TAILORABLE UNIVERSAL FEEDSTOCK FOR FORMING (*TUFF*): OVERVIEW AND PERFORMANCE

Shridhar Yarlagadda[1,2], Joseph Deitzel[1], Dirk Heider[1,2], John Tierney[1], and John W. Gillespie Jr.[1,3]

1) Center for Composite Materials, Newark, DE 19716
2) Electrical &Computer Engineering Department, Newark, DE 19716
3) Department of Materials Science and Engineering, Department of Civil and Environmental Engineering, Department of Mechanical Engineering, Newark, DE 19716

ABSTRACT

Under the Defense Advanced Research Projects Agency (DARPA) Tailorable Feedstock for Forming (TFF) program, the University of Delaware - Center for Composite Materials (UD-CCM) led-team proposed to develop a manufacturing process and pilot facility to produce novel discontinuous carbon fiber composite feedstock for forming, with the potential to revolutionize the use of composite materials, as a cost-effective replacement for small complex geometry metal parts (<2 sq. m.). The *TuFF* (Tailored Universal Feedstock for Forming) feedstock consists of a highly aligned discontinuous carbon fiber preform in thin-ply format, which can be combined with thermoplastic or thermoset resins for prepreg, or used in dry form for infusion-based manufacturing processes. A patent-pending discontinuous fiber alignment and preforming process has been developed and implemented in a pilot facility at UD-CCM. The alignment process is fiber agnostic and *TuFF* preforms have been manufactured with aerospace grade fiber (IM7, T800), pitch carbon fiber, and recycled carbon fiber. Using discontinuous IM7 carbon fiber and Polyetherimide (PEI) thermoplastic resin, TuFF composites with aerospace quality requirements (<1% voids, up to 63% fiber volume fraction) have demonstrated 100% translation of fiber stiffness and strength in tension, and >40% bi-axial in-plane strain capability during forming. The in-plane stretchability of *TuFF* preforms enables conformability of simple planar preforms to complex geometries, eliminating the need for darting and complex ply patterns while minimizing associated scrap during composite layup. Closed-loop recycling and reuse strategies are possible for the first time with the ability to reuse fiber and preform scrap, prepreg scrap and recycled composite parts.

1. INTRODUCTION

Advanced composite materials offer high specific stiffness and strengths, which are attractive for a number of commercial applications that are weight critical. Beginning with use in the aerospace and military sector, they are now being adopted in a number of commercial sectors, such as transportation, energy, marine, sporting goods and healthcare. Advanced composite materials generally consist of a reinforcement in fiber form (e.g. carbon fiber), in a polymer matrix with the manufacturing processes developed to create appropriate microstructures for desired properties of interest. Continuous fiber reinforcements are most commonly used, and carbon fiber has become the fiber of choice; however material cost and manufacturing challenges have limited widespread adoption.

Discontinuous fiber composites can alleviate manufacturing challenges by enabling sheet metal like processing [1] and reduce cost with the use of lower cost fiber feedstock, especially with the increase in recycled carbon fiber (discontinuous) that is now available in the market [2]. The use of discontinuous fiber has been long evaluated from a theoretical perspective with idealized microstructures (e.g. perfectly aligned fibers); however realistic microstructures differ significantly from idealized assumptions [1]. Manufacturing processes for discontinuous fiber composites typically result in random to aligned microstructures, with significant variability in microstructural parameters [1]. The ideal discontinuous fiber microstructure is highly aligned with well-controlled fiber spacing in all three directions, which has been predicted to have properties equivalent to continuous fiber systems when the aspect ratio is sufficiently high (e.g. 1000:1).

1.1 State of the Art in Discontinuous Fiber Composites

A recent overview of the history of aligned discontinuous fiber composites provides a comprehensive assessment of alignment processes and associated composite performance. Broadly, two ranges of fiber lengths have been evaluated: long discontinuous fibers (inch scale), and short fibers (mm scale), with a range of performance metrics documented. Figure 1 shows mechanical performance achieved using prior methods [3] for tension properties on an Ashby Chart, for the range of mm scale processes which retain high degree of formability.

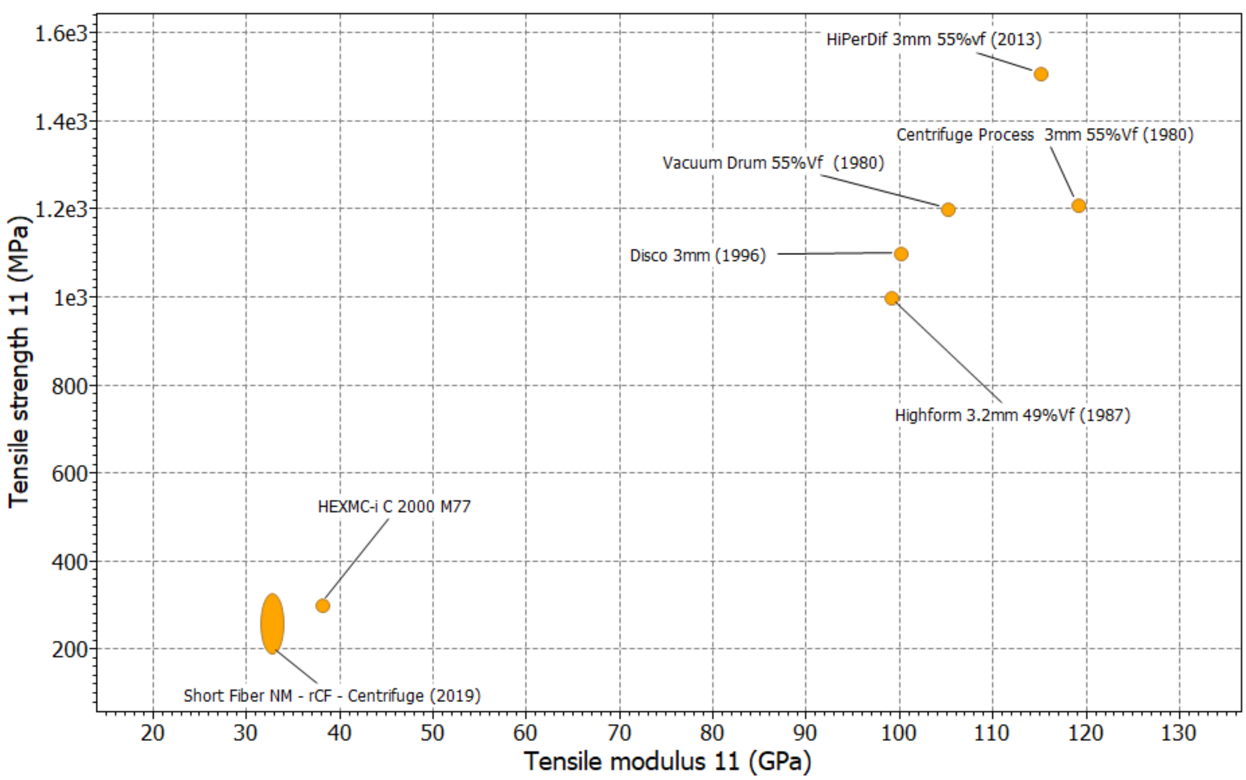

Figure 1: Asbhy Chart for tension performance of short fiber composite materials

Short fibers have been the focus of the most recent effort in the United Kingdon (UK) under the HiPerDif program [4], with the highest volume fraction, modulus and strengths achieved to date.

Nevertheless, the tensile strength translation remains significantly below continuous fiber properties. Long discontinuous systems have demonstrated better performance translation, with the Stretch-Broken Carbon Fiber (SBCF) process achieving properties similar to continuous fiber systems. However, the longer fiber lengths (50 mm average) and broad fiber length distributions pose significant challenges from a forming and repeatability perspective. Formability is driven by the effective viscosity of the discontinuous fiber/polymer system and proportional to $(L/D)^2$, where L is fiber length and D is fiber diameter [5], and the longer lengths govern processability and thus exponentially increase forming pressures. What is needed is a short fiber system (mm-scale) that retains formability with equivalent properties to continuous fiber systems.

2. *TUFF* PROGRAM OVERVIEW

Under the DARPA TFF program, the University of Delaware - Center for Composite Materials (UD-CCM) led-team proposed to develop a manufacturing process and pilot facility to produce novel discontinuous carbon fiber composite feedstock for forming, with the potential to revolutionize the use of composite materials, as a cost-effective replacement for small complex geometry metal parts (<2 sq. m.). The goal of *TuFF* (Tailored Universal Feedstock for Forming) program (Figure 2) was to develop a feedstock consisting of a highly aligned discontinuous carbon fiber preform in thin-ply format, which can be combined with thermoplastic or thermoset resins for prepreg formats and tailored blanks, or used in dry format for infusion-based processes.

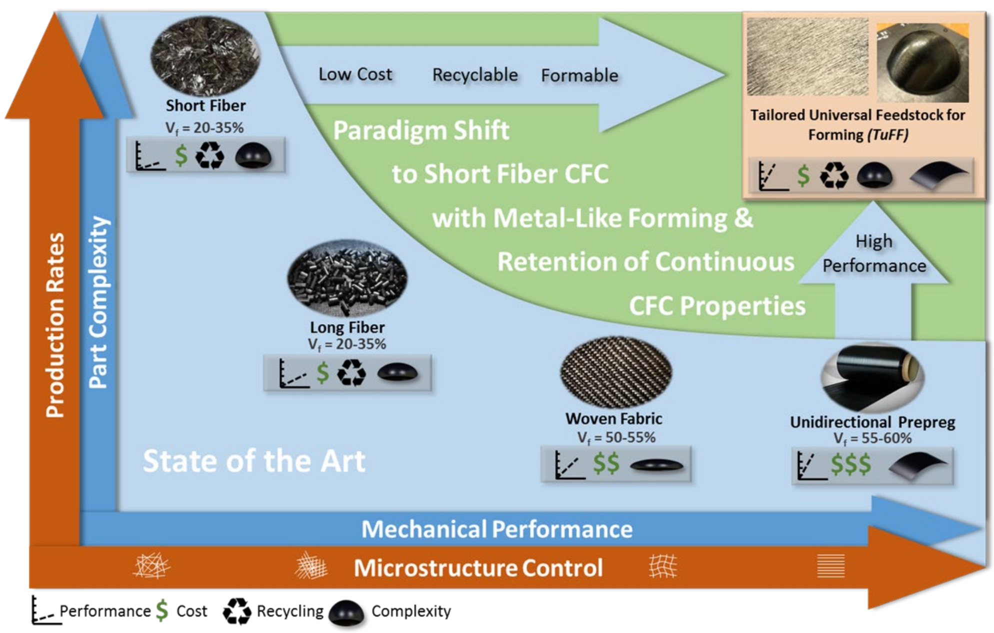

Figure 2: TuFF program proposes to achieve continuous fiber equivalent properties using highly-aligned discontinuous fibers while retaining metal like formability.

A patent-pending discontinuous fiber alignment and preforming process has been developed and implemented in a pilot facility at UD-CCM. The alignment process is fiber agnostic and *TuFF* preforms have been manufactured with aerospace grade fiber (IM7, T800), pitch carbon fiber, and recycled carbon fiber. Key metrics established in the program include:

- *TuFF* composite performance equivalent properties to continuous fiber (IM7/8552)
- *TuFF* microstructural control for properties and forming
  - Very high degree of alignment: ~ 95% (± 5°)
  - Fiber Length and Aspect Ratio control: Uniform and narrow length distribution
  - High Fiber Volume Fraction (>57%)
- *TuFF* composite formability like sheet metal (>40% in-plane extension)

The program is focused on short IM7 fiber (mm-scale) in combination with an engineering thermoplastic (PEI Ultem 1000) assess mechanical performance and formability. Fiber length and aspect ratio control was achieved by cutting continuous IM7 fiber to precise lengths, in the range from 1 to 7 mm lengths, with initial focus on 3 and 5 mm fiber lengths (aspect ratios of 600 and 1000).

2.1 TuFF Preform Characteristics

The patent-pending alignment process produces highly-aligned short fiber preforms with controllable Fiber Areal Weight (FAW) in thin-ply format, with results for 8gsm FAW 3mm IM7 short fiber documented in this paper. Fiber length distributions in these preforms have been measured pre- and post-alignment (Figure 3) and show no degradation in fiber length, meet alignment quality specifications and uniformity in FAW (within 3%). Eight (8) gsm FAW was selected for composite fabrication, performance and formability assessment, with mechanical performance results documented in the following sections. Additional microstructural details are documented in the paper on microstructural characteristics [6].

Composite Fiber Volume Fraction (FVF) was controlled through a resin film infusion approach, where the ratio of FAW and resin film thickness can be precisely controlled for the desired FVF. For example, 8 layers of 8 gsm FAW *TuFF* plies (total of 64 gsm) can be combined with 1 mil film of PEI for an effective FVF of 58.6% (8:1 build ratio). Similar methodologies can also be applied for thermoset resin systems with film-based prepreg processes. Resin film infusion process is then performed in the autoclave under typical process conditions, dependent on the resin selected. The overall approach is shown in Figure 4 below, providing a means to either fabricate thin-ply formats (30-60 gsm range) or standard prepreg FAW formats for thermoplastic and thermoset resin systems.

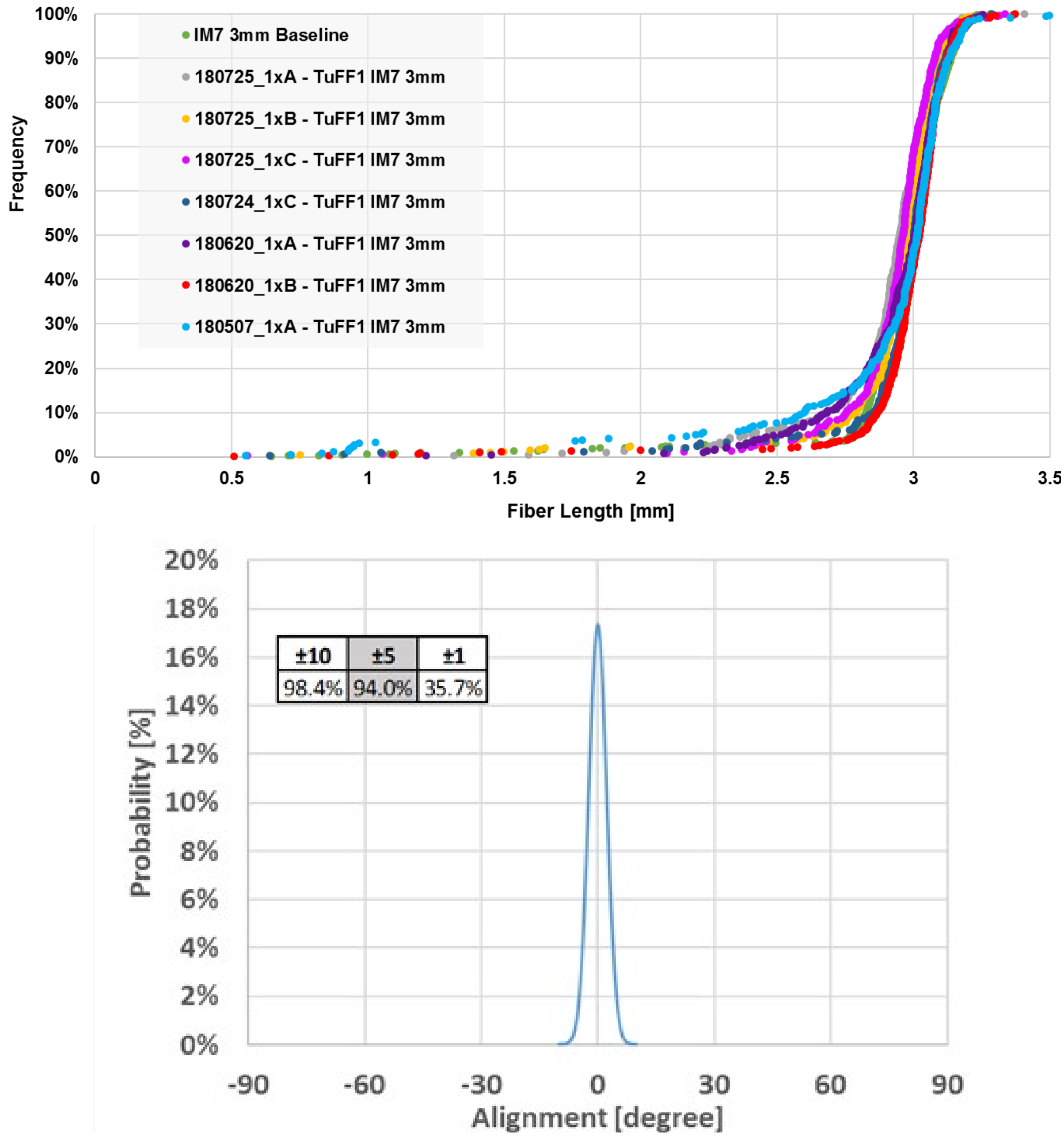

Figure 3: *TuFF* preforms show no fiber length degradation during alignment and achieve high alignment quality

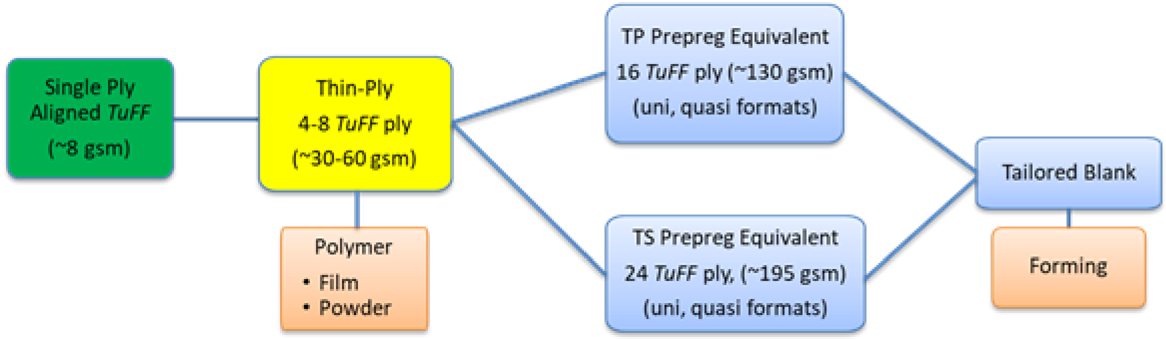

Figure 4: *TuFF* preforms and formats for thermoset and thermoplastics

3. *TUFF* MECHANICAL PERFORMANCE

High quality composite laminates were fabricated with 3 mm IM7 fibers from highly-aligned discontinuous fiber preforms and autoclave processing, for tension performance assessment. Five panels were fabricated over three run batches (one, two and two respectively) with FVF ranging from 52% to 63%. Ratios of *TuFF* preform layers to PEI film were adjusted to achieve the FVF range, and ranged from 7:1 to 9:1 build ratios, with total panel thicknesses in the ~0.2 mm range. This represents a range of 24-28 *TuFF* plies in the panels depending on the build ratios. Autoclave cycles were based on PEI process cycles, with a 4 hour soak at 335 C under vacuum and a consolidation pressure of 20.7 bar, with an initial 2 hour drying step to ensure removal of any trapped moisture. The extended soak was implemented to ensure complete resin impregnation of the preform. All autoclaved panels underwent ultrasonic scans, thickness mapping and cross-section microscopy for quality assessment. Figure 5 shows cross-section microscopy images of the 52% and 63% FVF *TuFF* samples, note the high degree of fiber alignment.

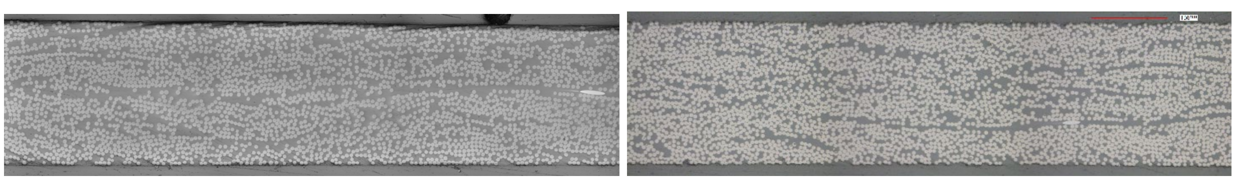

Figure 5: Cross-section microscopy images for 52% FVF (left) and 63% FVF (right) showing highly aligned *TuFF* short fiber microstructure

Mechanical tests were performed per ASTM D 3039 test procedure and data reduction, though at a shorter gage length (~3 inches). Back-to-back bi-axial strain gages were used to track possible asymmetry in the composite coupons and strain data was averaged between the two gages for data reduction. To address any potential concerns with the sample geometry used in tension testing of the *TuFF* composite panels, an equivalent 2-ply AS4/PEI composite panel (similar geometry and thickness) was also fabricated in the autoclave and tested. Test specimen configuration for the 2-ply AS4/PEI composite was identical to the *TuFF* composite panels.

Tension test results are summarized in Table 1 below. IM7/8552 and AS4/PEI (Cytec) are commercially available prepreg systems, results for IM7/8552 were obtained from the NIAR published dataset [7] and the AS4/PEI prepreg were from prior test data generated in-house for a carbon fiber thermoplastic production program. The 2-ply AS4/PEI prepreg composite panel shows similar results to the standard ASTM D 3039 configuration tension test data, alleviating any concerns with the modified geometry for the tension test.

All the 3mm results were averages of 5 samples, and show 100% modulus translation over the 52-63% FVF range. This is to be expected as theoretical predictions have indicated full translation for Aspect Ratios > 100. Tensile strengths for *TuFF* composites are equivalent to both continuous fiber systems (weighting for FVF), while also exhibiting very good variability metrics despite hand layup of thin-ply preforms. Note the consistency across three different batches, as evidenced by their manufacturing dates. A true baseline comparison would be with IM7/PEI prepreg; however this is not a commercially available system. Studies are underway to evaluate other thermoplastic (e.g. PEEK) and thermosets (e.g. 8552 epoxy) with *TuFF* preforms. Stress-strain curves are shown for one of the tested samples (180724_1xB_8:1) in Figure 6 showing the expected linear stress-strain behavior without any evidence of load drops prior to ultimate failure. Figure 6 also shows an example of longitudinal strains measured by back-to-back strain gages, demonstrating material symmetry and lack of bending. All *TuFF* samples showed similar stress-strain behavior. Failure modes were similar to continuous fiber with explosive failure modes characteristic of high tensile strength material.

Comparison to literature shows significant improvement over state of the art for short fiber composites, as shown in Figure 7. The HiPerDif process [4] demonstrated 55% FVF with 115 GPa modulus (16.7 msi) and 1510 MPa strength (219 ksi) with C124 3mm short fiber from Toho Tenax, with claimed efficiencies of 91% for modulus and 80% for strength, and an alignment metric of 67% ±3 degrees. *TuFF* composites show equivalent properties to continuous fiber (100% efficiency for modulus and strength, Table 1), while retaining the formability of 3mm short fiber lengths. Tests are underway for additional resins, as well as other mechanical properties of interest (e.g. compression, short beam shear, notched).

Table 1: Uniaxial Tension Results for *TuFF* Composites compared to Continuous Fiber systems

Sample	Fiber	Length (mm)	Resin	E_{11} (GPa)	CV (%)	X_T (MPa)	CV (%)	ε_{11}	FVF
IM7/8552	IM7	Cont	8552	**162**	**2.27**	**2558**	**4.1**	**1.58%**	**57.30%**
180507_1xA_6:1	IM7	3	PEI	**143**	1.61	**2255**	2.01	1.51%	52%
180620_1xA_8:1	IM7	3	PEI	**168**	1.46	**2503**	3.19	1.42%	61%
180620_1xB_9:1	IM7	3	PEI	**173**	1.71	**2668**	2.96	1.49%	**63%**
180724_1xC_7:1	IM7	3	PEI	**161**	1.36	**2579**	3.67	1.51%	**58%**
180724_1xB_8:1	IM7	3	PEI	**168**	1.78	**2551**	5.86	1.48%	**61%**
Commercial (Cytec)	AS4	Cont	PEI	**134**	1.3	**2406**	4.8	1.64%	55.5%
Cytec AS4/PEI 2-ply	AS4	Cont	PEI	**137**	5.46	**2289**	7.82	1.54%	55.5%

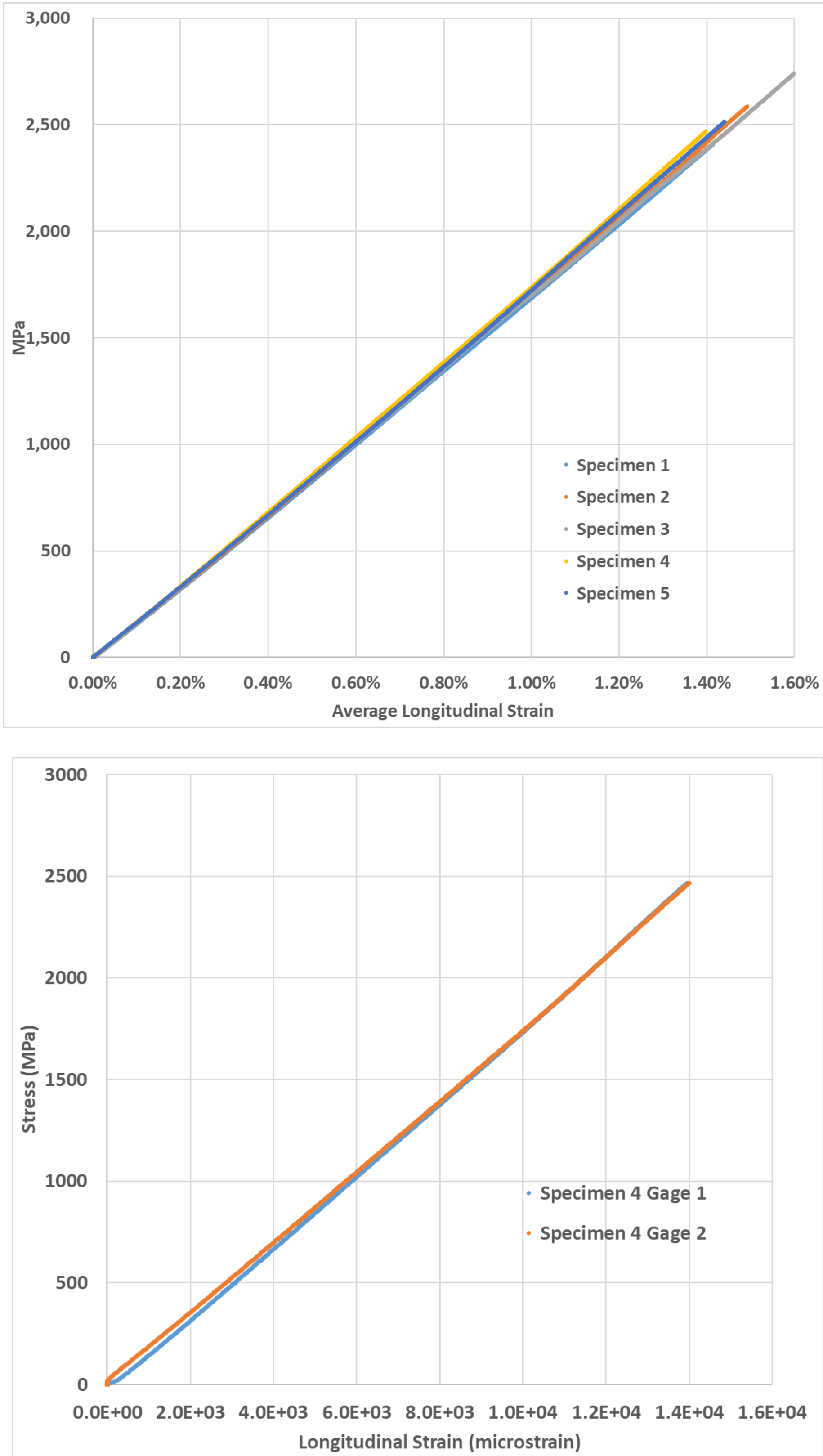

Figure 6: Stress-strain curves for the 5 specimens tested in 180724_1xB_8:1 (top) and individual back-to-back gages for Specimen 4 (bottom).

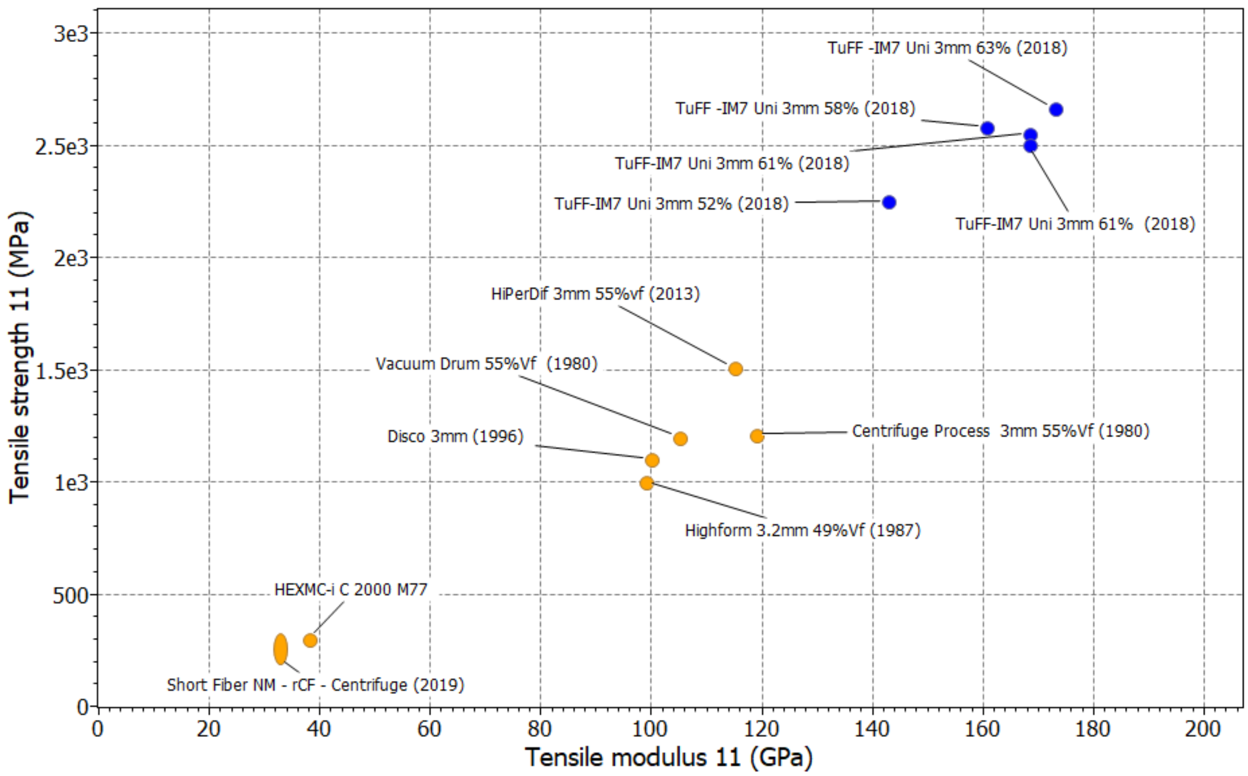

Figure 7: Comparison of *TuFF* mechanical performance to short fiber composites

4. *TUFF* ADVANTAGES

The highly-aligned microstructure of *TuFF* preforms enable several unique capabilities that are discussed briefly in the sections below.

4.1 Formability

TuFF enables sheet-metal like formability due to highly homogenous microstructure (Figure 5) and control of fiber length. Fiber length measurements in Figure 3 show low coefficient of variation with 90% of the fibers within 2.8-3.2 mm with an average fiber length of 3.0 mm. The uniformity in length and short fiber length compared to long discontinuous formats that have shown good property translation (e.g. SBCF) enables significantly lower effective viscosities resulting in much lower forming pressures. Figure 8 shows a comparison with SBCF for fiber length distribution (left) and forming stresses (right). Forming pressures for TuFF are based on effective viscosity calculations which are dependent on $(L/D)^2$.

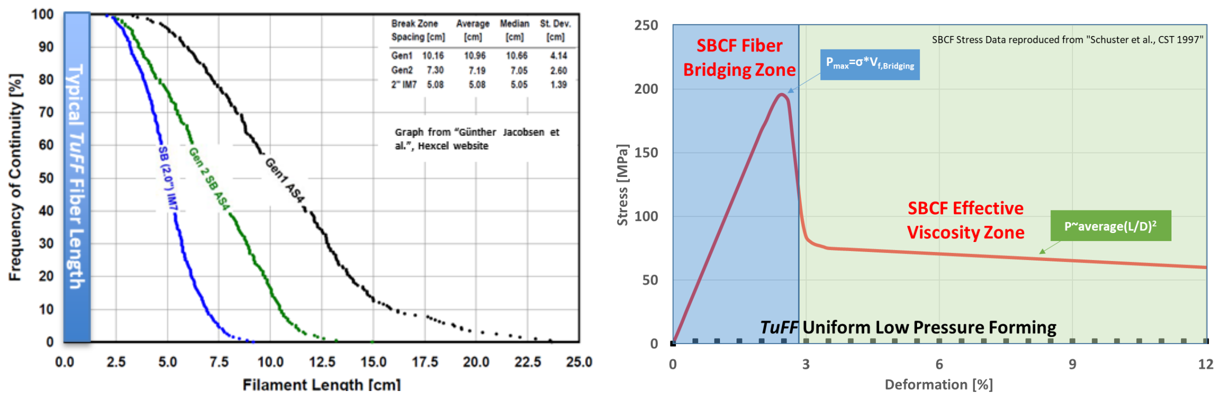

Figure 8: Comparison of fiber length uniformity with SBCF (left), and forming stress (right). Forming stress values for *TuFF* are calculated based on effective viscosity model [9].

4.1.1 Dry Preforming with TuFF

The in-plane stretchability of *TuFF* preforms enables conformability of simple planar preforms to complex geometries, eliminating the need for darting and complex ply patterns while minimizing associated scrap during composite layup. Figure 9 shows an example of a single preform that conforms to high strains (40% strain) and local small radii features (ribs). The same geometry with a conventional continuous fiber fabric preform results in edge pull-in and bridging at complex features. This is typically overcome by either complex ply patterns or the use of lower performing chopped fiber processes (e.g. injection molding or SMC).

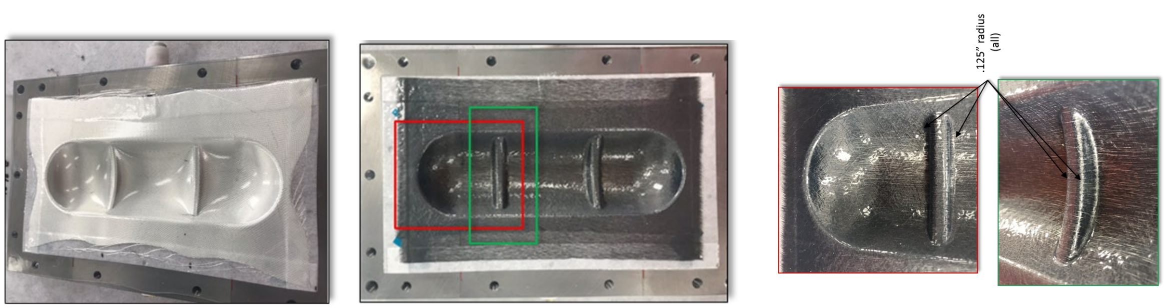

Figure 9: *TuFF* formability with composite blanks (left) and dry preforms (middle, right)

4.1.2 Composite Forming with TuFF

Composite laminates with 3mm IM7/PEI were fabricated as described previously and used as blanks for composite forming experiments. Details of forming experiments on *TuFF* composite blanks and are presented in a separate paper [8]. Figure 10 shows a snapshot of a challenge complex geometry part that was vacuum formed with a cross-ply 24 layer composite blank (same thickness as tension panels), demonstrating the potential for TuFF feedstock for formed complex geometry parts.

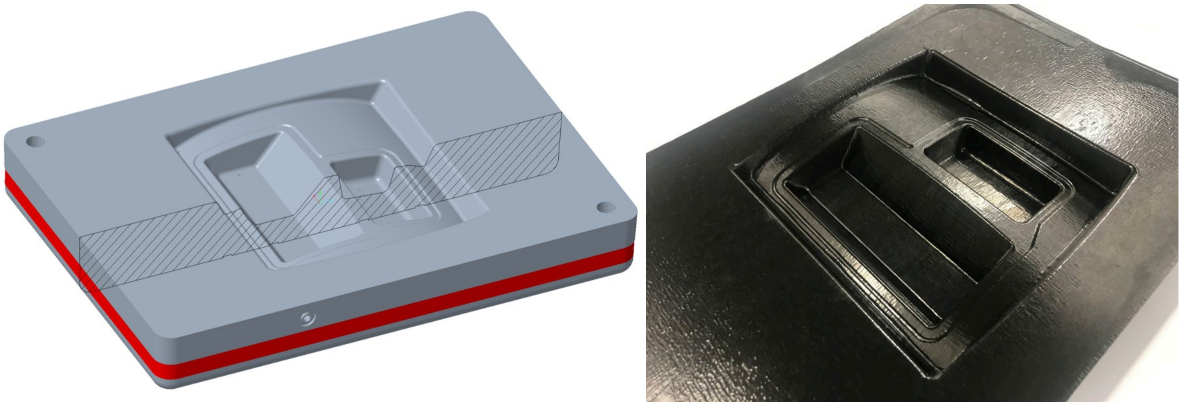

Figure 10: Demonstration of a vacuum formed complex geometry TuFF composite part with 3mm IM7/PEI blank with clamped boundaries. Effective maximum strain is 40%.

4.2 Recycling

The ability to create highly-aligned preforms with properties equivalent to continuous fiber systems fills a key need for the composite recycling industry. This enables true re-use and recycling of carbon fiber composites, as compared to the downcycling strategies currently in use. A key requirement is the need for controlled fiber lengths to ensure uniform microstructures in the aligned formats and this must be addressed by the recycling industry. Recycling demonstrations were performed with *TuFF* process and are presented in a separate paper [9].

4.3 Additive Manufacturing Feedstock

Additive manufacturing is seeing increasing use of short fiber reinforcements to improve part performance. As shown in Figure 8, *TuFF* composite performance far exceeds any additive manufacturing feedstock that is currently available in the market. *TuFF* in short fiber prepreg tape format provides a unique combination of composite performance and manufacturing flexibility, with short fibers enabling steered deposition paths. This applies to both additive manufacturing as well as tape placement (which is also an additive process) for large-scale structures.

5. CONCLUSIONS

As part of the DARPA TFF program, UD-CCM has demonstrated a process (*TuFF*) to create highly-aligned discontinuous fiber preforms that have demonstrated equivalent properties in tension to continuous fiber systems. TuFF composites comprised of 3mm IM7 fiber with PEI as the thermoplastic resin have demonstrated tension performance equivalent to continuous fiber, FVF as high as 63%, while retaining in-plane stretchability of up to 40%. TuFF has the potential to enable true re-use/recycling of carbon fiber composites, create highly drapeable dry preforms for complex geometries, enable metal-like stamp forming, and as a high performance feedstock for additive manufacturing.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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