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Increasing Z-Strength and Testing the Capabilities of Twin Screw Extruders in Large Format Polymer Additive Manufacturing

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Final CRADA Report

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Manufacturing Science Division

INCREASING Z-STRENGTH AND TESTING THE CAPABILITIES OF TWIN SCREW EXTRUDERS IN LARGE FORMAT POLYMER ADDITIVE MANUFACTURING

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ABSTRACT

During the first phase of this project, small and large Strangpresse extruders were assessed at Oak Ridge National Laboratory's Manufacturing Demonstration Facility (MDF). This phase resulted in Strangpresse exclusively licensing some of ORNL's previously developed extruder technology for high-volume thermoplastic additive manufacturing (AM). Phase II of this project will focus on further development and optimization of Strangpresse extruders for increased efficiency and increased throughput. The objective of this project is to develop a new extruder with a higher output and less energy usage than current AM thermoplastic extruders and to develop and evaluate a new tamper mechanism for increasing Z-strength resulting in an advanced and optimized extruder and tamper system.

1. Statement of Objectives

1.1 TASK 1 DESIGN AND FABRICATE TWIN-SCREW EXTRUDER

Strangpresse will design and manufacture a twin-screw extruder for large-format polymer AM with a target throughput of 150lbs/hr. This would be the **first** twin-screw extruder designed specifically for AM and would provide significant improvement to material mixing and flow control capabilities. Strangpresse will design the extruder to have a larger throughput than current BAAM extruders while saving energy. Benefits to Strangpresse include expanded AM product offerings with competitive advantages over single screw extruders.

1.2 TASK 2 EVALUATION OF TWIN-SCREW EXTRUDER

ORNL will evaluate the flowrate performance and fiber handling of the twin-screw extruder. Flowrate performance will be judged by maximum rate, linearity, and response time. Fiber handling will be judged by the fiber alignment using a microscope with polished samples. Polished samples will also be inspected to see if fibers are destroyed. ORNL will benefit through the collection of first-hand experience and performance data of twin-screw extruder utilization within large-format polymer AM, adding to its knowledge base of AM extrusion.

1.3 TASK 3 DESIGN AND FABRICATE NEW TAMPER

ORNL will design and manufacture a new tamper mechanism with the goal of increasing the compression capabilities of the tamper to improve the layer-to-layer bond thus increasing Z-Strength performance of printed parts. This will involve a new motion mechanism and stiffer springs which will create a new down-stroke that can be tuned based on layer height. The new tamper will be prototyped using traditional fabrication methods and tested.

1.4 TASK 4 EVALUATE TAMPER

ORNL will evaluate the performance of the new tamper, compared to the existing tamping technology used at the MDF, based on improvement of the Z-strength of a manufactured 2-bead wall. Tensile bars will be waterjet cut and tested for Z-Strength using an Instron Machine. Strangpresse will also evaluate the performance of the tamper with their production large-format system. ORNL will benefit from expansion of its knowledge base on tamper design and performance.

1.5 TASK 5 FINAL REPORT

Final report to document the findings of the twin-screw extruder and new tamper. ORNL will publish about the research in this project so that others may learn and implement the technology.

2. TECHNICAL DISCUSSION OF WORK PERFORMED

2.1 TWIN-SCREW EXTRUDER

Strangpresse is a designer and manufacturer of many different single screw extruders for AM, but they've never produced a twin-screw extruder for use with an AM system. There are also not any known large format systems using twin-screw extruders. The goal of the twin-screw extruder tasks was to understand the benefits and drawbacks of twin-screw extruders to see if they would be applicable to additive manufacturing. If the preliminary research suggested that a twin-screw extruder would be successful, Strangpresse would design and manufacture a system and ORNL would assist with testing and characterization.

During the research phase of the project, Strangpresse encountered many advantages and disadvantages of twin-screws designs and how they might be applied to AM. Twin-screws are great for compounding, or mixing, materials and additives such as fibers. Because of this, twin-screw extruders are often used by compounders to make pellets. These are great qualities for AM because most large format process rely on fibers to help reduce thermal expansions during printing by adding stiffness. One downside of the twin-screw extruder is that they are generally designed to run powdered thermoplastic material, rather than pellet, to reduce operating costs. However, conveying powder and fiber separately to the extruder head would add complexity to the process. Another concern is the requirement with a twin-screw extruder to add a melt-pump to the system to help precisely meter and control the extruder output. A melt pump adds weight, cost, and complexity to the system, but does allow for consistent extrusion output.

After researching designs and methods, Strangpresse proceeded with designing their twin-screw extruder to look at the manufacturability. As the design progressed challenges were encountered such as material feeding angle and handling the vibration from the dynamic conditions of printing. Single screw extruders are mounted vertically for AM with pellets feeding in the side coming from above. Twin-screw extruders have to be mounted horizontally with pellets feeding in directly from above. The change from vertical mounting to horizontal mounting is a concern that has to be addressed on every machine where the extruder would be used. Not all systems have enough space to horizontally mount an extruder without giving up considerable X/Y printing area. Another concern is the vibration coming from the dynamic conditions of the printing process. The extruder must be mounted on a gantry that is constantly in motion causing vibrations and disturbances for the system. The screws in a twin-screw extruder are a tightly matched pair with high tolerances. There is concern that the dynamic printing conditions could cause misalignment for the twin-screws and ultimately cause damage. Furthermore, once the final design was completed and the total weight, before melt pump, was estimated at 1500lbs. This is approximately one order of magnitude heavier than a comparable single screw extruder at 150lbs/hr output. The result of the design bought forward more concerns about the feasibility of using a twin-screw extruder, and ultimately it was decided that manufacturing was not a good idea.

2.2 TAMPER

For this CRADA, a new tamper was designed specifically around the Strangpresse Model 30 extruder. This new design was created from the ground up to avoid some of the reliability and manufacturability issues with the tamper currently used at ORNL.

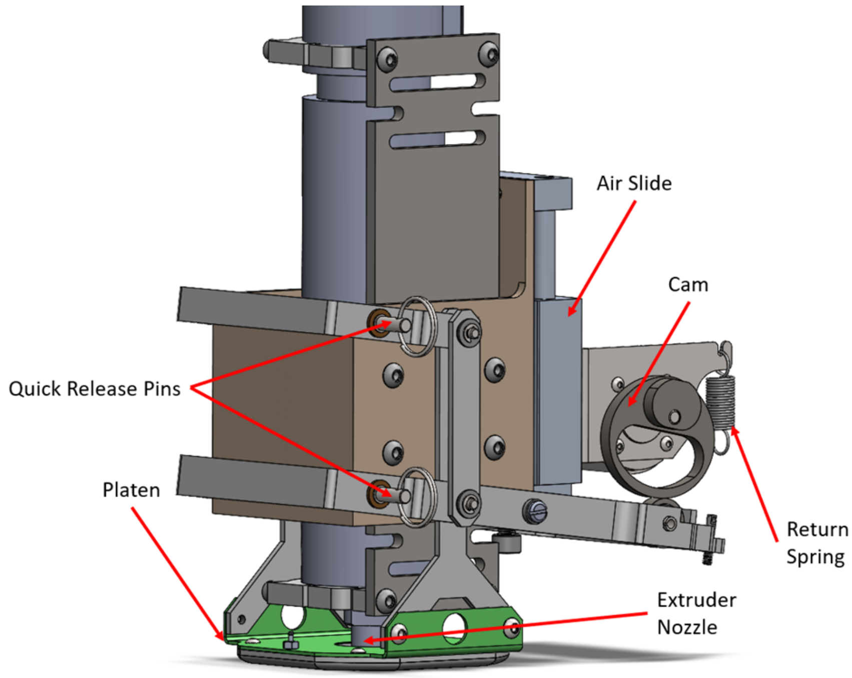


Figure 1: CAD representation of the new tamper design

Figure 1 shows the new tamper design. The needed function is a rapidly reciprocating foot or platen around the extruder nozzle. In this design the up and down motion is driven by a continuously rotating cam. By using a cam to drive the motion, the acceleration of the up and down motion was tuned to minimize maximum acceleration and jerk. The cam has counterbalances to prevent vibration during high-speed rotation.

A return spring is used to keep the platen assembly pulled tight against the cam. Finding the correct spring is an important consideration in the design. The spring must be stiff enough to keep the cam follower tight against the cam during the highest acceleration points, but not too stiff to prevent the motor from turning the cam. Furthermore, the spring must not fail in fatigue after many repeated cycles. The correct spring was chosen through a combination of analysis and trial and error.

The tamper must also be able to handle unexpected collisions with printed material on lower layers. This is often in the form of globs of solidified material that stick out above the top layer of the part. When the extruder passes over globs like this, there needs to be a release mechanism to prevent excessive force from damaging the mechanism. In the present design there is an air slide that will allow the mechanism to slide up if the forces get too high. This breakaway force can be set by changing the air pressure to the air slide.

An adjustable screw changes the bottom position of the air slide. This in turn adjusts the lowest position of the platen. By adjusting the screw, the lowest position of the tamper can be moved, so as to control the level of compression of the platen on the extruded material. There are two quick release pins that can be removed to drop the platen mechanism from the rest of the tamper. This allows quick access to the extruder nozzle without fully removing the tamper from the extruder. In Figure 2, the assembled tamper is shown. This was tested on the Strangpresse Model 30 extruder and the ORNL BAAM extruder.

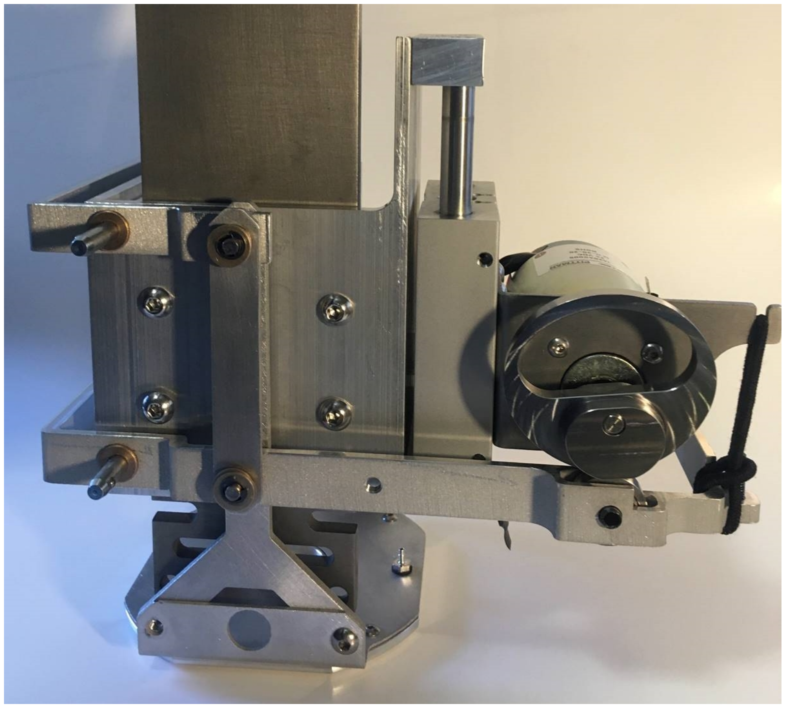


Figure 2: The new tamper fully assembled

3. RESULTS

To test and compare the new tamper design versus the original tamper, ORNL printed four 8in hexagons with 2 bead walls out of 20% carbon fiber ABS. One hexagon printed with the old tamper (Specimen 1), one with no tamper (Specimen 2), one with the tamper flush with the nozzle (Specimen 3), and one with the tamper 0.05" below the nozzle (Specimen 4). Each hexagon was waterjet cut into 7 tensile bars oriented in the Z-direction to test interlayer strength. The samples were machined flat on both faces, then pulled using an Instron machine to measure ultimate tensile strength. The results for each of the four samples is shown in Table 1. From this data it is clear that the new tamper with the platen flush with the nozzle provides the best performance, at least with this material.

Table 1

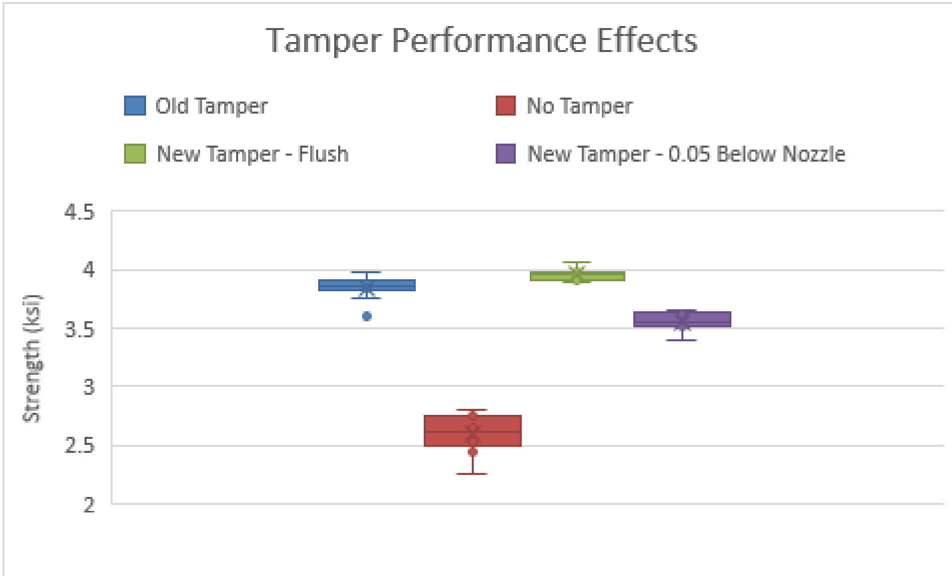
Mat: CF-ABS	Pre-Test		Ultimate Strength	
Specimen #	Thickness (in.)	Width (in.)	(lbs.)	(ksi)
Old Tamper				
1-1	0.277	0.512	544.03	3.84
1-2	0.2725	0.512	508.6	3.6
1-3	0.273	0.512	538.39	3.85
1-4	0.2735	0.5115	538.4	3.85
1-5	0.274	0.512	547.25	3.9
1-6	0.276	0.5125	548.86	3.88
1-7	0.2745	0.512	527.12	3.75
1-8	0.276	0.5115	551.28	3.9

1-9	0.274	0.512	556.92	3.97
1-10	0.276	0.512	547.25	3.87

No Tamper				
2-1	0.273	0.512	314.5	2.25
2-2	0.2745	0.512	370.88	2.64
2-3	0.276	0.512	388.6	2.75
2-4	0.2745	0.5115	357.19	2.54
2-5	0.275	0.512	394.24	2.8
2-6	0.272	0.512	351.55	2.52
2-7	0.274	0.5115	362.02	2.58
2-8	0.274	0.512	342.69	2.44
2-9	0.275	0.512	376.52	2.67
2-10	0.2735	0.512	384.57	2.75

New Tamper - Flush				
3-1	0.2745	0.512	546.45	3.89
3-2	0.276	0.512	574.63	4.07
3-3	0.275	0.5115	550.47	3.91
3-4	0.275	0.512	556.92	3.96
3-5	0.275	0.512	561.75	3.99
3-6	0.275	0.512	554.5	3.95
3-7	0.276	0.512	561.75	3.98
3-8	0.275	0.5115	552.08	3.92
3-9	0.2765	0.511	560.94	3.97
3-10	0.2745	0.5115	548.06	3.9

New Tamper – 0.05” Below Nozzle				
4-1	0.276	0.511	494.9	3.51
4-2	0.2745	0.5115	494.1	3.52
4-3	0.276	0.512	498.93	3.53
4-4	0.275	0.5115	509.4	3.62
4-5	0.2755	0.5115	499.74	3.55
4-6	0.275	0.512	502.15	3.57
4-7	0.2745	0.512	497.32	3.54
4-8	0.275	0.5115	514.23	3.66
4-9	0.2745	0.5115	513.43	3.66
4-10	0.276	0.5115	480.41	3.4



4. SUBJECT INVENTIONS

There were no new subject inventions as a result of this project.

5. IMPACTS

Strangpresse has a company goal to be the leading innovator of high-performance extruders for large-format additive manufacturing. Partnership with ORNL is key to Strangpresse's success because of the previous research and experience ORNL has with large-format AM polymer systems. ORNL originated the initial design for the AM polymer tamper and is the ideal partner for further research and development efforts. Strangpresse currently licenses and sells the existing tamper designs to US manufacturers and will continue to offer new capabilities that result from this collaboration.

The tamper is a fundamental attachment for large-format polymer extruders and redesigning the tamper concept to maximize Z-strength will greatly improve the material properties of printed parts. The project delivers on three important elements: 1.) alignment with AMO's goal to drive U.S. manufacturing to become more efficient and productive, 2.) a path toward transition of new technology to U.S. manufacturers for commercialization, 3.) advancement of the state of the art of large-scale polymer AM deposition techniques and ORNL expertise.

6. PLANS FOR FUTURE COLLABORATION

ORNL and Strangpresse have celebrated two successful tech collaboration projects thus far and look forward to additional research focused on improving the polymer printing process. Strangpresse currently licenses and sells ORNL extruder technology and is looking forward to future collaboration to continue developing new products.

7. CONCLUSIONS

This project led to deeper research and understanding of the use cases for twin screw extruders. While twin screw extruders have their many benefits, they don't seem well suited for the additive manufacturing applications of this project. Future work may focus on design iterations with smaller twin screw extruders where the costs and weight are decreased.

Data for the tamper showed intriguing results. A 52% increase in strength is seen from Test #3 to Test #2, where the new tamper used flush with the nozzle compared to a sample with no tamper. This shows the significance of printing with a tamper. The new tamper showed marginal, 3%, improvement over the old tamper. Similar performance here is to be expected. The data for the last specimen, #4, proved to be most interesting. It showed a loss of strength when using the tamper below the nozzle to provide extra compression when compared with a tamper kept flush with the nozzle. There are many theories about what is causing this, but the prevailing hypothesis is that the tamper is providing too much cooling which prevents good layer to layer bonding. Additional testing is needed to understand, and hopefully improve, the tamper with platen below the nozzle.