# INTRODUCTION OF CONTINUOUS FIBER THERMOPLASTIC TAPES AND LAMINATES INTO 3D PRINTED STRUCTURES UTILIZING ULTRASONIC SCAN WELDING

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## Abstract

There are several methodologies currently employed to introduce continuous fiber thermoplastic materials into the 3D extrusion printing process. Most of these processes require the presentation of fiber tows through an extrusion head or nozzle. These fiber tows may be introduced dry, and impregnated in-situ in the extrusion process, they may be pre-impregnated with a thermoplastic matrix and extruded in conjunction with additional material, or they may comprise the entirety of extrudate. These existing processes face some inherent limitations. In particular, due to the nature of the extrusion process, proper alignment and tensioning of reinforcing fibers (critical to optimizing mechanical performance) can be challenging to achieve. Additionally, throughput is limited to the volume of material that can be introduced through the extrusion head/nozzle in a given timeframe.

The technique outlined in this presentation will demonstrate a method that introduces pre-impregnated and pre-consolidated continuous fiber thermoplastic tapes and multi-axial laminates into the 3D printing process as a secondary operation. This can be performed in parallel with the extrusion printing process, allowing the selective addition of these higher strength materials where needed in a particular structure. Depending on the size and shape of the structure being printed, this methodology could be employed with little to no impact to the throughput of standard extrusion printing technology. Data collected from testing of a representative component will be presented to show the possible improvement in properties that can be achieved.

## Background

The addition of discontinuous short fiber reinforcement in the 3D extrusion printing process is now a well known and commonly used methodology for improving the strength and stiffness of parts manufactured using this type of additive process, with an added benefit of increasing the dimensional stability of these parts via reduction of CLTE (coefficient of linear thermal expansion). Many factors influence the effectiveness of fiber reinforcement used in thermoplastic matrices.

The improvements realized can differ based on many variables, such as the chosen polymer matrix, fiber type, fiber length, and fiber volume fraction. Fiber diameter, dispersion, length, orientation, and volume fraction are also important. There are also process factors that significantly influence the properties of 3D printed parts, such as print speed, print direction, layer thickness, nozzle diameter, and other parameters. In the case of continuous fiber, proper alignment and tensioning of the fibers can provide a substantially more significant contribution to the performance of the finished product. An important thing to note, however, is that in most cases, with the addition of fiber content there is usually a marked decrease in impact performance versus neat polymers, which is also well documented in other manufacturing processes using similar materials, such as injection molding. The addition of *continuous* fiber to discontinuous fiber filled thermoplastic parts, however, is understood as a method to not only further improve overall strength and stiffness, but also helpful in regaining a significant measure of impact performance.

When using continuous fiber in the manufacture of thermoplastic parts, it is important to consider the overall construction of the product. In many cases, it makes sense to use conventional discontinuous fiber reinforced materials for the bulk of the structure, and use the addition of continuous fiber to selectively reinforce areas where it will provide the added strength and stiffness needed based on the load case that the part will experience. Neat polymer is not recommended for use in conjunction with continuous fiber reinforcements, as the differences in CLTE between unfilled polymer and continuous fiber reinforcements can contribute to significant warping and higher stress concentrations at the interfaces.

The introduction of continuous fiber into the 3D extrusion printing process therefore offers significant benefits to the finished part, but also introduces new challenges. Existing technologies provide several methods of continuous fiber introduction into the 3D extrusion printing process:

1. Dry fiber tows are used as an input, and impregnated with molten polymer matrix either in the extrusion head, or just previous to the extrusion head.
2. Pre-impregnated fiber tows are introduced through the extrusion head, either in conjunction with other extrudate or comprising the entirety of extrudate.
3. AFP (Automated Fiber Placement) - pre-impregnated fiber tows are consolidated onto the part in a secondary process, generally using heat from a laser source or hot gas impingement followed by a consolidating/cooling roller or anvil.
4. ATL (Automated Tape Laying) – pre-impregnated unidirectional continuous fiber reinforced thermoplastic tapes are consolidated onto the part in a secondary process, also using heat from a laser source or hot gas impingement followed by a consolidating/cooling roller or anvil. This process is very similar to AFP but in a wider format.

In the first two process methods, where fiber is introduced through an extrusion process, significant improvements in properties are realized, but optimization of fiber alignment and tensioning is more challenging than AFP or ATL processes. While the latter processes can provide further improvements, the tradeoff is that the surface finish of the underlying substrate is critical to allow proper bonding to the tows or tapes. In order to achieve a consistent bond between the materials, a flat, smooth surface is generally necessary to eliminate voids at the bonding interface. In many large area extrusion printing cells, a secondary machining operation is used to provide a desired surface finish. The secondary machining operation is generally performed in-situ in the manufacturing cell, via additional automated equipment that can perform the machining operation without removal of the part from the print bed.

This subtractive manufacturing step is commonly used to machine 3D printed parts to precise finished dimensions or to provide more features that cannot be accurately printed. This process is performed while the parts are still attached to the print bed, which eliminates the need for additional handling and fixturing in an external machining process. Ideally, the AFP and ATL processes can also be performed in-situ, with the addition of the appropriate equipment in the manufacturing cell in conjunction with the existing printing and machining tools.

# Introduction of Continuous Fiber Thermoplastic Tapes and Laminates into 3D Printed Structures Utilizing Ultrasonic Scan Welding

As a novel approach, a method similar to Automated Tape Laying is explored here, using pre-impregnated, multi-axial continuous fiber reinforced thermoplastic laminates that are bonded to an extrusion printed profile. In a process that is closely related to ATL, detailed above, we partnered with Center Street Technologies, a hybrid manufacturing company specializing in large scale additive manufacturing and 5-axis subtractive milling, based in Youngstown, Ohio, and Agile Ultrasonics, who designs and manufactures customized ultrasonic systems used for continuous ultrasonic scan welding demonstrated in these trials. Agile is based in Columbus, Ohio. Unique to this project is the use of multi-axial thermoplastic laminates as the continuous fiber media, along with the use of continuous ultrasonic scan welding as the joining process. The combination of these two components potentially provides significant promise of greater mechanical property improvements, and the possibility of much higher throughput than existing technology.

## Profile selection

A hat section profile was selected as a representative part, as this shape is commonly used in the automotive industry as both a structural member (such as a drivetrain or suspension crossmember), and as a reinforcement for large panels, such as roof or door skins. The profile was designed as a flat, constant cross-section part in order to facilitate ease of manufacture and testing.

## Material Selection

Materials were chosen based on their relevance to automotive applications.

1. Polypropylene was chosen as the resin matrix, as it is commonly used in a variety of automotive applications, with well understood properties and applications.
2. Polystrand IE 6337T, a continuous glass fiber reinforced polypropylene laminate consisting of 3 layers of continuous glass fiber unidirectional thermoplastic tapes, pre-consolidated in a 0/90/0 layup, was chosen as the secondary reinforcement to be ultrasonically welded to the hat section. Unlike AFP or ATL, which typically use individual layers of unidirectional material, we wanted to demonstrate the use of a multi-layer laminate, which can provide additional reinforcement and dimensional stability along a secondary axis.
3. Xtellar GR900PP-CF, a 20% recycled carbon fiber reinforced polypropylene homopolymer, was chosen as the print media. While carbon is a more expensive reinforcement option than glass, it is significantly stronger than glass fiber. Also, it would allow us to highlight the fact that a significant improvement in strength and stiffness could be achieved by adding a lower cost material as a secondary reinforcement in the welding process.

## Process Steps

Since a manufacturing cell containing all of the necessary processes in-situ is not yet available, an analog of the proposed process was established to emulate the required steps.

1. The hat section profiles were printed at Center Street Technologies, using the Xtellar GR900PP-CF material. These parts were combined and printed vertically, which allowed for efficient use of material and maximum throughput, since horizontal printing would have required an internal support structure that would require removal.
2. The hat section parts were cut into separate pieces, and then surface machined to accept the laminate materials. The surface machining could have been performed in-situ, but availability of machine time was limited, so the decision was made to perform this as a secondary operation.


*Figure 1: Center Street Technologies manufacturing cell features a build envelope of 24 ft by 12 ft x 8 ft build volume with 30 tons of weight capacity. The two gantry set up allows for 3-axis additive manufacturing and 5-axis subtractive milling*

*Figure 2: Top hat sections being printed in vertical orientation*

*Figure 3: Top hat sections after separation and surface finishing*

3. The laminate reinforcement material was cut to length and width, and ultrasonically scan-welded to the top surface of the hat sections at the Agile Ultrasonics facility.

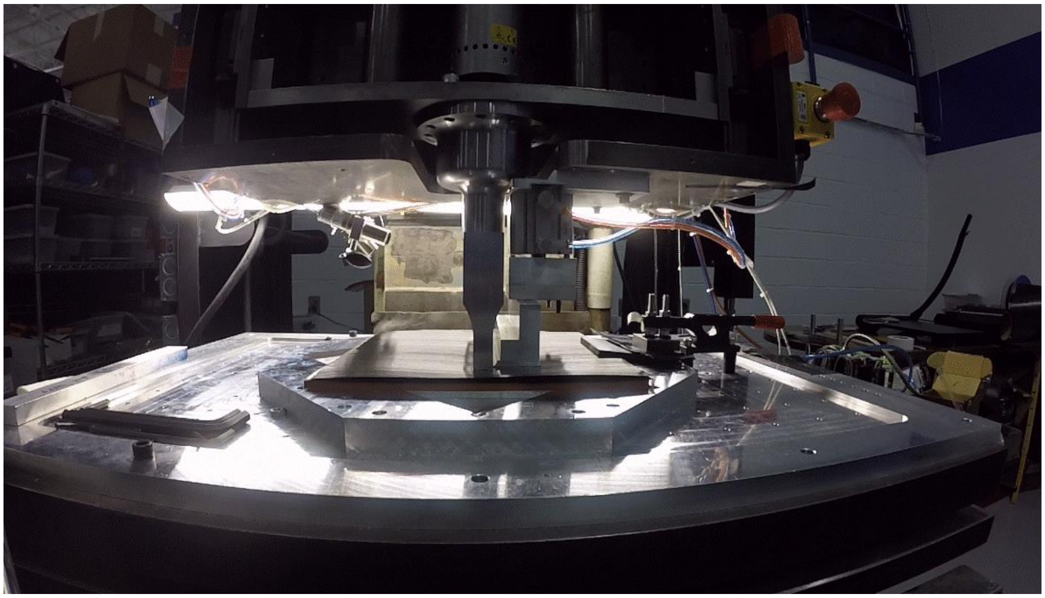

*Figure 4: Agile Ultrasonics prototype welding cell*

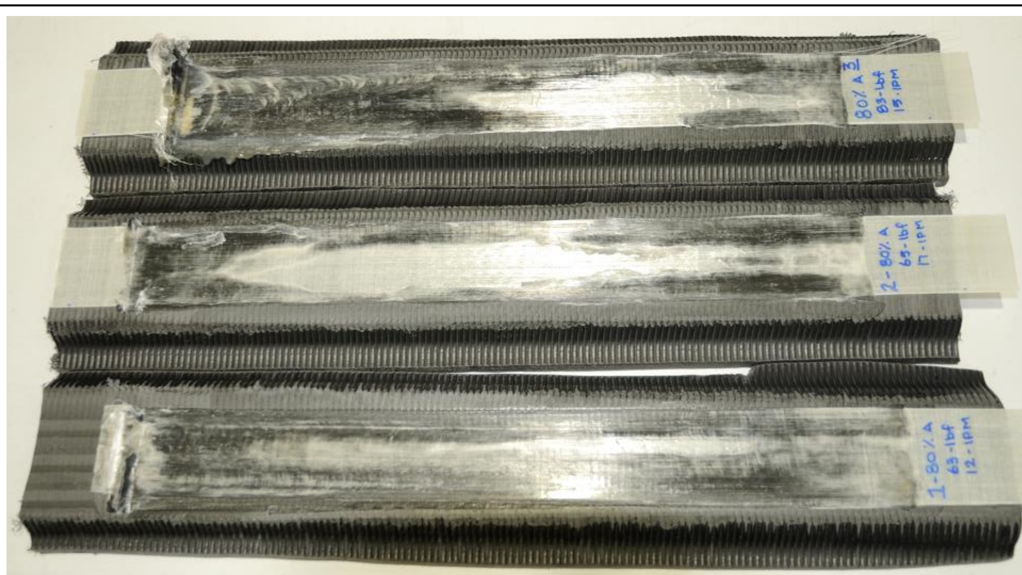


*Figure 5: Top hat sections showing results of various process iterations*

*Notes on Ultrasonic Scan Welding*

While ultrasonic welding is commonly used to spot weld preliminary layups prior to further consolidation in other processes, the technology employed by Agile Ultrasonics allows continuous welding and consolidation in a form factor up to 13” in width. This can be employed in an automated process in-situ in a 3D extrusion printing environment (e.g., deployed on a gantry or as an end of arm process on a robot). Various process parameters, such as frequency, amplitude, speed, pressure, and cooling can be adjusted to optimize weld quality.

## Testing and Results

After trialing several process conditions, a small number of samples were selected for mechanical testing, performed at Polystrand in Englewood, Colorado. Samples were tested for flexural strength and stiffness, based on a modified ASTM D790 test procedure. Control samples (3D printed hat sections, machined but without laminate reinforcement) were tested as a baseline. Samples were tested at both a 6” span and a 12” span.

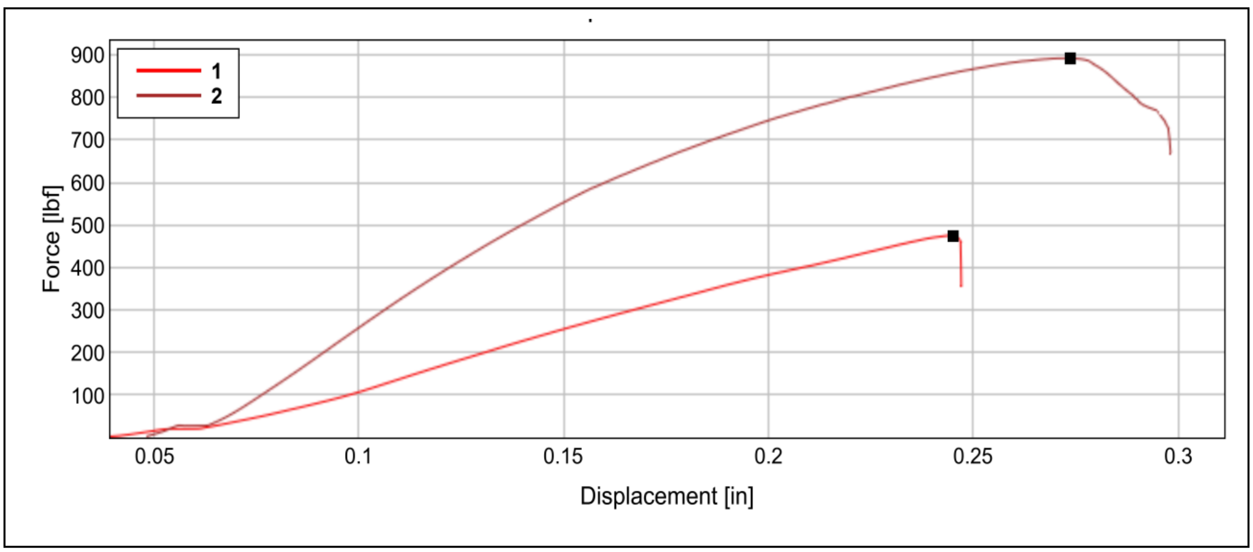


*Figure 6: Load vs. Deflection for 6” control and welded sample*

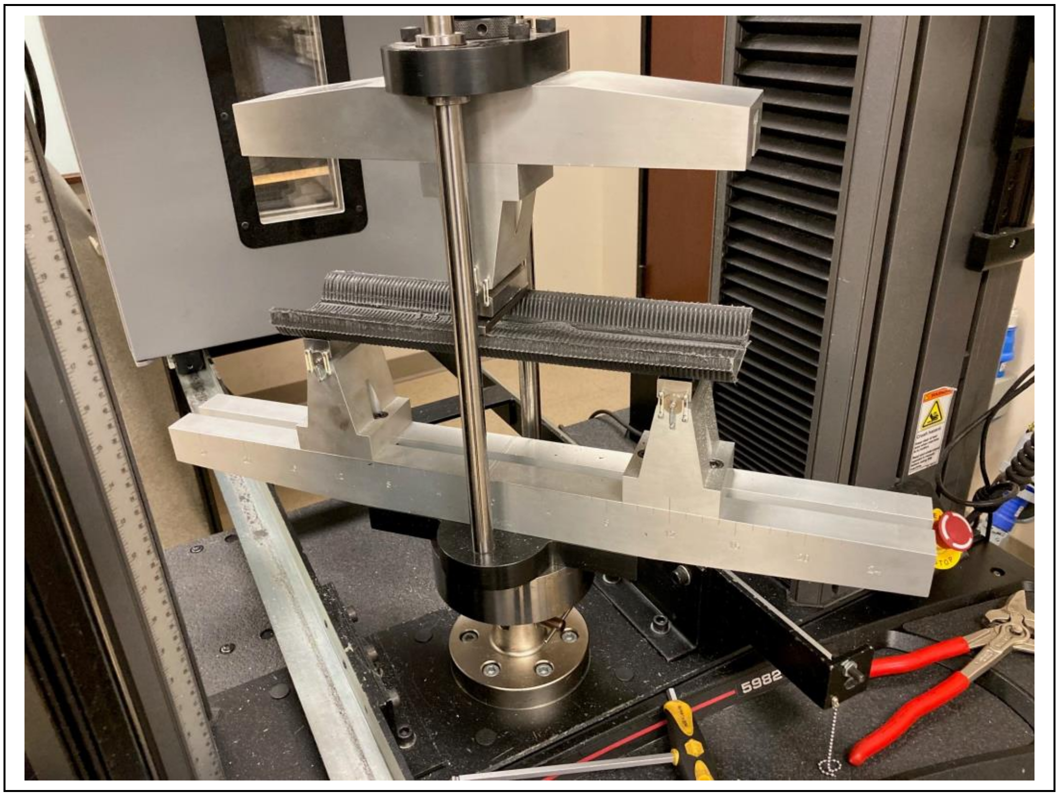

*Figure 8: 3 point bend test of 3D printed and welded hat section*

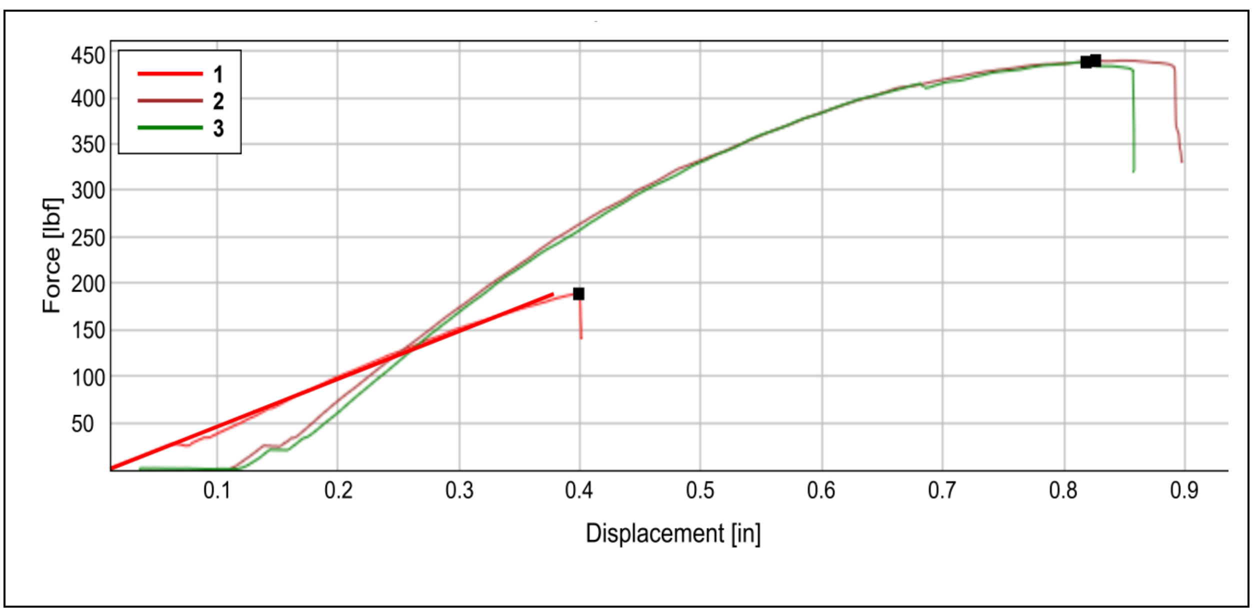


*Figure 8: Load vs. Deflection for 12" control and welded samples*

*Table I: Strength and Stiffness Tested in 3 Point Bending*

| Modified D790 Test Results | | |
|---|---|---|
| **Sample Description** | **Maximum Load (lb)** | **Load rate (lb/in)** |
| 6" span (control) | 475 | 2851 |
| 6" span (welded) | 893 | 6609 |
| 12" span (control) | 189 | 523 |
| 12" span (welded) | 440 | 915 |

## Summary

Based on the significant improvements that were realized, further development and testing is warranted to accurately quantify the gains that can be achieved with this approach. In particular, achieving consistency in the welding process was hampered by the finish and flatness of the printed samples. 3D printing of polypropylene based materials is particularly challenging due to the tendency of these parts to warp. Once removed from the print bed and cut into individual pieces, the relieving internal stresses inherent in the process caused some warping and twisting of the parts, making accurate machining of the weld surface difficult. These significant challenges were a direct result of the methodology we chose for initial trials.

We believe these problems can be mitigated with the integration of the printing, machining, and welding processes in-situ in the same manufacturing cell. Other techniques can also be employed in the printing process, such as horizontal printing with a printed supporting structure (which reduces throughput, requires extra material, and possibly requires additional machining to remove the support if desired). Material selection can also play a significant role in reducing these kinds of problems.

While choosing a less complex profile (such as flat plaques) would likely yield better results, it was felt that the profile chosen would demonstrate this technology in a more realistic application. Based on the success of this trial, next steps would likely include a standardized plaque configuration, suitable for more extensive property characterizations, to include tensile, compressive, and shear properties.

## Acknowledgements

This project would not have been possible without the cooperation of Bob Berardino and the team at Center Street Technologies, Jim Stratton and Matt Short of Agile Ultrasonics, and the support of Avient Corporation. This collaboration of three distinctly different companies was a rewarding experience, and the results are something we take great pleasure in sharing.