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Oak Ridge National Laboratory: Relevant Additive Manufacturing Materials for Wind Industry

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Energy Transportation Sciences Directorate
Manufacturing Sciences Division

RELEVANT ADDITIVE MANUFACTURING MATERIALS FOR WIND INDUSTRY

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ABBREVIATIONS

(In the order of occurrence in the document)

AM	Additive Manufacturing
LFAM	Large Format Additive Manufacturing
BAAM	Big Area Additive Manufacturing
MVP	Magnum Venus Products
ASTM	American Society for Testing and Materials/ ASTM International
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactic acid
PS	Polystyrene
PE	Polyethylene
PC	Polycarbonate
PA	Polyamide
PPS	Polyphenylene sulfide
PPSU	Polyphenylsulfone
PESU	Polyethersulfone
PEI	Polyetherimide
PEEK	Poly ether ether ketone
PEKK	Poly ether ketone ketone
CF	Carbon Fiber
GF	Glass Fiber
ORNL	Oak Ridge National Laboratory
TPU	Thermoplastic polyurethane
CTE	Coefficient of Thermal Expansion
PETG	Polyethylene terephthalate glycol
T_g	Glass transition temperature
HGM	Hollow glass microspheres
FGM	Functionally graded materials
MDF	Manufacturing Demonstration Facility
DSC	Differential Scanning Calorimetry
TGA	Thermogravimetric analysis
DHR	Discovery hybrid rheometer
LCR	Laboratory capillary rheometer
ILSS	Interlaminar shear stress
DMA	Dynamic mechanical analysis
TMA	Thermo mechanical analysis
DIC	Digital image correlation
UTK	University of Tennessee Knoxville
FCMF	Fibers and Composites Manufacturing Facility
ECM	Extrusion compression molding
IM	Injection molding

ABSTRACT

The purpose of this report is to equip wind industry professionals with the relevant material testing procedures and printed material properties of large format extrusion-based additive manufacturing processes. This report has been generated through the course of WETO project 1.5.0.40X – 3D Printed Blade Core Material, which aimed to assess alternative materials and additive manufacturing strategies in the making of the core of a wind turbine blade. Currently the most common materials used for blade core are balsa and structural foams. Market projections of blade production show large increases in the number and size of blades produced over the coming decades. However, balsa is grown in a limited geographic area, which implies a limited supply rate. This research project has been motivated by supply chain constraints on current materials, and potential improvements to recyclability and further light-weighting opportunities for blades and other sandwich core components. Discussion on the printability and processing of different classes of materials (i.e. low temperature, high temperature, thermoplastics, elastomeric, foam, etc.) is provided as well as relevant test standards and methods. Existing results for materials and properties are detailed. The materials discussed are specific to existing extrusion-based large scale additive manufacturing processes and may also be relevant for use in wind turbine components other than blades. A companion document titled "Additive Manufacturing Design Guidelines for Wind Industry" covers the seven families of additive manufacturing, the relevance of each family to manufacturing large scale components for the wind industry, and design guidelines and considerations for the most relevant processes. While large scale additive manufacturing processes identified as relevant in the design guidelines companion document include processes from four additive families, the material extrusion-based polymer processes implemented on the Big Area Additive Manufacturing (BAAM) platform and Magnum Venus Products (MVP) platform are the focus of this document as they are the most well-developed and well-documented to date at the scale relevant to blade core structures.

1. OVERVIEW OF MATERIALS FOR LARGE-SCALE EXTRUSION ADDITIVE MANUFACTURING (AM)

Large format additive manufacturing (LFAM) of polymers and composites has been possible with a variety of thermoplastics and their reinforced composites, as well as thermoset polymeric materials. Successful printing of parts with desired properties on extrusion based LFAM platforms primarily depends on feed material properties, material behavior at processing conditions, part geometry, print parameters and environment. Several thermoplastic composites have been successfully printed on the Big Area Additive Manufacturing (BAAM) system and their properties have been evaluated for intended applications. Likewise, reactive extrusion using thermoset polymers has been possible using the MVP Thermobot system. In this document, we first outline different materials that have been developed for large scale extrusion-based printing and are relevant to 3D printed wind turbine blade core applications. Mechanical properties and densities of some of the printed materials evaluated using the ASTM standards typically used in AM are discussed. Testing standards relevant to the current application, test plans, and results from relevant tests conducted for this project are also documented here.

Table 1 provides a list of some thermoplastic composites processed on BAAM, along with relevant publications on large-scale printing and properties evaluation of these materials.

Table 1. Materials used for printing on the BAAM system.

Material Class	Thermoplastic Matrix	Fillers	References (From ORNL)
Low temperature	Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polystyrene (PS), polyethylene (PE), polycarbonate (PC), Polyamides (PA6)	Carbon fiber (CF), glass fiber (GF)	[1-6]
High temperature	Polyphenylene sulfide (PPS), polyphenylsulfone (PPSU), polyethersulfone (PESU), polyetherimide (PEI), poly ether ether ketone (PEEK), poly ether ketone ketone (PEKK)	Carbon fiber	[7-16]
Bio-derived materials	Polylactic acid (PLA)	Bamboo, flax, wood flour, micro cellulose, poplar fibers	
Elastomers	Thermoplastic polyurethane (TPU)- rigid and flexible grades		
Foams	Low temperature matrix (ABS, PLA, PS), Elastomers (TPU)	Carbon fiber	[17]
Magnetic materials	Polyamides (PA6, PA12)	NdFeB powder	[18, 19]
Multi-materials printing	Low temperature matrices: Polymer blends, foams, functionally graded materials (with and without fillers)	Carbon fiber glass fiber	[20]

1.1 PRINTABILITY & PROCESSING [21]

The development of a variety of new materials that can be successfully printed for structural and multi-functional applications involves a fundamental understanding of ‘what makes a material printable?’. Although several of these materials are often processed using traditional manufacturing techniques such as injection and compression molding, extrusion, thermoforming, etc., processing them through an extrusion AM platform, followed by deposition onto a print bed in ambient environment, requires knowledge of the relevant process-structure-property relationship for each material system. For a successful print, the material should first be dispensed out of the extruder nozzle, then form a stable deposited bead, and finally be able to form a stable structure which makes up the desired component. As a methodical approach towards characterizing the printability of a material, Duty et.al. developed a simple, practical viscoelastic model for evaluating the printability of various polymer feedstock materials [2, 3]. The model describes a fundamental set of print conditions based on certain viscoelastic and thermo-mechanical properties of polymers measured using small quantities of materials in a controlled test environment. The primary conditions for successful printing of a material have been classified into four different print criteria: material extrusion, bead formation (geometry), bead functionality, and component functionality, as shown in Figure 1.

For material extrusion, pressure-driven extrusion of the material must occur through an orifice of a given geometry at a certain specified flow rate (Criteria Ia and Ib in Figure 1). The pressure required by the material to flow must be below the system limit. For fiber-reinforced systems, there can also be potential fiber entanglement leading to restricted flow and clogging of the nozzle during the print. For these systems, the fiber volume fraction is also accounted for while estimating the pressure drop to achieve a desired throughput, and this value must again be lower than the maximum system pressure.

Once the material is dispensed through the nozzle, the next criteria require the material to form a stable bead of a semi-rectangular geometry, having a consistent height and width (Criteria IIa in Figure 1). The free-standing height of the deposited bead should be at least the spacing between the substrate and the nozzle (i.e., the bead height). This free-standing height depends on melt density of the deposited material and the surface energy of the material, which is dependent upon the material in contact. If the free-standing height of a material is lower than the desired bead height, then the material will not be able to form a consistent bead, i.e., the material would flow too freely from the nozzle without achieving the desired bead height. In addition to the formation of a semi-rectangular bead, the deposited bead must also remain geometrically stable over time, typically for the duration of the processing time (Criteria IIb in Figure 1). The material should be able to support the entire weight of the bead (can be calculated as a simple hydrostatic pressure) during the print layer time and at the deposition temperature. The extent of deformation of the material subjected to this hydrostatic pressure over time is dependent on the viscoelastic characteristics of the material, ranging between that of an elastic solid and a viscous liquid.

The third criteria, bead functionality, calls for the extruded material to be able to successfully bridge an unsupported gap (often required while printing structures with sparse in-fill patterns and complex geometries with overhangs) (Criteria IIIa), serve as a substrate for subsequent layers (Criteria IIIb), and provide a strong foundation for building tall structures with a significant number of layers (Criteria IIIc). The successful bridging of a gap is evaluated by determining the time required to achieve a certain permitted level of deflection in the bead. For substrate support functionality (IIIb), it is essential to have the total stress on the substrate material be lower than the yield stress of the extruded material at T_g for thermoplastics, and in a partially cured state for thermosets. In addition, the elastic strain of the substrate should also be below a certain defined limit. For successful printing of tall structures (IIIc), the criteria are similar to that of substrate support, but also account for the number of deposited layers in the structure. Overall, for bead functionality criteria, factors such as bead geometry, print conditions, and extruded material's viscoelastic and thermo-mechanical properties play a critical role.

The fourth criteria in the printability model describes the functionality of the entire printed component. For each substrate layer, the printed component should maintain some degree of dimensional stability and integrity (Criteria IV in Figure 1). Deformation and residual stresses induced in the part due to thermal contractions during printing can become more significant as the size of the printed structure increases. The coefficient of thermal expansion (CTE) of the material and the thermal profiles encountered during printing play a critical role in determining dimensional changes to the part. For printing a part without significant distortion, the printability model defines a quantity, distortion ratio, which is the ratio of structure deformation to the layer height. A distortion ratio greater than unity implies that the previously deposited layers have deflected more than the layer height, thereby physically preventing subsequent material deposition. The printability criteria for cracking (Criteria IVb) are defined based on stresses at the bead interface relative to the interfacial bond strength.

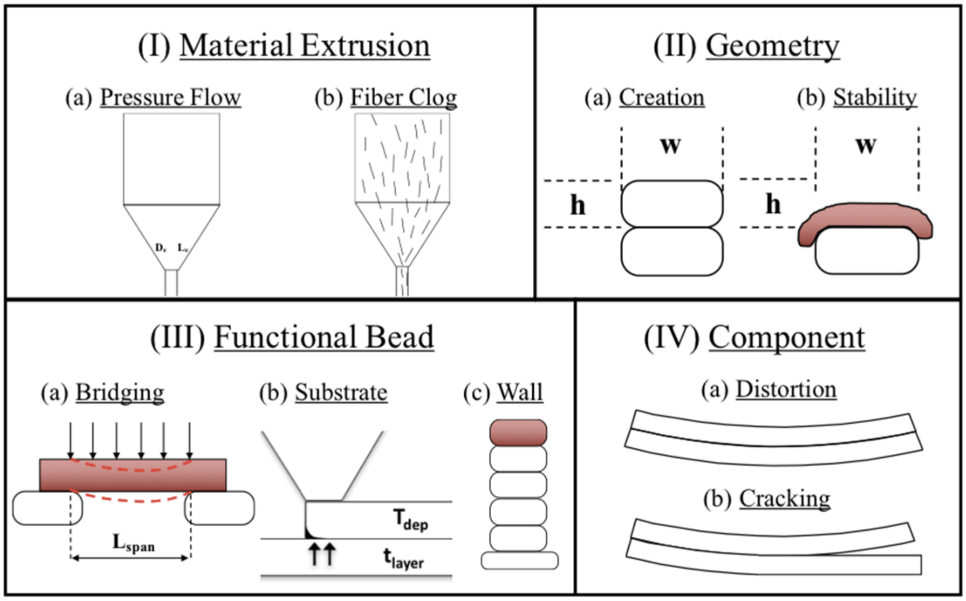


Figure 1. Primary conditions for successful printing, classified into four different print criteria: (I) Material extrusion, (II) Bead geometry, (III) Bead functionality, and (IV) Component functionality [2].

2. CLASSES OF MATERIALS RELEVANT TO THE PROJECT: OVERVIEW

2.1 LOW TEMPERATURE THERMOPLASTICS AND COMPOSITES: LARGE SCALE PROCESSING

In general, low temperature thermoplastics and composites are selected for their ease of processing at large scale, low cost, and good mechanical performance. Composites of low temperature thermoplastic matrices such as ABS, PLA, PS, PETG, etc. are often employed for applications below the glass transition temperature (T_g) of these materials. Fillers often used with the materials include carbon fibers, glass fibers, as well as bio-derived materials such as bamboo, wood flour, poplar fibers, micro cellulose, poplar fibers, flax, and nanocellulose, etc. For this work, one of the candidate materials chosen for validating in the characterization program developed is 20 wt.% carbon fiber reinforced ABS (20CF/ABS). This is one of the most commonly used materials for large scale printing and can be used for printing parts using a variety of nozzle sizes, with diameters ranging from 2.54 mm to 10.16 mm (0.1in to 0.4 in), with throughput close to 45 kg/hr (100 lb/hr). In addition, adding fillers such as CF with negative CTE helps lower the overall CTE of the composite, thereby reducing warping and distortion while printing large structures. From a printability standpoint, adding fillers increases the shear thinning behavior of composite melts during processing. This enables a wider processing window, especially for printing parts at high flow rates. The maximum filler loading for a given thermoplastic matrix depends on factors such as viscoelastic properties of the matrix material, shape factor of fillers, wettability of fillers (for good filler-matrix interaction), and viscoelastic properties of the composite to be able to extrude the material at the desired throughput. For CF/ABS, the commonly used filler content is 10-20 wt.% and for GF/ABS, filler loadings vary from 10-30 wt.%. For bamboo filled PLA, maximum filler loading has been 40 wt.%.

2.2 FOAMS AND MULTI-MATERIAL PRINTING: LIGHT-WEIGHTING

ORNL developed and patented strategies to successfully print thermoplastics and their composites-based lightweight foams on large format AM platform [22]. Two types of printable foams have been developed, namely, syntactic foams, and foams using blowing agents such as expandable microspheres. Syntactic foams contain lightweight fillers such as hollow glass microspheres (HGM) and weight reduction is caused by the porosity enclosed inside these thin stiff shells of particles (Figure 2). Syntactic foams have been shown to reduce the density of parts by about 30-35%. Different compositions of syntactic foams, typically containing the thermoplastic matrix, a filler such as CF or GF (if needed) and hollow glass microspheres, are typically pre-compounded and produced in the form of pellets suitable for printing from material suppliers such as Techmer PM. A change in composition in this case would require compounding a new grade of material at the supplier's facility. Syntactic foams are closed cell foams, and they offer uniform foaming upon extrusion and the printed parts also offer good mechanical performance. The maximum HGM loading is limited by the extrudability of the material based on its viscoelastic properties in the melt state. The filler loadings of syntactic foams successfully extruded on the BAAM have varied between 10- 50 vol.%.

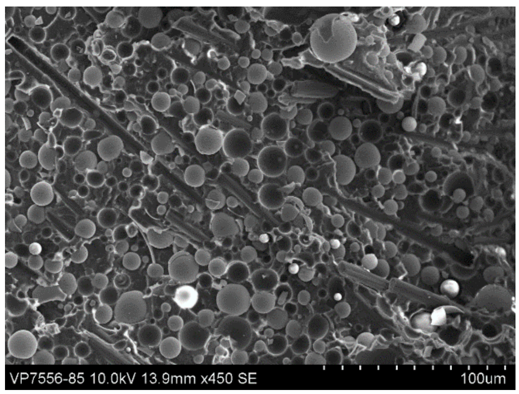


Figure 2. SEM of ABS syntactic foam containing hollow glass microspheres.

The second foaming method is using blowing agents such as expandable microspheres, as shown in Figure 3. These microspheres are commercially available blowing agents in the form of pellets which can be blended with any of the low temperature thermoplastic or composite pellets used for printing on the BAAM using a gravimetric blender, as shown in Figure 4. Expandable microspheres comprise of a thermoplastic polymer shell encapsulating a low boiling hydrocarbon. When subjected to heat from the extruder, the thermoplastic shell softens and the gas expands, causing an increase in volume (Figure 5, Figure 6). Using these blowing agents, printing foams with density as low as 0.2 g/cm^3 has been possible on the BAAM system. The density achievable depends on several parameters such as the properties of matrix material, fillers, concentration of blowing agent, processing temperature and shear rates, nozzle size, etc. Increasing nozzle size or screw speed during processing typically leads to increased bead size and porosity (lower density). However, the surface quality of the bead deteriorates, as observed in Figure 7. Processing conditions, blowing agent loading, matrix material type, etc. will have to be chosen such that the foam is printable with the desired bead quality, and at the desired throughput rate.

Figure 3. Expandable microspheres pellets (as received) [Photo from: https://www.nouryon.com/products/expancel-microspheres/blowing-agents/].

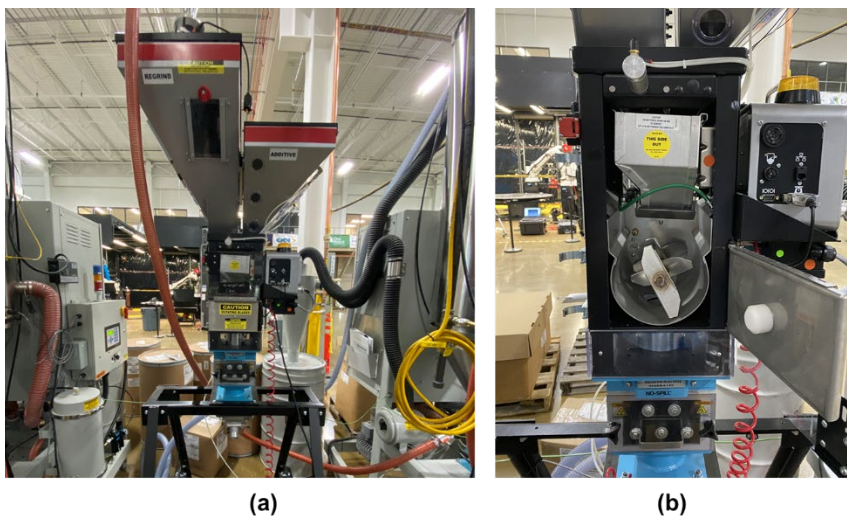


Figure 4. (a) Gravimetric blender connected to the BAAM, (b) Mixing chamber in the blender.

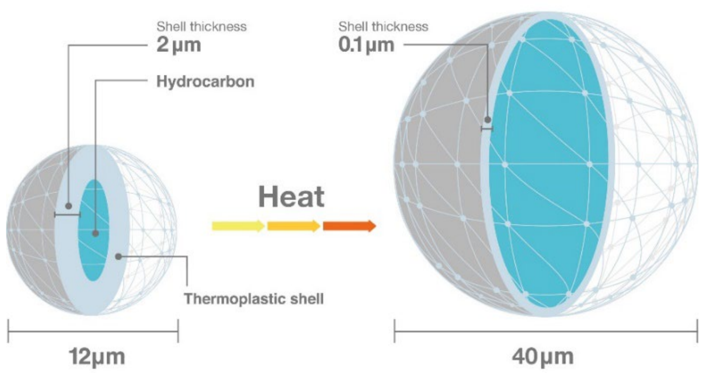


Figure 5. Mechanism of foaming using expandable microspheres. Image from: https://www.nouryon.com/products/expancel-microspheres/blowing-agents

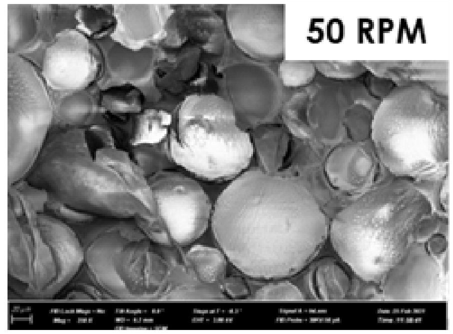


Figure 6. SEM micrograph of PLA foam bead extruded on the BAAM using expandable microspheres as blowing agent.

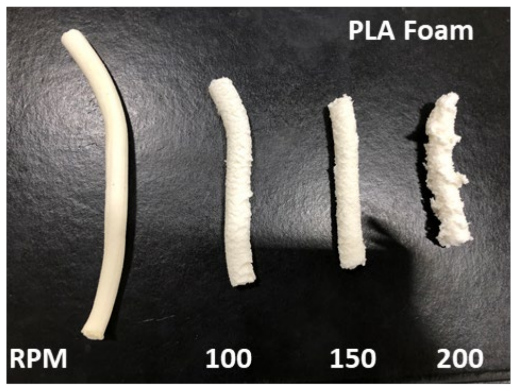


Figure 7. PLA foam extrudates showing the effect of screw speed on bead size and surface quality. Blowing agent: Expandable microspheres (4wt.%).

In addition to the ability to print lightweight foams as well as a variety of other reinforced composites, the BAAM system also has a unique multi-material printing capability. The dual feed hopper set-up, pictured in Figure 8, enables switching between two materials on the fly, thereby enabling continuous printing of structures involving multiple materials. The transition region, i.e., the region with mixed material composition in the extruder can be incorporated into the part to obtain functionally graded material (FGM) structures or can be purged out periodically in case the part printed demands site-specific deposition of materials. The purge time is typically 0.5-2 min. Figure 9 shows the two dryers and the blender connected to the BAAM to feed materials for multi-material printing. The combination of materials chosen for a multi-material build depends on the desired properties and functionality for end-use application and must be such that they are melt processable in a similar temperature range and have good rheological and chemical compatibility. Some examples of multi-material printing demonstrations are shown in Figures 10-12.

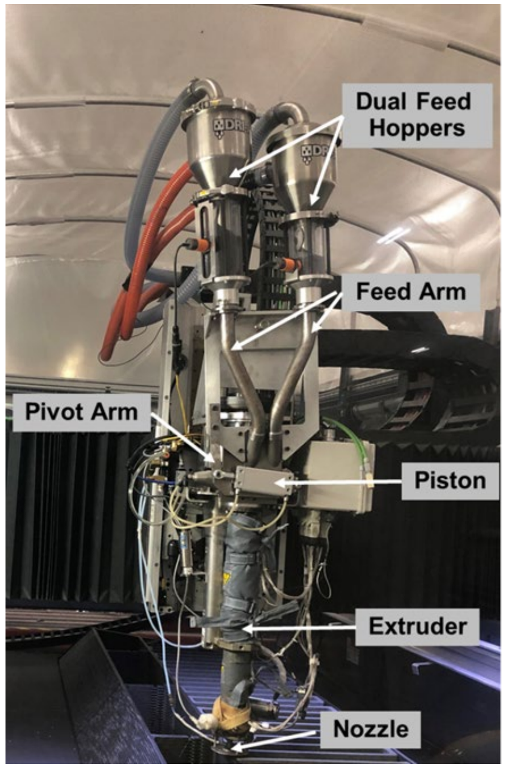


Figure 8. Dual feed hopper set-up on the BAAM to enable multi-material printing.

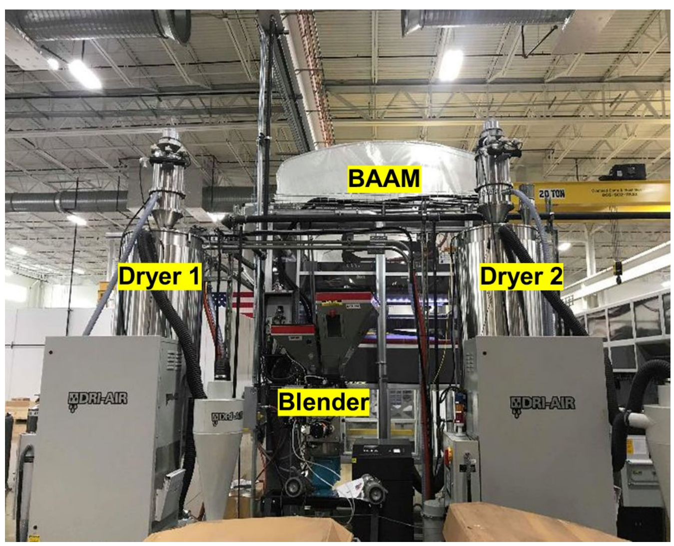


Figure 9. Dryers and blender connected to the BAAM to enable multi-material printing.

Figure 10. A demonstration of multi-material printing of complex structures using bio-derived materials.

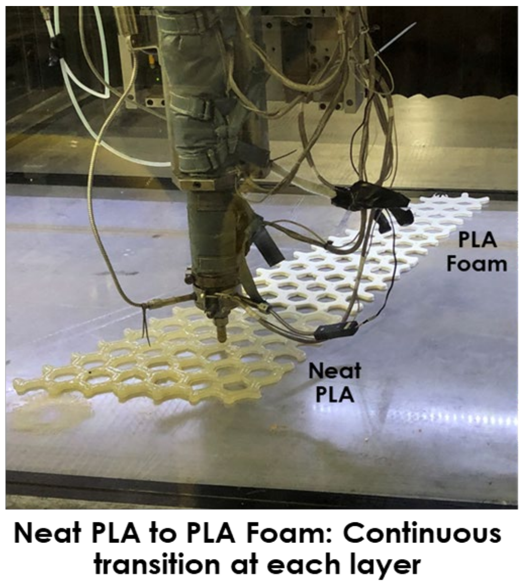


Figure 11. Demonstration of continuous printing of functionally graded structures.

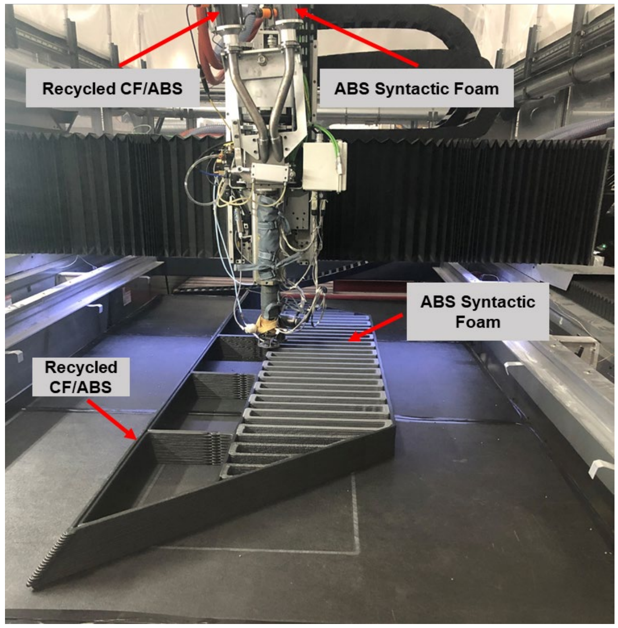


Figure 12. A tool being printed using recycled CF/ABS and ABS syntactic foam.

2.3 RECYCLED MATERIALS

There exists a growing interest in zero waste processes, and the incorporation of post-industrial and post-consumer materials into other newly manufactured components to lower the cost and environmental impact of composite processing. LFAM of thermoplastic composites is potentially a viable platform for such applications as it uniquely enables low volume production of highly customized components. Currently, the use of recycled materials for AM and other composite processing techniques is one of the core areas of research at ORNL. For preliminary developmental work, recycled material feedstock was obtained by compounding shavings obtained by milling composite AM parts. The shavings were re-compounded into BAAM-compatible feed pellets at a Techmer PM facility. Two materials were explored for initial mechanical properties characterization work, namely, CF/ABS and CF/PC. Using recycled feedstock can alter printability and the part's mechanical and thermal performance when compared to non-recycled or virgin feedstock due to the variations in filler shape factor, matrix material chemistry, viscoelastic properties of the melt during processing, etc. caused by the reprocessing step. In addition to obtaining recycled pellets from industry partner, capabilities are also being developed in-house at the Manufacturing Demonstration Facility (MDF) at ORNL for recycling/reprocessing thermoplastics and composite parts. Water-jet cutter, shredder, granulator, and twin-screw extruder are some of the equipment available in-house for reprocessing composites.

3. TESTING STANDARDS & CAPABILITIES

To determine material suitability for wind blade core applications, testing methods were considered to accurately evaluate how an additively manufactured part would behave in a sandwich composite configuration representative of a wind turbine blade. Constraints specific to both additive manufacturing processes and sandwich construction composites for wind blade applications informed the selection and development of testing methods. This section discusses the testing and characterization methods used for additive materials and components for the properties of interest to the project.

3.1 ASTM STANDARDS FOR AM PARTS

For AM parts printed on large-scale systems, material characterization comprises of testing both the feed pellets as well as the printed components for specific applications. Properties of feed materials such as chemical structure, melt rheological properties, specific heat capacity, thermal conductivity, density, thermal degradation onset temperature, glass transition and melting temperatures, etc. play a crucial role in determining factors such as maximum throughput (in turn related to print time), nozzle size, thermal properties of beads after deposition, as well as mechanical and thermal properties of the printed part. At the minimum, any new material or composition tested or developed will involve thermal and rheological analysis shown in Table 2 tested as per the corresponding ASTM standards. These tests at the minimum would help determine optimal processing conditions for extrusion-based platforms, processing limits, and any potential processing risk.

For post-deposition scenarios, mechanical and thermal characterization (depending upon the need for specific applications) is conducted on test coupons harvested from printed samples as per ASTM standards shown in Table 3. The tests commonly conducted on composite AM samples printed at large-scale and the standards used for the same have been provided here as an overview of test methods typically employed for developing materials for large-scale AM. Therefore, specific details of each of these standards are not provided here. Standards specific to sandwich constructions (relevant to this project) are discussed in the next sub-section (Section 3.2). However, for the existing test data provided for materials relevant to this project in Section 4.1, details of ASTM standard used, and sample dimensions, etc. are provided (as available).

Table 2. Testing standards for thermal and rheological characterization of feed materials.

Characterization	Equipment and Standards	Primary Properties Evaluated
Differential Scanning Calorimetry (DSC)	TA Q 2000, ASTM D7426 − 08	Glass transition temperature, melting temperature, crystallization temperature, degree of crystallinity of the material.
Thermogravimetric Analysis (TGA)	TA Q 500	Material's degradation onset temperature
Rotational Rheometry (Small amplitude oscillatory shear testing)	Discovery Hybrid Rheometer (DHR)-2, ASTM D4440 − 15	Effect of processing environment, shear rate, temperature on viscoelastic properties of feed materials. These tests are very sensitive to small chemical changes in the material.
Capillary rheometry (steady shear testing)	Dynisco LCR 7001, ASTM D3835 − 16	Effect of temperature, shear rates on the material's viscosity.

Table 3. Commonly conducted tests and ASTM standards used for testing large-scale AM parts. The tests for which no specific standard has been provided indicate that these tests were conducted on non-standard test coupons or some modified ASTM standards.

Test Type	ASTM Standards for BAAM-Printed Specimens
Tensile testing	ASTM D638- Type I
Flexural testing	ASTM D790
Dual cantilever beam	-
Interlaminar shear stress (ILSS)	ASTM D2344
Compression testing	ASTM D6641
Dynamic mechanical analysis (DMA)	ASTM D5279
Coefficient of thermal expansion (CTE) with Thermomechanical analyzer (TMA)	ASTM E831 − 14
Coefficient of thermal expansion (CTE) with Digital image correlation (DIC)	-
Thermal conductivity	-
Specific gravity	ASTM D792

3.2 ASTM STANDARDS FOR SANDWICH COUPONS & TESTING CAPABILITIES

Primary material properties of interest for this project are mechanical properties, namely: tensile strength, flexural strength and shear strength, as well as the density of printed parts. This section details ASTM standards relevant to testing sandwich structures, along with a brief description of sample types to which these standards apply, and the properties that can be obtained from these test methods. Specific experimental details such as sample geometry, test fixture requirement, sample loading rate, etc. are provided in Section 4.2 in detail along with the results and discussion.

3.2.1 Tensile Properties

Standard: ASTM C297- Standard test method for flatwise tensile strength of sandwich constructions [23].

Primary properties evaluated: “This test method determines the flatwise tensile strength of the core, the core-to-facing bond, or the facing of an assembled sandwich panel” [23].

Sample types: “Permissible core material forms include those with continuous bonding surfaces (such as balsa wood and foams) as well as those with discontinuous bonding surfaces (such as honeycomb)” [23].

Testing capabilities: Test fixtures for flatwise tensile strength testing are available both at ORNL, as well as at the Fibers and Composites Manufacturing Facility (FCMF) at the University of Tennessee, Knoxville (UTK). The test fixture at UTK (shown in Figure 13) can handle composite samples with dimensions 25.4 mm X 25.4 mm X 25.4 mm (1in X 1in X 1in, L X W X T), which would have to be bonded to 25.4 mm (1 in) aluminum loading blocks (shown in Figure 14). It is recommended to conduct some surface treatment such as sanding, sand blasting, or plasma treatment on the loading blocks prior to bonding the sample. An adhesive that has worked very well in the past for bonding thermoset fiber reinforced composite samples to aluminum loading blocks is JB Weld. Choosing an appropriate adhesive to bond thermoplastic composite with aluminum would be a critical step. Figure 15 shows a large tensile test frame available at ORNL, which can be used for the same sample dimensions or longer samples, with a maximum length of about 0.6 - 1 m (2-3 feet) for 25.4 mm (1 in) sample thickness. The factor that determines maximum sample dimensions for a given material would be the load cell limit. It should be noted that to test samples on the fixture at ORNL, some adapters and loading blocks will have to be machined.

Figure 13. Tensile test frame at FCMF, UTK.

Figure 14. Loading blocks to be bonded to test samples.

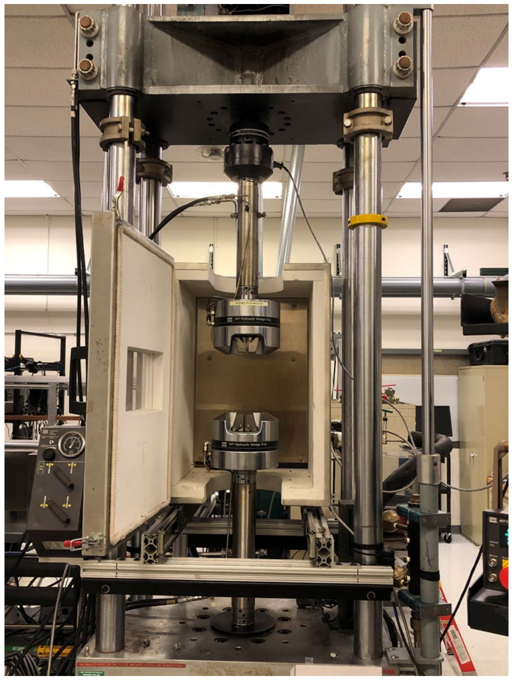


Figure 15. Tensile test frame at ORNL.

3.2.2 Shear Properties

Standard: ASTM C273- Standard test method for shear properties of sandwich core materials [24].

Primary properties evaluated: Shear strength parallel to the plane of the sandwich and shear modulus associated with strains in a plane normal to the facings.

Sample types: This standard is used for evaluating shear properties of sandwich core materials wherein the core materials can be bonded directly to the loading plates or the sample can have a sandwich construction with facing bonded to the loading plates. Core materials that can be tested using this standard include those with continuous bonding surfaces such as balsa wood and foams, as well as discontinuous bonding surfaces such as honeycomb.

Testing capabilities: The test fixture for this standard was procured in FY21 Q2 of this project (Figure 16), the specific details of which are available in Section 4.2, and several test frames are available at the mechanical testing facility at ORNL for conducting these tests.

Figure 16. ASTM C273 test fixture procured for this project.

Figure 17. One of the available test frames on which ASTM C273 test was conducted.

3.2.3 Compressive Properties

Standard: ASTM C365- Standard test method for flatwise compressive properties of sandwich cores [25].

Primary properties evaluated: "This test method covers the determination of compressive strength and modulus of sandwich cores. These properties are usually determined for design purposes in a direction normal to the plane of facings as the core would be placed in a structural sandwich construction. The test procedures pertain to compression in this direction in particular, but also can be applied with possible minor variations to determining compressive properties in other directions" [25].

Sample types: "Permissible core material forms include those with continuous bonding surfaces (such as balsa wood and foams) as well as those with discontinuous bonding surfaces (such as honeycomb)" [25].

Testing capabilities: Test fixtures for flatwise compression testing are available both at ORNL, as well as at the Fibers and Composites Manufacturing Facility (FCMF) at the University of Tennessee, Knoxville (UTK). For testing at the FCMF at UTK, preferred sample dimensions are 25.4 mm X 25.4 mm X 12.7

mm (1 in X 1in X 0.5in). For testing at ORNL, since the platen size is large, sample size can vary, with a maximum cross-sectional area of 5 in X 5in (Figure 18). The maximum load on the load cell currently available on the test frame is 100,000 lbf. However, the test machines at ORNL are customizable to fit large samples if needed (may require procuring some load cells and fixtures depending upon the specific requirements).

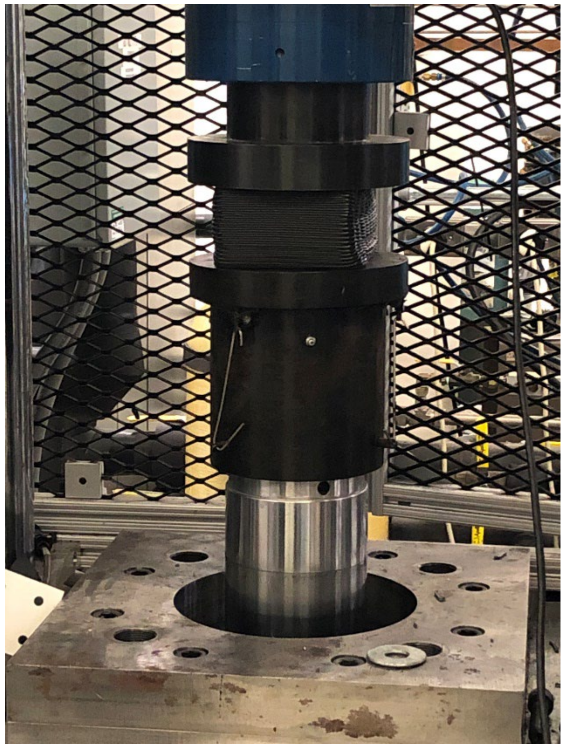


Figure 18. Flatwise compression testing capability at ORNL.

3.2.4 Density

Standard: ASTM C271- Standard test method for density of sandwich core materials [26].

Primary properties evaluated: This test method covers the determination of the density of sandwich construction core materials.

Sample types: "Permissible core material forms include those with continuous bonding surfaces (such as balsa wood and foams) as well as those with discontinuous bonding surfaces (such as honeycomb)" [26].

Testing capabilities: According to this standard, the apparatus required for density measurements include:

i. Oven or Vacuum Drying Chamber—An air-circulating oven is required that shall be capable of maintaining the required uniform temperatures to within 63°C [65°F]. A vacuum drying chamber or a vacuum oven may also be used.
ii. Desiccator—A clean, dry desiccator in which specimens being oven-dried shall be brought to laboratory temperature following removal of the specimens from the oven.
iii. Micrometers and Calipers—A micrometer having a flat anvil interface, or a caliper of suitable size, shall be used.
iv. Balance or Weighing Scale—An analytical balance or weighing scale is required that can measure accurately to ±0.5 %.

v. Gloves—Clean, non-linting gloves for use when handling specimens.

Vacuum oven, desiccator, calipers, balance and gloves are all available at both MDF, ORNL as well as UTK facilities.

4. MATERIAL PROPERTIES

4.1 PROPERTIES OF RELEVANT MATERIALS: USING ASTM STANDARDS FOR AM PARTS

Mechanical properties characterization from the past work done at the MDF has been provided in this section for low temperature composite thermoplastics such as blends of glass fiber with ABS and carbon fiber with ABS and foamed materials. For other material classes listed in Table 1 such as high temperature polymers, magnetic materials, and foam blends, the properties available from years of past work on material characterization conducted at the MDF are available in Appendix A. Data on recycled materials mechanical properties[1] is not included in this publication as these results have not been made public because of intellectual property concerns at the time of publishing this report. Rheological characterization of these materials is available [27].

4.1.1 Properties of CF/ABS

4.1.1.1 Tensile Properties

Figure 20 shows the tensile strength of some of the BAAM-printed materials tested as per ASTM D638 Type - I standard (sample dimensions as shown in Figure 19) at room temperature. Test samples were harvested from hexagons which were 70 cm along each side, 17 cm tall and 2.5 cm thick, printed on the very first version of the BAAM system (referred to as blue gantry). Processing temperature, deposition rate, along with tensile strength and modulus are provided in Table 4. In Figure 20 and Table 4, X-axis refers to sample orientation wherein the beads (or layers) are along the print direction (test direction is the same as print direction) and the Z-axis refers to sample orientation case wherein the beads are along the transverse direction (test direction is perpendicular to the print direction).

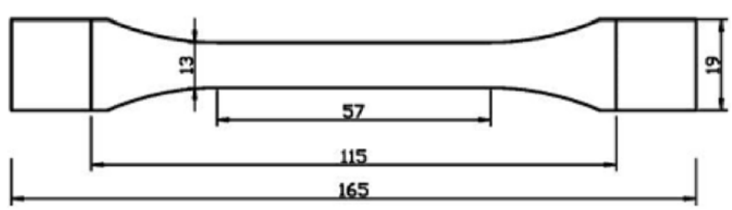


Figure 19. Dimensions for ASTM D638 Type-I sample. Sample thickness: 7mm.

[1] Reach out to the corresponding authors for further details. Additional datasets may be shared once a suitable NDA has been established.

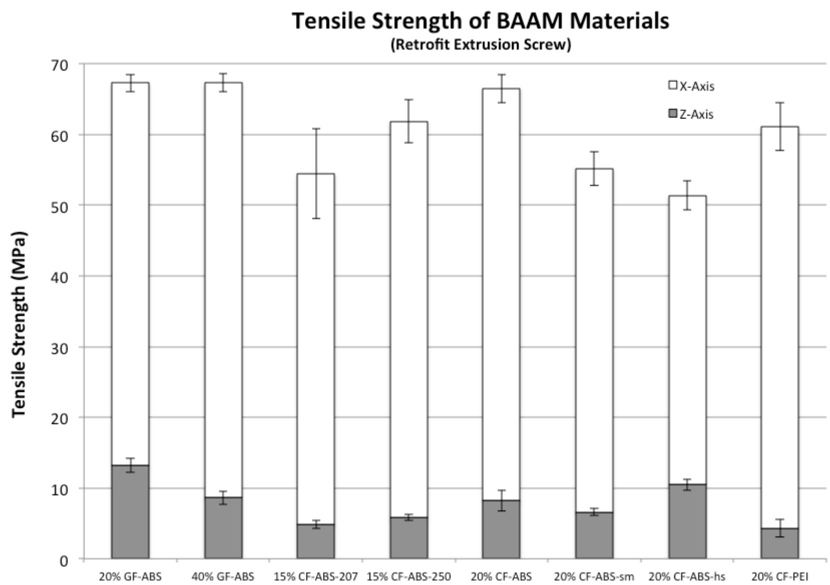


Figure 20. Tensile strength of some materials printed on the BAAM [1].

Table 4. Tensile properties of some BAAM-printed materials [1].

Sample Name	Material	Screw Design	Deposition Rate (kg/h)	Deposition Temperature (°C)	Strength x-axis (MPa)	Strength z-axis (MPa)	Stiffness x-axis (GPa)	Stiffness z-axis (GPa)
20% GF-ABS	(3)	Retrofit	4.5	250	67.3	13.2	3.33	1.71
40% GF-ABS	(8)	Retrofit	4.5	225	67.3	8.6	5.73	1.48
15% CF-ABS-207	(9)	Retrofit	16	207	54.5	4.9	10.51	2.05
15% CF-ABS-250	(9)	Retrofit	16	250	61.9	5.8	11.88	1.83
20% CF-ABS	(5)	Retrofit	4.5	225	66.5	8.2	6.33	2.04
20% CF-ABS-sm	(5)	Retrofit	4.5	220	55.2	6.6	6.04	1.73
20% CF-ABS-hs	(5)	Retrofit	16	225	51.4	10.5	9.50	2.65
20% CF-PEI	(9)	Retrofit	4.5	364	61.1	4.3	8.36	1.10

(3) Techmer HiFill J-1200/20 NAT (5) Techmer Electrafil J-1200/CF/20 (8) Techmer custom blend
(9) Sabic custom blend

4.1.1.2 Flexural Properties

Flexural strength and modulus for 20 wt.% CF ABS is shown in the boxed/highlighted portion of Figure 21. The tests were conducted as per ASTM D790 standard- Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. Test coupons were rectangular samples measuring ~ 140 mm X ~ 25 mm X ~ 7.1 mm (L x W x T) harvested from 10in panels printed on the BAAM. The span to thickness ratio used in testing was 16:1. The charts in Figure 21 also show flexural properties of this material processing using other techniques: extrusion compression molding (ECM) and injection molding (IM). These are a part of the charts obtained from data intended for other applications and not relevant for the current discussion.

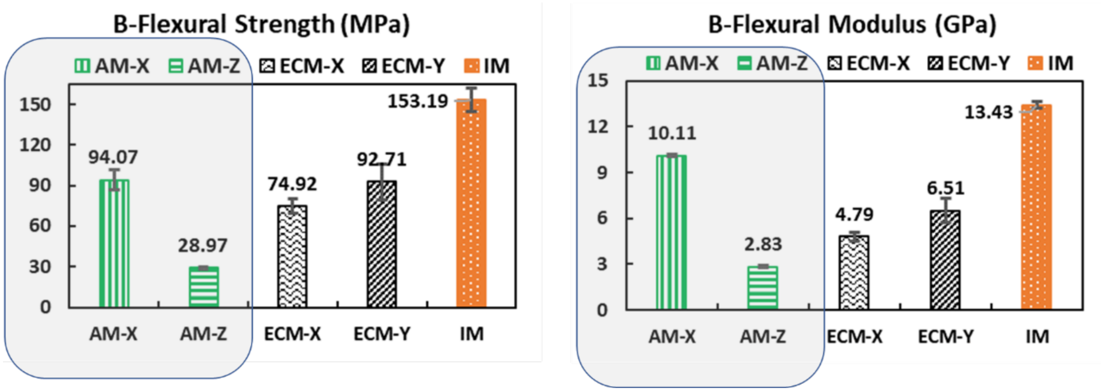


Figure 21. Flexural properties of 20 wt.% CF ABS.

4.1.1.3 Compressive Properties

Compressive strength for 20 wt.% CF ABS is shown in the boxed/highlighted portion of Figure 22. The tests were conducted as per ASTM D6641- Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture. Test coupons were rectangular samples measuring ~ 140 mm X ~ 12 mm X ~ 7.1 mm (L x W x T) harvested from 255 mm X 255 mm (10 in X 10 in) panels printed on the BAAM. The chart in Figure 22 also shows compressive strength of this material processing using other techniques: extrusion compression molding (ECM) and injection molding (IM). These are a part of the charts obtained from data intended for other applications and not relevant for the current discussion.

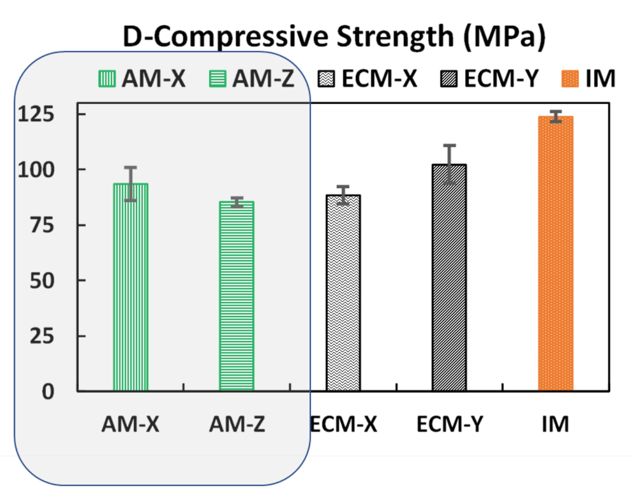


Figure 22. Compressive strength of 20 wt.% CF ABS.

4.1.1.4 Interlaminar Shear Stress (ILSS)

Interlaminar shear stress testing of 20 wt.% CF ABS was conducted as per ASTM D2344- Standard test method for short-beam strength of polymer matrix composite materials and their laminates and the results are shown in Figure 23. Test coupons were rectangular samples measuring ~ 50 mm X ~ 8 mm X ~ 4 mm (L x W x T) harvested from 255 mm X 255 mm (10 in X 10 in) panels printed on the BAAM. The chart in Figure 23 also shows compressive strength of this material processing using other techniques: extrusion compression molding (ECM) and injection molding (IM). These are a part of the charts obtained from data intended for other applications and not relevant for the current discussion.

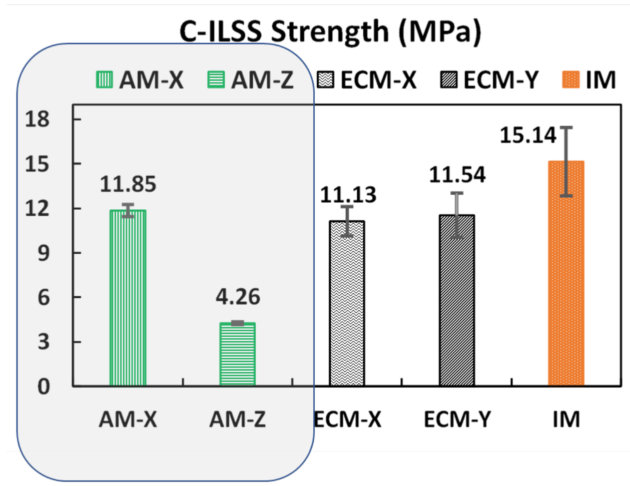


Figure 23. Interlaminar shear strength of 20 wt.% CF ABS.

4.1.2 Properties of ABS Syntactic Foam

4.1.2.1 Tensile properties

Tensile modulus and strength of ABS syntactic foam containing ABS with 33 wt.% (50 vol.%) hollow glass microspheres and 10 wt.% carbon fiber were evaluated using ASTM D638 Type - I standard at room temperature and the results are as shown in Figure 24 for test coupons harvested from samples printed with 20s layer time and 40s layer time, with each case being tested along the x-direction (along the print direction) as well as the z-direction (transverse to print direction).

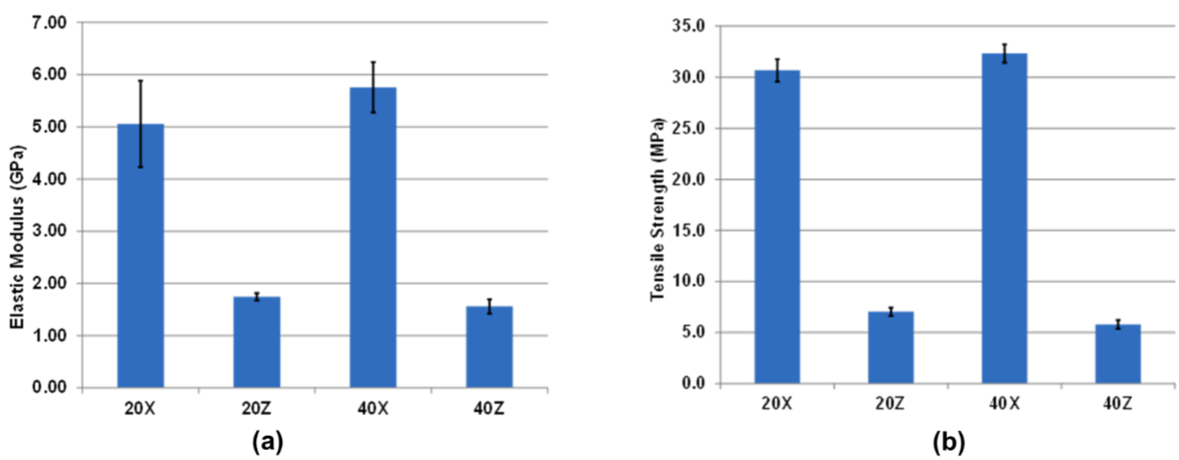


Figure 24. Tensile modulus and strength of ABS syntactic foam. 20x refers to test coupons harvested from sample printed with 20s layer time and tested along the x-direction; 20z refers to test coupons harvested from sample printed with 20s layer time and tested along the z-direction; 40x refers to test coupons harvested from sample printed with 40s layer time and tested along the x-direction; 40z refers to test coupons harvested from sample printed with 40s layer time and tested along the z-direction.

4.2 PROPERTIES OF RELEVANT MATERIALS: USING ASTM STANDARDS FOR SANDWICH COUPONS (EVALUATED IN THIS PROJECT)

4.2.1 Initial BAAM Printing of Test Samples

In FY21 Q1, for preliminary testing of mechanical properties, three materials were chosen for print trials on the BAAM system, namely, 20 wt.% CF ABS, 20 wt.% CF ABS foam (foamed using expandable microspheres) and PLA foam (foamed using expandable microspheres). The initial plan incorporated testing mechanical properties (tensile, compression, interlaminar shear stress (ILSS) and flexural) using the standards typically used for AM testing (described in Section 2.1). Figure 27 shows hexagon test samples being printed on the BAAM using the three chosen materials and Table 8 lists the processing conditions set for the three prints.

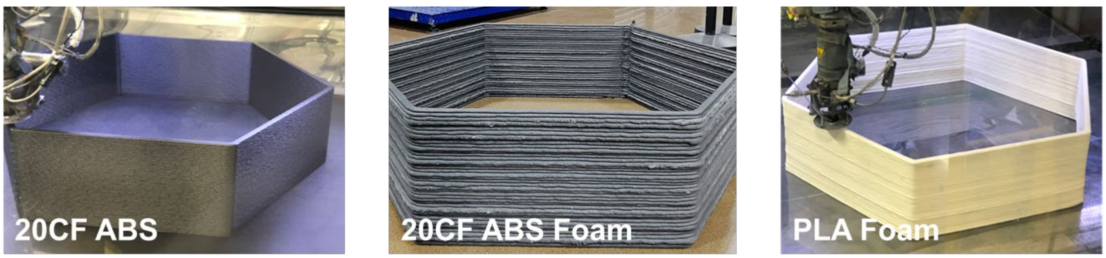


Figure 25. Test samples printed on the BAAM.

Table 5. Processing parameters for BAAM prints.

Materials	20 CF ABS	20 CF ABS Foam	PLA Foam
Part dimension	20" hexagon		
No. of layers	50	42	42
Layer time (min)	2	2	2
Printed bead width (in)	0.65	0.6	0.58
Printed bead height (in)	0.2	0.24	0.24
Bed Temperature (°C)	100	100	60
Extruder Barrel Zone 1 (°C)	176	176	135
Extruder Barrel Zone 2 (°C)	176	176	150
Extruder Barrel Zone 3 (°C)	249	230	190
Extruder Barrel Zone 4 (°C)	249	230	210
Nozzle Tip (°C)	249	240	210
Melt Temperature (°C)	264	252	220

In FY21 Q2, the ASTM test standards relevant for sandwich core structures testing were identified to be more relevant for future testing throughout this project when compared to using the standards otherwise used for testing AM samples. The standards for sandwich construction seemed more relevant to future testing especially for cases where the printed cores would not necessarily be a solid sample but could have different lattice structures such as a honeycomb configuration. Therefore, the data already available from past work by ORNL for materials such as 20 wt.% CF ABS, foams, and recycled materials printed on the BAAM, that are currently relevant for this project, were considered for providing some baseline guidance for mechanical performance. For 20 wt.% CF ABS, tensile, flexural, compressive and interlaminar shear stress (ILSS) properties were documented from past work (provided in Section 4.1) and tensile properties of ABS syntactic foam were documented as well (provided in Section 4.1).

Since shear properties were identified to be critical for sandwich core design, test method used for characterizing shear properties of sandwich construction (ASTM C273) was identified to be the most relevant for this application. To establish test method, apparatus to be used, and identify any roadblocks or risks associated with testing moving forward, one material, 20 wt.% CF ABS was first chosen to evaluate shear properties using ASTM C273 standard.

4.2.1.1 ASTM C273: Test Trial 1

The objective of this test was to determine shear properties: shear strength and shear modulus of samples printed on the BAAM system. For the first test trial, shear properties were obtained by testing printed samples in the weakest direction, i.e., shear between the printed layers. To harvest test coupons, 255 mm X 255 mm (10 in X 10 in) square panels were printed on the BAAM using 20 wt.% CF ABS and 20 wt.% CF ABS foam (for future testing) using a 7.62 mm (0.3 in) diameter nozzle, as shown in Figure 26 (a) and (b). The printed panels were 3 layers thick for 20 wt.% CF ABS and 2 layers thick for 20 wt.% CF ABS foam.

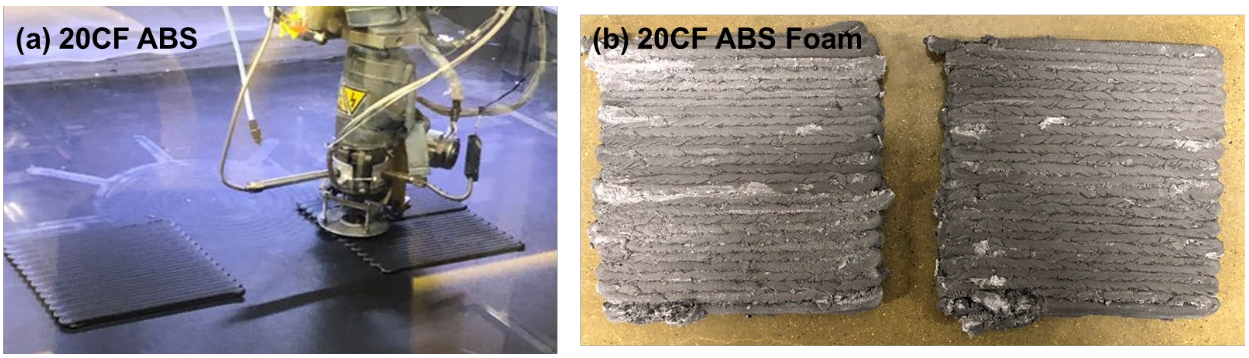


Figure 26. Panels printed on the BAAM for harvesting test coupons for ASTM C273 testing using (a) 20 wt. % CF ABS, and (b) 20 wt.% CF ABS foam (foamed using expandable microspheres).

To conduct the first test trial for establishing test protocol, equipment to be used, and identifying challenges and risks from a testing standpoint for future work, 20 wt.% CF ABS was the chosen material. For machining out test coupons from the printed panels, recommendations from ASTM C273 for sample dimensions was used. The details from the standard for test set-up, sample geometry and testing parameters are provided below. No facesheets were used for these tests.

<u>ASTM C273 Recommendations [24]:</u>

<u>Test Mode</u>: Tension or compression

<u>Test Fixtures</u>: The test specimen shall be rigidly supported by means of steel plates bonded to the facings (as shown in Figure 27b). The thickness of these plates can be varied depending up on the strength of the sandwich. However, the plate length should be such that the line of action of the direct tensile or compressive force passed through the diagonally opposite corners of the sandwich (Figure 27b) and as calculated per Figure 28. A correct line of force action could also be obtained by modifying the core length to thickness ratio, provided the specimen dimensional requirements for this standard are fulfilled.

<u>Number of Test Samples</u>: At least five specimens shall be tested per test condition.

<u>Sample Geometry</u>: “The test specimens shall have a thickness equal to the thickness of the sandwich, a width not less than 50 mm [2.0 in], and a length not less than twelve times the thickness.”

<u>Conditioning</u>: “The recommended pre-test specimen condition is effective moisture equilibrium at a specific relative humidity as established by Test Method D5229/D5229M; however, if the test requester

does not explicitly specify a pre-test conditioning environment, conditioning is not required, and the test specimens may be tested as prepared.”

Dimensional Accuracy: Specimen length and width are to be measured before conditioning and testing and the accuracy of measurements are to be within 1% of the dimension. The dimensions are to be recorded to three significant figures in units of millimeters [inches].

Testing Speed: The speed of testing is to be set such that it can produce failure within 3 to 6 min. If the ultimate strength of the material cannot be reasonably estimated, initial trials should be conducted using standard speeds until the ultimate strength of the material and the compliance of the system are known, and speed of testing can be adjusted. The suggested standard head displacement rate is 0.50 mm/min [0.020 in/min].

Data Recording: Force versus head displacement and force versus axial displacement to be recorded continuously, or at frequent regular intervals. A sampling rate of 5-10 data recordings per second and a minimum of 300 data points per test is recommended.

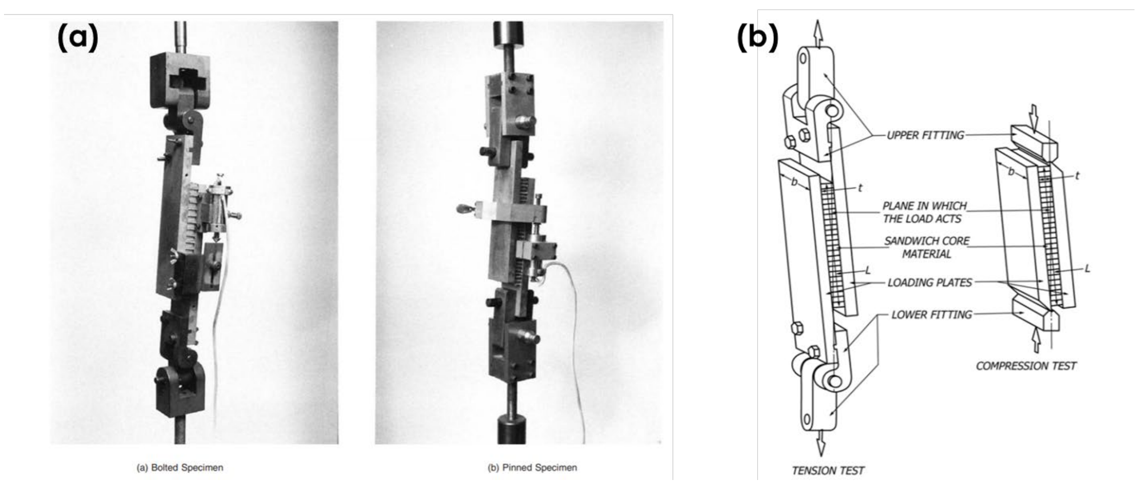


Figure 27. (a) Tensile plate shear test set-up, (b) Test set-up indicating force line of action [24].

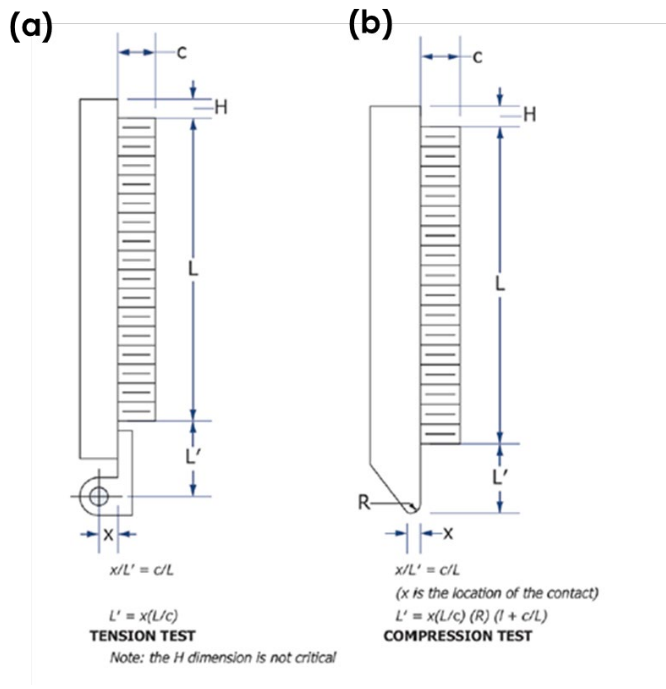


Figure 28. Fixture length calculations for testing in (a) tension mode and (b) compression mode [24].

ASTM C273 standard test fixture was procured from Wyoming Test Fixtures (shown in Figure 29). To harvest test coupons from the printed samples, firstly a band saw was used to obtain smaller sections, followed by milling for surface smoothing. After milling, the samples were sanded to remove any surface defects due to heat from milling process. The targeted sample dimensions were 200 mm x 75 mm x 12.7 mm (L x W x T).

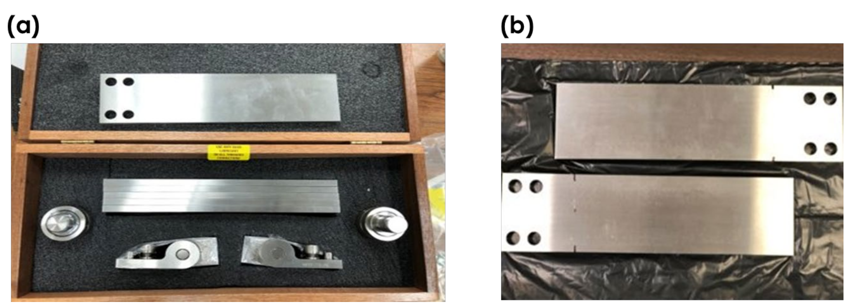


Figure 29. (a) Test fixtures (as received), (b) Loading plates.

Figure 30 and Figure 31 show test coupons machined from the panels and how the printed beads were positioned along the centerline to be able to measure shear properties between the layers. Although 5 samples were machined, initial testing involved testing 2 samples first. This was due to limited availability of loading plates and machining or procurement of new loading plates were on hold until test results were obtained from two tests. The average sample dimensions of the two coupons tested were:
Avg. sample length (L) = 200.15 ± 0.5 mm (7.88 ± 0.02")
Avg. sample width = 75 ± 0.5 mm (2.98 ± 0.02")
Avg. sample thickness (c) = 11.96 ± 0.38 mm (0.471 ± 0.015")

It was ensured that the faces to be bonded to the loading plates were flat and parallel. Thickness of each coupon was well-controlled with variations within ± 0.1 mm (0.004") across each sample.

Figure 32 shows a schematic indicating sample orientation during printing and testing and the positioning of the loading plates with respect to the sample. For the first set of test trials, the adhesive used was Loctite EA9460 ™ (2-part adhesive, 1:1 mixing ratio, room temperature cure followed by curing at elevated temperatures). The technical datasheet (TDS) for this adhesive, which includes specific lap shear strength values of this adhesive with different materials, has been provided in Appendix A.

It should be noted that from the TDS, for this adhesive cured for 3 days at 25 °C, the lap shear strength of this adhesive with ABS tested using ISO 4587 standard is 2.8 MPa. Ideally, it is preferred to have an adhesive with a shear strength with thermoplastics such as ABS > 20MPa. However, at the time of conducting these test trials, due to the unavailability of specific recommendations from adhesive manufacturers such as Loctite, 3M etc., and based on earliest available adhesive, this grade was chosen.

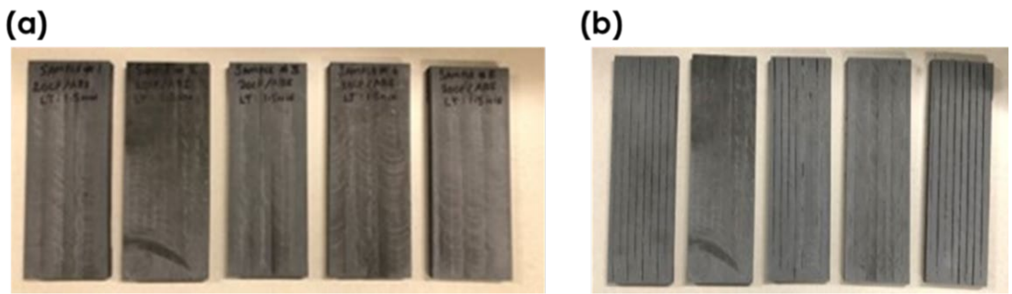


Figure 30. Test coupons harvested from printed panels (a) front face, (b) back face.

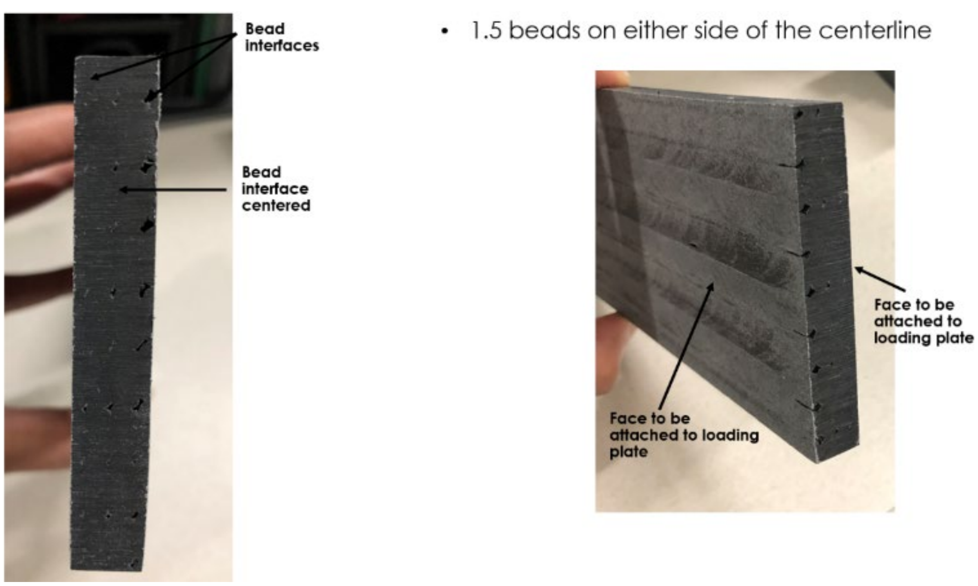


Figure 31. Cross sectional view of the test coupon indicating bead interfaces.

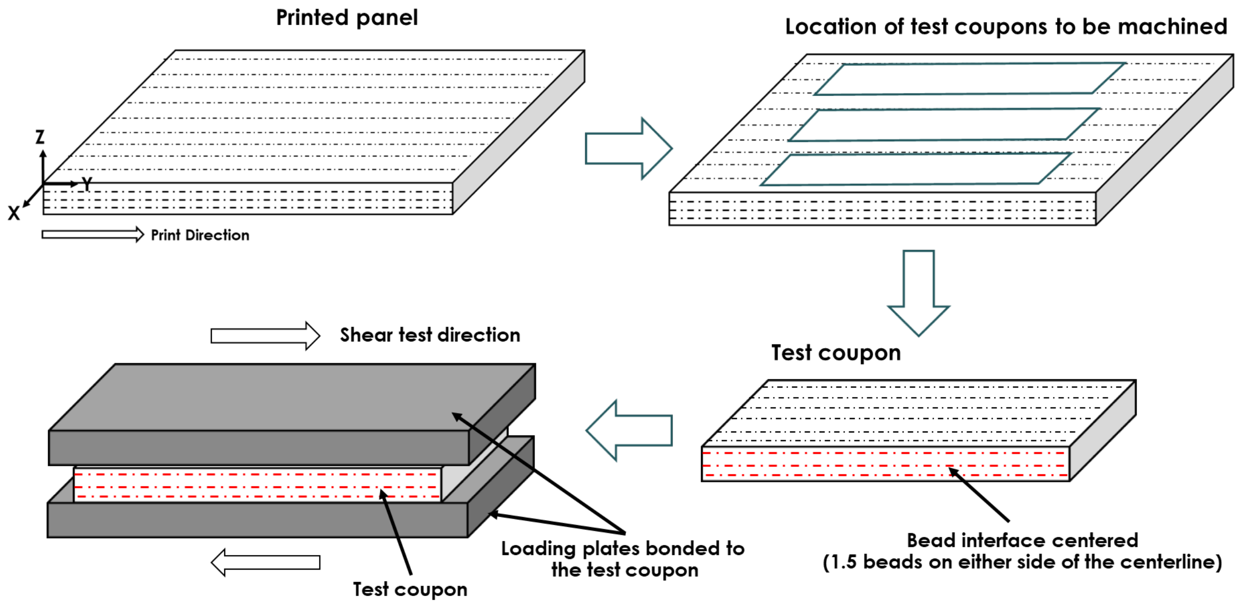


Figure 32. Schematic indicating sample orientation during printing and testing.

Prior to bonding with the loading plates, the surfaces of the test coupons were cleaned using isopropyl alcohol (IPA). Samples were bonded to the loading plates such that x/L' = c/L (from Figure 28), as per ASTM C273 recommendations. With a 1:1 mixing ratio, the adhesive was dispensed using a nozzle with static mixers and smeared on to the loading plates using a spatula to create a fairly uniform spread. After placing the test coupons between the loading plates, the samples were clamped (as shown in Figure 33) and allowed to cure at room temperature for ~ 7 days, followed by curing at 60°C for 1 hour. As per the technical data sheet, curing at room temperature for ~ 72 hour completes the curing process.

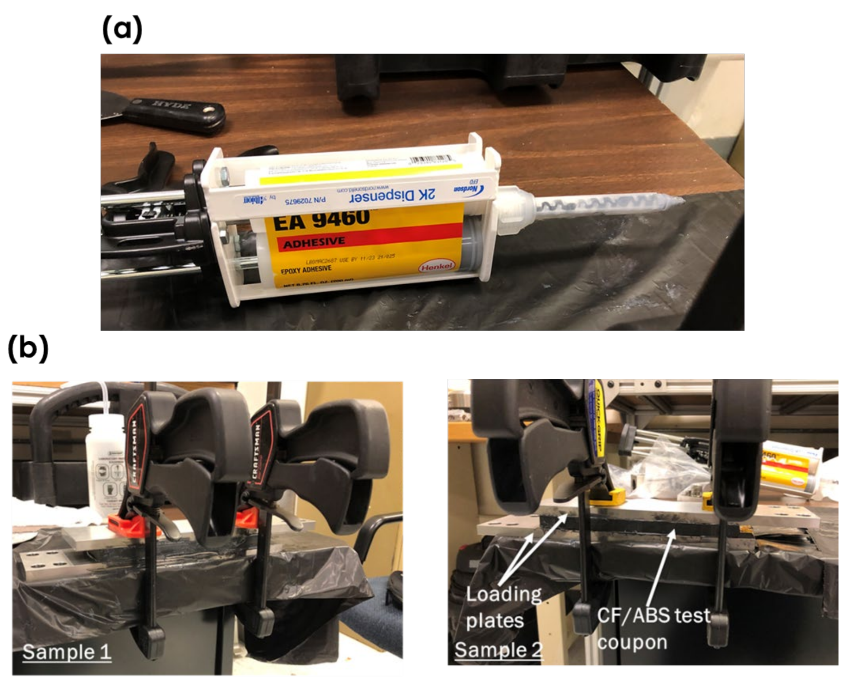


Figure 33. (a) 2-part adhesive used for bonding test coupon to loading plates, (b) Samples clamped for curing.

After curing, the samples were tested on an Instron test machine (test set-up as shown in Figure 34). The loading rate for the first sample was 0.5 mm/min (ASTM recommends starting with this rate). For sample 2, it was then changed to 0.25 mm/min to increase the test time. The load-displacement data from these tests is as shown in Figure 35. The results showed ultimate shear strength to be 1.35 MPa for sample 1 and 1.33 MPa for sample 2. For both the samples, failure was in the CF/ABS section of the test sample. A thin layer of CF/ABS bonded to the adhesive was ripped off with the loading plate up on failure (as seen in Figure 34b). The exact mechanism for this behavior is not yet well understood. Surface defects from machining and chemical reaction between ABS and the adhesive are some of the possible reasons for this failure mode. However, moving forward, for future test trials using this ASTM C273 standard, the recommendations from discussions included replacing the currently used adhesive with a different one that has a higher shear strength (> 20MPa with thermoplastics like ABS) and also using a machining method that may involve lesser thermal effect on sample surface such as water jet cutting or milling with the use of a coolant (depending upon equipment availability at the time of machining and testing). Identifying new adhesives with better shear strength and identifying the suppliers for the same are in progress. Adhesive recommendations from Composites One and Ellsworth Adhesives (Loctite adhesives supplier) are some of the options being considered. TDS for those adhesives under consideration are included in the appendix.

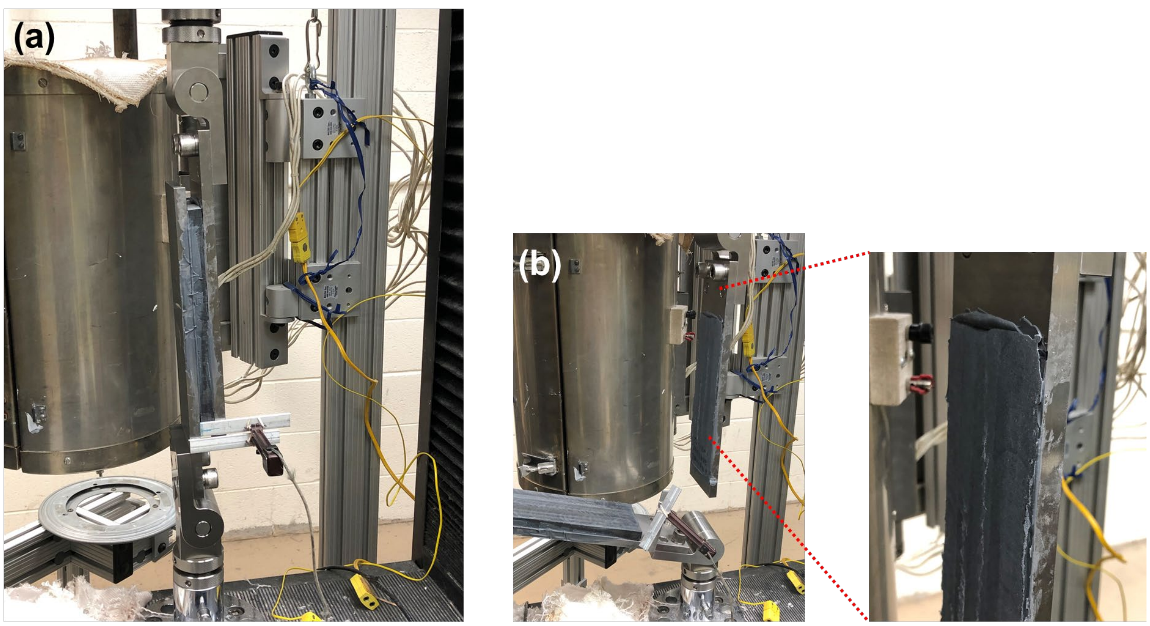


Figure 34. (a) Test set-up, (b) Sample after failure.

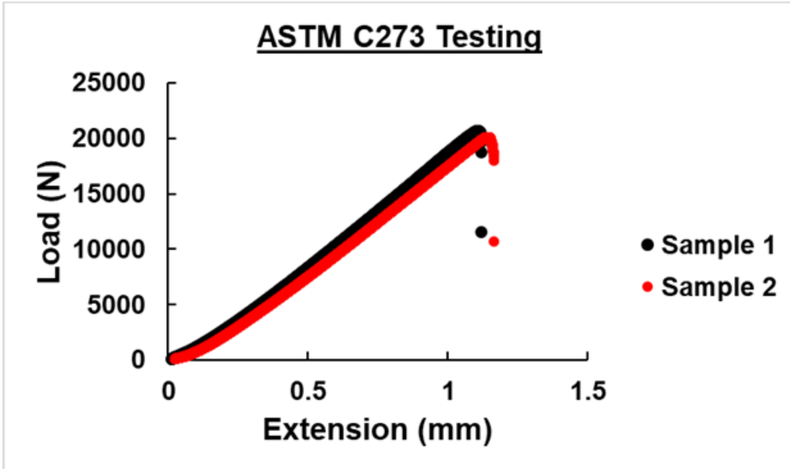


Figure 35. Load vs extension for the two tests conducted.

As adhesives are being identified, new loading places have been machined (20 plates) for future test trials (Figure 36).

Figure 36. Newly machined loading plate.

V-Notched Beam Test for Shear Properties

In addition, to obtain shear properties using an alternative test method, testing 20 wt.% CF ABS samples using ASTM D5379- "Standard test method for shear properties of composite materials by the V-Notched beam method" was also conducted [28]. Figure 37 and Figure 38 show the schematic of test fixture and test coupon dimensions, respectively. Test coupons were harvested from BAAM-printed hexagon (Figure 25 in Section 4.2) in two different orientations, as shown in Figure 39 with dimensions following the standard and testing was conducted using the fixture shown in Figure 40.

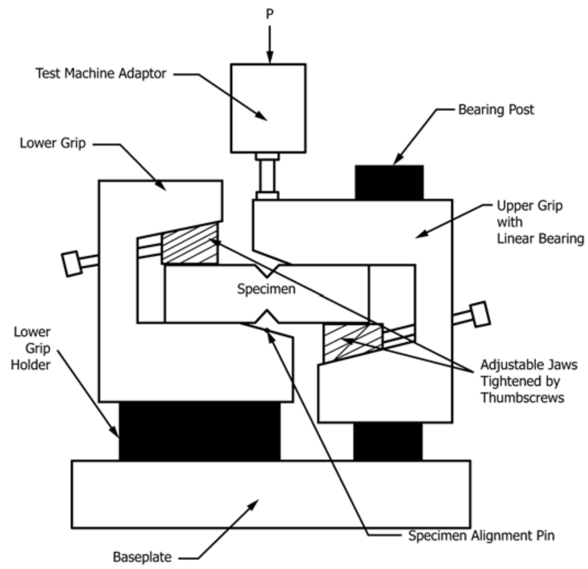
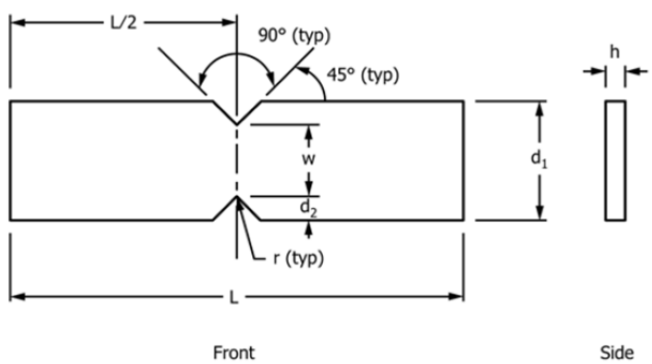


Figure 37. Schematic of the V-notched beam test fixture[28].



Nominal Specimen Dimensions

d_1	=	19 mm [0.75 in.]
d_2	=	3.8 mm [0.15 in.]
h	=	as required
L	=	76 mm [3.0 in.]
r	=	1.3 mm [0.05 in.]
w	=	11.4 mm [0.45 in.]

Figure 38. Schematic of V-Notched beam test coupon [28].

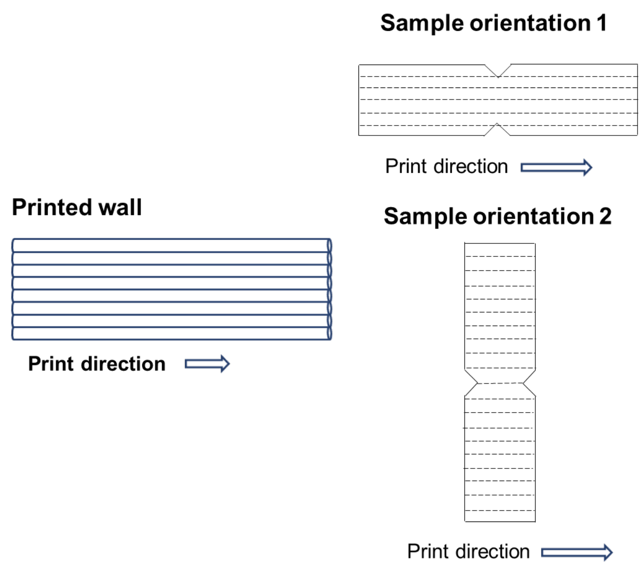


Figure 39. Schematic showing sample orientations for BAAM-printed V-noted test coupons.

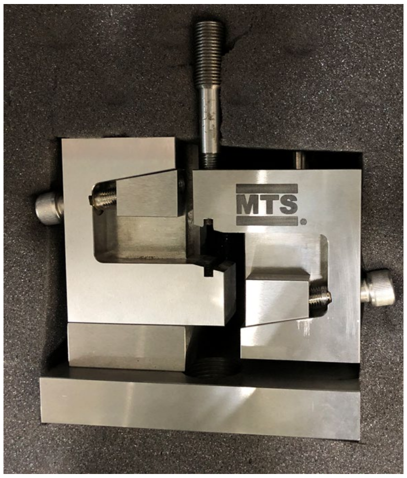


Figure 40. Test fixture used.

The coupons were tested using a loading rate of 0.25mm/min such that the samples failed between 1.5 min - 8 min. Four samples were tested for each orientation and the shear stress values are reported in Table 6. The values reported are shear stress at 5% strain or stress at a strain where there is a significant change in slope or the ultimate shear stress (if lower than stress at 5% strain).

Table 6. Ultimate shear stress for 20CF/ABS from V-notched beam method.

Sample #	Shear Stress (MPa)	Shear Stress Value Reported At
Z1	3.429	4% strain, slope changes after 4%
Z2	9.407	5% strain
Z3	6.071	Stress at max strain (~3.5%)
Z4	5.398	4% strain, slope changes after 4%
Z5	N/A	N/A
Average Z	**6.076 ± 2.487**	
X1	8.194	5% strain
X2	9.987	5% strain
X3	3.217	3% strain, slope changes after 3%
X4	12.198	5% strain
Average X	**8.399 ± 3.823**	

4.2.2 Initial Thermoset Printing of Test Samples

In FY22 Q2, for testing material properties on thermoset materials, two materials were chosen for print trials in collaboration with Polynt Composites, namely PRD EX1631 and PRD EX1631 LS. PRD EX1631 was developed as a prototype low-density print media for large scale parts, while EX1631 LS was developed as a low shrink and more dimensionally stable version of EX1631. The datasheet for EX1631 is included in the appendix, but no datasheet was created for EX1631 LS. Both formulations have similar densities, but their mechanical and thermal properties were anticipated to differ. The plan for these prints was to evaluate shear properties using ASTM C273 standard at the materials testing lab at the National Renewable Energy Laboratory. However, these samples were never machined nor tested.

Figure 41. Example printed samples of PRD EX1631 and PRD EX1631 LS to be tested.

At the time of this report, several thermoset material systems have been printed and their rheological and mechanical properties tested through other research projects [29-36].

5. CONCLUSION

Additive manufacturing methods and materials expand the opportunity space for manufacturing solutions, yet further work remains to characterize what materials, processes, and geometries may lead to feasible solutions for the wind industry. Pressure to explore alternative material and manufacturing solutions to today's balsa core increases as the scale of wind blades and the market for wind farms increases with time due to limited supply of balsa. Opportunities to further improve blade core in light-weighting, cost, and recyclability may yet be realized through advanced and additive manufacturing methods and materials. This document has described major classes of printable materials and their processing requirements, detailed relevant characterization and testing methods, and collated currently available properties for the most mature, well-documented, and wind industry relevant materials used in large scale additive manufacturing systems to date. Future research and development opportunities may expand this materials library further, analyze blade core geometries enabled by advanced manufacturing methods, and demonstrate prototypes and testing at the subcomponent or component scale.

6. REFERENCES

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APPENDIX A. AM MATERIAL PROPERTIES FROM PRIOR WORK

Neat, 20%CF, 40%CF ABS

Base (Neat) Material	ABS
Material Type	Low Temp
Additives/Reinforcements	Neat, 20%CF, 40%CF

Printability

Rheological Properties During Deposition

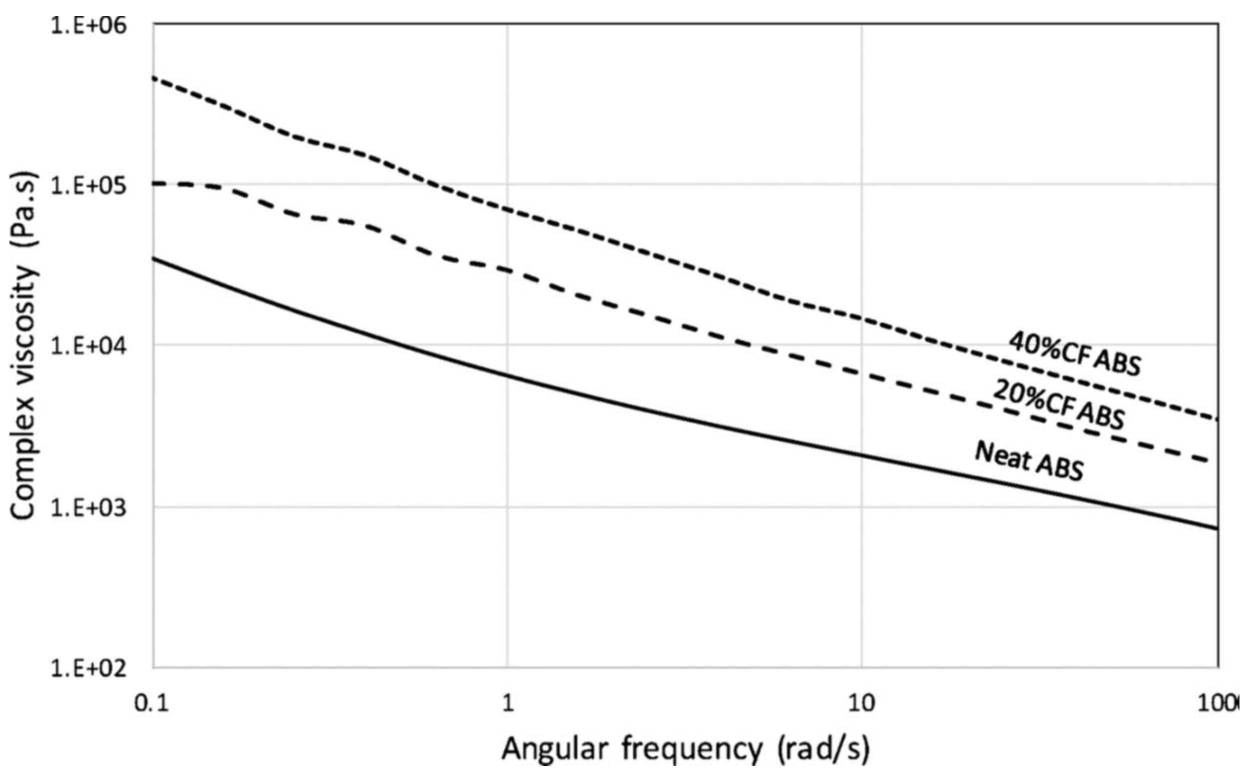


Figure 42: Figure from Duty, C., Ajinjeru, C., Kishore, V., Compton, B., Hmeidat, N., Chen, X., Liu, P., Hassen, A.A., Lindahl, J. and Kunc, V., 2018. What makes a material printable? A viscoelastic model for extrusion-based 3D printing of polymers. Journal of Manufacturing Processes, 35, pp. 526-537.

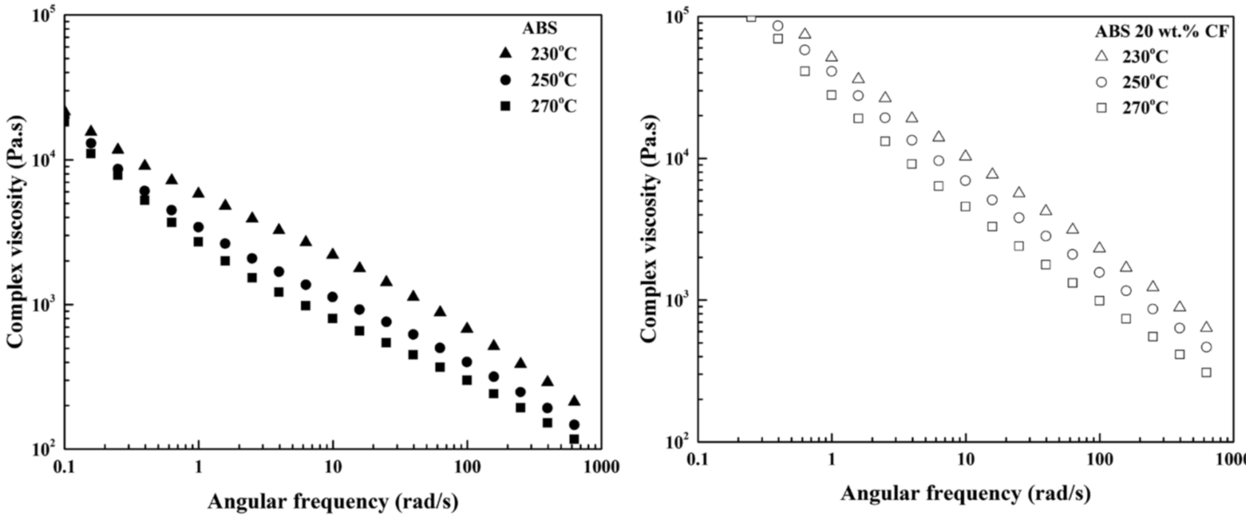


Figure 43: Ajinjeru, C., Kishore, V., Liu, P., Lindahl, J., Hassen, A.A., Kunc, V., Post, B., Love, L. and Duty, C., 2018. Determination of melt processing conditions for high performance amorphous thermoplastics for large format additive manufacturing. Additive Manufacturing, 21, pp.125-132.

Thermal Properties

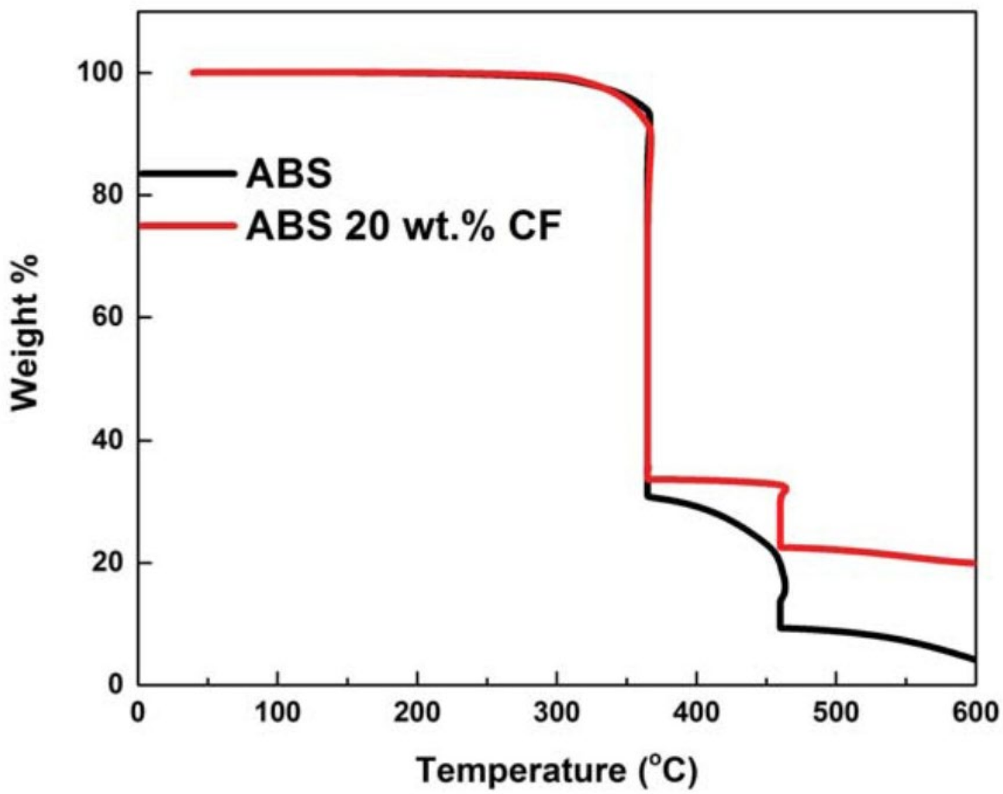


Figure 44: Ajinjeru, C., Kishore, V., Chen, X., Lindahl, J., Sudbury, Z., Arabi, A., Hassen, A.A., Kunc, V., Post, B., Love, L. and Duty, C.E., 2016. The Influence of Rheology on Melt Processing Conditions of Amorphous Thermoplastics for Big Area Additive Manufacturing (BAAM). In Solid Freeform Fabrication Symposium, Austin, TX.

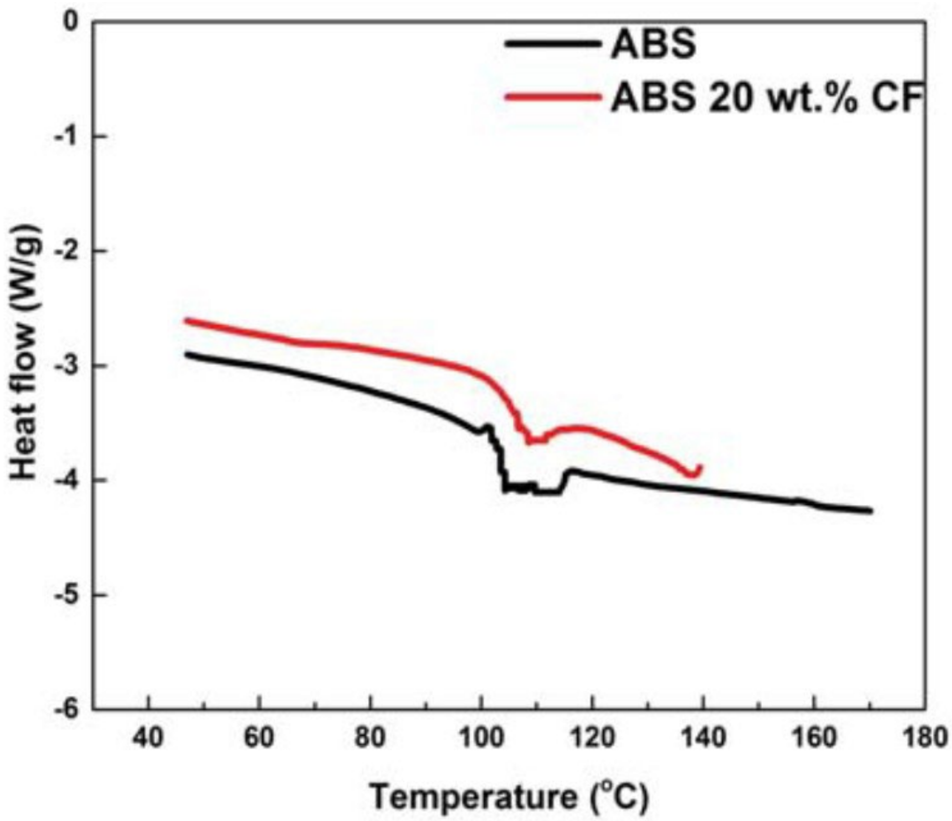


Figure 45: Ajinjeru, C., Kishore, V., Chen, X., Lindahl, J., Sudbury, Z., Arabi, A., Hassen, A.A., Kunc, V., Post, B., Love, L. and Duty, C.E., 2016. The Influence of Rheology on Melt Processing Conditions of Amorphous Thermoplastics for Big Area Additive Manufacturing (BAAM). In Solid Freeform Fabrication Symposium, Austin, TX.

Printed Parts

Mechanical Properties

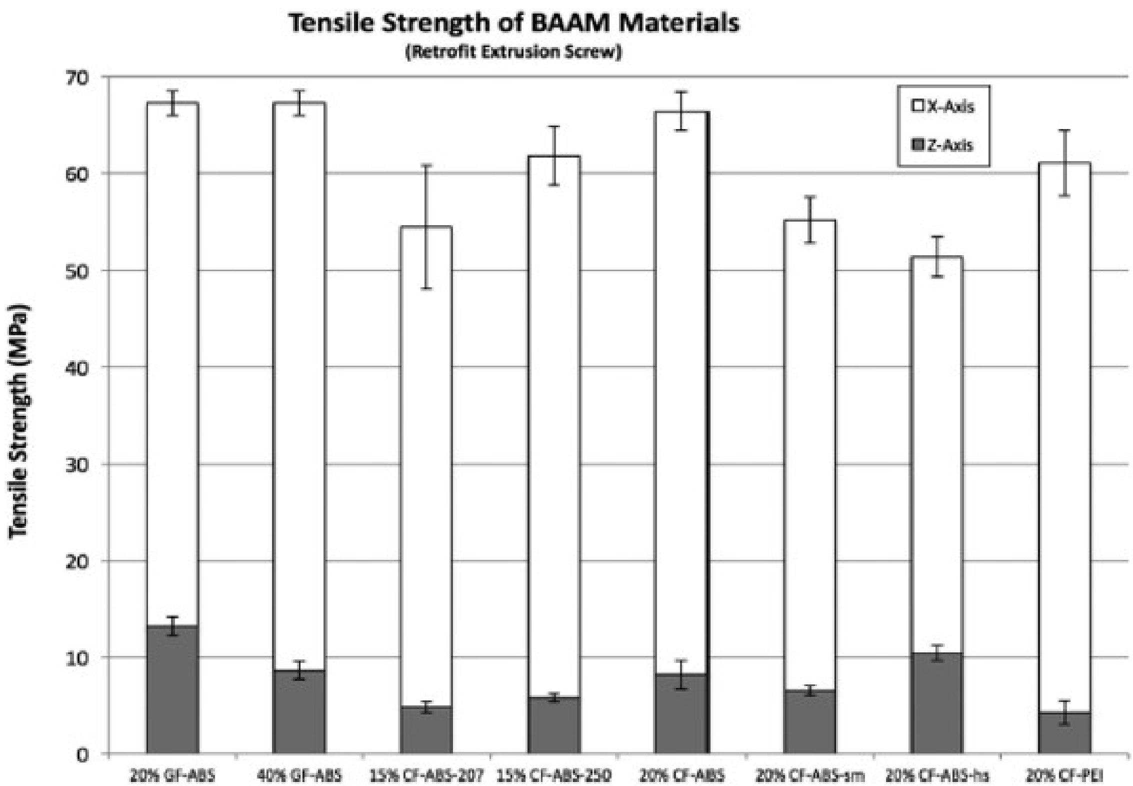


Figure 46: Duty, C.E., Kunc, V., Compton, B., Post, B., Erdman, D., Smith, R., Lind, R., Lloyd, P. and Love, L., 2017. Structure and mechanical behavior of Big Area Additive Manufacturing (BAAM) materials. Rapid Prototyping Journal.

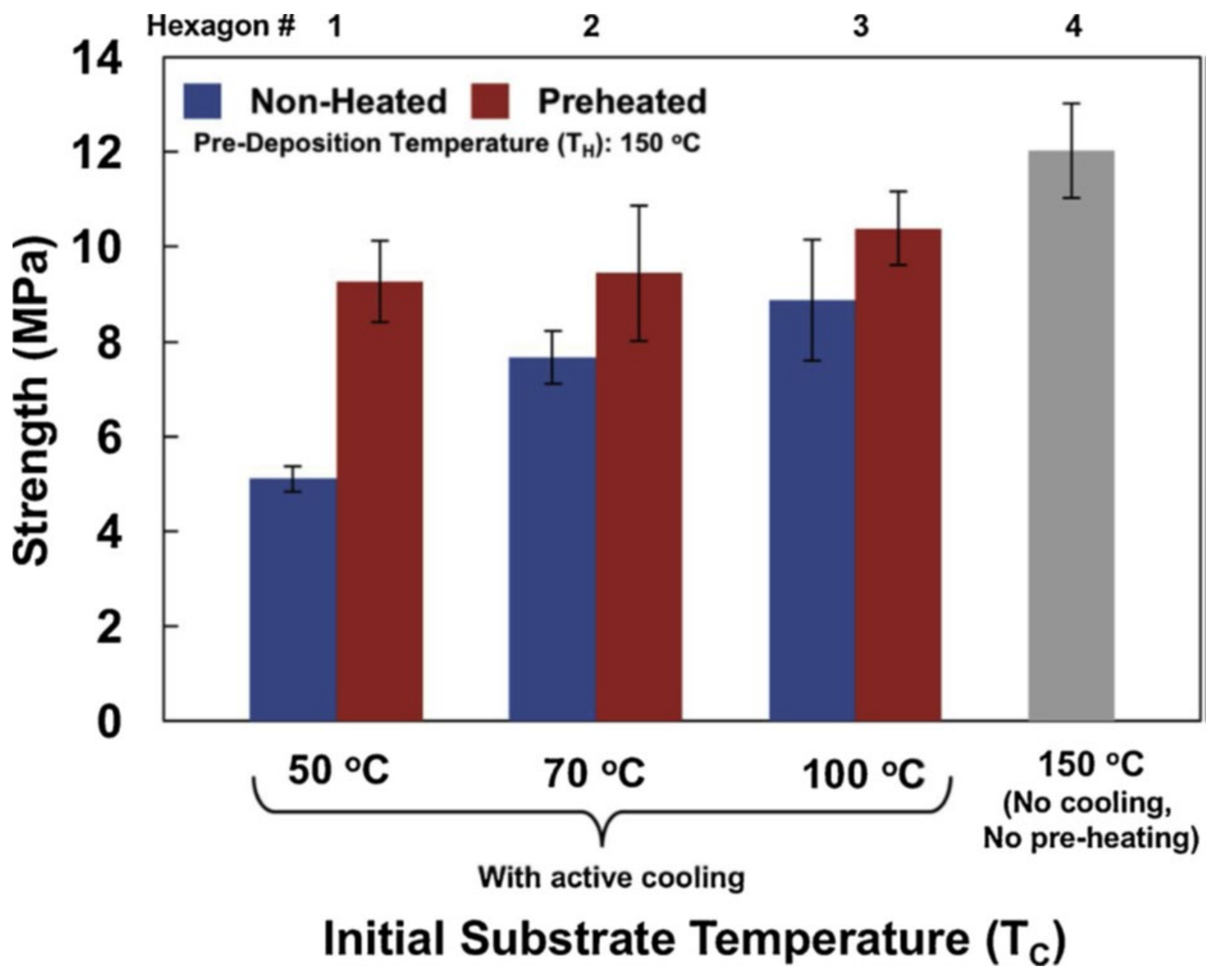


Figure 47: Nycz, A., Kishore, V., Lindahl, J., Duty, C., Carnall, C., Kunc, V., Controlling substrate temperature with infrared heating to improve mechanical properties of large-scale printed parts. Additive Manufacturing, 2020.

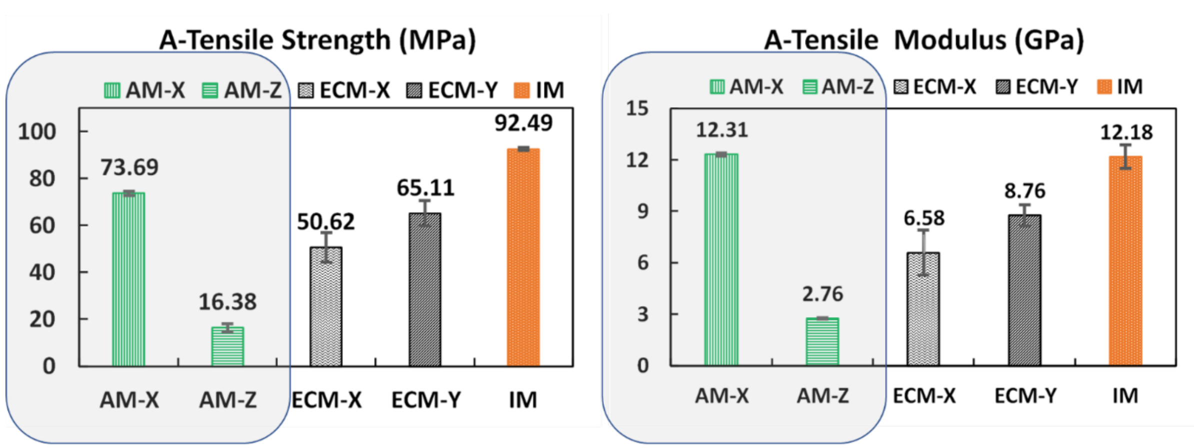
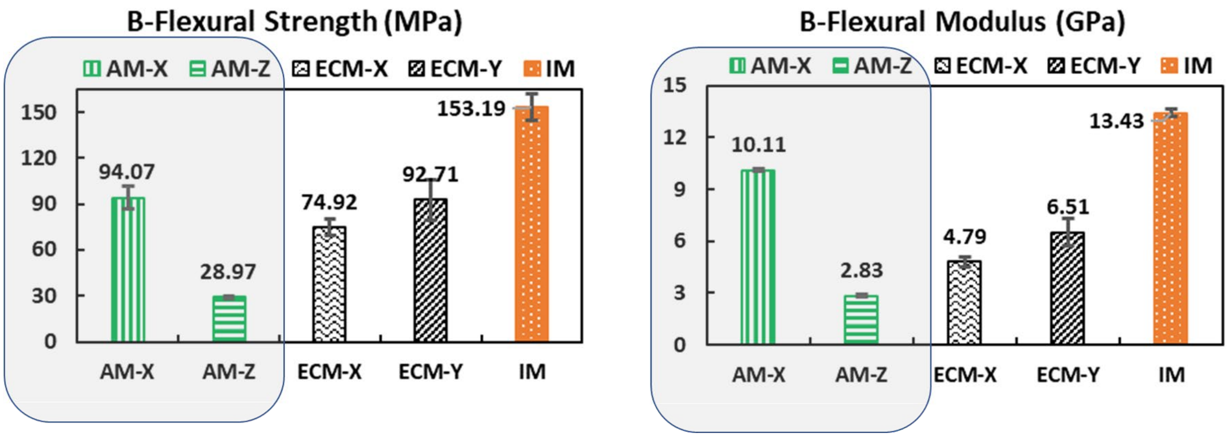


Figure 48: Unpublished data.



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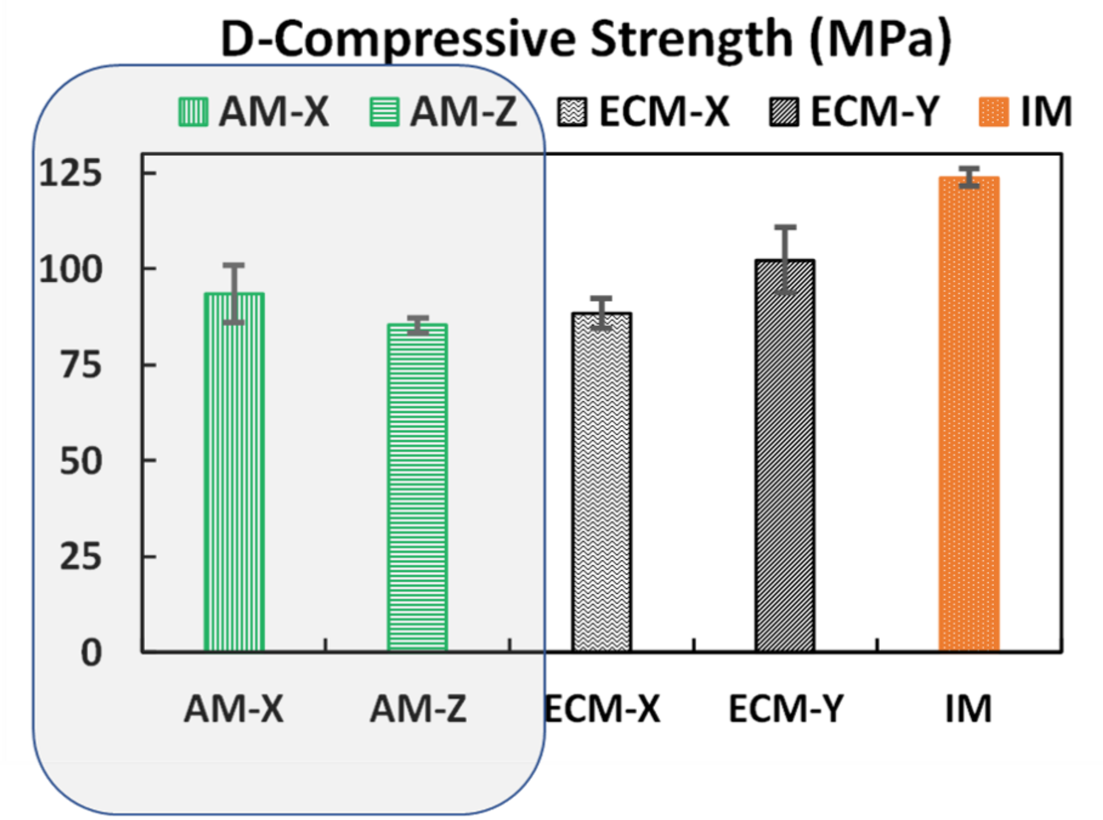

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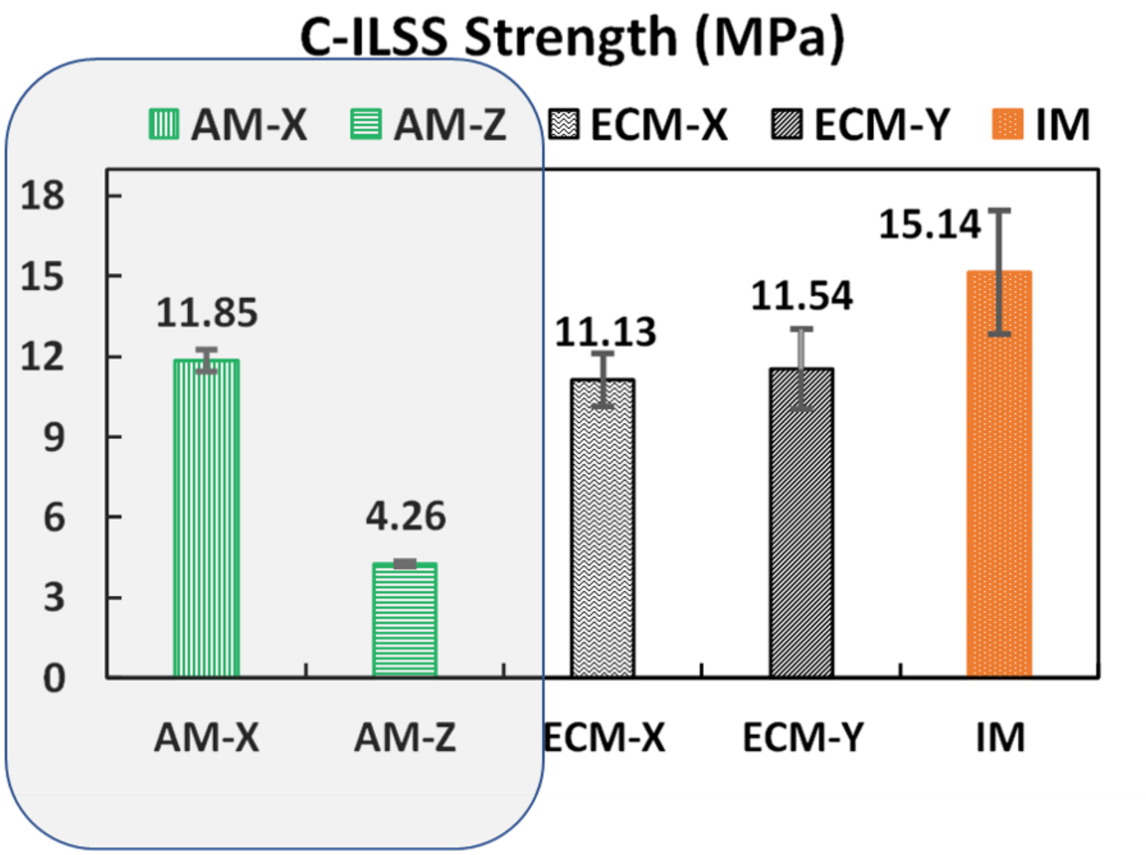


Figure 51: Unpublished data.

Neat, 40%CF, 50%CF PPS

Base (Neat) Material	PPS
Material Type	High Temp
Additives/Reinforcements	Neat, 40%CF, 50%CF

Printability

Rheological Properties During Deposition

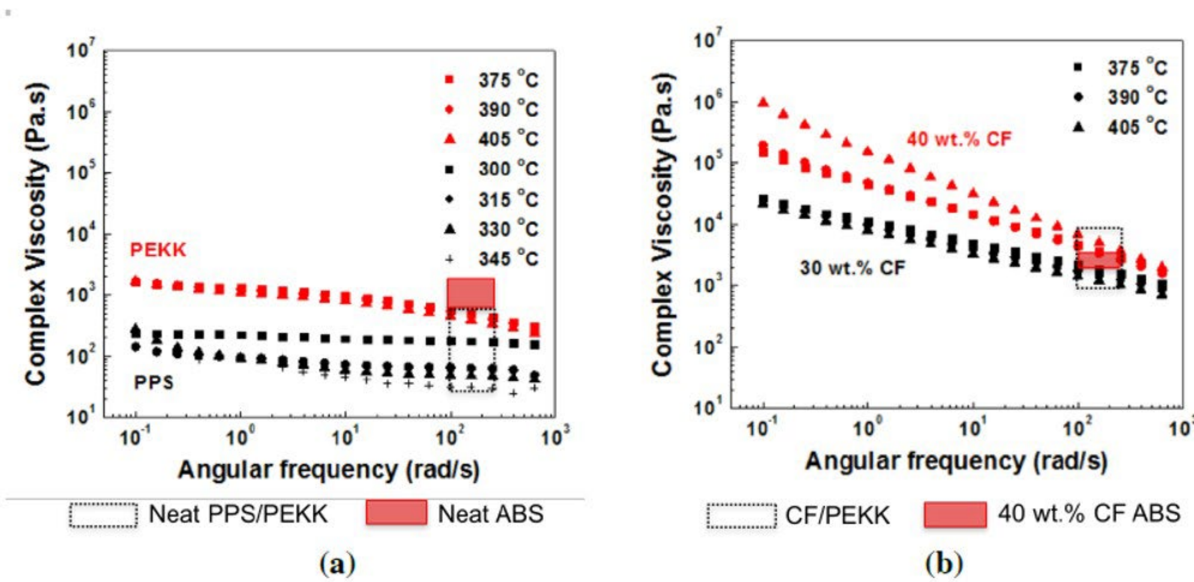


Figure 52: Kishore, V., Chen, X., Ajinjeru, C., Hassen, A.A., Lindahl, J., Faila, J., Kunc, V. and Duty, C., 2016. Additive Manufacturing of High Performance Semi-Crystalline Thermoplastics and Their Composites. In Solid Freeform Fabrication Symposium, Austin, TX.

Thermal Properties

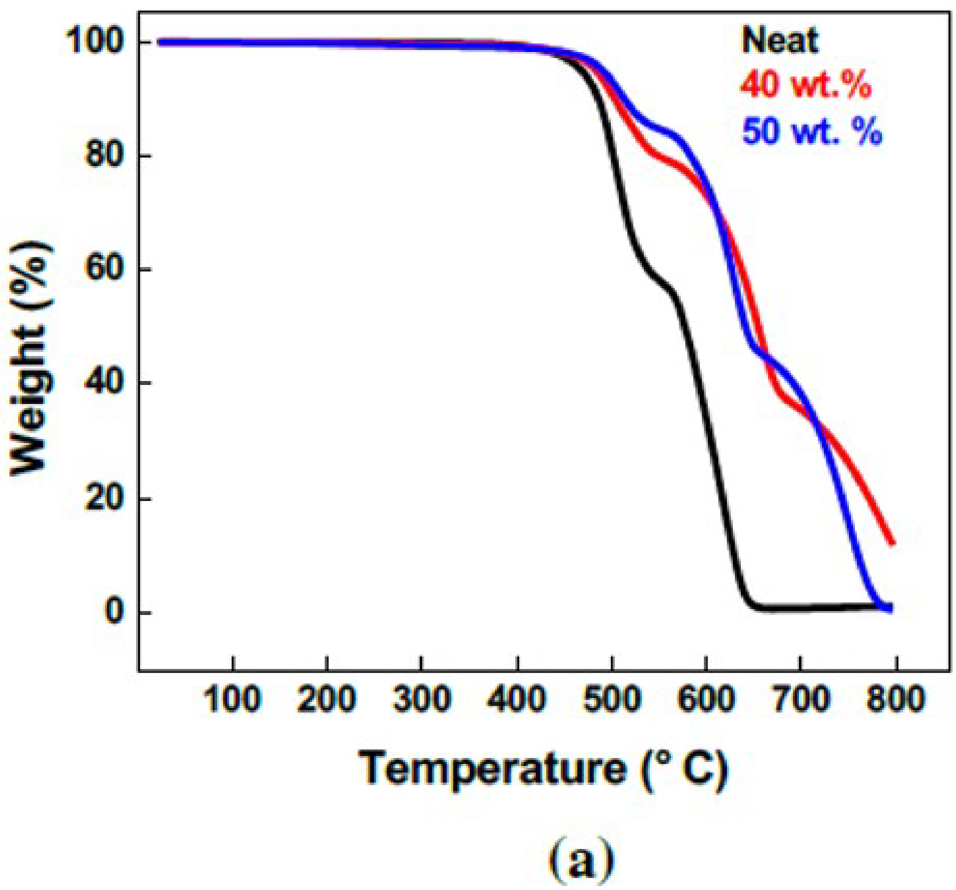


Figure 53: Kishore, V., Chen, X., Ajinjeru, C., Hassen, A.A., Lindahl, J., Faila, J., Kunc, V. and Duty, C., 2016. Additive Manufacturing of High Performance Semi-Crystalline Thermoplastics and Their Composites. In Solid Freeform Fabrication Symposium, Austin, TX.

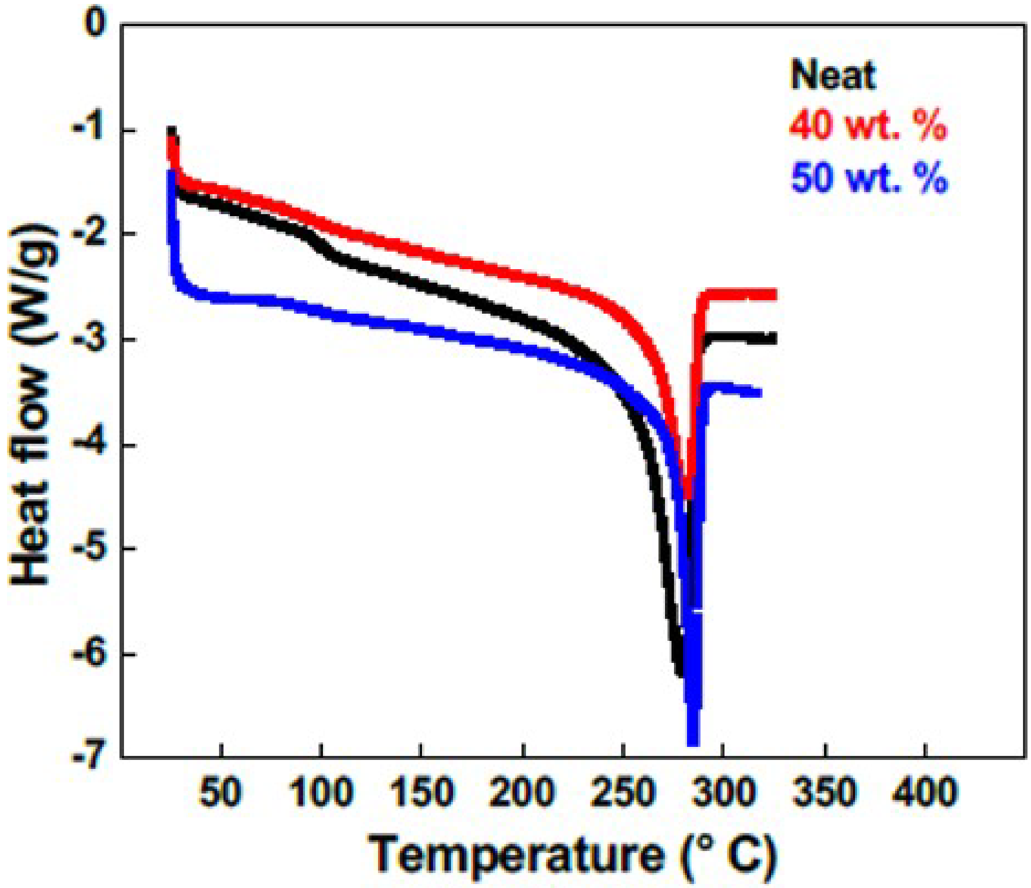


Figure 54: Kishore, V., Chen, X., Ajinjeru, C., Hassen, A.A., Lindahl, J., Faila, J., Kunc, V. and Duty, C., 2016. Additive Manufacturing of High Performance Semi-Crystalline Thermoplastics and Their Composites. In Solid Freeform Fabrication Symposium, Austin, TX.

Printed Parts

<u>Mechanical Properties</u>

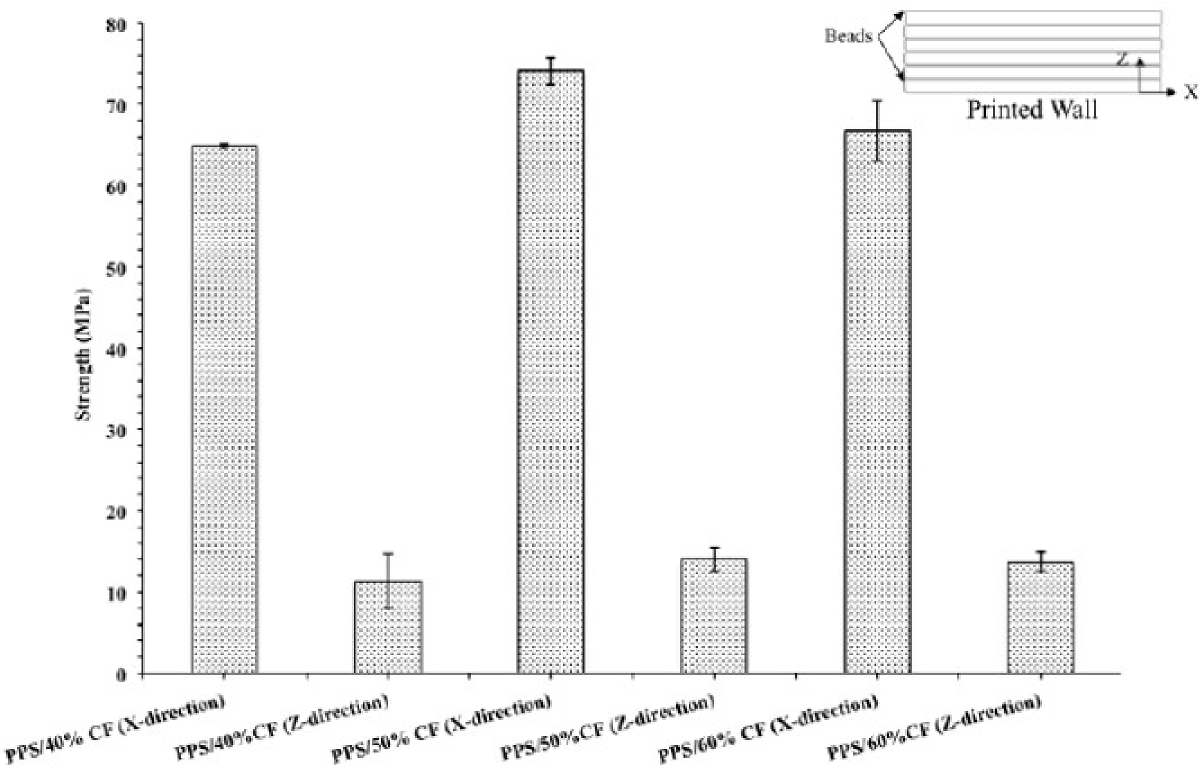


Figure 55: Hassen, A.A., Lindahl, J., Chen, X., Post, B., Love, L. and Kunc, V., 2016, May. Additive manufacturing of composite tooling using high temperature thermoplastic materials. In SAMPE Conference Proceedings, Long Beach, CA, May (pp. 23-26).

Table 3. Tensile strength properties for PPS / CF with different fiber loading

	Average Strength (MPa)	STDV
PPS / 40 % CF (X-direction)	64.83	± 0.33
PPS / 40 % CF (Z-direction)	11.25	± 3.39
PPS / 50% CF (X-direction)	74.03	± 1.65
PPS / 50 % CF (Z-direction)	14.06	± 1.53
PPS / 60 % CF (X-direction)	66.69	± 3.69
PPS / 60 % CF (Z-direction)	13.68	±1.17

Figure 56: Hassen, A.A., Lindahl, J., Chen, X., Post, B., Love, L. and Kunc, V., 2016, May. Additive manufacturing of composite tooling using high temperature thermoplastic materials. In SAMPE Conference Proceedings, Long Beach, CA, May (pp. 23-26).

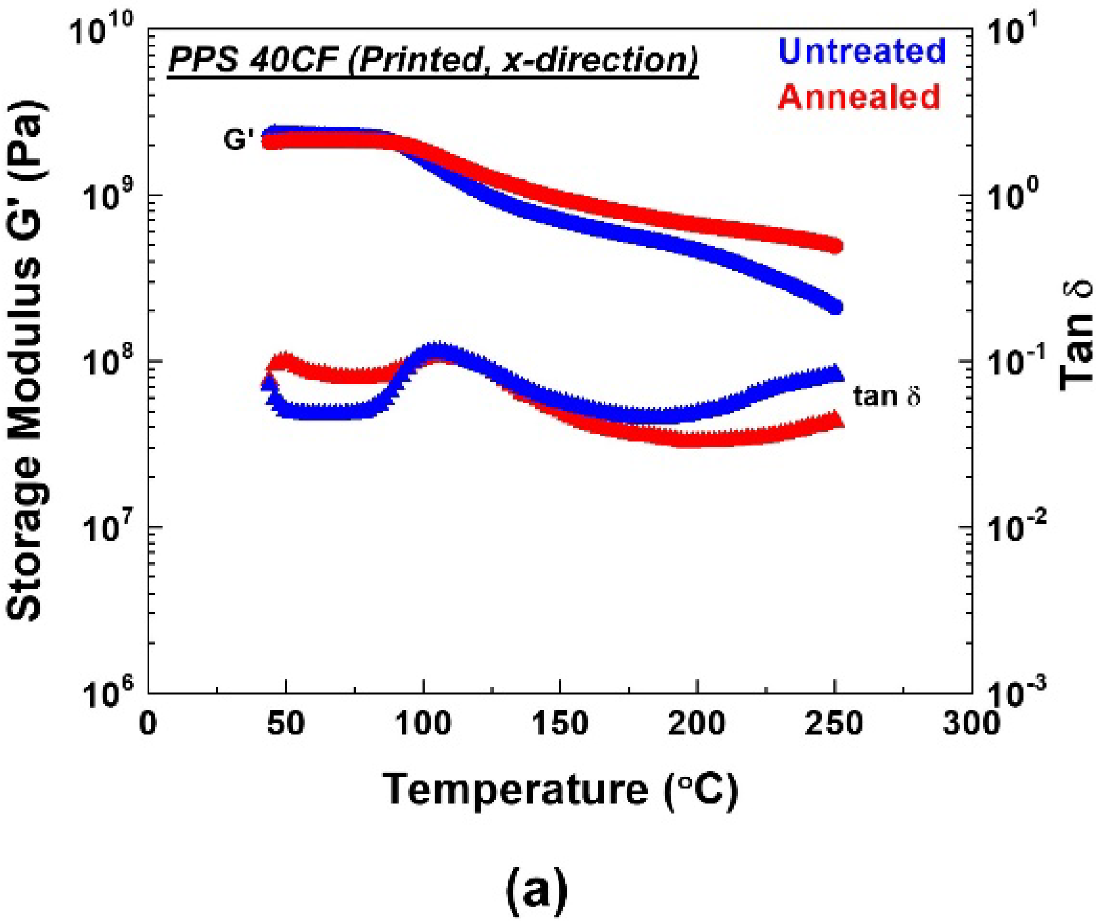
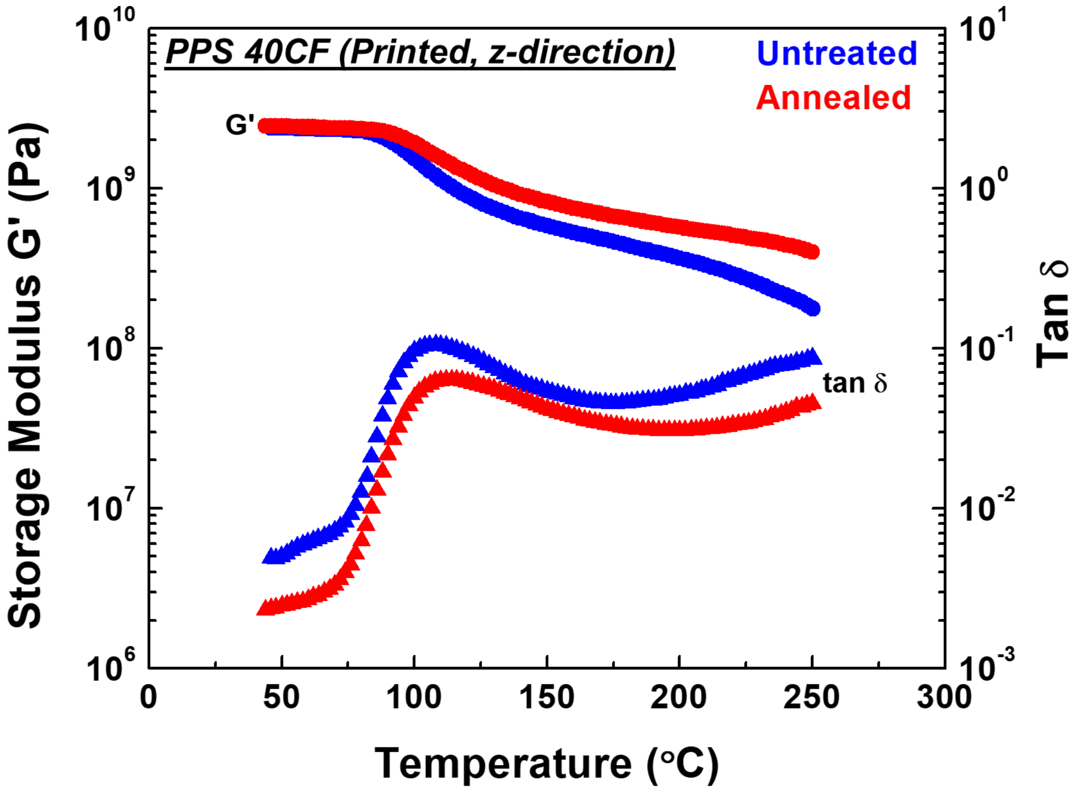


Figure 57: Kishore, V., Chen, X., Hassen, A. A., Lindahl, J., Kunc, V., & Duty, C. (2020). Post-Process Annealing of Large-Scale 3D Printed Polyphenylene Sulfide Composites. Additive Manufacturing, 101387.



(b)

Figure 58: Kishore, V., Chen, X., Hassen, A. A., Lindahl, J., Kunc, V., & Duty, C. (2020). Post-Process Annealing of Large-Scale 3D Printed Polyphenylene Sulfide Composites. Additive Manufacturing, 101387.

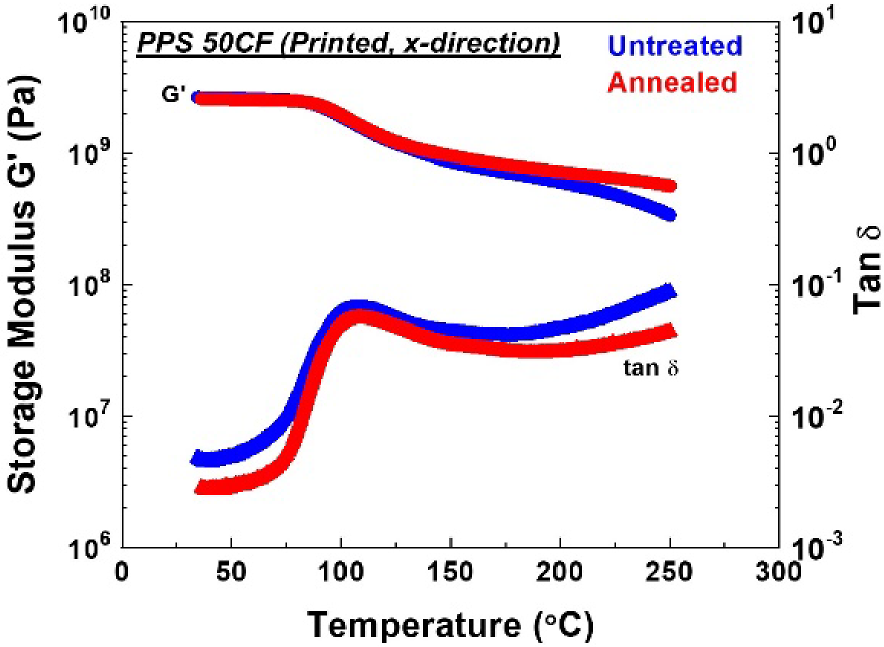


Figure 59: Kishore, V., Chen, X., Hassen, A. A., Lindahl, J., Kunc, V., & Duty, C. (2020). Post-Process Annealing of Large-Scale 3D Printed Polyphenylene Sulfide Composites. Additive Manufacturing, 101387.

Thermal Properties

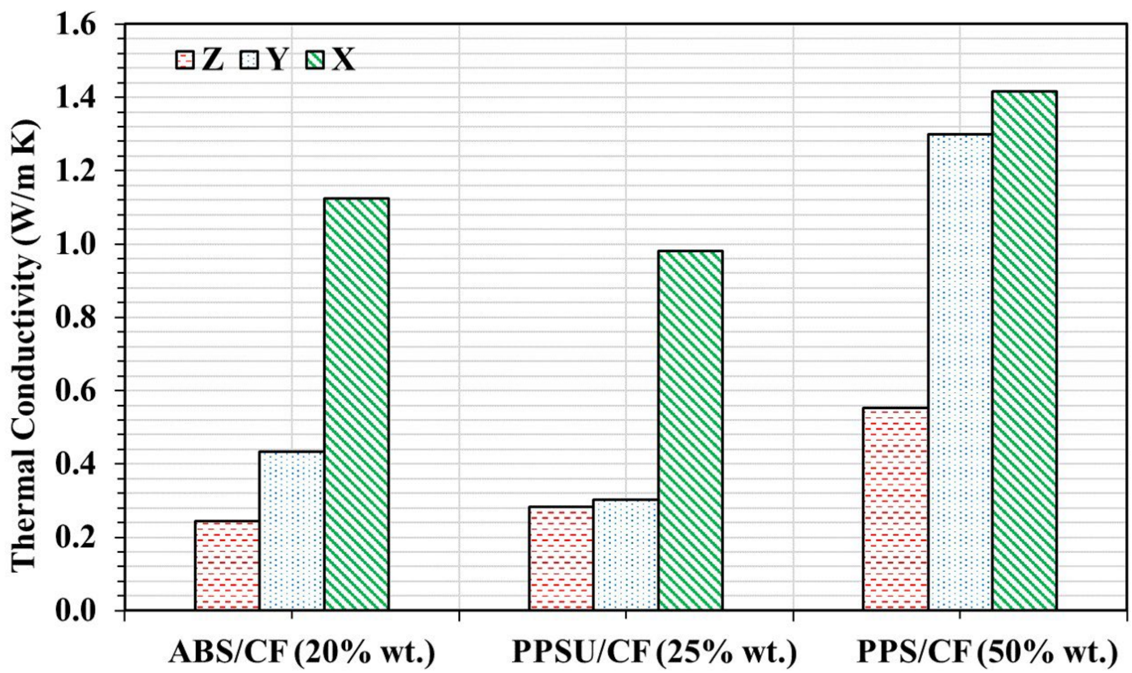


Figure 60: Data unpublished, for internal use only.

Neat, 25%CF, 35%CF PPSU

Base (Neat) Material	PPSU
Material Type	High Temp
Additives/Reinforcements	Neat, 25%CF, 35%CF

Printability

Rheological Properties During Deposition

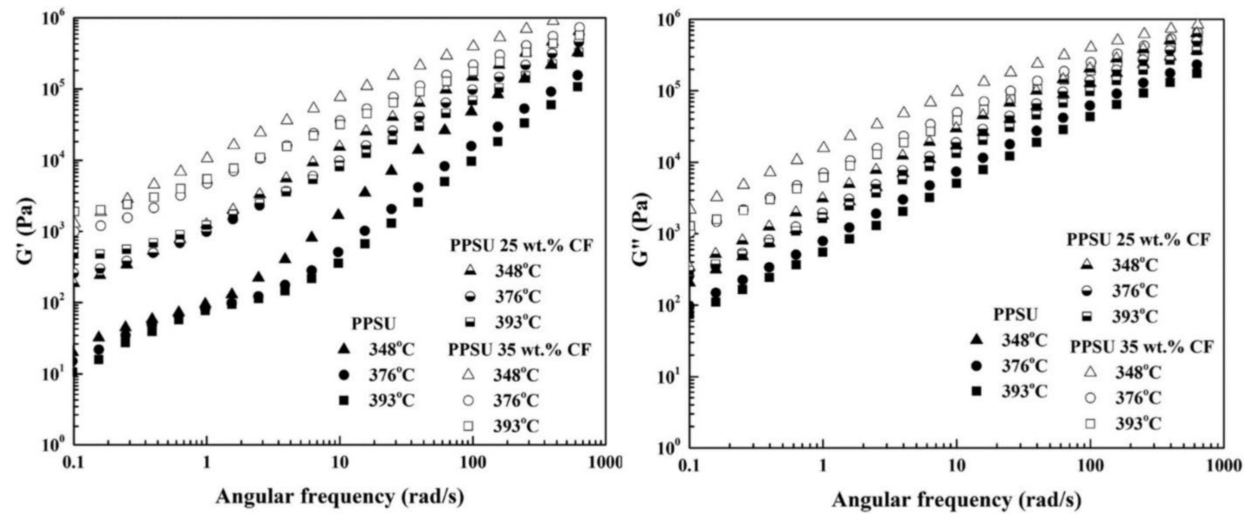


Figure 61: Ajinjeru, C., Kishore, V., Liu, P., Lindahl, J., Hassen, A. A., Kunc, V., ... & Duty, C. (2018). Determination of melt processing conditions for high performance amorphous thermoplastics for large format additive manufacturing. Additive Manufacturing, 21, 125-132.

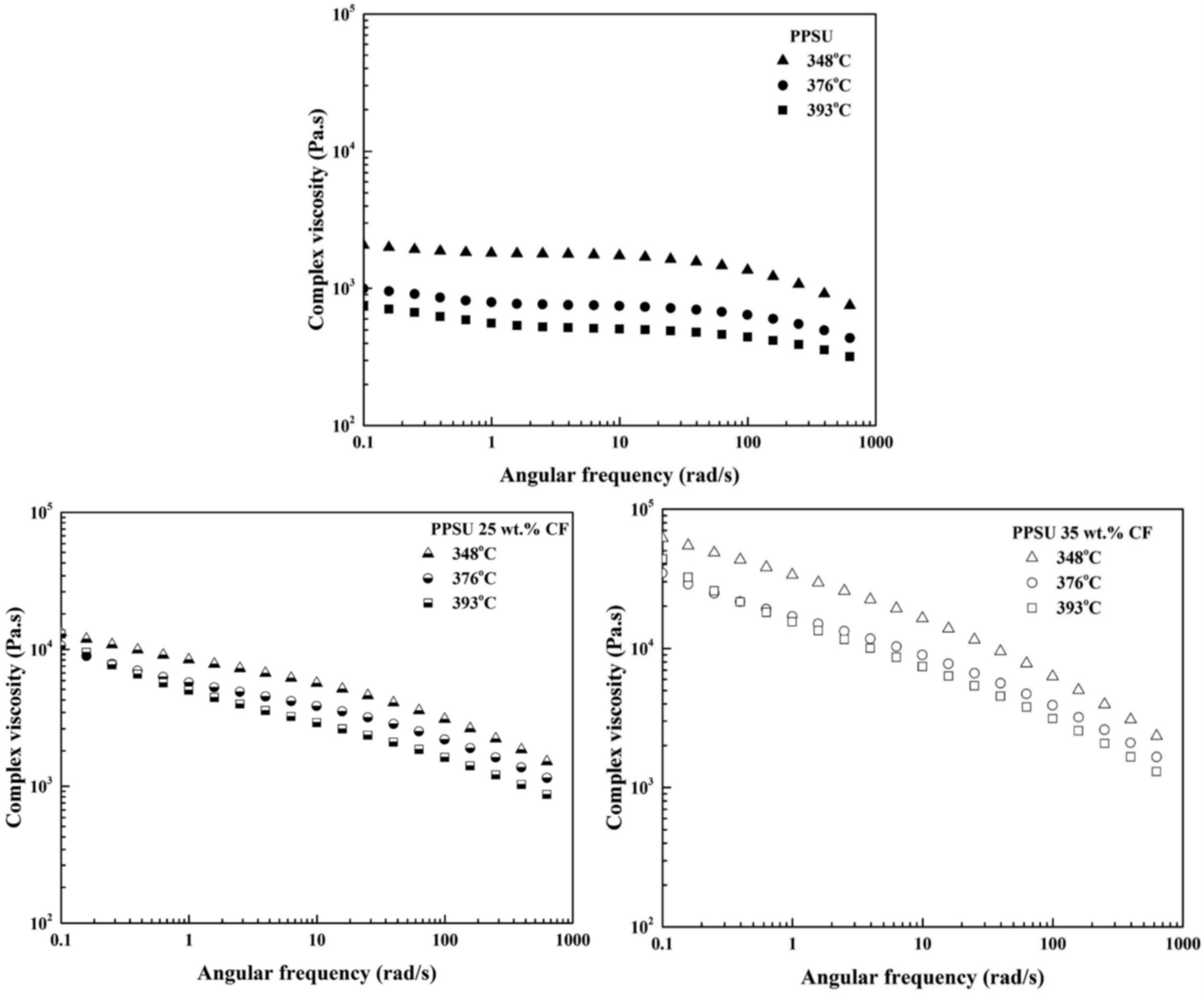


Figure 62: Ajinjeru, C., Kishore, V., Liu, P., Lindahl, J., Hassen, A. A., Kunc, V., ... & Duty, C. (2018). Determination of melt processing conditions for high performance amorphous thermoplastics for large format additive manufacturing. Additive Manufacturing, 21, 125-132.

Rheological Properties Post-Deposition

Thermal Properties

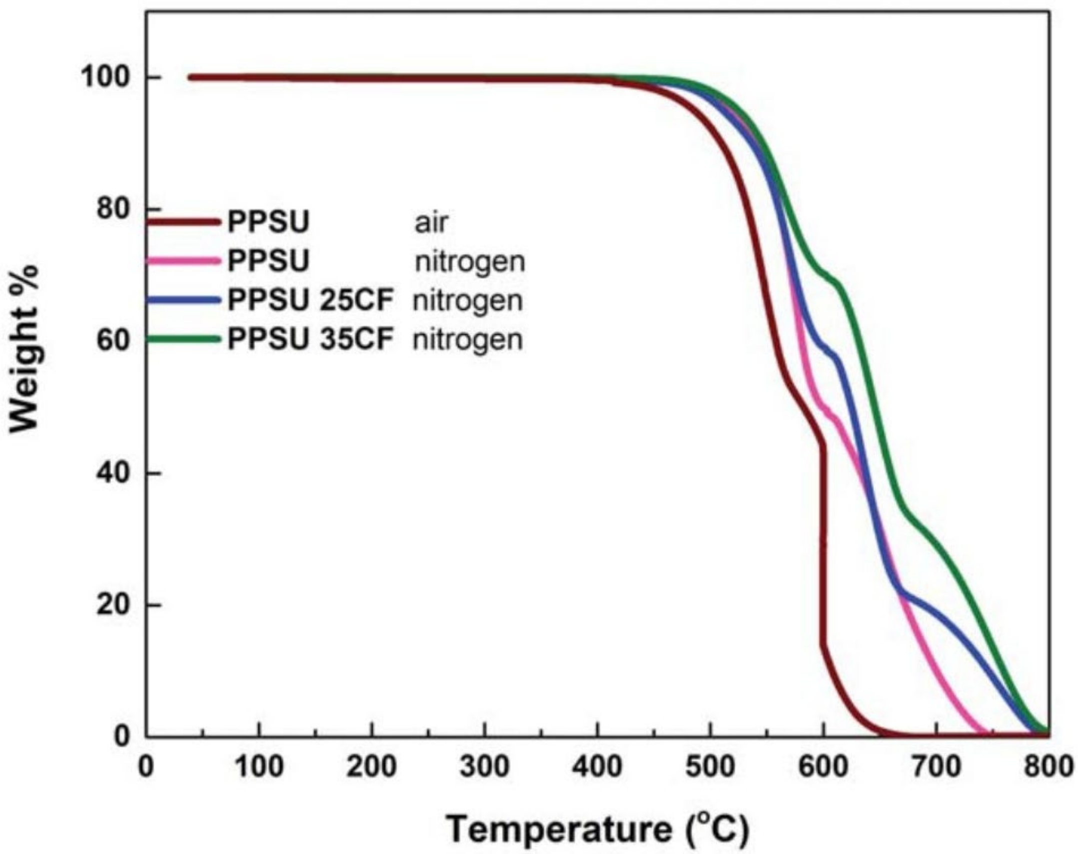


Figure 63: Ajinjeru, C., Kishore, V., Chen, X., Lindahl, J., Sudbury, Z., Hassen, A. A., ... & Duty, C. (2016). The influence of rheology on melt processing conditions of amorphous thermoplastics for big area additive manufacturing (BAAM). Solid Freeform Fabrication, 2016, 754-761.

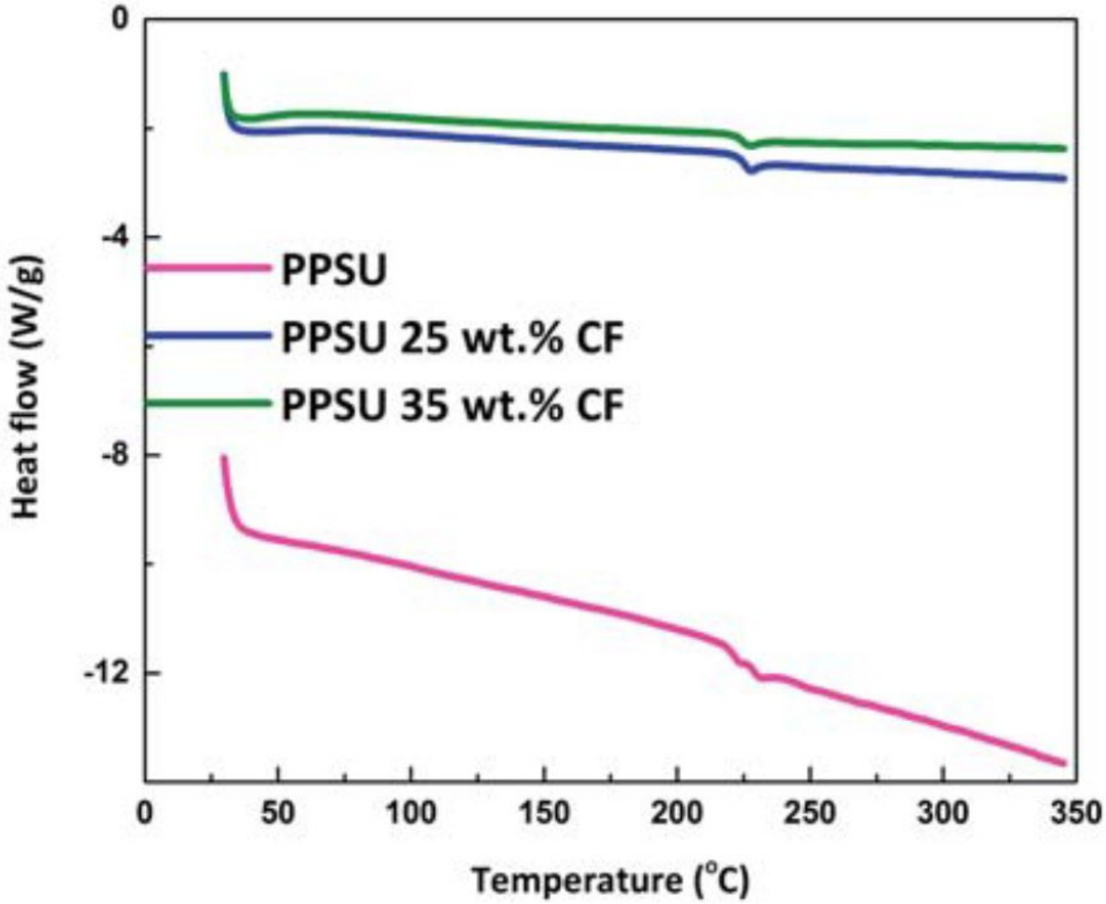


Figure 64: Ajinjeru, C., Kishore, V., Chen, X., Lindahl, J., Sudbury, Z., Hassen, A. A., ... & Duty, C. (2016). The influence of rheology on melt processing conditions of amorphous thermoplastics for big area additive manufacturing (BAAM). Solid Freeform Fabrication, 2016, 754-761.

Printed Parts

<u>Mechanical Properties</u>

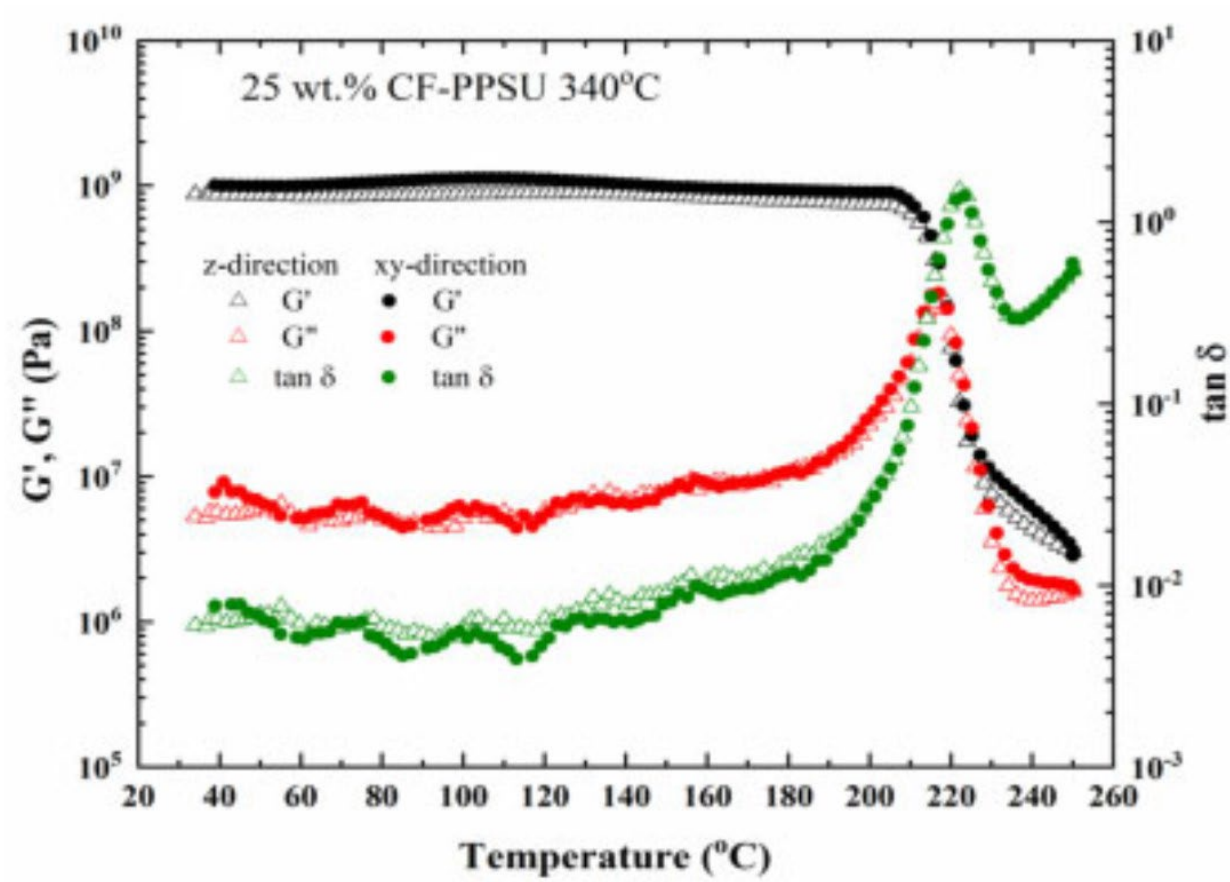


Figure 65: Ajinjeru, C., Kishore, V., Chen, X., Hershey, C., Lindahl, J., Kunc, V., ... & Duty, C. (2019). Rheological survey of carbon fiber-reinforced high-temperature thermoplastics for big area additive manufacturing tooling applications. Journal of Thermoplastic Composite Materials, 0892705719873941.

Thermal Properties

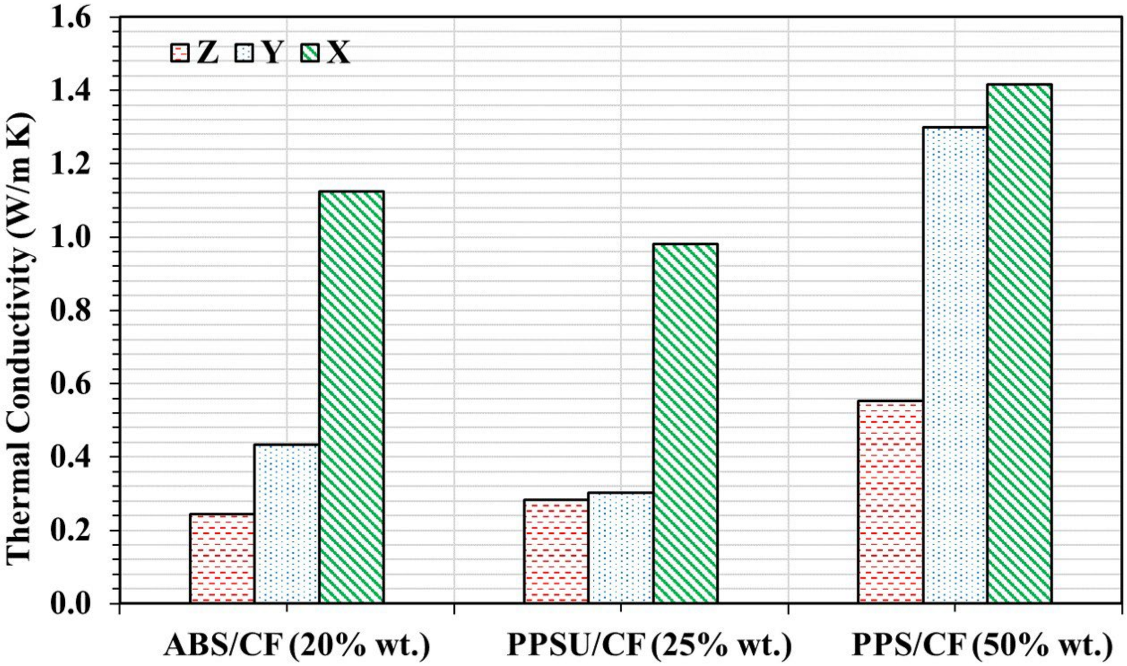


Figure 66: Data unpublished. For internal use only.

Neat, 20%CF, 30%CF PEI

Base (Neat) Material	PEI
Material Type	High Temp
Additives/Reinforcements	Neat, 20%CF, 30%CF

Printability

<u>Rheological Properties Post Deposition</u>

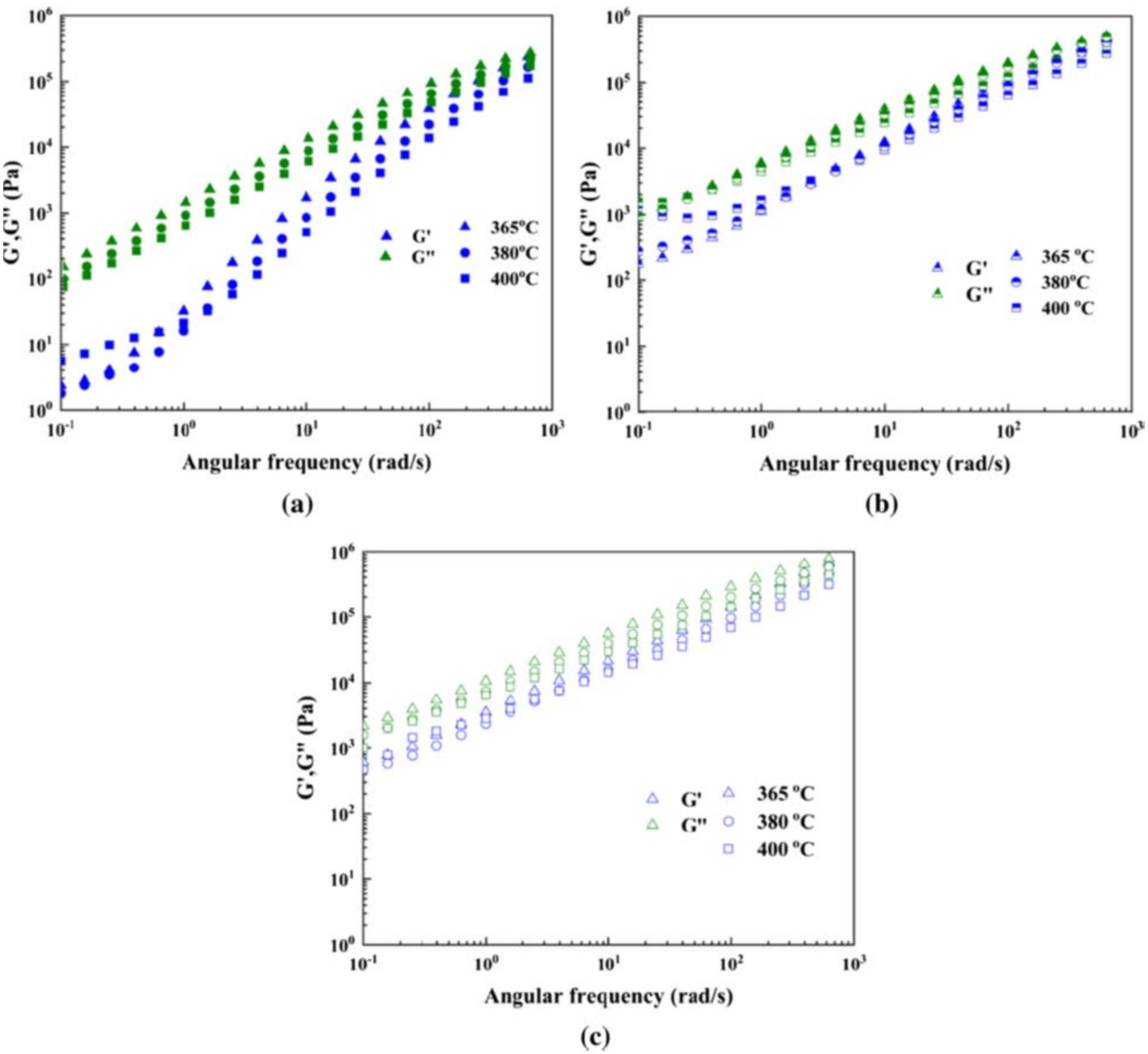


Figure 67: Storage modulus (G') and loss modulus (G") versus angular frequency at various temperatures. (a) Neat PEI, (b) CF-PEI with 20% by weight, (c) CF-PEI with 30% by weight.

Ajinjeru, C., Kishore, V., Lindahl, J., Sudbury, Z., Hassen, A. A., Post, B., ... & Duty, C. (2018). The influence of dynamic rheological properties on carbon fiber-reinforced polyetherimide for large-scale extrusion-based additive manufacturing. The International Journal of Advanced Manufacturing Technology, 99(1-4), 411-418.

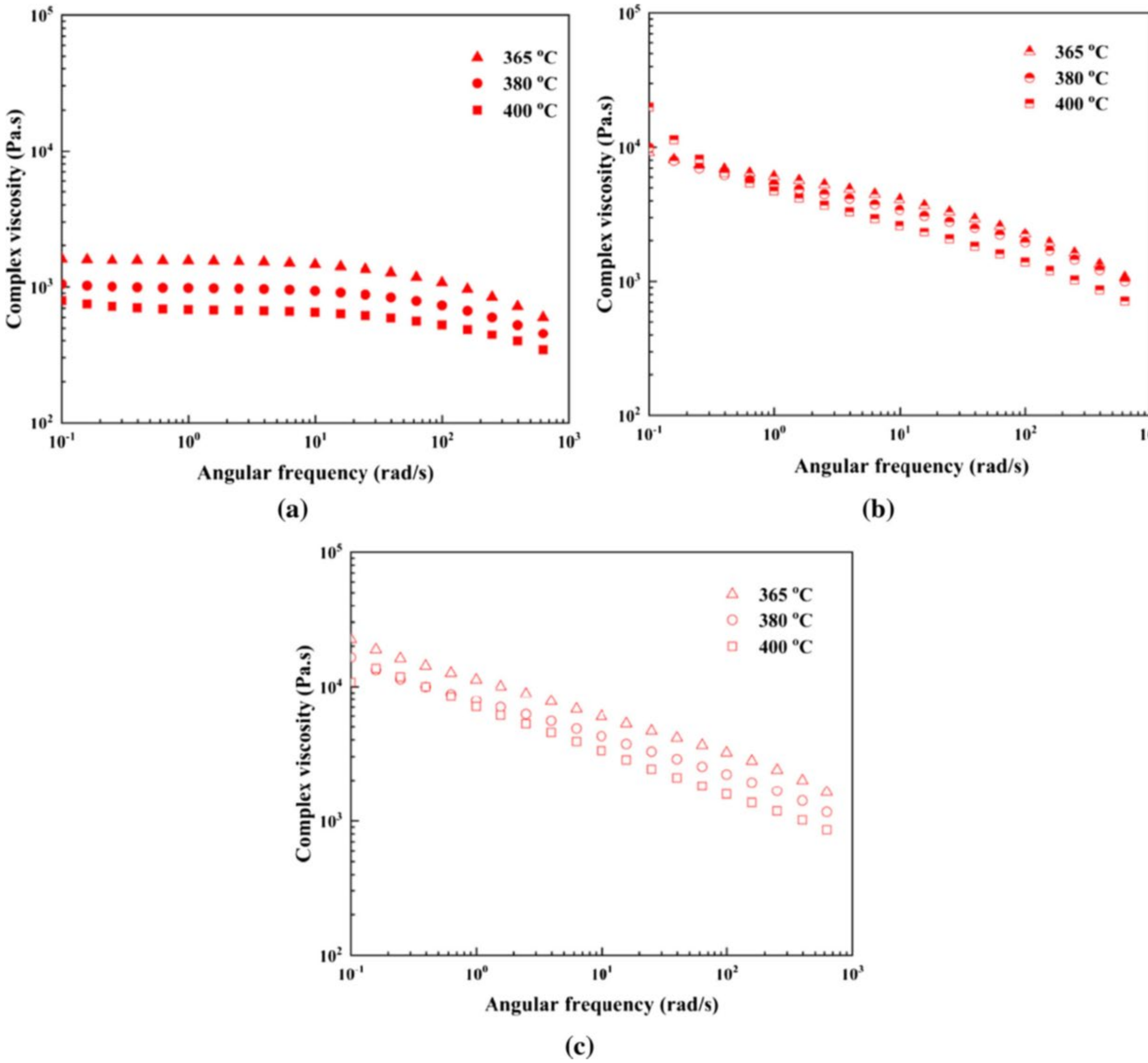


Figure 68: Complex viscosity versus angular frequency at various temperatures. (a) Neat PEI, (b) CF-PEI with 20% by weight, (c) CF-PEI with 30% by weight.

Ajinjeru, C., Kishore, V., Lindahl, J., Sudbury, Z., Hassen, A. A., Post, B., ... & Duty, C. (2018). The influence of dynamic rheological properties on carbon fiber-reinforced polyetherimide for large-scale extrusion-based additive manufacturing. The International Journal of Advanced Manufacturing Technology, 99(1-4), 411-418.

Thermal Properties

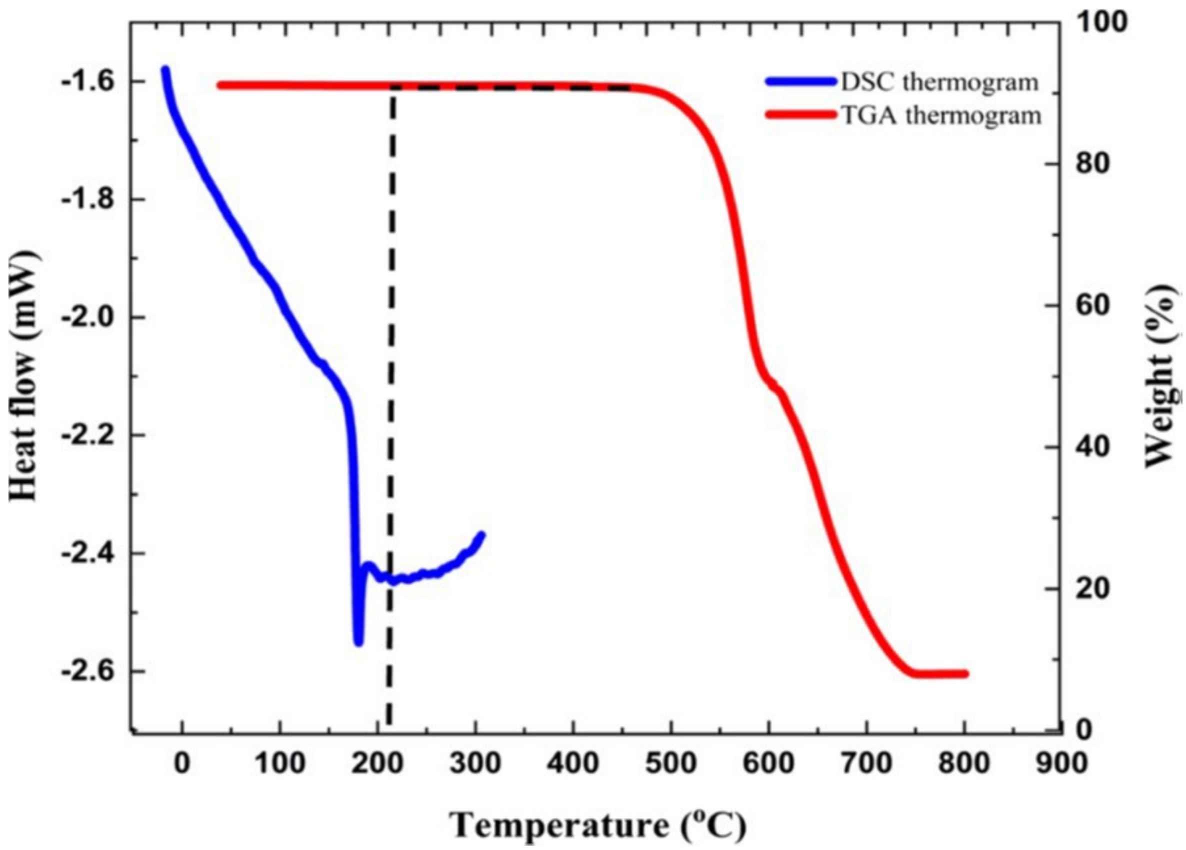


Figure 69: Ajinjeru, C., Kishore, V., Lindahl, J., Sudbury, Z., Hassen, A. A., Post, B., ... & Duty, C. (2018). The influence of dynamic rheological properties on carbon fiber-reinforced polyetherimide for large-scale extrusion-based additive manufacturing. The International Journal of Advanced Manufacturing Technology, 99(1-4), 411-418.

Neat, 30%CF, 40%CF PEKK

Base (Neat) Material PEKK

Material Type High Temp

Additives/Reinforcements Neat, 30%CF, 40%CF

Printability

Rheological Properties During Deposition

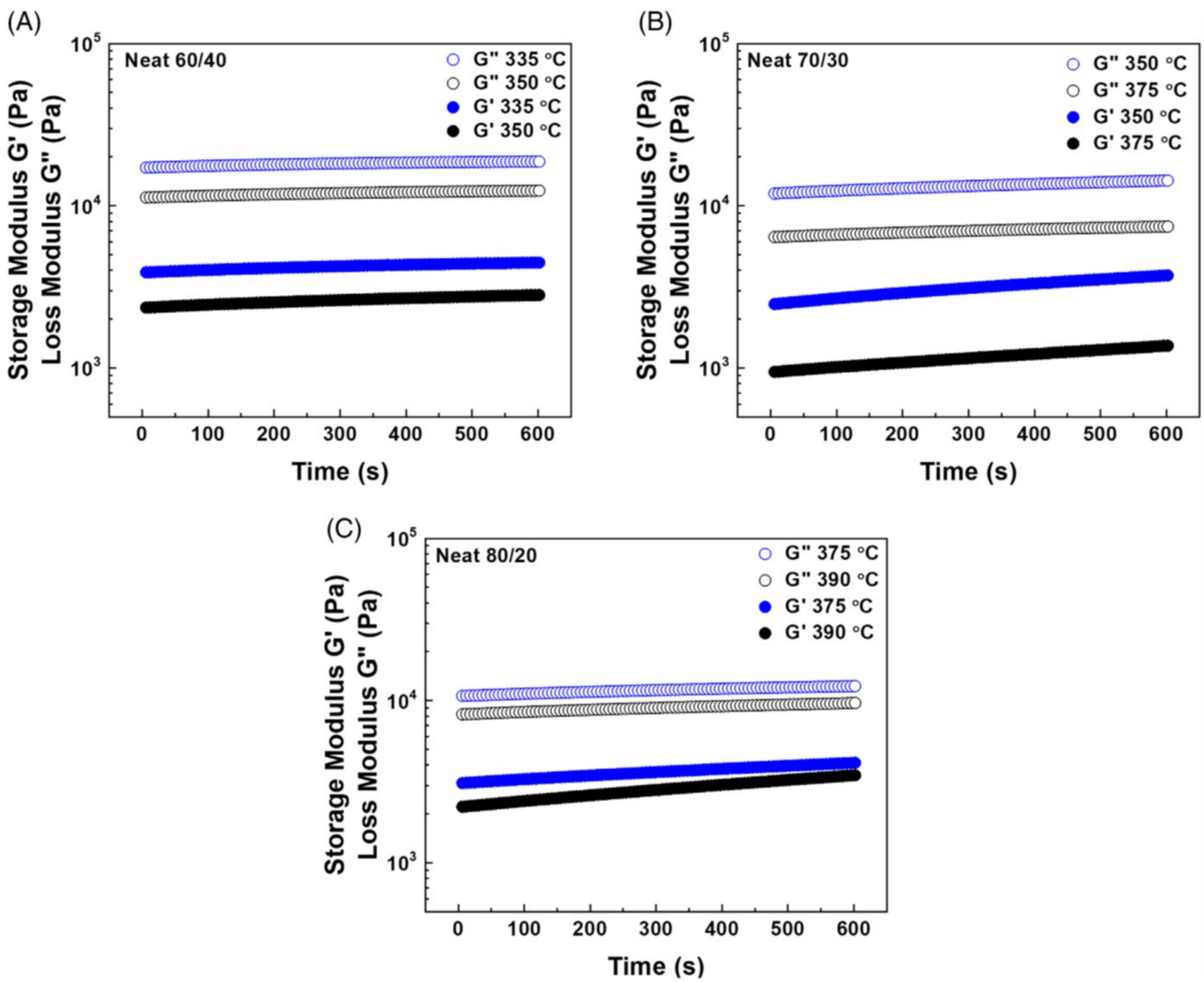


Figure 70: Kishore, V., Ajinjeru, C., Hassen, A. A., Lindahl, J., Kunc, V., & Duty, C. (2020). Rheological behavior of neat and carbon fiber-reinforced poly (ether ketone ketone) for extrusion deposition additive manufacturing. Polymer Engineering & Science, 60(5), 1066-1075.

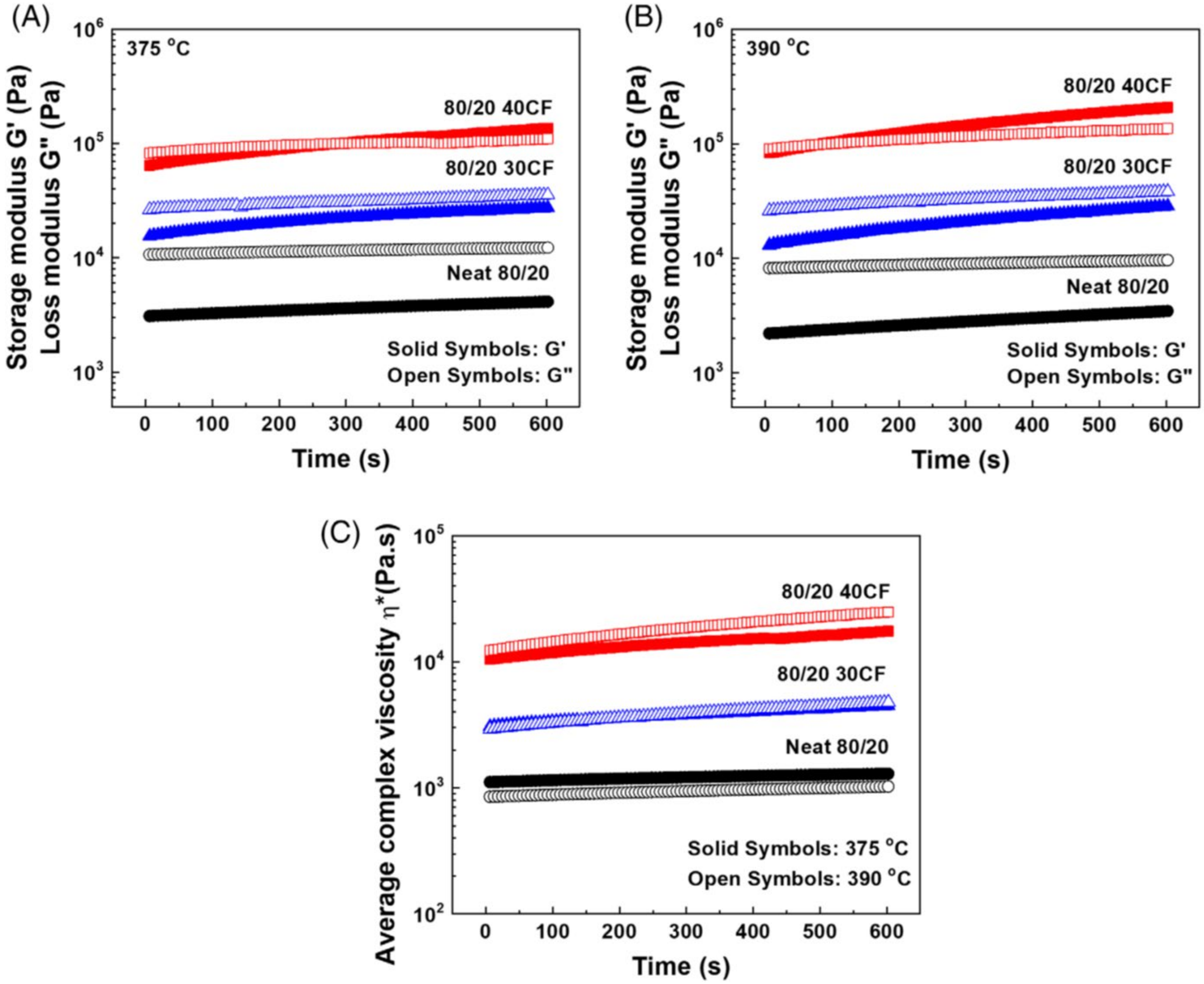


Figure 71: Kishore, V., Ajinjeru, C., Hassen, A. A., Lindahl, J., Kunc, V., & Duty, C. (2020). Rheological behavior of neat and carbon fiber-reinforced poly (ether ketone ketone) for extrusion deposition additive manufacturing. Polymer Engineering & Science, 60(5), 1066-1075.

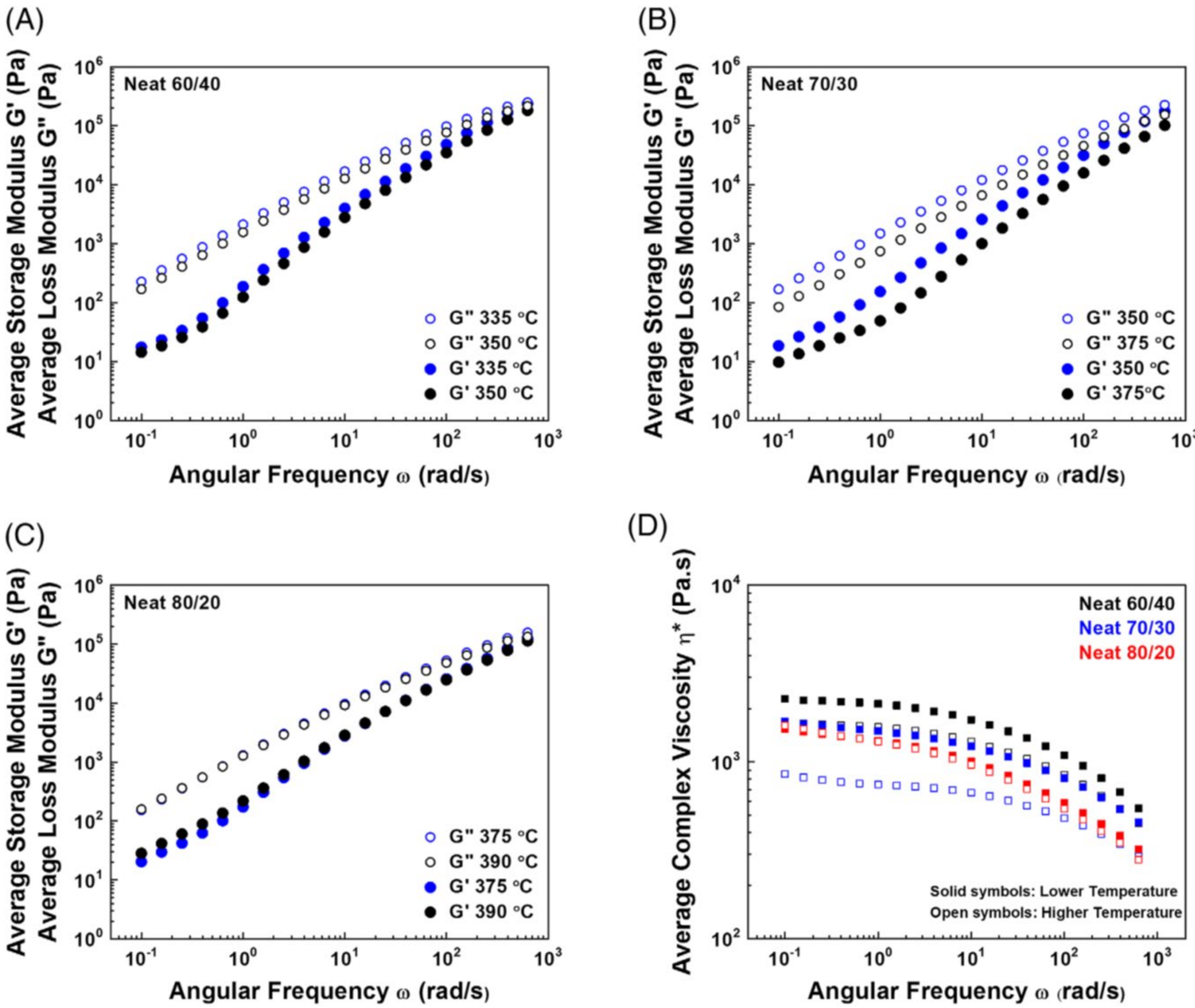


Figure 72: Kishore, V., Ajinjeru, C., Hassen, A. A., Lindahl, J., Kunc, V., & Duty, C. (2020). Rheological behavior of neat and carbon fiber-reinforced poly (ether ketone ketone) for extrusion deposition additive manufacturing. Polymer Engineering & Science, 60(5), 1066-1075.

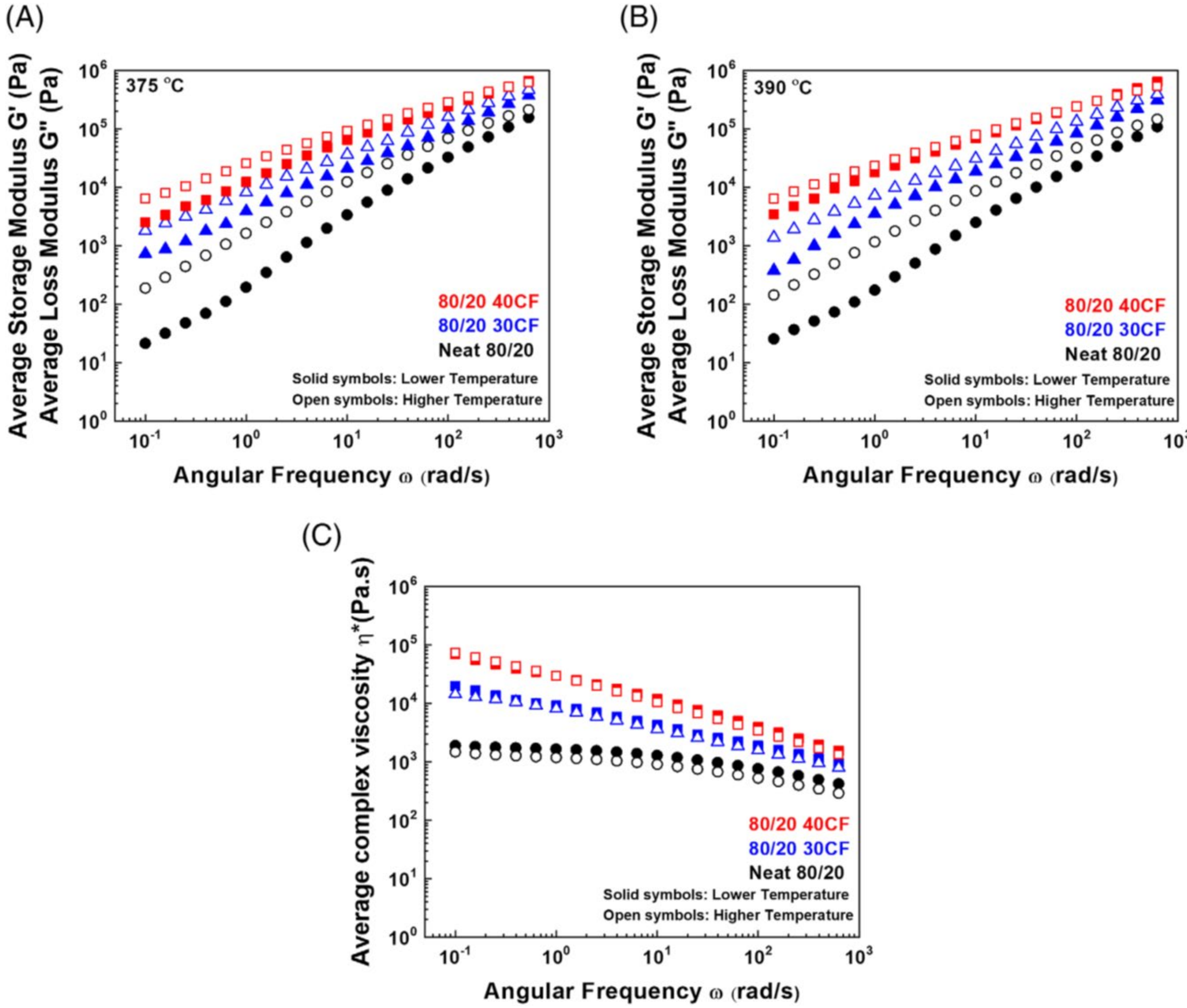


Figure 73: Kishore, V., Ajinjeru, C., Hassen, A. A., Lindahl, J., Kunc, V., & Duty, C. (2020). Rheological behavior of neat and carbon fiber-reinforced poly (ether ketone ketone) for extrusion deposition additive manufacturing. Polymer Engineering & Science, 60(5), 1066-1075.

Thermal Properties

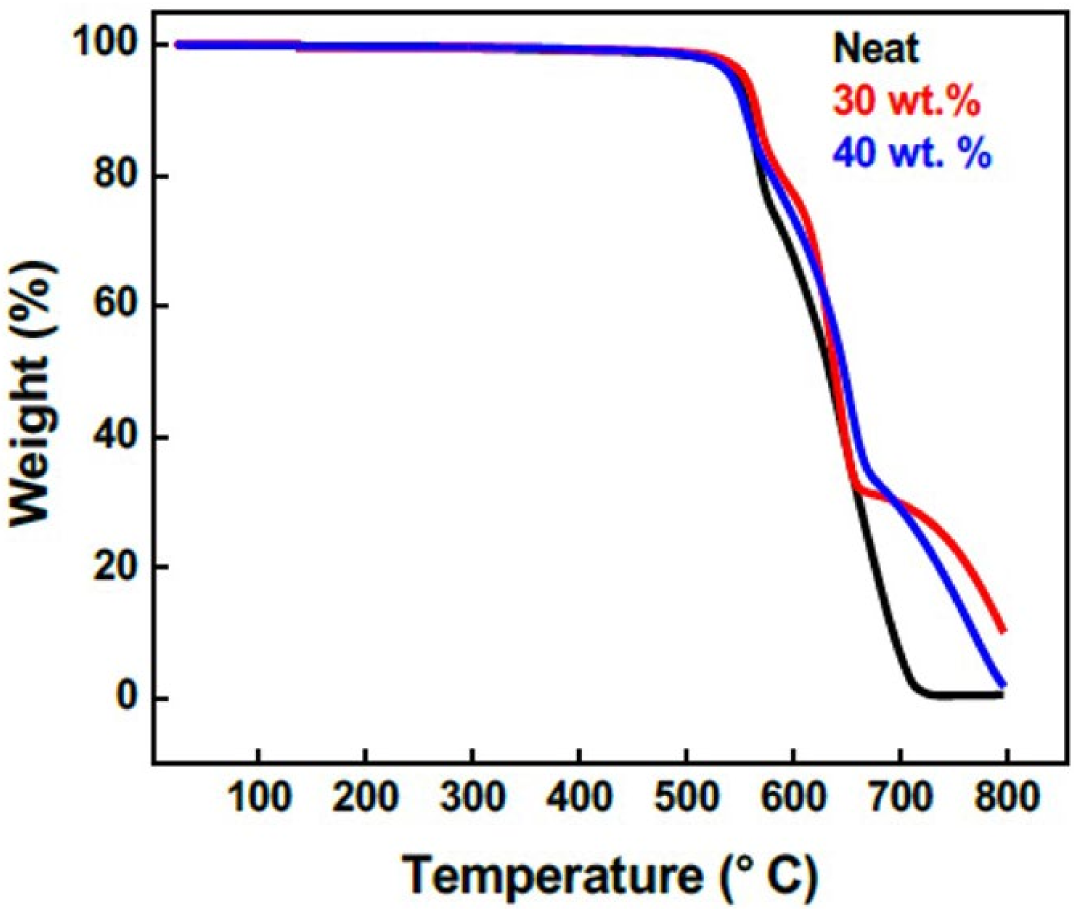


Figure 74: Kishore, V., Chen, X., Ajinjeru, C., Hassen, A. A., Lindahl, J. M., Failla, J., Kunc, V., & Duty, C. E. (2016). Additive manufacturing of high performance semicrystalline thermoplastics and their composites. Solid Freeform Fabrication Symposium, Austin, TX.

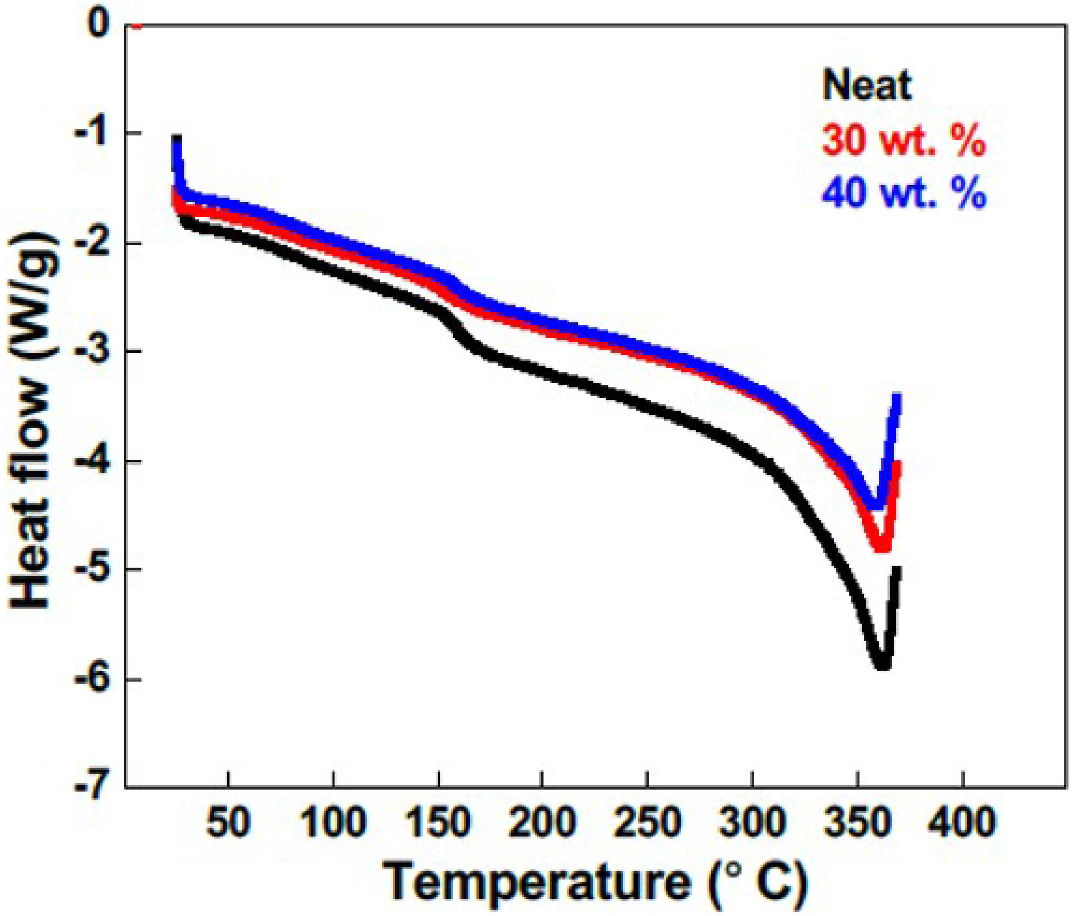


Figure 75: Kishore, V., Chen, X., Ajinjeru, C., Hassen, A. A., Lindahl, J. M., Failla, J., Kunc, V., & Duty, C. E. (2016). Additive manufacturing of high performance semicrystalline thermoplastics and their composites. Solid Freeform Fabrication Symposium, Austin, TX.

Hollow glass microspheres, CF ABS (Syntactic)

Base (Neat) Material	ABS (Syntactic)
Material Type	Foam
Additives/Reinforcements	Hollow glass microspheres, CF

Printability

Rheological Properties During Deposition

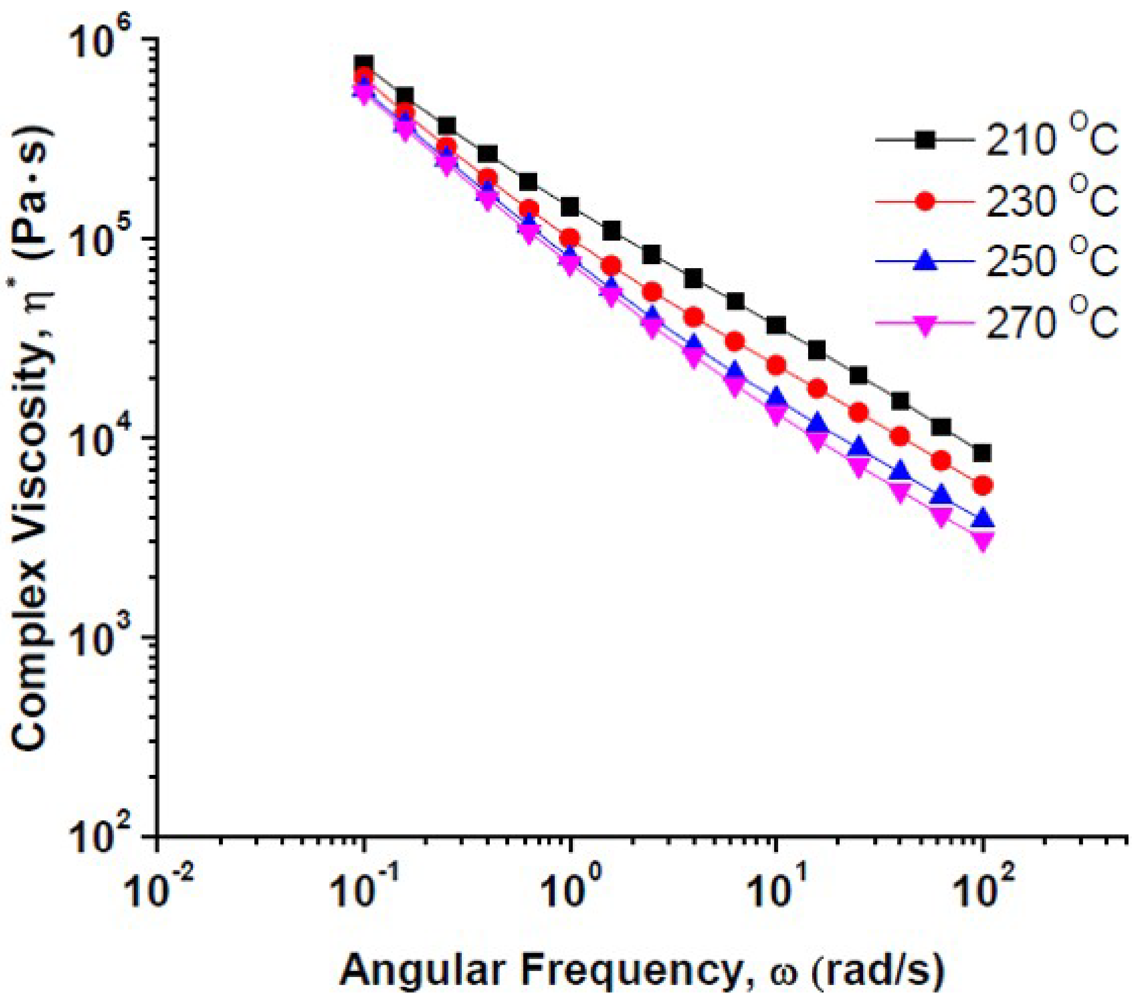


Figure 76: Liu, P., Lindahl, J., Hassen, A., & Kunc, V. (2017). Rheology of Acrylonitrile Butadiene Styrene with Hollow Glass Microspheres for Extrusion Process. ANTEC 2017.

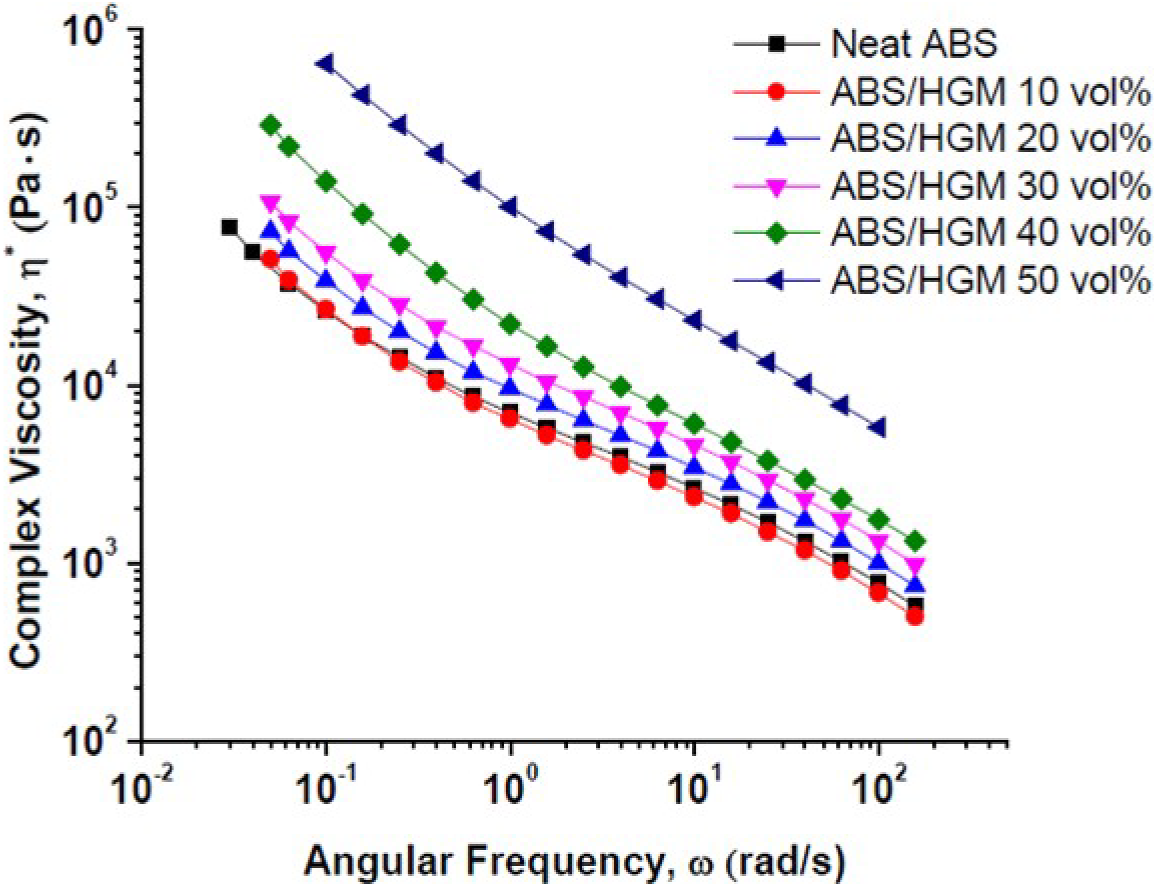


Figure 77: Liu, P., Lindahl, J., Hassen, A., & Kunc, V. (2017). Rheology of Acrylonitrile Butadiene Styrene with Hollow Glass Microspheres for Extrusion Process. ANTEC 2017.

NdFeB-PA12

Base (Neat) Material	NdFeB-PA12
Material Type	Magnets

Processing

<u>Processing Parameters</u>

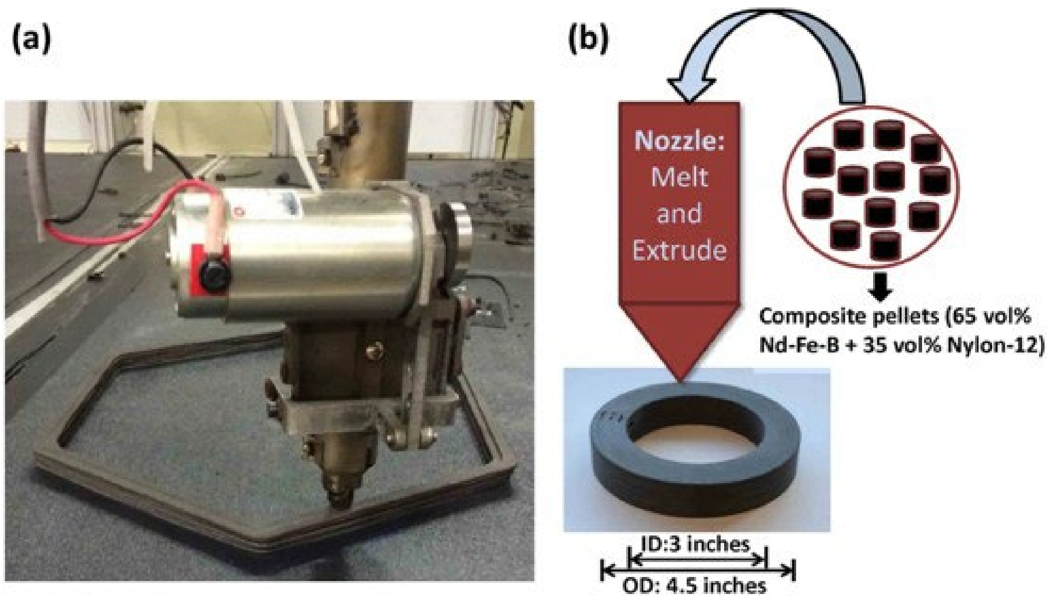


Figure 78: Li, Ling, Angelica Tirado, I. C. Nlebedim, Orlando Rios, Brian Post, Vlastimil Kunc, R. R. Lowden et al. "Big area additive manufacturing of high performance bonded NdFeB magnets." Scientific reports 6 (2016): 36212.

Printed Parts

Mechanical Properties

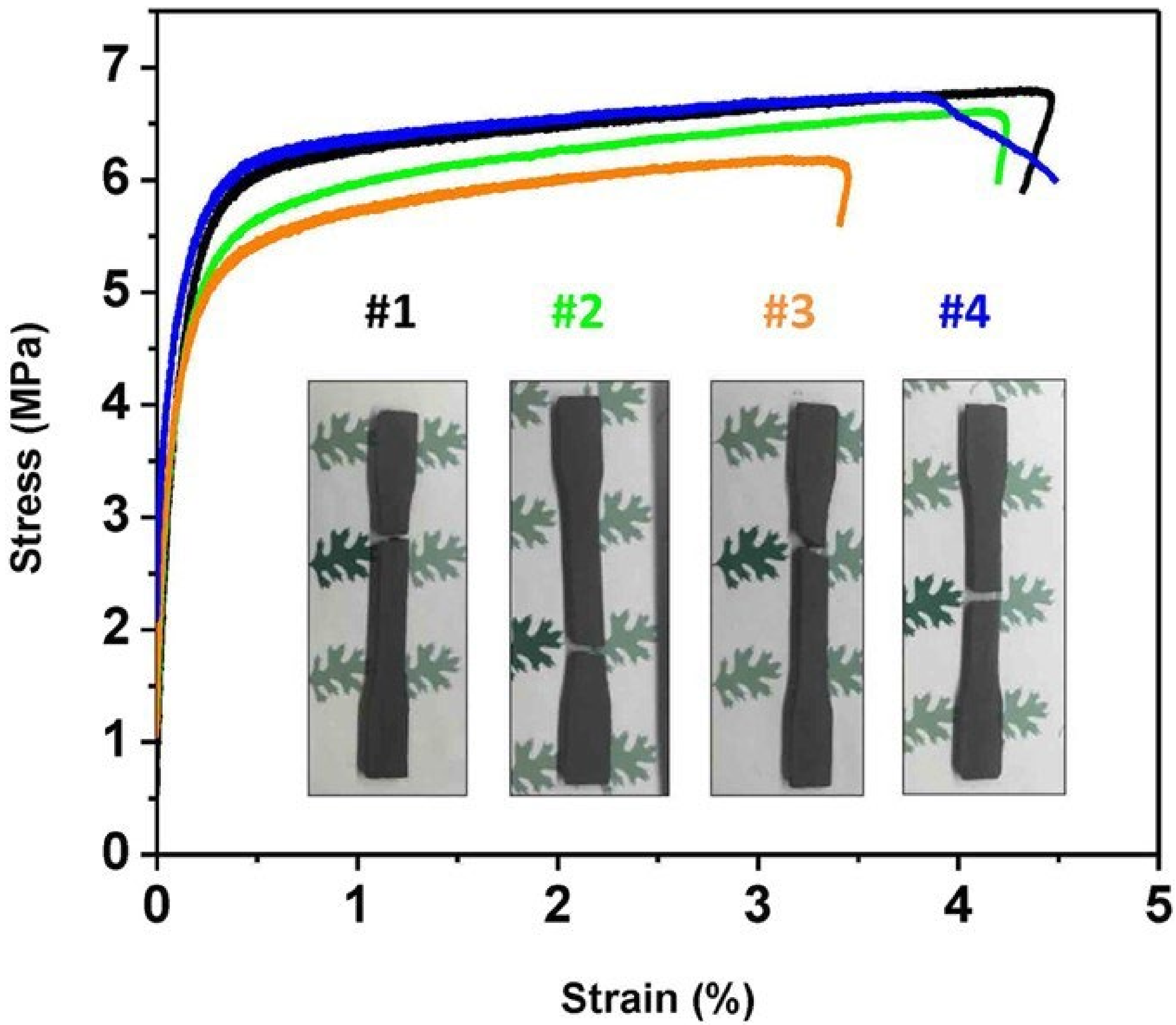


Figure 79: Li, Ling, Angelica Tirado, I. C. Nlebedim, Orlando Rios, Brian Post, Vlastimil Kunc, R. R. Lowden et al. "Big area additive manufacturing of high performance bonded NdFeB magnets." Scientific reports 6 (2016): 36212.

PRODUCT BULLETIN

September 2021

PRD-EX1631

Thermoset Print Media for Low Density Additive Manufacturing

DESCRIPTION

Polynt's Reactive Deposition (PRD)-EX1631 is a pre-promoted, pre-compounded unsaturated, vinyl ester paste in styrene. Polynt's PRD-EX1631 is specifically formulated for use with a 3D printer designed for pumping, mixing, and extruding viscous materials. PRD-EX1631 is an ambient cured media that requires a peroxide initiator.

BENEFITS & FEATURES

- Developed for use with mid-size and large-scale two-component thermoset printers
- Carbon fiber reinforced for increased mechanical strength and dimensional stability
- Superior interlaminar adhesion for high Z-axis property retention
- Liquid properties designed for both standard and high-resolution printing
- Rheological package created for multiple print speeds
- Easy to repair and coat with like materials, including Polynt tooling gel coats and TruDesign sealers and topcoats
- Low density for weight reduction and increased print volume
- Patent pending

PROPERTIES – UNCATALYZED

Property(1)	Unit	PRD-EX1631
Appearance	-	Black paste
NVM	%	80
Viscosity(2)	cps	750,000
Thix Index(3)	-	8.0
Gel Time(4)	minutes	16
Gel to Peak	minutes	21
Peak Exotherm	°C/°F	153/307
Specific Gravity	g/cm^3	0.86
Flash Point (Seta Closed Cup)	°C/°F	32/89

1) All properties at 25°C/77°F unless otherwise noted
2) Brookfield Viscometer DV-II, HB, Spindle T-E at 10 rpm
3) Brookfield Viscometer DV-II, HB, Spindle T-E at 1/10 rpm
4) 2.5% by weight CHP

PRODUCT BULLETIN

September 2021

PROPERTIES – CURED

Property [1][2]	Unit	X-axis	Test Method
Tensile Strength	psi	3,500	ASTM D 638
Tensile Modulus	psi	951,000	ASTM D 638
Tensile Elongation	%	0.50	ASTM D 638
Flexure Strength	psi	7,200	ASTM D 790
Flexure Modulus	psi	986,000	ASTM D 790
Compressive Strength	psi	8,500	ASTM D 695
Compressive Modulus	psi	637,000	ASTM D 695
Heat Deflection Temperature[3]	°C/°F	Pending	TA Instruments
Glass transition temp, Tg[4]	°C/°F	100/212	ASTM D 5279
CLTE[5]	um/m-°C	35	ASTM E 831

1) Physical properties were determined using internal Polynt test methods that are like those listed above.
2) Data collected on panels printed at 25°C with 2.5% CHP Peroxide. Post cured for 2 hrs. each @ 65°C, 121°C, 160°C
3) By DMA on TA RSA-3
4) By DMA on TA Q800
5) By TMA on TA Q400

APPLICATION

This material was originally designed for use with mid-size and large-scale two-component thermoset 3D printers. PRD-EX1631 is specially formulated for exposure temperatures that do not exceed 150°F (65°C). For high temperature tooling and molding, please refer to the Technical Data Sheets of other PRD print media.

SHELF LIFE & STORAGE

The shelf life of PRD-EX1631 is 90 days from the date of manufacture from Polynt. To maximize usage life and maintain optimum properties, resins and gel coats should be stored in the original closed container at temperatures below 23°C/73°F and away from ignition sources and sunlight. Keep containers sealed to prevent moisture pick-up and monomer loss.

RELATED PRODUCTS

PRD-1520 – Thermoset Print Media for General Purpose Additive Manufacturing
PRD-1586 – Lower Viscosity Thermoset Print Media for General Purpose Additive Manufacturing
PRD-EX1630 – Styrene-free Thermoset Print Media for General Purpose Additive Manufacturing
PRD-EX1632 – Thermoset Print Media for Shrink-Controlled and High-Temp Additive Manufacturing
PRD-EX1633 – Thermoset Print Media for Thermally Conductive Additive Manufacturing

SAFETY & WARRANTY

To receive a copy of our safety and warranty information, please email safetyandwarranty@polynt.com.

APPENDIX B. PROPERTIES OF ADHESIVES FOR TESTING

Technical Data Sheet

LOCTITE® EA 9460™

Known as LOCTITE® Hysol® 9460™
December 2013

PRODUCT DESCRIPTION

LOCTITE® EA 9460™ provides the following product characteristics:

Technology	Epoxy
Chemical Type	Epoxy
Appearance (Resin)	white[LMS]
Appearance (Hardener)	Black[LMS]
Appearance (Mixture)	gray
Components	Two part - Resin & Hardener
Mix Ratio, by weight - Resin : Hardener	1 : 1
Mix Ratio, by volume - Resin : Hardener	1 : 1
Cure	Room temperature cure after mixing
Secondary Cure	Heat
Application	Bonding
Specific Benefit	• Non-sag slump resistance • Smooth paste • Easy to mix • Easy to dispense • Extended working life • Quick heat response • Resistant to automotive fluids • Impact resistant • Fatigue resistant

LOCTITE® EA 9460™ is a thixotropic, modified, two-component epoxy adhesive formulated for ease of use as well for a good balance of properties. This two-part adhesive is formulated to give very high peel strength coupled with excellent shear strength. The flexibility of the cured adhesive makes it useful for bonding dissimilar substrates. Recommended substrates include metals, engineering thermoplastics, and thermoset laminates such as sheet molding compound (SMC) without the use of primers.

TYPICAL PROPERTIES OF UNCURED MATERIAL

Resin:

Specific Gravity @ 25 °C	1.35
Viscosity, Brookfield - HB, 25 °C, mPa·s (cP):	
Spindle 6, speed 20 rpm	150,000 to 300,000[LMS]
Weight Per Gallon, lbs/gal	11.3
Flash Point - See SDS	

Hardener:

Specific Gravity @ 25 °C	1.31
Viscosity @ 25°C, mPa·s (cP)	100,000 to 250,000
Weight Per Gallon, lbs/gal	10.9
Flash Point - See SDS	

Mixed:

Specific Gravity @ 25 °C	1.33
Viscosity @ 25°C, mPa·s (cP)	150,000 to 250,000
Peak Exotherm Temperature, °C,	93
Weight Per Gallon, lbs/gal	11.1
Pot life @ 25 °C, minutes	40 to 65[LMS]

TYPICAL PROPERTIES OF CURED MATERIAL

Cured @ 25 °C except where noted

Physical Properties:

Shore Hardness, ISO 868, Durometer D:		
Cured for 2 hours @ 60 °C		≥75[LMS]
Glass Transition Temperature, °C		68
Elongation, ISO 527-2, %		3.5
Tensile Strength, ISO 527-2	N/mm²	30.3
	(psi)	(4,400)
Tensile Modulus, ISO 527-2	N/mm²	2,758
	(psi)	(400,000)

TYPICAL PERFORMANCE OF CURED MATERIAL

Adhesive Properties

Cured for 3 days @ 25 °C

Lap Shear Strength, ISO 4587:

Aluminum (etched):		
0.125 mm gap, tested @ -53 °C	N/mm²	20.7
	(psi)	(3,000)
0.125 mm gap, tested @ 25 °C	N/mm²	24.1
	(psi)	(3,500)
0.125 mm gap, tested @ 82 °C	N/mm²	6.7
	(psi)	(1,000)
0.125 mm gap, tested @ 121 °C	N/mm²	2.1
	(psi)	(300)
0.25 mm gap, tested @ 25 °C	N/mm²	22.1
	(psi)	(3,200)
0.75 mm gap, tested @ 25 °C	N/mm²	15.2
	(psi)	(2,200)
1.5 mm gap, tested @ 25 °C	N/mm²	13.8
	(psi)	(2,000)
Aluminum (degreased):		
0.125 mm gap, tested @ 25 °C	N/mm²	22.1
	(psi)	(3,200)

Aluminum (grit blasted):		
0.125 mm gap, tested @ 25 °C	N/mm² (psi)	24.1 (3,500)
Steel (cold rolled) (grit blasted):		
0.125 mm gap, tested @ 25 °C	N/mm² (psi)	24.1 (3,500)
Steel (cold rolled) (degreased):		
0.125 mm gap, tested @ 25 °C	N/mm² (psi)	22.1 (3,200)
Primed steel (black e-coated):		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	9.0 (1,300)
Steel (coil coated):		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	13.8 (2,000)
Rynite:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	1.7 (250)
ABS:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	2.8 (400)
PVC (clear):		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	4.3 (620)
PVC (filled):		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	3.7 (540)
Polycarbonate:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	4.8 (700)
Eagle Picher 218-2, SMC:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	3.4 (500)
0.75 mm gap, tested @ 82 °C	N/mm² (psi)	2.8 (400)
Budd DSM-950, SMC:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	3.9 (560)
0.75 mm gap, tested @ 82 °C	N/mm² (psi)	3.1 (450)
Diversitech 8002:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	3.7 (535)
0.75 mm gap, tested @ 82 °C	N/mm² (psi)	2.4 (350)
Premix EMS 30271, SMC:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	3.4 (500)
0.75 mm gap, tested @ 82 °C	N/mm² (psi)	2.9 (425)
Ashland Phase Alpha:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	3.1 (445)
0.75 mm gap, tested @ 82 °C	N/mm² (psi)	2.0 (290)
Rockwell 9465:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	3.8 (550)
0.75 mm gap, tested @ 82 °C	N/mm² (psi)	3.8 (550)
Derakane 790 HSMC:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	7.6 (1,100)
Fiberite:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	6.8 (980)
Lytex 9063 Epoxy SMC:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	8.6 (1,250)
Graphite Epoxy Laminate:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	13.8 (2,000)
Spectrim HF-85 RIM:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	2.7 (390)
Arimax RTM:		
0.75 mm gap, tested @ 25 °C	N/mm² (psi)	6.6 (950)

Peel Strength, ASTM D 3167:		
Aluminum (etched):		
Tested @ -55 °C	N (lb)	4.4 (25)
Tested @ 25 °C	N (lb)	5.3 (30)
"T" Peel Strength, ISO 11339:		
Aluminum (etched):		
Tested @ -55 °C	N (lb)	3.5 (20)
Tested @ 25 °C	N (lb)	2.6 (15)

Cured for 8 hours @ 25 °C followed by 1 hour @ 121 °C

Peel Strength, ASTM D 3167:		
Aluminum (etched):		
Tested @ -55 °C	N (lb)	7.0 (40)
Tested @ 25 °C	N (lb)	5.3 (30)
"T" Peel Strength, ISO 11339:		
Aluminum (etched):		
Tested @ -55 °C	N (lb)	4.4 (25)
Tested @ 25 °C	N (lb)	3.5 (20)

TYPICAL ENVIRONMENTAL RESISTANCE

Chemical/Solvent Resistance

Aged under conditions indicated and tested @ 22 °C

		% of initial strength
Environment	**°C**	**720 h**
Air	25	100
Water	54	75
Salt fog	35	63
Water/glycol 50/50	130	50
ATF	25	100
ATF	82	100
Brake fluid	25	100
Windshield wiper fluid	25	88
Motor oil (10W40)	25	100
Motor oil (10W40)	141	100
Gasoline (unleaded)	25	100
Diesel fuel	25	100
100% RH	38	75

GENERAL INFORMATION

This product is not recommended for use in pure oxygen and/or oxygen rich systems and should not be selected as a sealant for chlorine or other strong oxidizing materials.

For safe handling information on this product, consult the Safety Data Sheet (SDS).

Directions for use:

Mixing:

1. **When mixing by hand**, combine Part A (Resin) and Part B (Hardener) in the correct ratio and mix thoroughly until the color and consistency are uniform. EPOXI-PATCH® Tube Kits have been designed so that squeezing **EQUAL LENGTH BEADS of Part A & Part B** will give the proper ratio.
2. Mixing the adhesive just prior to use is recommended. The temperature of the separate components prior to mixing is not critical, but they should be close to room temperature.
3. Heat buildup during and after mixing is normal. To reduce the likelihood of exothermic reaction or excessive heat buildup, mix less than 4,500 grams at a time. Mixing smaller amounts will minimize heat buildup.
4. **When mixing using a cartidge**, place cartridge in proper dispenser. To begin using a new cartridge, remove the cap and dispense a small amount of adhesive, making sure both parts A & B are extruding. Attach nozzle and dispense approximately 2.5 to 5.0 cm before applying onto the part to be bonded. Partially used cartridges should be stored with the mixing nozzle attached. To reuse, remove and discard the old nozzle, attach the new nozzle, and begin dispensing.

Applying

1. Bonding surfaces should be clean, dry, and free of contamination.
2. Once the adhesive is applied, the bonded parts should be held in contact until the part has developed handling strength. Fixturing can be removed at this point. Since the full bond strength has not yet been attained, load application should be small at this time.

Cure

1. Complete cure is obtained after 72 hours @ 25 °C. LOCTITE® EA 9460™ can also be fully cured with heat such as; 6 to 8 hours at a maximum temperature of 149 °C.
2. After 24 hours, approximately 90% of full cure properties are attained at room temperature.
3. Other times and temperatures (149°C is a suggested maximum) can be used depending on the application.
4. Heat cures can be modified to achieve a desired degree of cure from handling strength to full cure.

Clean up

1. It is important to clean up excess adhesive from the work area and application equipment before it hardens.
2. Denatured alcohol and many common industrial solvents are suitable for removing uncured adhesive.

Loctite Material SpecificationLMS

LMS dated June 10, 2005 (Resin) and LMS dated October 18, 2004 (Hardener). Test reports for each batch are available for the indicated properties. LMS test reports include selected QC test parameters considered appropriate to specifications for customer use. Additionally, comprehensive controls are in place to assure product quality and consistency. Special customer specification requirements may be coordinated through Henkel Loctite Quality.

Storage

Store product in the unopened container in a dry location. Storage information may be indicated on the product container labeling.

Optimal Storage: 8 °C to 21 °C. Storage below 8 °C or greater than 28 °C can adversely affect product properties. Material removed from containers may be contaminated during use. Do not return product to the original container. Henkel Corporation cannot assume responsibility for product which has been contaminated or stored under conditions other than those previously indicated. If additional information is required, please contact your local Technical Service Center or Customer Service Representative.

Conversions

(°C x 1.8) + 32 = °F
kV/mm x 25.4 = V/mil
mm / 25.4 = inches
µm / 25.4 = mil
N x 0.225 = lb
N/mm x 5.71 = lb/in
N/mm² x 145 = psi
MPa x 145 = psi
N·m x 8.851 = lb·in
N·m x 0.738 = lb·ft
N·mm x 0.142 = oz·in
mPa·s = cP

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Reference 0.1

3M™ Wind Epoxy Structural Adhesive W1125

Description

3M™ Wind Epoxy Structural Adhesive W1125 is a two-part, room temperature-curing epoxy adhesive for bonding composite wind blades and for other general purpose applications. This high performance, rigid adhesive combines high shear strength along with excellent peel strength, impact stength, and durability.

Features

3M Wind Epoxy Structural Adhesive W1125 provides the following benefits:

- 90 minute work life
- 8 hour set time
- Sag-resistant viscosity
- Tough
- High peel strength
- High shear strength

Note: The following information and data should be considered representative or typical only, and should not be used for specification purposes.

Typical Uncured Physical Properties

Properties	Part B (Base) Resin	Part A (Accelerator) Hardener
Chemistry	Epoxy	Amine
Color	Black	Off-White
Density	1.31 g/cm³	1.28 g/cm³
Viscosity	800,000 cP	450,000 cP
Mix Ratio (by Weight)	100 parts B	45 parts A
Mix Ratio (by Volume)	100 parts B	50 parts A
Mixed Viscosity	Sag-resistant Paste	
Work Life	90 minutes at 73°F (23°C)	
Set Time	8 hours at 73°F (23°C)	
Full Cure Time	28 days at 73°F (23°C)	

Note: Viscosity measured using a Brookfield RVF Viscometer at 23°C.

Typical Cured Physical Properties

Properties		Value	
Color		Black	
Density		1.30 g/cm³	
Overlap Shear	Aluminum	3,660 psi	25.2 MPa
	Steel	2,460 psi	17.0 MPa
	Stainless Steel	3,560 psi	24.5 MPa
	Glass Fiber Reinforced Epoxy	3,300 psi	22.8 MPa
	Glass Fiber Reinforced Polyester*	880 psi	6.1 MPa
	Polycarbonate	430 psi	3.0 MPa
	Acrylic*	400 psi	2.8 MPa
	ABS*	1,360 psi	9.4 MPa
	PVC	550 psi	3.8 MPa
	Nylon	200 psi	1.4 MPa
	Wood*	1180 psi	8.1 MPa
Shore D Hardness		83	

Notes: 1. Overlap shear values measured using DIN 1465 / ISO 4587 test method "Adhesives – Determination of Tensile Lap Shear Strength of Rigid-to-Rigid Bonded Assemblies;" 0.5 mm bond line thickness; samples pulled at 1 mm/min; adhesive cured for 28 days at room temperature; metal surface cleaned with the following procedure: (1) tissue wipe using MEK, (2) light abrasion with orbital sander using Scotch-Brite™ 7447 maroon pad, (3) tissue wipe using IPA; substrates for overlap shear testing were 1.6 mm thick aluminum, 1.0 mm thick steel, 3.2 mm thick epoxy, polyester, polycarbonate, and acrylic, and 6.4 mm thick ABS, PVC, and wood. Materials indicated by an asterisk (*) exhibited primarily substrate failure.

2. Hardness values measured using ASTM D2240 "Standard Test Method for Rubber Property – Durometer Hardness".

Properties	Temperature	Value	
Overlap Shear	-40°F (-40°C)	2,350 psi	16.2 MPa
	72°F (22°C)	3,660 psi	25.2 MPa
	122°F (50°C)	2,030 psi	14.0 MPa
	176°F (70°C)	300 psi	2.1 MPa

Tensile Properties

Properties	Value	
Tensile Modulus (E)	565,000 psi	3,890 MPa
Tensile Strength	4,290 psi	29.6 MPa
Strain at Break	5%	5%

Note: Tensile properties measured using ISO 527 test method "Plastics – Determination of Tensile Properties" and Type IV test specimens made according to ASTM D638 "Standard Test Method for Tensile Properties of Plastics;" adhesive cured for 4 hours at 149°F (65°C); samples pulled at 1 mm/min.

Environmental Resistance

Properties		Value	
Overlap Shear	No exposure	3,660 psi	25.2 MPa
	1000 hours in salt water	3,070 psi	21.2 MPa
	1000 hours in diesel fuel	3,500 psi	24.1 MPa
	1000 hours in acid solution (pH=4)	3,180 psi	21.9 MPa
	1000 hours in base solution (pH=10)	3,170 psi	21.9 MPa
	1000 hours at 50°C	3,560 psi	24.5 MPa
	1000 hours in 50°C water	1,930 psi	13.3 MPa
	1000 hours at 50°C and 80% relative humidity	2,820 psi	19.4 MPa
	1000 hours weathering cycle	2,600 psi	17.9 MPa

Notes: 1. Overlap shear values measured using DIN 1465/ISO 4587 test method; adhesive cured for 28 days at room temperature; lightly abraded 1.6 mm thick aluminum test substrates; 0.5 mm bond line thickness; samples pulled at 1 mm/min.

2. Weathering cycle involves daily humidity changes and temperature variations from -40°C to 60°C.

Directions for Use

1. To obtain high strength structural bonds, all surfaces must be clean, rough, and dry. For molded composite laminates, these conditions can typically be achieved using a peel-ply material that must be removed immediately prior to adhesive application. Otherwise, the surface must be prepared using the following procedure:

A. Dust, mold release agents, oils, and all other surface contaminants must be completely removed using a solvent or some other degreaser.**

B. The surface must then be lightly abraded using either Scotch-Brite™ pads or fine to medium grit sandpaper to increase surface area and remove gloss.

C. The loose debris from abrasion must then be removed using a clean cloth and solvent (such as a 50:50 mixture of isopropyl alcohol and water).**

2. The two adhesive components must be thoroughly mixed using either the weight or volume mix ratio specified in this document. The mixed adhesive should be a uniform black color with no streaks.

When using a cartridge, follow these instructions: Store adhesive cartridges upright (cap end up). Place cartridge into applicator and remove cap. Dispense and discard a small amount of adhesive to ensure free flow from both sides of cartridge, then attach mixing nozzle. Store unused adhesive with mixing nozzle attached, then remove and attach new mixing nozzle when ready to continue use.

3. The mixed adhesive should be applied to the bond area, and the two surfaces mated together, before the work life stated in this document expires. Keep the joined parts together using contact pressure or clamps during the cure process until the set time is reached. Optimal bond line thickness ranges from 4 to 40 mils (0.1 to 1.0 mm).

4. Although this two-part epoxy adhesive will cure at room temperature, a thermal cure can also be used to accelerate the curing process. Allow sufficient time for the bonded parts and adhesive to reach the desired temperature. The optimal cure cycle will need to be determined for each specific application.

****Note:** When using solvents, extinguish all ignition sources, including pilot lights, and follow the manufacturer's precautions and directions for use. Use solvents in accordance with local regulations.

Storage

Store products at 59–77°F (15–25ºC) for maximum shelf life. Opened bulk containers with leftover adhesive should be resealed after applying a nitrogen purge of the headspace.

Shelf Life

This product has a shelf life of 24 months in bulk containers, or 15 months in cartridges from date of manufacture, when stored in the original sealed containers at room temperature.

Precautionary Information

Refer to the product label and Material Safety Data Sheet for health and safety information before using this product. For additional health and safety information, call 1-800-364-3577 or (651) 737-6501.

For more information on our wind energy product line, contact 3M Renewable Energy at 800-755-2654 or visit us at www.3M.com/wind.

The technical information, recommendations, and other statements contained in this document are based upon tests or experience that 3M believes are reliable, but the accuracy or completeness of such information is not guaranteed.

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www.3M.com/wind

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3M™ Wind Acrylic Structural Adhesive W1210

Note: The following information and data should be considered representative or typical only, and should not be used for specification purposes.

Description

3M™ Wind Acrylic Structural Adhesive W1210 is a two-part, room temperature-curing acrylic adhesive for bonding composite wind blades and for other general purpose applications. This high performance, rigid adhesive combines high shear strength along with excellent toughness and durability.

Features

3M Wind Acrylic Structural Adhesive W1210 provides the following benefits:

- 10 minute work life
- 20 minute set time
- Sag resistant
- Tough
- Medium peel strength
- High shear strength

Typical Uncured Physical Properties

Properties	Part B (Base) Resin	Part A (Accelerator) Hardener
Chemistry	Acrylic	Acrylic
Color	Off-white	Yellow
Density	0.98 g/cm³	0.96 g/cm³
Viscosity	35,000 cP	75,000 cP
Mix Ratio (by Weight)	100 parts B	100 parts A
Mix Ratio (by Volume)	100 parts B	100 parts A
Mixed Viscosity	55,000 cP	
Work Life	10 minutes at 73°F (23°C)	
Set Time	20 minutes at 73°F (23°C)	
Full Cure Time	1 day at 73°F (23°C)	

Note: Viscosity measured using a Brookfield RVF Viscometer with a #7 spindle at 20 rpm and 73°F.

Typical Cured Physical Properties

Properties		Value	
Color		Off-white	
Density		0.97 g/cm³	
Overlap Shear	Aluminum	2,640 psi	18.2 MPa
	Steel	2,450 psi	16.9 MPa
	Stainless Steel	2,790 psi	19.2 MPa
	Glass Fiber Reinforced Epoxy	3,030 psi	20.9 MPa
	Glass Fiber Reinforced Polyester*	1,200 psi	8.3 MPa
	Polycarbonate*	1,290 psi	8.9 MPa
	Acrylic*	800 psi	5.5 MPa
	ABS*	1,450 psi	10.0 MPa
	PVC*	2,100 psi	14.5 MPa
	Nylon	490 psi	3.4 MPa
	Wood*	960 psi	6.6 MPa
Floating Roller Peel		30 lb/in	5.3 N/mm
Shore D Hardness		70	

Notes: 1. Overlap shear values measured using DIN 1465 / ISO 4587 test method "Adhesives – Determination of Tensile Lap Shear Strength of Rigid-to-Rigid Bonded Assemblies;" 0.5 mm bond line thickness; samples pulled at 1 mm/min; adhesive cured for 1 day at room temperature; metal surface cleaned with the following procedure: (1) tissue wipe using MEK, (2) light abrasion with orbital sander using Scotch-Brite™ 7447 maroon pad, (3) tissue wipe using IPA; substrates for overlap shear testing were 1.6 mm thick aluminum, 1.0 mm thick steel, 3.2 mm thick epoxy, polyester, polycarbonate, and acrylic, and 6.4 mm thick ABS, PVC, and wood. Materials indicated by an asterisk (*) exhibited primarily substrate failure.

2. Floating roller peel values measured using ISO 4578 test method "Adhesives – Determination of Peel Resistance of High-Strength Adhesive Bonds – Floating Roller Method;" 0.5 mm bond line thickness; samples pulled at 100 mm/min; adhesive cured for 1 day at room temperature; etched aluminum substrates.

3. Hardness values measured using ASTM D2240 "Standard Test Method for Rubber Property – Durometer Hardness".

Properties	Temperature	Value	
Overlap Shear	-40°F (-40°C)	1,380 psi	9.5 MPa
	72°F (22°C)	2,640 psi	18.2 MPa
	122°F (50°C)	1,390 psi	9.6 MPa
	176°F (70°C)	560 psi	3.9 MPa

Tensile Properties

Properties	Value	
Tensile Modulus (E)	235,000 psi	1,620 MPa
Tensile Strength	3,280 psi	22.6 MPa
Strain at Break	20%	20%

Note: Tensile properties measured using ISO 527 test method "Plastics – Determination of Tensile Properties" and Type IV test specimens made according to ASTM D638 "Standard Test Method for Tensile Properties of Plastics;" adhesive cured for 1 day at room temperature; samples pulled at 5 mm/min.

Environmental Resistance

Properties		Value	
Overlap Shear	No exposure	2,640 psi	18.2 MPa
	1000 hours in salt water	2,670 psi	18.4 MPa
	1000 hours in diesel fuel	3,370 psi	23.2 MPa
	1000 hours in acid solution (pH=4)	2,810 psi	19.4 MPa
	1000 hours in base solution (pH=10)	2,920 psi	20.1 MPa
	1000 hours at 50°C	3,350 psi	23.1 MPa
	1000 hours in 50°C water	1,490 psi	10.3 MPa
	1000 hours at 50°C and 80% relative humidity	2,160 psi	14.9 MPa
	1000 hours weathering cycle	1,330 psi	9.2 MPa

Notes: 1. Overlap shear values measured using DIN 1465/ISO 4587 test method; adhesive cured for 1 day at room temperature; lightly abraded 1.6 mm thick aluminum test substrates; 0.5 mm bond line thickness; samples pulled at 1 mm/min.

2. Weathering cycle involves daily humidity changes and temperature variations from -40°C to 60°C.

Directions for Use

1. To obtain high strength structural bonds, all surfaces must be clean, rough, and dry. For molded composite laminates, these conditions can typically be achieved using a peel-ply material that must be removed immediately prior to adhesive application. Otherwise, the surface must be prepared using the following procedure:

A. Dust, mold release agents, oils, and all other surface contaminants must be completely removed using a solvent or some other degreaser.**

B. The surface must then be lightly abraded using either Scotch-Brite™ pads or fine to medium grit sandpaper to increase surface area and remove gloss.

C. The loose debris from abrasion must then be removed using a clean cloth and solvent (such as a 50:50 mixture of isopropyl alcohol and water).**

2. The two adhesive components must be thoroughly mixed using either the weight or volume mix ratio specified in this document. The mixed adhesive should be a uniform off-white with no streaks.

When using a cartridge, follow these instructions: Store adhesive cartridges upright (cap end up). Place cartridge into applicator and remove cap. Dispense and discard a small amount of adhesive to ensure free flow from both sides of cartridge, then attach mixing nozzle. Store unused adhesive with mixing nozzle attached, then remove and attach new mixing nozzle when ready to continue use.

3. The mixed adhesive should be applied to the bond area and the two surfaces mated together before the work life stated in this document expires. Keep the joined parts together using contact pressure or clamps during the cure process until the set time is reached. Optimal bond line thickness ranges from 4 to 40 mils (0.1 to 1.0 mm).

4. Although this two-part acrylic adhesive will cure at room temperature, a thermal cure can also be used to accelerate the curing process. The following are approximate times required to achieve full cure at several different temperatures.

Temperature	Time
73°F (23°C)	1 day
120°F (49°C)	30 minutes
150°F (66°C)	10 minutes

These values represent the actual adhesive bond line temperature, not the oven temperature. Allow sufficient time for the bonded parts and adhesive to reach the desired temperature. Other times and temperatures are also possible depending on the exact cure conditions and performance attributes desired. The optimal cure cycle will need to be determined for each specific application.

****Note:** When using solvents, extinguish all ignition sources, including pilot lights, and follow the manufacturer's precautions and directions for use. Use solvents in accordance with local regulations.

Storage

Store products at 40–60°F (4–16ºC) for maximum shelf life. Colder temperatures will help extend the shelf life. Opened bulk containers with leftover adhesive should be resealed after applying a nitrogen purge of the headspace.

Shelf Life

This product has a shelf life of 12 months in bulk containers, or 6 months in cartridges from date of manufacture, when stored in the original sealed containers within the recommended temperature range.

Precautionary Information

Refer to the product label and Material Safety Data Sheet for health and safety information before using this product. For additional health and safety information, call 1-800-364-3577 or (651) 737-6501.

For more information on our wind energy product line, contact 3M Renewable Energy at 800-755-2654 or visit us at www.3M.com/wind.

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APPENDIX C. PROPERTIES OF COMMERCIAL BLADE CORE MATERIALS FOR COMPARISON

BALTEK® SB

GM--TDS-103

Select Grade Structural Balsa **DATA SHEET 02.2016 - Replaces 10.2014**

DESCRIPTION

BALTEK® SB is a core material produced from select kiln-dried balsa wood in the 'end-grain' configuration. It has extremely high strength and stiffness to weight ratios, and achieves an excellent bond with all types of resins and adhesives. It is compatible with a variety of manufacturing processes and is resistant to temperature changes, or exposure to fire, or chemicals such as styrene.

BALTEK® SB is an ideal core material for an extensive range of applications subjected to static or dynamic loads in service. All while being a renewable resource.

CHARACTERISTICS

- Outstanding strength and stiffness to weight ratios
- First-class, select grade lumber
- Ecological product
- Broadest range of available balsa densities worldwide
- Certified for a range of applications by DNV, Germanischer Lloyd, Lloyd's Register, American Bureau of Shipping and Korean Register
- Excellent fatigue and impact resistance
- Fulfills most FST (flame, smoke, toxicity) requirements
- Good sound and thermal insulation
- Extremely wide operating temperature range (-212 °C to +163 °C (-414 °F to +325 °F)

APPLICATIONS

- **Marine**: Hulls, decks, bulkheads, superstructures, interiors, tooling/molds
- **Road and Rail:** Floors, roofs, side skirts, front-ends, doors, interiors, covers
- **Wind energy:** Rotor blades (shear webs and shells), nacelles, spinners
- **Industrial:** Tanks, containers, architectural panels, impact limiters, sporting goods
- **Aerospace:** Floors, cargo pallets, cargo containers, bulkheads, general aviation
- **Defense:** Naval vessels, containers, cargo pallets, shelters, ballistic panels

PROCESSING

- Adhesive bonding
- Compression molding
- Contact molding (hand/spray)
- Pre-preg processing (up to 180 °C, 355 °F)
- Resin injection (RTM)
- Vacuum infusion

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MECHANICAL PROPERTIES						
Typical properties for BALTEK® SB		**Unit (metric)**	**SB.50**	**SB.80**	**SB.100**	**SB.150**
Apparent nominal density	ASTM C-271	kg/m³	109	132	148	285
Minimum sheet density	ASTM C-271	kg/m³	84	113	136	248
Compressive strength perpendicular to the plane	ISO 844	N/mm²	5.5	7.7	9.2	22
Compressive modulus perpendicular to the plane	ISO 844	N/mm²	1616	2187	2526	4428
Tensile strength perpendicular to the plane (polyester)	ASTM C-297	N/mm²	3.9	5.0	5.7	12.2
Tensile strength perpendicular to the plane (epoxy)	ASTM C-297	N/mm²	9	10.9	12	18.3
Tensile modulus perpendicular to the plane	ASTM C-297	N/mm²	1682	2337	2791	6604
Shear strength[1]	ASTM C-273	N/mm²	1.8	2.3	2.6	5.2
Shear modulus	ASTM C-273	N/mm²	136	166	187	362
Thermal conductivity at room temperature	ASTM C-177	W/m*K	0.048	0.059	0.066	0.084
Standard sheet	Width	mm ± 5	610	610	610	610
	Length	mm ± 10	1220	1220	1220	1220
	Thickness	mm +0.25 -0.75	4.7 to 76	4.7 to 76	4.7 to 76	6 to 76
ContourKore (CK)	Thickness	mm +0.25 -0.75	4.7 to 50	4.7 to 50	4.7 to 50	6 to 50

Please specify Lamprep surface treatment or AL600 coating (decreases porosity and increases bond strength) when ordering.
Perforations (breether holes), grooves and other finishing options are also available. Other sheet sizes are available on request.

1) All samples tested @ ¾" thick. Please apply appropriate shear strength reduction factors for greater thickness.

Fire Performance+	Standard		SB.50	SB.100	SB.150
Aircraft	FAR 25.853	Flammability Smoke density Toxicity Heat release	Passed Passed Passed Failed	Passed Passed Passed Failed	Not tested
Rail	ASTM E 162	Flame spread factor Heat Evolution factor Flame spread index	2.22 6.24 14	2.22 6.24 14	Not tested
Rail	ASTM E 662 (non-flaming mode)	Ds @ 90 sec Ds @ 4min	3 39	3 39	Not tested
Rail	ASTM E 662 (flaming mode)	Ds @ 90 sec Ds @ 4min	8 25	8 25	Not tested

+ All samples tested with phenolic resin FRP skins.

MECHANICAL PROPERTIES

Typical properties for BALTEK® SB		Unit (imperial)	SB.50	SB.80	SB.100	SB.150
Nominal sheet density	ASTM C-271	lb/ft³	6.8	8.2	9.3	17.8
Minimum sheet density	ASTM C-271	lb/ft³	5.2	7.1	8.5	15.5
Compressive strength perpendicular to the plane	ISO 844	psi	798	1117	1336	3184
Compressive modulus perpendicular to the plane	ISO 844	psi	234400	317198	366200	642000
Tensile strength perpendicular to the plane (polyester)	ASTM C-297	psi	558	725	831	1770
Tensile strength perpendicular to the plane (epoxy)	ASTM C-297	psi	1299	1581	1737	2654
Tensile modulus perpendicular to the plane	ASTM C-297	psi	243900	338954	404700	957600
Shear strength[1]	ASTM C-273	psi	267	334	378	761
Shear modulus	ASTM C-273	psi	19700	24076	27100	52600
Thermal conductivity at room temperature	ASTM C-177	BTU.in/ft².hr.°F	0.331	0.407	0.456	0.581

Standard sheet	Width	in ± $^{3}/_{16}$	24	24	24	24
	Length	in ± $^{3}/_{8}$	48	48	48	48
	Thickness	in +0.01 -0.03	$^{3}/_{16}$ to 3	$^{3}/_{16}$ to 3	$^{3}/_{16}$ to 3	¼ to 3
ContourKore (CK)	Thickness	in +0.01 -0.03	$^{3}/_{16}$ to 2	$^{3}/_{16}$ to 2	$^{3}/_{16}$ to 2	¼ to 2

Please specify Lamprep surface treatment or AL600 coating (decreases porosity and increases bond strength) when ordering.
Perforations (breether holes), grooves and other finishing options are also available. Other sheet sizes are available on request.

1) All samples tested @ ¾" thick. Please apply appropriate shear strength reduction factors for greater thickness.

Fire Performance[+]	Standard		SB.50	SB.100	SB.150
Aircraft	FAR 25.853	Flammability Smoke density Toxicity Heat release	Passed Passed Passed Failed	Passed Passed Passed Failed	Not tested
Rail	ASTM E 162	Flame spread factor Heat Evolution factor Flame spread index	2.22 6.24 14	2.22 6.24 14	Not tested
Rail	ASTM E 662 (non-flaming mode)	Ds @ 90 sec Ds @ 4min	3 39	3 39	Not tested
Rail	ASTM E 662 (flaming mode)	Ds @ 90 sec Ds @ 4min	8 25	8 25	Not tested

+ All samples tested with phenolic resin FRP skins.

The data provided gives approximate values for the nominal density. Due to density variations these values can be lower than indicated above. Minimum values to calculate sandwich constructions can be provided upon request. The information contained herein is believed to be correct and to correspond to the latest state of scientific and technical knowledge. However, no warranty is made, either expressed or implied, regarding its accuracy or the results to be obtained from the use of such information. No statement is intended or should be construed as a recommendation to infringe any existing patent.

End Grain Balsa

Part # - 229, 230, 232

Standard Marine Grade Core

End Grain Balsa is the most widely used core material. We offer three grades of marine grade balsa, all available in 2' x 4' sheets of individual small blocks of end grain balsa bonded to a light scrim fabric that holds the blocks together during lamination. Sheets of this core will conform to practically any simple curve and most gradual compound curves. 9.5# density.

This balsa is a high-quality composite core material made from end-grain balsa wood. The end grain, micro-honeycomb structure offers exceptional shear and compressive strength. In addition this balsa offers good fatigue properties, high thermal and sound insulation and low FST properties.

This balsa is best suited for dynamic structures where performance and efficiency are paramount. All balsa materials are particularly easy to work using conventional woodworking tools. They can be drilled, milled, turned and sawn to close tolerances. This balsa can be used in hand lay-up, vacuum bag and infusion applications. It is also suitable for elevated temperature cure pre-preg systems.

Property	Method	Unit	#230, #232
Density	ASTM C 271	Kg/m^3	155
		Lb/ft^3	9.7
Compressive Strength 1)	ASTM C 365	MPa	12.7
		psi	1,842
Compressive Modulus 1)	ASTM C 365	MPa	4,100
		psi	594
Tensile Strength 1)	ASTM C 297	MPa	13.5
		psi	1,958
Shear Strength 2)	ASTM C 273	MPa	3.0
		psi	435
Shear Modulus 1)	ASTM C 273	MPa	166
		psi	24
Thermal Conductivity 2)	ASTM C 377	W/m K	0.064
		$Btu \cdot in/(ft^2 \cdot h \cdot °F)$	0.44
R-value	Based on +10°K factor	12mm / 0.5 in	1.1
		25 mm / 1.0 in	2.3
		51 mm / 2.0 in	4.5

1) All values measured at +22°C (+72°F).
2) Thermal conductivity at +10°C (+50°F).

Nominal Moisture Content: 12%
Coefficient of linear expansion (ASTM D-696):

Longitudinal	3.6×10^{-6} / °C	2.0×10^{-6} / °F
Radial	14.4×10^{-6} / °C	8.0×10^{-6} / °F
Tangential	21.6×10^{-6} / °C	12.0×10^{-6} / °F

Shrinkage and swelling of wood due to moisture changes will overshadow thermal expansion.

Fibre Glast Developments Corporation
385 Carr Drive
Brookville, Ohio 45309
Phone ï 800.214.8579
Fax ï 937.833.6555
www.fibreglast.com

PDCT-PDS-00342-B-08/13-CC

Gurit® Balsaflex™

BALSA WOOD CORE MATERIAL

¬ High quality composite core material made from end-grain Balsa

¬ Exceptional shear and compressive strength

¬ Made from ecological and renewable resources

¬ Suitable for wind energy, marine, transportation, industrial, and any other application designed with the properties of Balsa

¬ Suitable for hand lay-up, vacuum bag and infusion processes

¬ Gurit® Balsaflex™ is approved by DNV GL

¬ Gurit® Balsaflex™ Lite is new format also available

INTRODUCTION

G rit Balsaflex™ is the classic balsa wood core material.

When an application requires high strength, stiffness and cost effectiveness, Gurit® Balsaflex™ is a suitable solution due to a good balance between cost, properties and weight.

Gurit® Balsaflex™ is available in all infusion formats including:

¬ Uncoated or coated for resin uptake control

¬ Perforations and grooves to aid infusion

¬ Rigid or flexible to conform to complex tool geometry

Please refer to the Gurit® Balsaflex™ product brochure for full details.

PRODUCT INFORMATION

Gurit® Balsaflex™ density or format availability is summarised in the table below. The product formats listed to the right also benefit from 3rd Party Certification.

P U E P	E
Gurit® Balsaflex™ 150	DNV GL

ME	U	BALSAFLEX™ 0 0
Length	mm	1220
	in	48
Width	mm	610
	in	24
Thickness[2]	mm	6.35 to 50.8
	in	¼ to 2

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[2] *a r ar r t r r r at r t ar a a a r r a t a*
ata a a a a r Gurit® Balsaflex™ 220 r t t r t a rt

MECHANICAL PERFORMANCE

P PE E GE [3]	U	G rit Balsaflex™ 110	G rit Balsaflex™ 150	E
Nominal Density	kg/m3	110	155	-
	lb/ft3	6.9	9.7	
Typical Density range	kg/m3	100 – 125	135 – 176	-
	lb/ft3	6.2 – 7.8	8.4 – 11.0	
Compression Strength	MPa	8.3	13.0	ASTM C-365
	Psi	1204	1885	
Compression Modulus	MPa	2130	3518	ASTM C-365
	Psi	308930	510243	
Shear Strength	MPa	2.0	2.8	ASTM C-273
	Psi	290	406	
Shear Modulus	MPa	103	163	ASTM C-273
	Psi	14939	23641	
Compression Strength (transverse to fibre)	MPa	0.56	0.75	ASTM C-365
	Psi	81	108	
Compression Modulus (transverse to fibre)	MPa	35	57	ASTM C-365
	Psi	5076	8267	

[3] *a r ar r t r r r at r t ar a a a r r a t a*
r rt a ar a a a r t t r t a rt
r rt ar a a a t a a ™ t r t r at
ata a a a a r Gurit® Balsaflex™ 220 r t t r t a rt

INSTRUCTIONS FOR USE

PACKAGING AND HANDLING RECOMMENDATIONS

Gurit® Balsaflex™ can be packaged in three types of packaging.

1. Boxes with sealed plastic bags inside allowing easy access to the panels while keeping the remainder protected
2. Boxes with plastic film inside allowing for faster access to panels
3. Shrink-wrapped plastic pallets which allow the fastest access to the panels with a reduction in packaging waste

ONCE THE PACKAGE IS OPEN

As Gurit® Balsaflex™ only absorbs moisture in the direction of its fibres, only the widest surface of the panel needs to be protected.

Boxes:

- Slit 3 sides of the top bag
- The top side of the bag can be used to cover the remaining balsa and reduce its exposure to the atmosphere

Shrink wrapped plastic pallets:

- Cover the panels with plastic once the pallet is opened

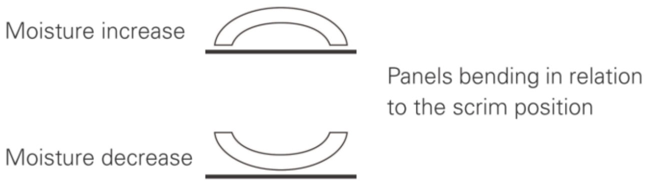
Don't leave balsa sheets lying on the floor or cutting table without protection. It is better to keep them inside the original packaging until needed.

Reduce the humidity exposure time to a minimum by ensuring a dry working atmosphere.

Never store balsa directly on a cement floor, always use pallets and protect the surfaces that can absorb moisture.

When using VIP (Vacuum Infusion Process) leave the vacuum on the part for as long as possible before introducing the resin as during this time excess moisture is being removed from both the reinforcements and core.

Panels expand as moisture increases and shrinks as moisture decreases (see below).



NOTICE

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The Company strongly recommends that Customers make test panels in the final process conditions and conduct appropriate testing of any goods or materials supplied by the Company prior to final use to ensure that they are suitable for the Customer's planned application. Such testing should include testing under conditions as close as possible to those to which the final component may be subjected. The Company specifically excludes any warranty of fitness for purpose of the goods other than as set out in writing by the Company. Due to the varied nature of end-use applications, the Company does, in particular, not warrant that the test panels in the final process conditions and/or the final component pass any fire standards.

The Company reserves the right to change specifications and prices without notice and Customers should satisfy themselves that information relied on by the Customer is that which is currently published by the Company on its website. Any queries may be addressed to the Technical Services Department.

Gurit is continuously reviewing and updating literature. Please ensure that you have the current version by contacting your sales contact and quoting the revision number in the bottom left-hand corner of this page.

TECHNICAL CONTACT INFORMATION

For all other enquiries such as technical queries:

Telephone	+ 44 1983 828000 (08:30 – 17:00 GMT)
Email	technical.support@gurit.com

24-HOUR CHEMICAL EMERGENCY NUMBER

For advice on chemical emergencies, spillages, fires or exposures:

Europe	+44 1273 289451
Americas	+1 646 844 7309
APAC	+65 3158 1412

E customer.support@gurit.com

www.gurit.com

Gurit® Corecell™ T

STRUCTURAL FOAM CORE

- Suitable for all PVC core applications
- Excellent mechanical properties
- Outstanding chemical resistance
- 120°C processing
- Ideal for resin infusion

INTRODUCTION

Gurit® Corecell™ T shares the benefits of SAN chemistry common to all Gurit® Corecell™ products.

En iron ental sta ility - High tolerance for heat and chemical exposure
B ilt in to hness - High ductility and damage tolerance compared to cross-linked PVC and Balsa
ine ell si e - Resin absorption is very low, saving both weight and cost
perior ni or ity - Low density variation
Eli inatin o t assin - Gurit® Corecell™ eliminates the problems of foam outgassing
o pati ility - Suitable for use with all polyester, vinylester and epoxy resins
o inhi ition - Gurit® Corecell™ does not inhibit any epoxy resin curing mechanisms
andlin - Tough and easy to machine

Gurit® Corecell™ T has been developed as a technological step-change from traditional PVC and Balsa structural core. It has slightly higher stiffness properties and even greater styrene resistance than the more ductile Gurit® Corecell™ A. This makes it ideal for applications where loads are less dynamic in nature. Conceived for use above the waterline on yachts, on wind turbines and in mass transport, Gurit® Corecell™ T is an outstanding core material in every application where balsa or X-PVC is commonly used.

High mechanical toughness and thermal stability give Gurit® Corecell™ T excellent fatigue characteristics. This reliability makes Gurit® Corecell™ T a natural replacement for cross-linked PVC or balsa in applications where a significant service life is required.

The high temperature stability of Gurit® Corecell™ T also means that it can be used in manufacturing processes to at least 120°C with short durations during a cure cycle to over 150°C. This makes it ideal for use with conventional prepregs and in some liquid infusion processes where high resin exotherms can often be seen.

Gurit® Corecell™ T is available in every resin infusion format and is compatible with polyester, vinylester and epoxy resin systems. The low resin absorption characteristics of Gurit® Corecell™ and it's unique knife cut formats allow for higher performing infusions, lower resin cost and lower weight than any other structural core material. Gurit's global technical team have 10 years experience in resin infusion and offer on-site support for Corecell customers. This combination makes Gurit® Corecell™ a key part of the most reliable resin infusion package available.

Gurit® Corecell™ T is approved by The American Bureau of Shipping, Germanischer Lloyd, Det Norske Veritas.

INSTRUCTIONS FOR USE

General working practices apply to these products, details of which can be obtained from the Gurit Guide to Composites or by contacting a Gurit representative (contact details provided at the end of this datasheet).

MECHANICAL PERFORMANCE

ype	est Method	Units	00		00	
Short Edge Marking	-	-	White	Green	White	Blue
Nominal Sheet Size	-	mm	1285 x 2605		1195 x 2440	
		inches	50.5 x 102.5		47 x 96	
Nominal Density		kg/m³	71		94	
		lb/ft³	4.4		5.9	
Density Range		kg/m³	66-76		89-99	
		lb/ft³	4.1-4.7		5.6-6.2	
Compressive Strength	ISO 844	MPa	0.92		1.59	
		psi	133		231	
Compressive Modulus	ISO 844	MPa	59		101	
		psi	8557		14649	
Shear Strength	ASTM C273	MPa	0.81		1.20	
		psi	117		174	
Shear Modulus	ASTM C273	MPa	29		40	
		psi	4206		5802	
Shear Elongation at break	ASTM C273	%	28%		14%	
Tensile strength	ASTM D1623	MPa	1.30		1.72	
		psi	189		249	
Tensile modulus	ASTM D1623	MPa	85		152	
		psi	12328		22046	
Thermal Conductivity	ASTM C518	W/mK	0.03		0.04	
HDT	DIN 53424	ºC	100		100	
		ºF	212		212	

* Peak change rate under static load

Intermediate densities may be available on request subject to minimum order quantities.

Please ote

Data quoted is average data at each product's nominal density, and is derived from our regular testing of production materials.
Statistically derived minimum value data, satisfying the design requirements of various classification societies, is available on request.

NOTICE

All advice, instruction or recommendation is given in good faith but the selling Gurit entity (the Company) only warrants that advice in writing is given with reasonable skill and care. No further duty or responsibility is accepted by the Company. All advice is given subject to the terms and conditions of sale (the Conditions) which are available on request from the Company or may be viewed at Gurit's Website: www.gurit.com/terms-and-conditions.aspx

The Company strongly recommends that Customers make test panels in the final process conditions and conduct appropriate testing of any goods or materials supplied by the Company prior to final use to ensure that they are suitable for the Customer's planned application. Such testing should include testing under conditions as close as possible to those to which the final component may be subjected. The Company specifically excludes any warranty of fitness for purpose of the goods other than as set out in writing by the Company. Due to the varied nature of end-use applications, the Company does, in particular, not warrant that the test panels in the final process conditions and/or the final component pass any fire standards.

The Company reserves the right to change specifications and prices without notice and Customers should satisfy themselves that information relied on by the Customer is that which is currently published by the Company on its website. Any queries may be addressed to the Technical Services Department.

Gurit is continuously reviewing and updating literature. Please ensure that you have the current version by contacting your sales contact and quoting the revision number in the bottom left-hand corner of this page.

TECHNICAL CONTACT INFORMATION

For all other enquiries such as technical queries:

Telephone	+ 44 1983 828000 (08:30 – 17:00 GMT)
Email	technical.support@gurit.com

24-HOUR CHEMICAL EMERGENCY NUMBER

For advice on chemical emergencies, spillages, fires or exposures:

Europe	+44 1273 289451
Americas	+1 646 844 7309
APAC	+65 3158 1412

E customer.support@gurit.com

www.gurit.com