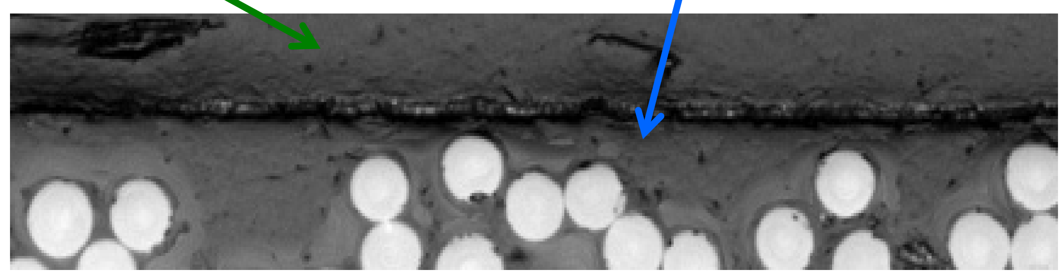
Anatomy of a Typical Adhesive Joint

Bonding Interfaces are:

- MO_x to Adhesive
- Resin to Adhesive (no fiber reinforcement)
- Planar (nice place for crack propagation)



Typical Failure Surface



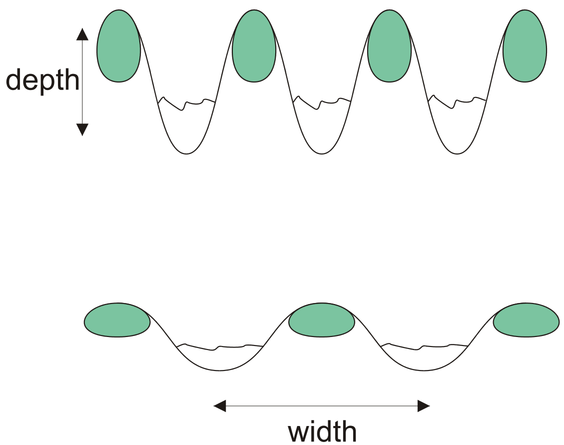
SEM of Bonded Composite Panel

Therefore, Joint properties are those of the Interface

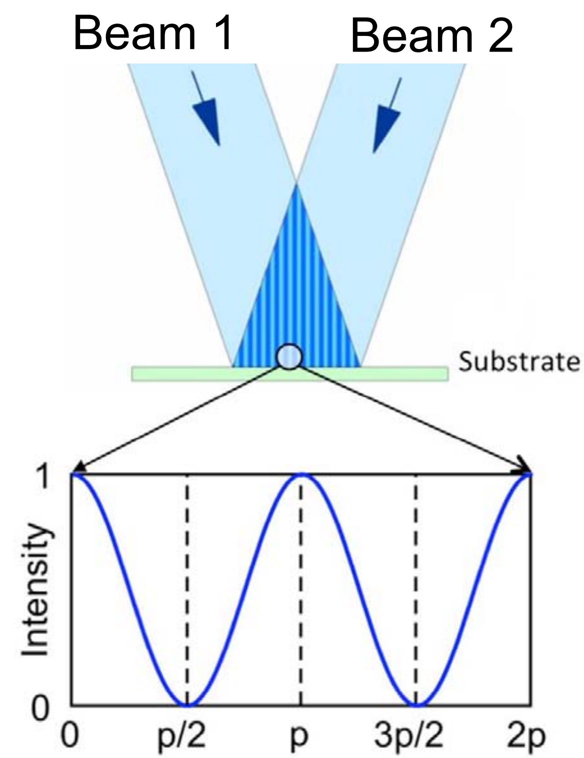
Approach: Aluminum - ORNL Used both Laser-Interference (2-beam) in a Spot by Spot and Rastering for Structuring the Surface

Laser-interference technique systematically “roughens” the surface:

- Constructive interference of two (or more) laser beams intensifies power creating pits on the surface,
- Destructive interference leaves the surface unchanged



Alternating, high-power and low-power profile created by wave interference yields localized melting, solidification, and surface structuring.



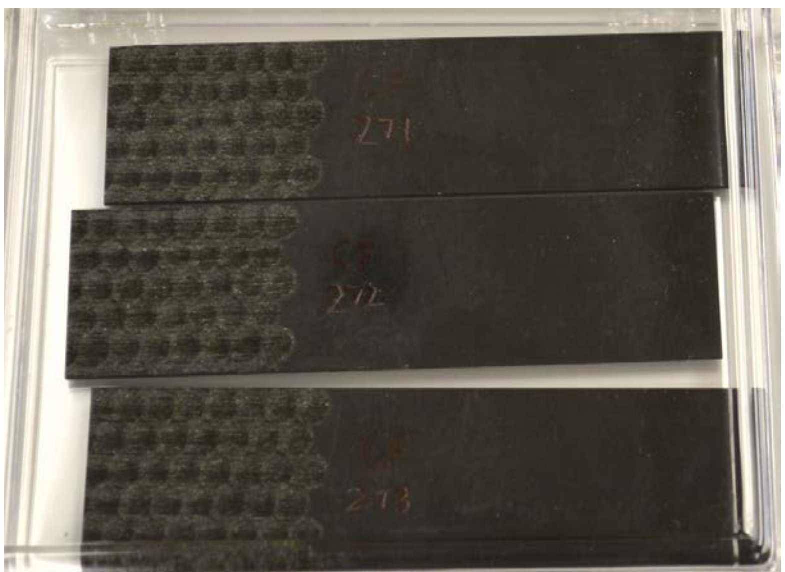
Processed region

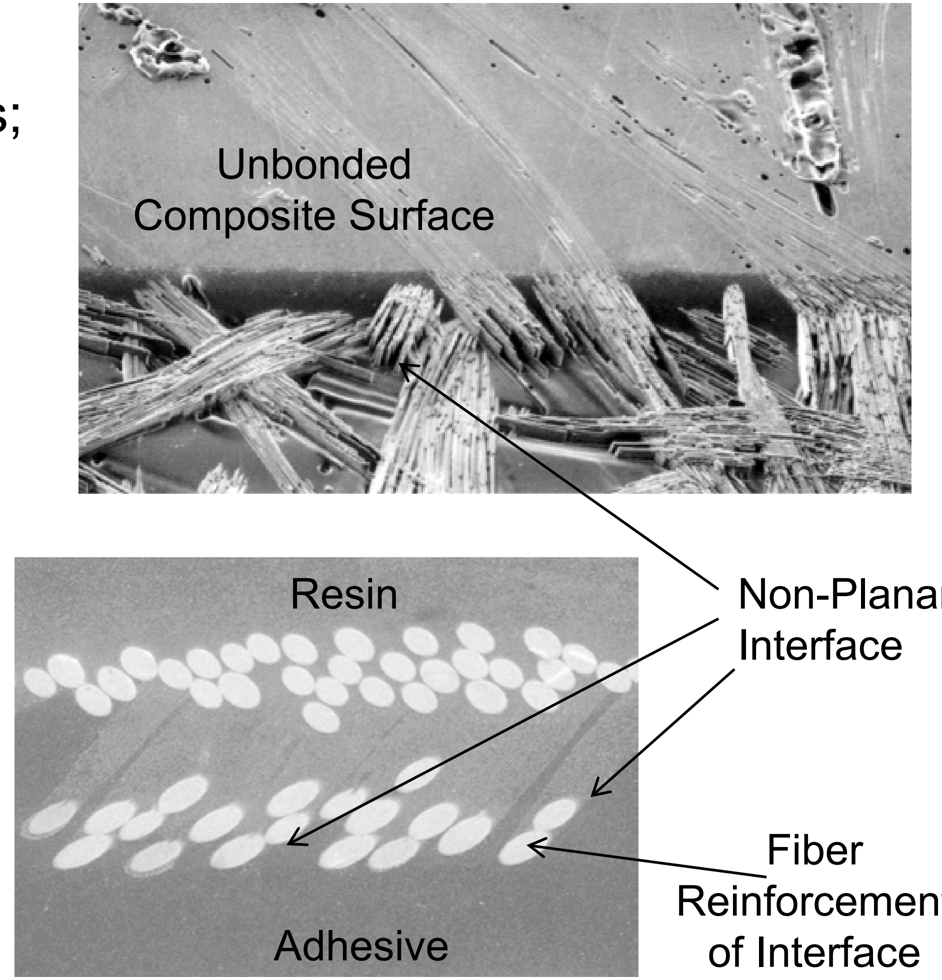
Unprocessed region

Approach: Composites - Both 2 Beam and Rastering were used on the CFRC as well.

The innovations:

- Increased surface area;
- Elimination of surface contaminates;
- Removal of mold release;
- Removal of resin rich layer;
- Fiber reinforcing the interface.





Bonded Composite Surface

Results: Surface Cleaning - The Depth Profile for Aluminum Specimens in the As-Received and Laser-Structured Conditions

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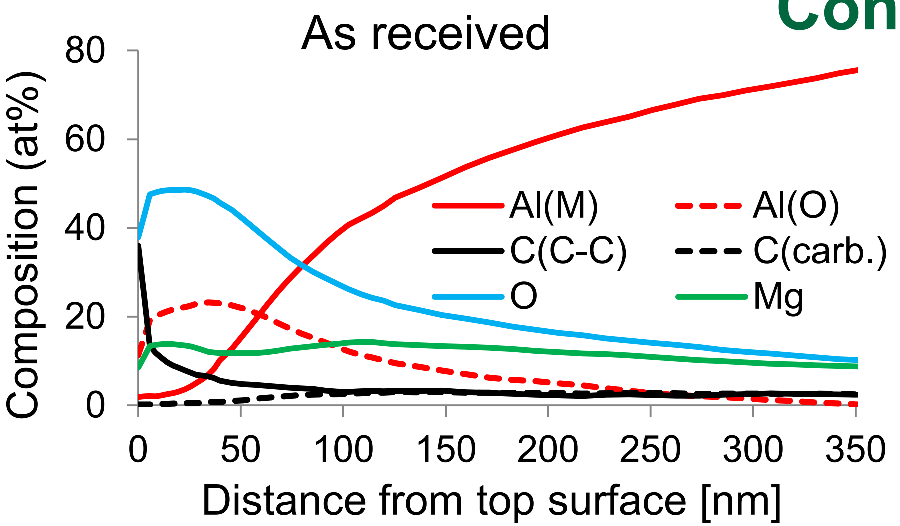
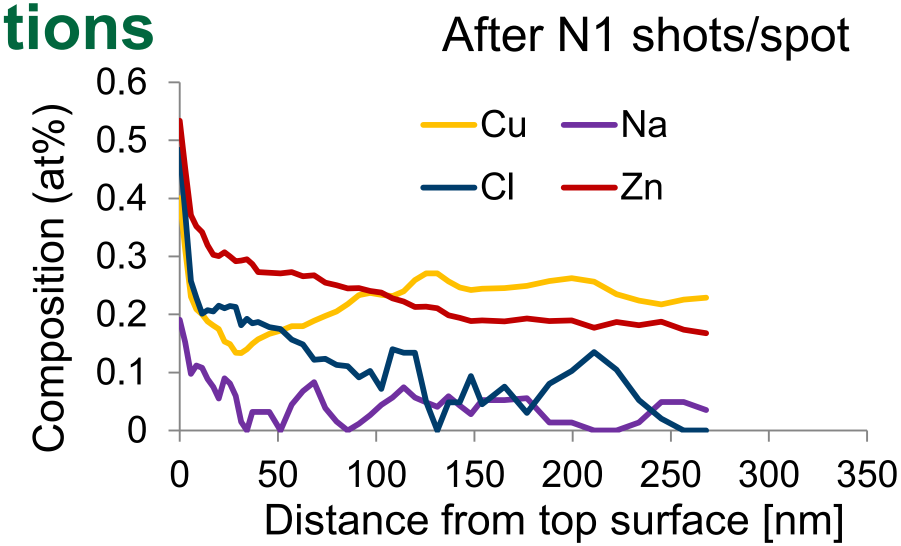
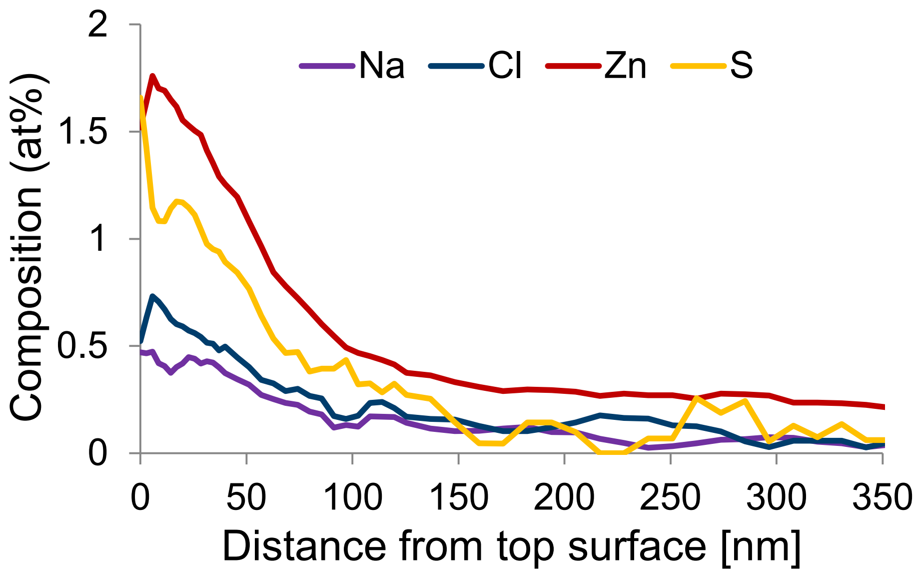
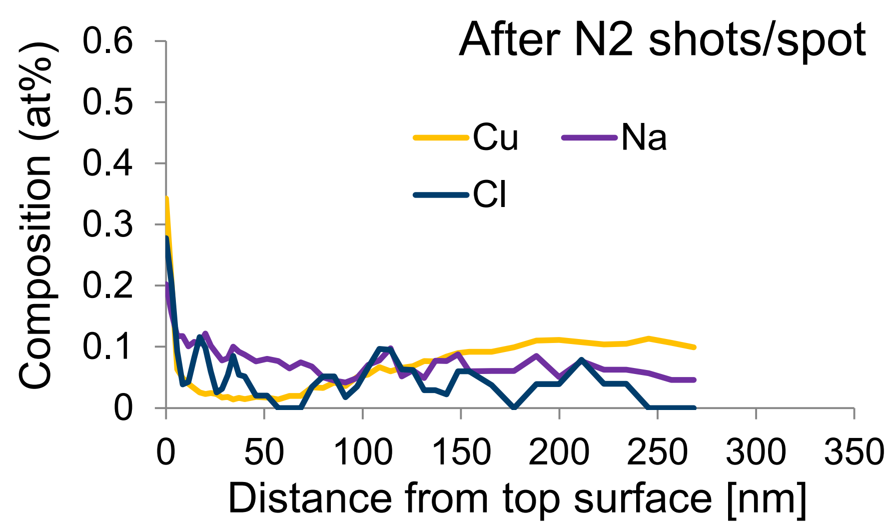




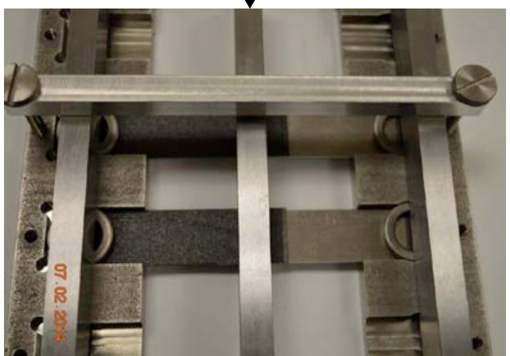


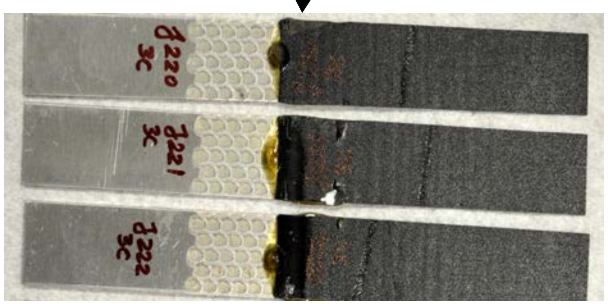


Very Effective in Cleaning the Surface

Solvent Cleaning and Wiping were Eliminated

Results: Laser-Structured Joints are more Ductile, Indicating an Enhanced Bonding of Adhesive to Both Al and CFPC





3M provided 3 different adhesives. (Urethane, Acrylic and Epoxy)

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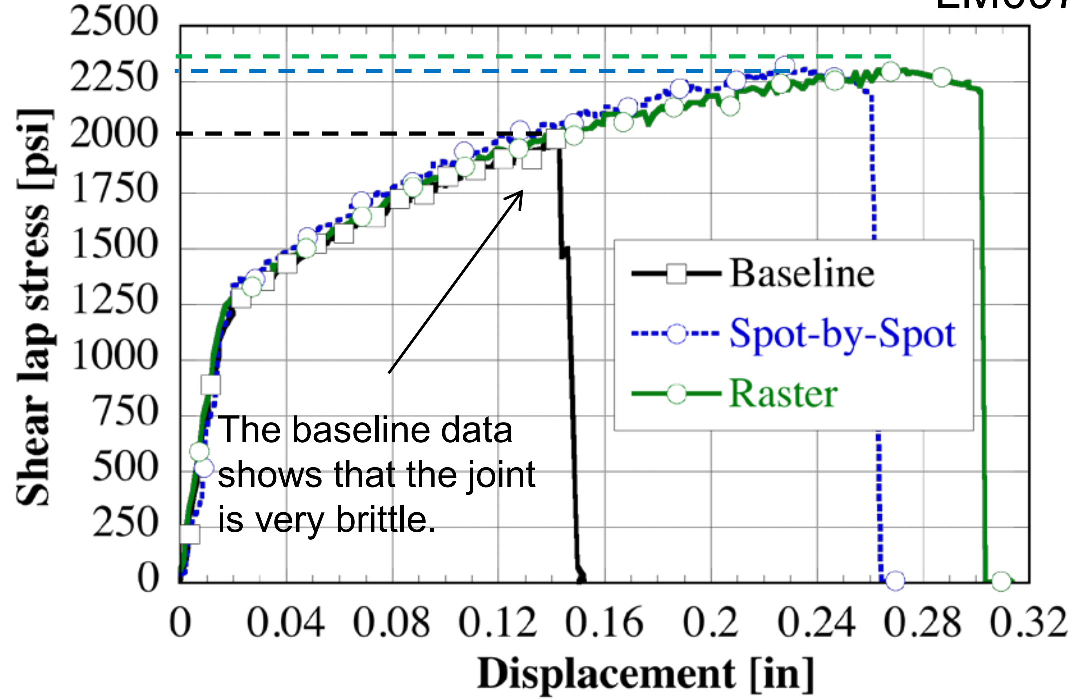
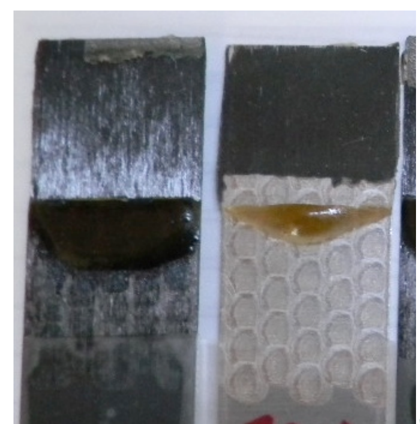


Non-Structured Baseline

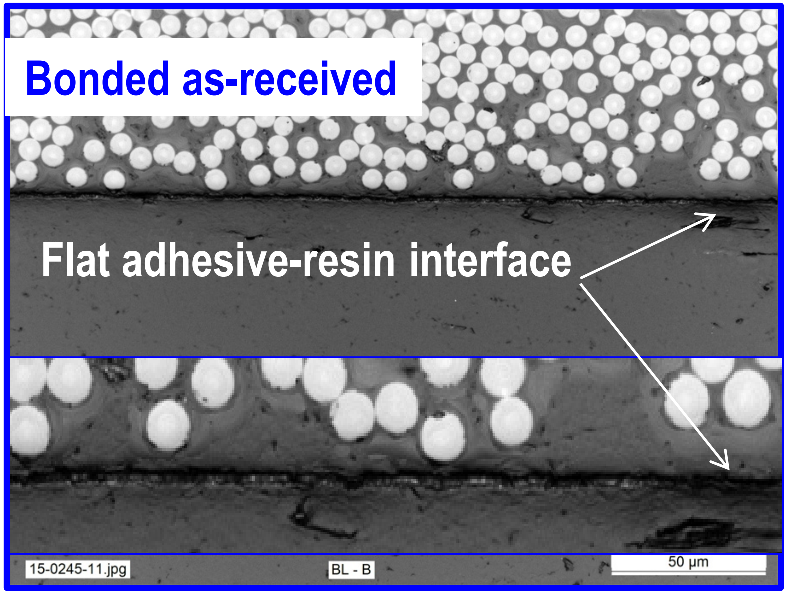


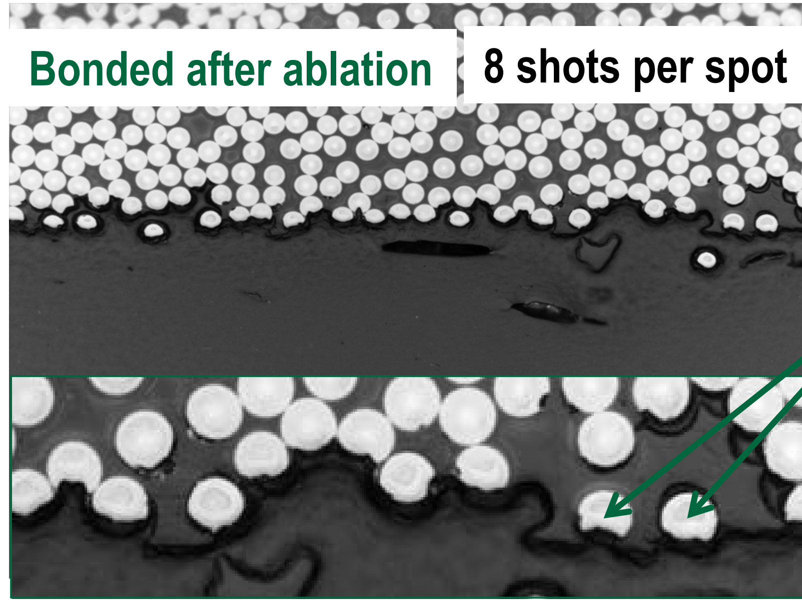
Laser Structured

After Testing

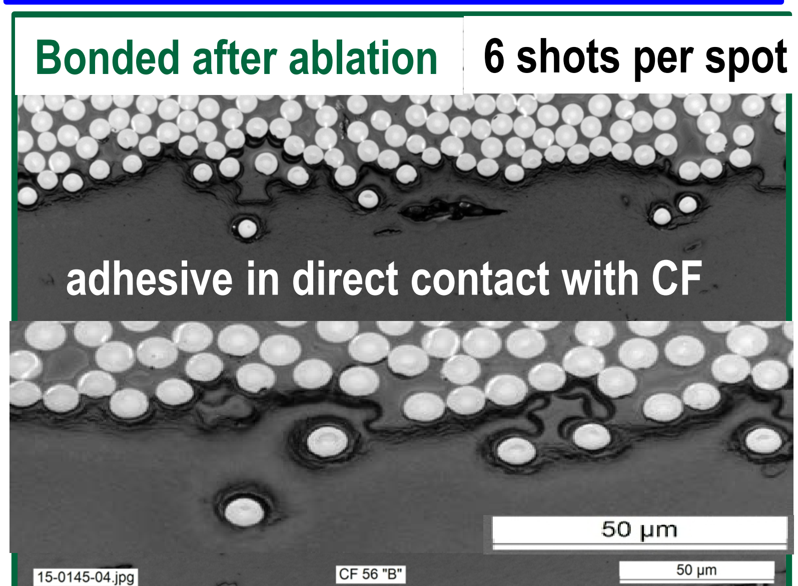
Oak Ridge National Laboratory

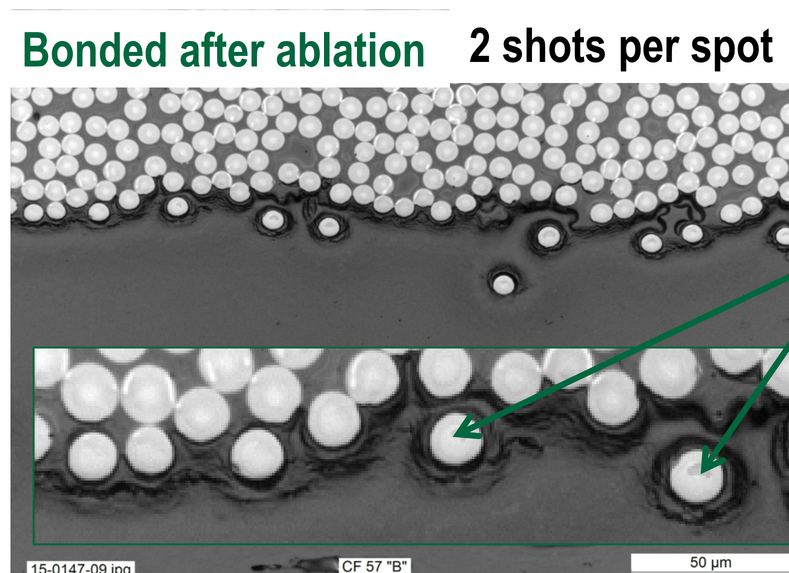
Results: Adhesive Composite Interface is Non-Planar and Fiber Reinforced.





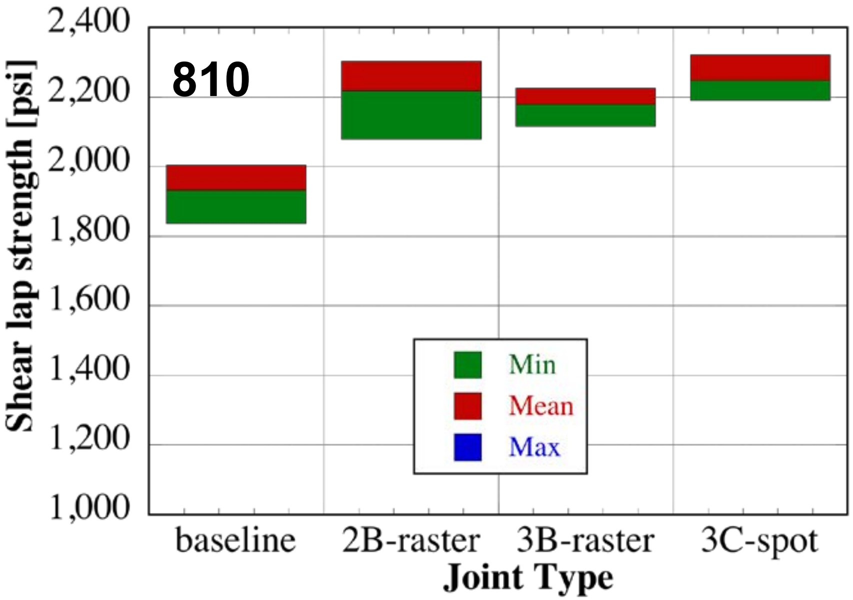
Damaged CF

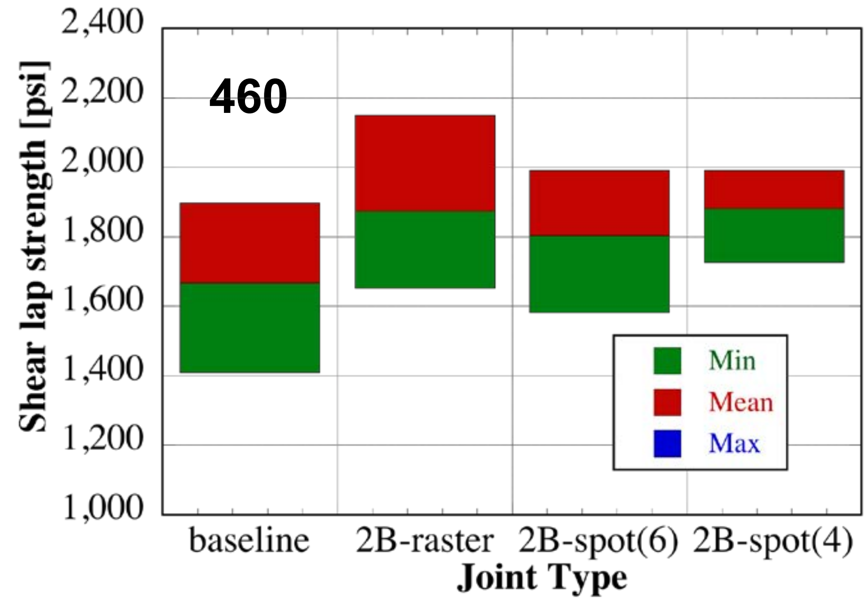




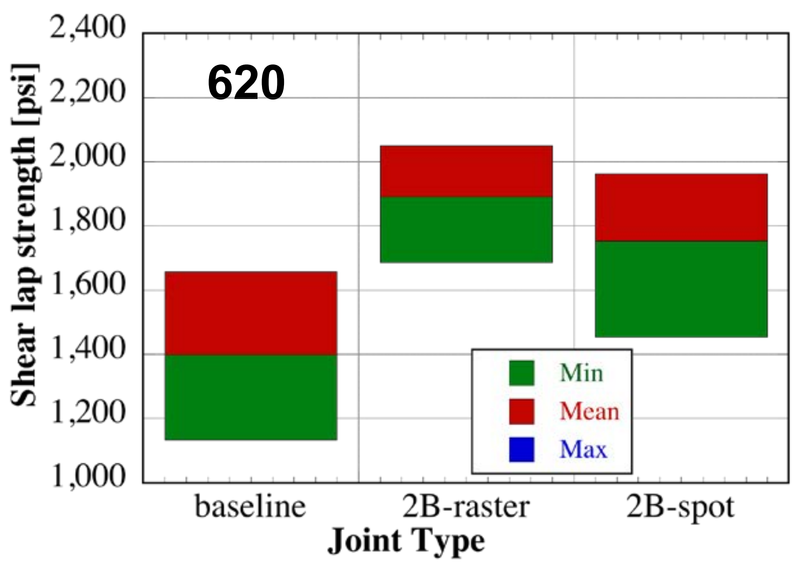
Undamaged CF

SLS strength laser structured vs Raster - all adhesives





Adhesive	% increase by raster
810	12.7-14.8
460	12.8
620	35.3



Adhesive	% increase Spot-by-spot
810	16.3
460	8.2-12.8
620	25.4

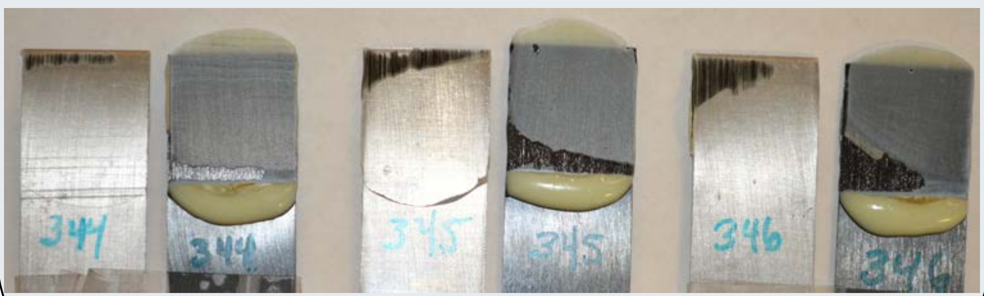
In most cases Rastering was as Effective as Spot-by-Spot

Results: Effect of Laser Structuring on Failure Mode

Baseline = No laser structuring

Clean fracture surfaces indicate poor adhesive adherence

Baseline joints: 620 adhesive



Baseline joints: 460 adhesive

Adhesive – Al Interface Failure

Laser structured joints

Both surfaces have residual adhesive

Laser-structured joints: 620 adhesive

Failure in the composite

Laser-structured joints: 460 - adhesive

Top Ply of Composite Delaminated

Failure mode changed due to laser-structuring

Discussion: Evaluated the Effects of Several Variables
(Representative Data from Large Data Sets. Processing was various conditions.)

Beam Angle (Slight Effect)

Beam Angle	Processing	% increase (of mean)
3	2B-raster	14.8
3	3B-raster	12.7
3	3C-spot	16.3
12	3B-raster	16
12	2C-raster	17.6

Beam Size: 6 mm was somewhat better

Beam size [mm]	Processing	% increase shear lap (of mean)
4	2B	14.6
4	4D	12.3
4	3C	16.5
6	4D	16.1
6	3C	17.4
6	2B	22.2

Rastering ID Number	% lap shear increase (of mean)	% load increase (of mean)
1-1b-A	10.8	14.8
2-1b-B	17.8	23.4
3-1b-C	21.2	17.8
4-1b-D	22.7	18.4
6-1b-D	23.7	20.3

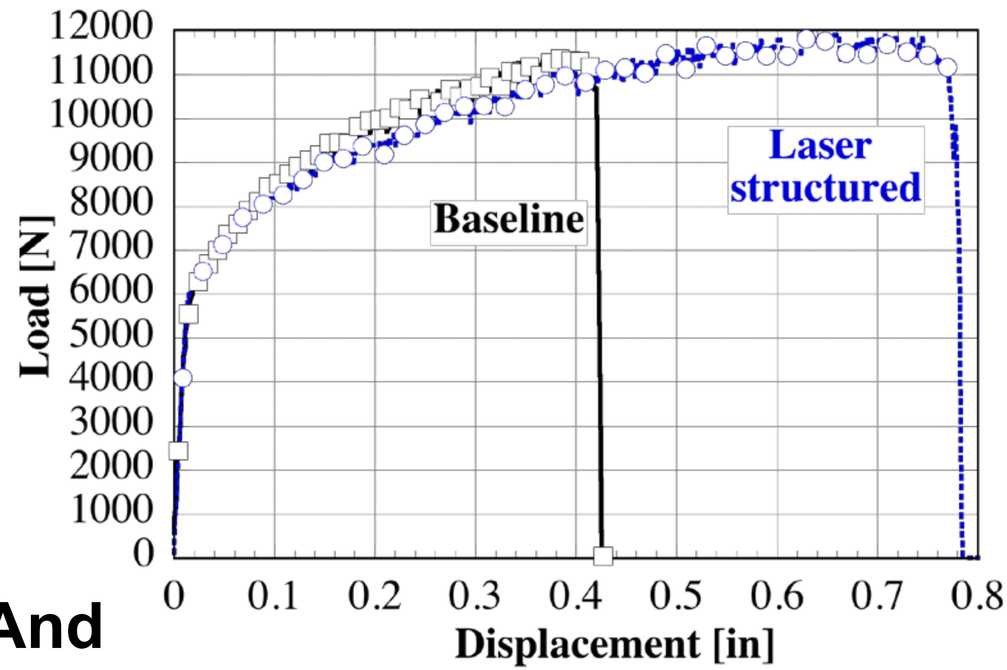
Rastering VS Interference (Some indication rastering may be better)

Interference ID Number	% lap shear increase (of mean)	% load increase (of mean)
2B_6	22.2	16.3
3C_6	19	15
4D_6	18	12.7

Results: Evaluated Double Lap Shear vs Single Lap Shear for Ablated Samples, [0.25 mm, 6mm beam, 810 Adhesive]

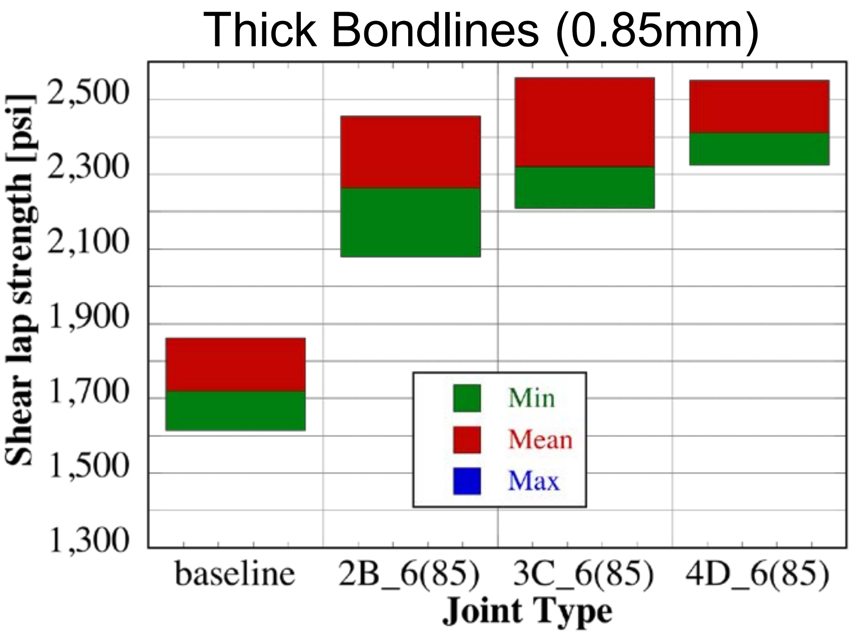
Laser Structured Samples still showed a significant increase in ductility.

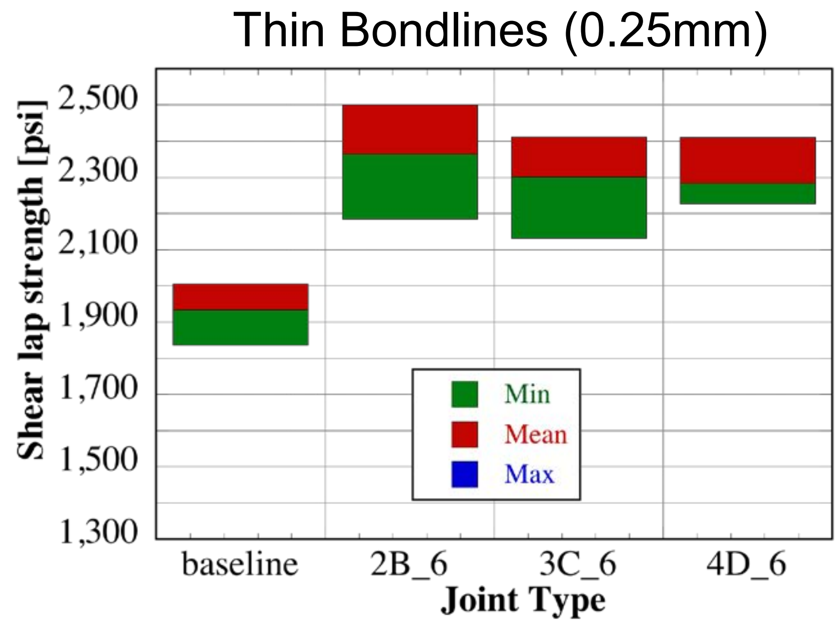
And



50% of the samples failed in the bulk of the aluminum away from the joint.

Results: Thick (0.85mm) vs Thin (0.25mm) Bondline Thickness [6mm beam, 810 Adhesive]



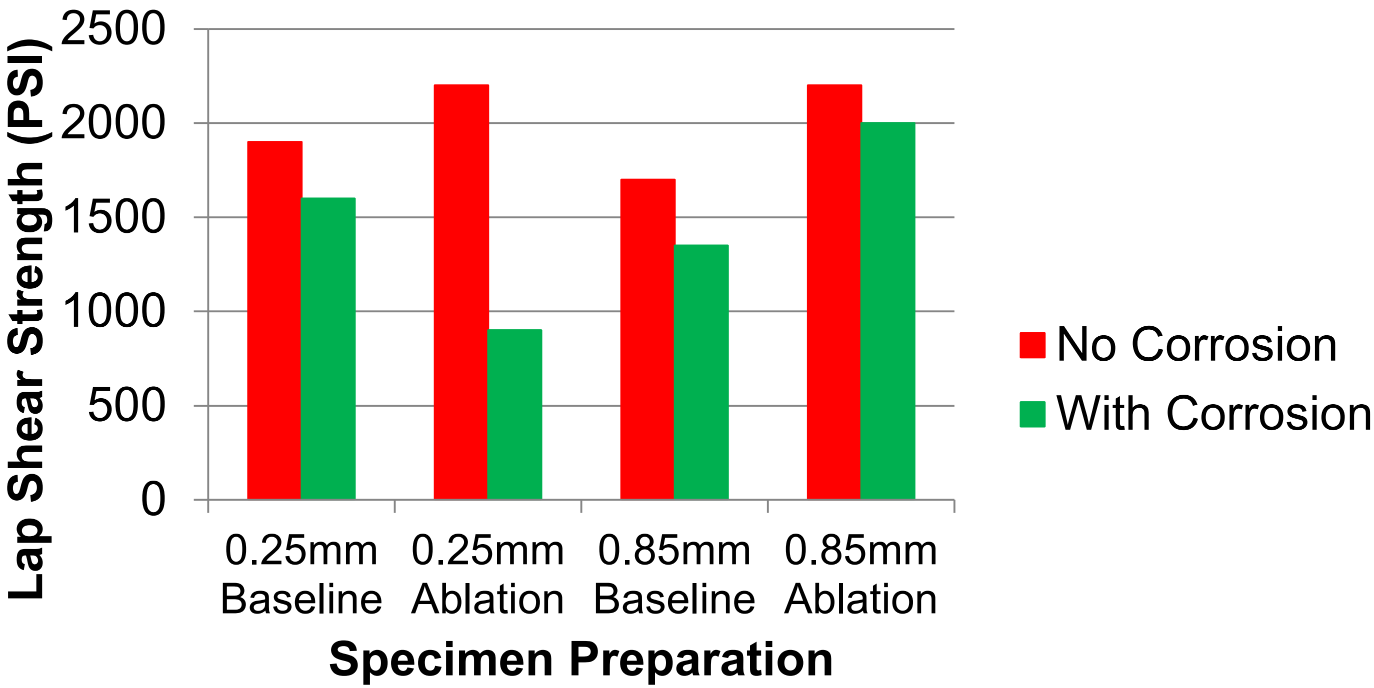


Processing	% shear lap increase (of mean)
2B-6 (.85)	31.5
3C-6 (.85)	34.8
4D-6 (.85)	40.1
2B-6 (.25)	22.2
3C-6 (.25)	17.6
4D-6 (.25)	16.0

Thick Bondlines had lower baseline strengths but improved to be equal or better than thinner bondline strengths with varying ablation conditions.

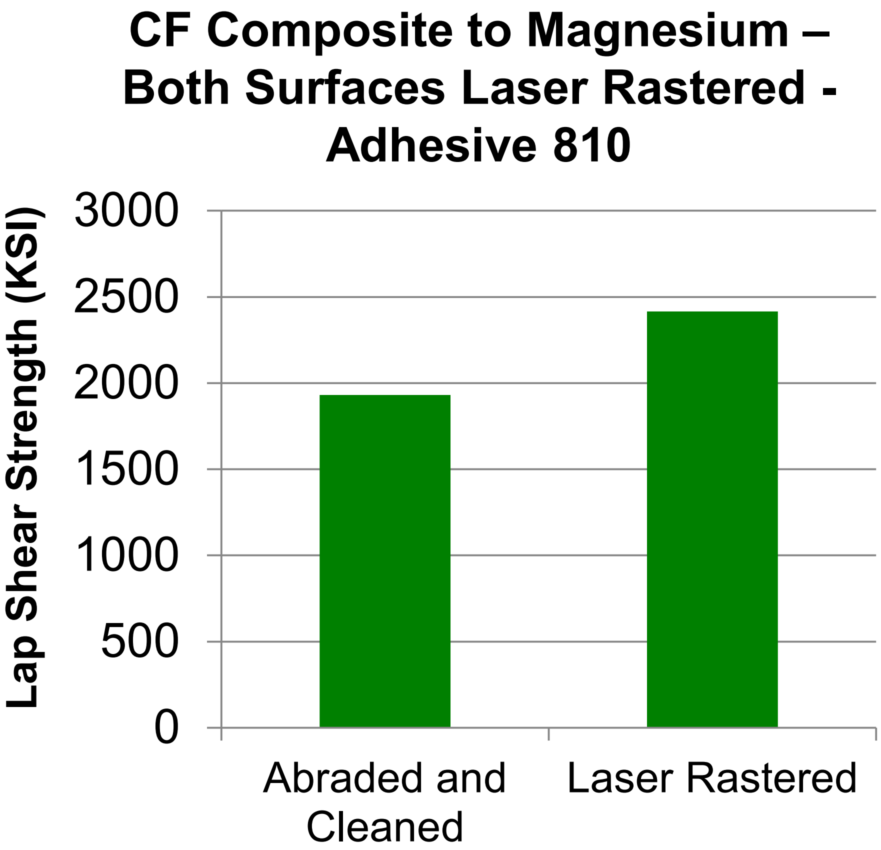
Thoughts: With ablation we are now measuring the properties of the top ply of the composite.

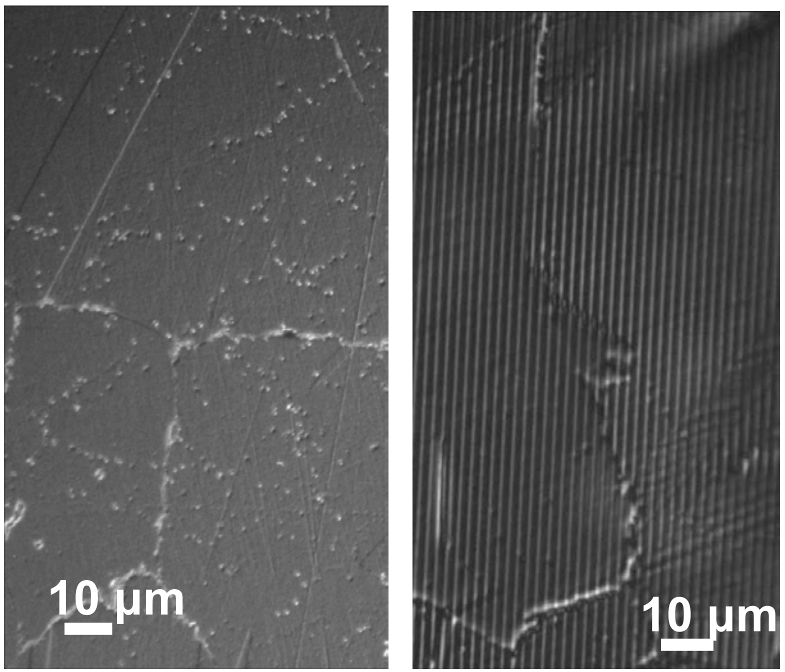
Results: Corrosion - (Single Lap Shear; Bondline Thicknesses: 0.25 mm and 0.85mm; Exposure: ASTM B117 Performed by Cosma)



1. After corrosion performance was worse for all samples. (No surprise)
2. Bondline thickness had minimal effect on the ablated samples.
3. The reduction was most dramatic for the thin bondline.
4. The reduction in strength was minimal for the thicker bondline.
5. For ablated samples, the thick bondline provided far superior corrosion resistance.
6. For Non-ablated samples the thicker bondline resulted in higher retained properties.

Discussion: Can This Approach be Extended to AHSS, Mg Alloys and other Materials? – We Believe So





As Recieved   Laser Processed

DP980

Remaining Challenges and Barriers

- Scaling to automated robotic control
- Demonstration at production intent scale.
- Assessment of corrosion for in-service parts.
- Demonstration with other material systems.

Proposed Future Work

- Scaling to include automated surface preparation and bonding operations.
- Dynamic shear lap testing of joints (different loading rates)
- 2 proposals are currently in evaluation for scaling this technology.
- Next steps:
  - A follow-on effort is needed to demonstrate the laser-assisted joining technology of composite and aluminum in a production environment.

Although not required, the project was conducted in collaboration with 3 Industrial Partners

- **The Cosma International hoses product engineering and prototype-build facilities in Troy, Michigan and Brampton, Ontario.**
  - production scale prototype capability: metal stamping, robotic welding, rivet bonding, laser cutting and CMM dimensional inspection equipment.
  - metallography & metrology materials characterization laboratory, x-ray, production scale rivet, bonding and welding, laser cutting.
- **3M's Corporate Materials Research Laboratory is capable of formulating the appropriate adhesive and testing:**
  - 3M is engaged with external vendors for the raw materials and have access to the appropriate mixing and processing equipment to manufacture adhesives.
- **Plasan Carbon Composites (PCC) is the leading Tier I supplier of carbon fiber parts and assemblies in the United States:**
  - PCC has developed a new high volume, out-of-autoclave process for Class A, structural and semi-structural components for mainstream automotive.
  - PCC is the manufacturer and supplier of the hood, roof and liftgate of the new SRT Viper, and the hood and roof (new 2014 Corvette).
  - Past parts include: fenders (Corvette Z06); hood, fenders, roof, roof bow, lower rocker moldings and front splitter (2009 Corvette ZRl); rear spoilers, front splitters, and front dive planes (2008 Viper SRT-1 0 ACR); and the splitter, hood assembly and mirror caps (2008 Ford Shelby GT500KR).

Responses to Previous Year Reviewers' Comments

1. Project need Go-No-Go Decision points. Had one which was met.

2. More realistic joint configurations would be better (i.e. peel). Agreed. This was a proof of concept project. The proposed follow-on will use production intent joint configurations.

3. Presentation needed to be clearer. The presentation style was significantly changed for the 2016 review.

4. More statistical sampling is needed. Data was given for only one coupon. It should have been clarified that a minimum of 6 samples are used for each data point reported.

Summary

- Significantly increase joint strength.
- Effective for Al and CFC and indicated applicability to other materials.
- Demonstrated using epoxy, urethane and acrylic adhesives.
- Significantly increase the surface roughness of all adherends.
- Demonstrated to effectively clean contaminates from both adherends.
- Demonstrated to remove the resin rich layer from the composite.
- Demonstrated to increase SLS sample strain by 2X
- Results in a fiber reinforced adhesive/adherend interface in composites.
- Resulted in a 12-46% improvement in SLS strength.
- Found that simple rastering is nearly as effective as spot-by-spot.
- Produced a shift in failure mode from adherend/adhesive interfacial to adherend failure.
- Little impact of beam angle was noted.
- Larger beam sizes seem to be more effective.
- Thicker bond lines had lower baseline strengths but this was mitigated by the rastering and by enhanced corrosion mitigation.
- The increase in strength was not as dramatic for DLS samples as for SLS, however the 2x increase in energy absorption was still present and the failure mode shifted to occur within the adherends.

Technical Back-Up Slides

Publications and Patents

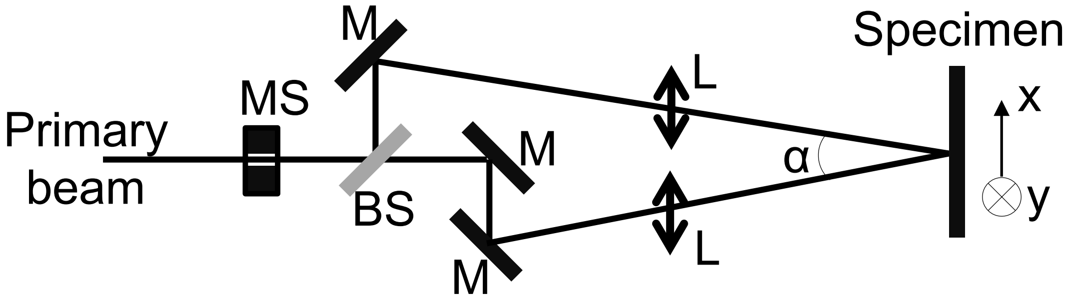
1. Sabau, A. S., Chen, J., Jones, J. F., Hackett, A., Jellison, G. D., Daniel, C., Warren, D. and Rehkopf, J. D. (2015) Surface Modification of Carbon Fiber Polymer Composites after Laser Structuring, in Advanced Composites for Aerospace, Marine, and Land Applications II (eds T. Sano and T. S. Srivatsan), John Wiley & Sons, Inc., Hoboken, NJ, USA. doi: 10.1002/9781119093213.ch23

2. J. Chen, A.S. Sabau, J. F. Jones, A. Hackett, G. D. Jellison, C. Daniel, and D. Warren, "Aluminum Surface Texturing by Means of Laser Interference Metallurgy," 2015 TMS Annual Meeting & Exhibition, Proceedings: Light Metals 2015: Aluminium Processing, pp. 427-429, Orlando, FL.

3. Provisional patent application: “Laser Nanostructured Surface Preparation for Joining Dissimilar Materials”

2 Additional Papers are in the works to be published in SAMPE and JOM.

Background: Principle of the laser interference technique



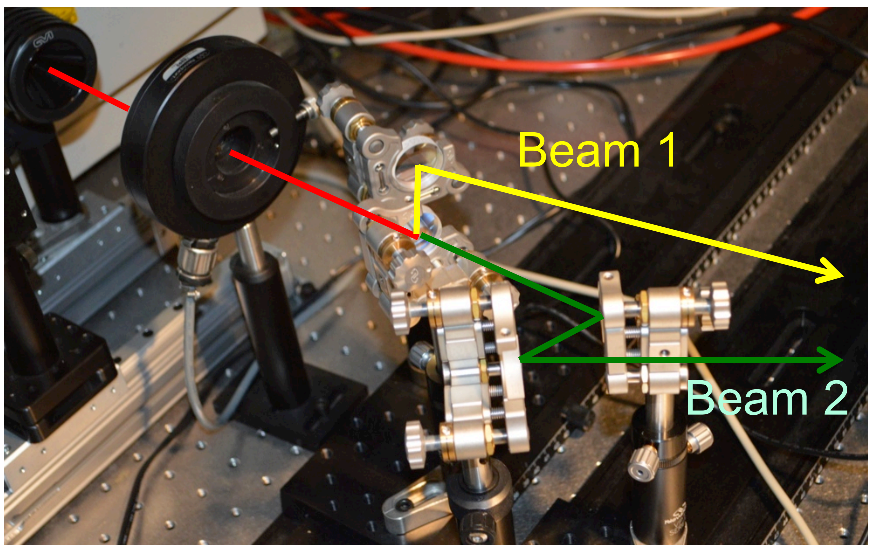
- *Wavelength λ*
- *Pulse frequency 10Hz*

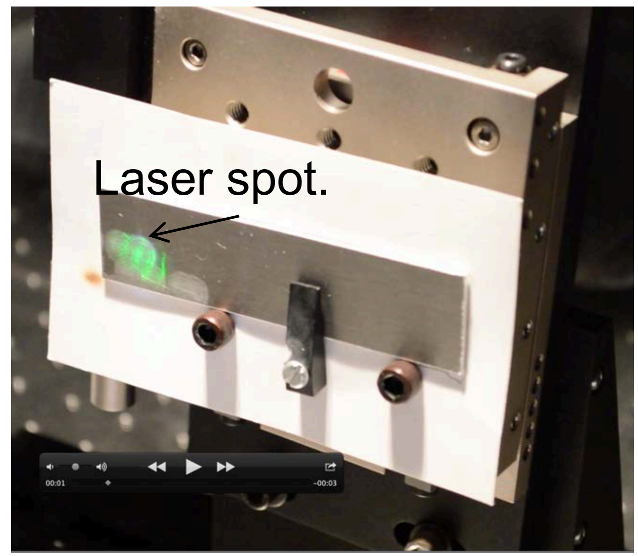
Periodic spacing formed by 2 beam interference

$$d = \frac{\lambda}{2\sin(\alpha/2)}$$

MS – mechanical shutter
BS – beam splitter

M – mirror
L – lens



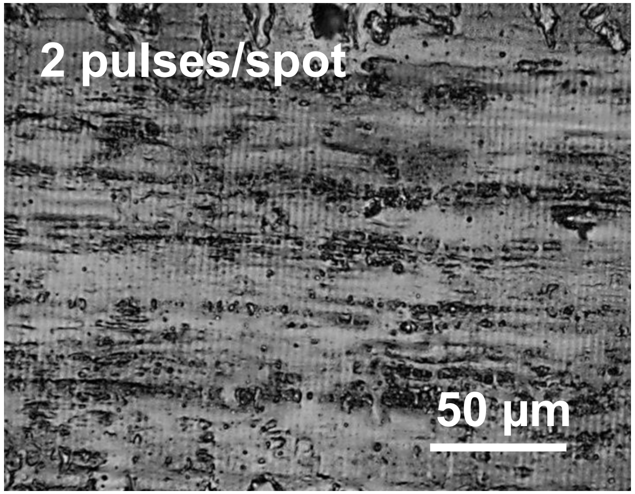


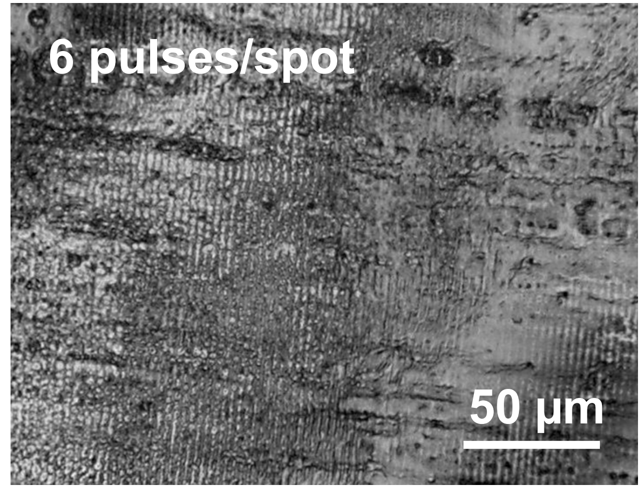
Sample mounted on a translational stage controlled by Labview.

- Q-switched Nd:YAG laser system with an harmonic generator enabling the selection of one very sharp wavelengths of 1064, 532, 355, or 266nm.
- Pulse duration 10ns (heating and cooling rates above 10^{12}K/s, frequency = 10Hz

Influence of laser wavelength

λ=266 nm and pulse fluences of 1.2 J/cm^2





λ=355 nm and pulse fluences of 1.2 J/cm^2