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Tensile Properties of Additively Manufactured PLA Material

by Julia E Cline

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14. ABSTRACT
The tensile properties of an additively manufactured PLA sample are explored in this work to ascertain the effect of annealing on the material properties. Five samples are tested as manufactured and five are annealed in an oven for 45 min at 90 °C. Tensile tests are performed using an electromechanical test frame and digital image correlation is used for deformation measurement. Analysis shows that the ultimate tensile strength and strain to failure decreased for the anneal samples, while the tensile modulus increased slightly for annealed samples. The failure location on all specimens is consistently at the location where the print initiates in the gage section. The results are contradictory to the data sheet supplied by the manufacturer and it is recommended that a more comprehensive study be performed to determine the annealing parameters necessary to increase the tensile strength of the material beyond what is achievable with an as-printed part.

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1. Introduction/Motivation

The product data sheet for 3D-Fuel Advanced PLA Filament[1] recommends that to achieve maximum strength out of the material, additively manufactured parts should be annealed after manufacture. To understand this effect, test samples are manufactured, annealed, and subjected to tensile loading. Digital image correlation (DIC) is used to measure the surface deformation during testing.

2. Experimental Design

Ten test samples are manufactured in a tensile dogbone shape (Fig. 1) using additive manufacturing techniques. The samples are nominally 2.5 inches long and 0.15 inches thick with a gage section width of 0.13 inch.

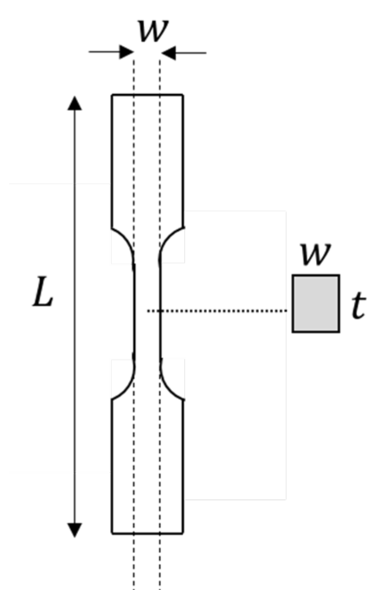


Fig. 1 Tensile specimen geometry, where L is length, w is gage section width, and t is thickness

Five samples are tested as manufactured and five are annealed in a Symphony VWR vacuum oven at 90 °C for 45 min. The annealing procedure from 3D-Fuel is followed.[2] Specimen dimensions are measured before and after the annealing process to assess any geometrical changes due to the heat treatment process. A speckle pattern is applied to the surface of the specimen using black and white spray paint.

ASTM D638[3] is used as a reference for the test method. Figure 2 shows the experimental setup. An Instron 1123 electromechanical test frame with wedge action grips and a 5-kN load cell is used to apply tensile load to the samples at 0.025 inch/min until ultimate failure. All specimens failed in the grip section.

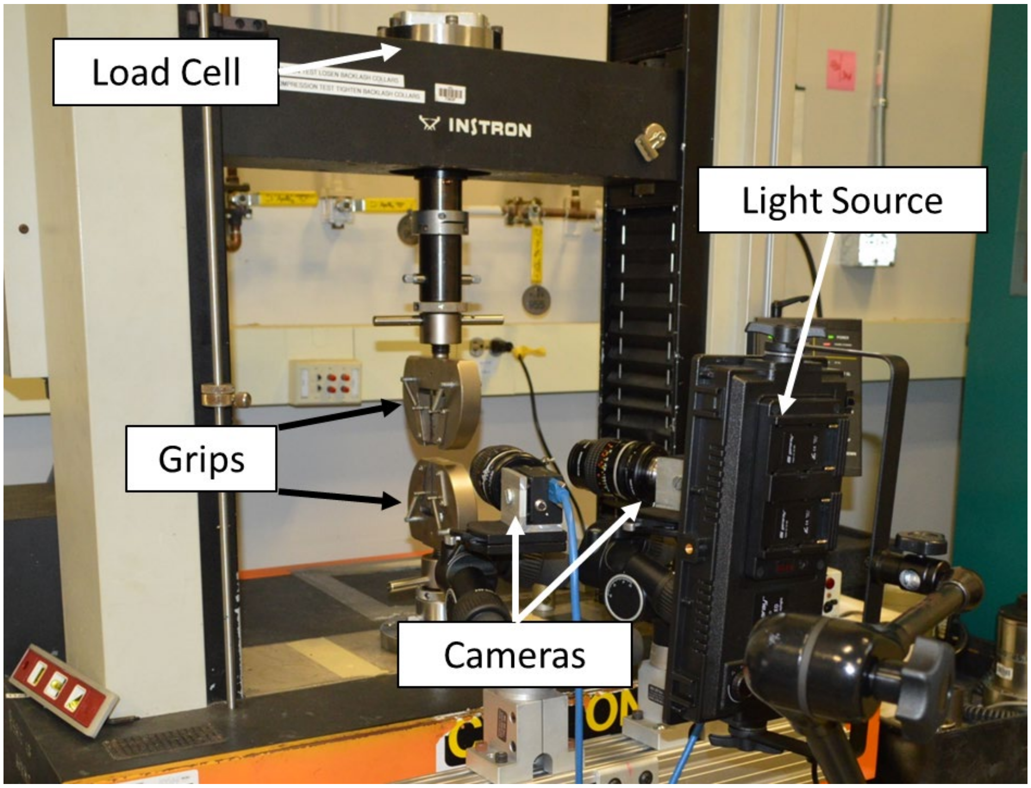


Fig. 2 Test setup for measuring the tensile properties of the PLA specimens

Stereovision DIC cameras are set up to image the surface of the samples during testing. The 2.3-MPixel cameras (FLIR cameras with 50-mm lenses) are oriented vertically so that the long axis coincides with the loading direction. Images are captured at 2 fps. Load and crosshead displacement voltage signals are recorded for each image. VIC3D-7[4] is used to process the images for analysis.

3. Methodology

The engineering strain is extracted from the DIC data. Engineering stress values will be calculated from the applied load and the undeformed cross-sectional area measured prior to testing. The tensile modulus is calculated as the slope of the engineering stress–engineering strain curve between strain values of 0.001 and 0.003. The ultimate tensile strength is taken as the maximum engineering stress before failure. The strain to failure is taken as the strain at the maximum engineering stress.

4. Results

The dimensions of the specimens before and after annealing are presented in Table 1. An average change in the cross-sectional area of 2.6% is measured for specimens T_06A to T_10A. The specimens flatten out during annealing, that is, the width increases while the thickness decreases. The increase in the cross-sectional area occurs because the change in width is much larger (average of 3.1%) than the change in thickness (average –0.8%). For the annealed samples, the cross-sectional area after annealing is used to calculate the applied stress.

Table 1 Dimensions of tensile specimens before and after annealing

	Before annealing			After annealing	
Specimen	**Length (inch)**	**Width (inch)**	**Thickness (inch)**	**Width (inch)**	**Thickness (inch)**
T_01	2.5150	0.1293	0.14910		
T_02	2.5100	0.1267	0.16203		
T_03	2.5140	0.1315	0.15483	Not annealed	
T_04	2.5125	0.1272	0.16158		
T_05	2.5145	0.1305	0.14788		
T_06A	2.5120	0.1283	0.15222	0.1329	0.14873
T_07A	2.5260	0.1288	0.15050	0.1342	0.14615
T_08A	2.5135	0.1283	0.14643	0.1334	0.14487
T_09A	2.5120	0.1285	0.16053	0.1325	0.16375
T_10A	2.5145	0.1273	0.16273	0.1300	0.16402
Average	**2.5144**	**0.1286**	**0.15479**	**0.1326**	**0.15350**
Standard deviation	**0.0041**	**0.0014**	**0.00608**	**0.0014**	**0.00857**
Coefficient of variation	**0.16%**	**1.10%**	**3.93%**	**1.08%**	**5.58%**

The values for ultimate tensile strength, strain to failure, and tensile modulus are presented numerically in Table 2 and graphically in Fig. 3.

Table 2 Calculated values of tensile modulus, ultimate tensile strength, and strain to failure for the PLA specimens tested

Specimen	Tensile modulus (ksi)	Ultimate tensile strength (ksi)	Strain to failure (%)
T_01	0.461	6.52	1.64
T_02	0.411	5.74	1.58
T_03	0.415	5.87	1.61
T_04	0.439	5.73	1.56
T_05	0.461	5.55	1.44
T_06A	0.431	5.55	1.44
T_07A	0.457	5.05	1.16
T_08A	0.447	5.48	1.41
T_09A	0.444	5.34	1.30
T_10A	0.435	5.47	1.53
Average	0.440	5.63	1.47
Standard deviation	0.017	0.37	0.14
Coefficient of variation	3.79%	6.52%	9.75%

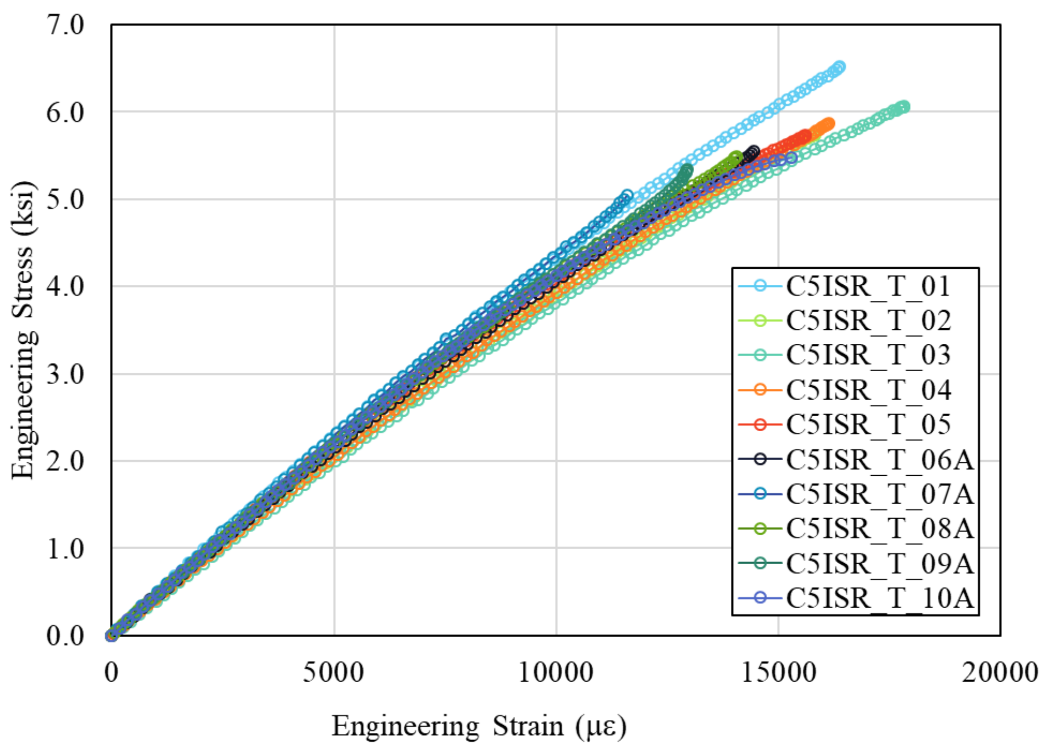
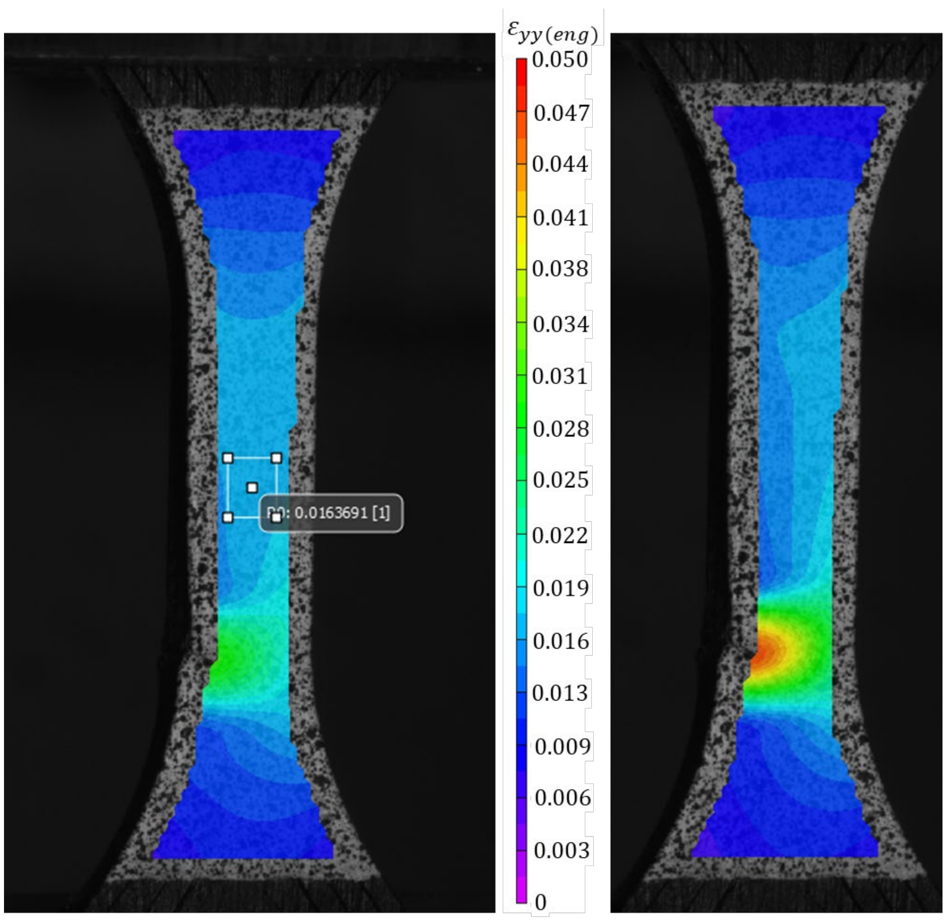


Fig. 3 Tensile stress–strain plot for the PLA samples with and without annealing

There is little observable difference in the material response between annealed and not annealed specimens judging from the plot in Fig. 3. We actually measure a decrease in both ultimate tensile strength (–9.3%) and strain to failure (–14.7%) for the annealed samples. The modulus increases slightly for the annealed samples (1.3%).

Figure 4 shows an example of the strain contours generated using DIC. At the maximum applied stress (Fig. 4a), the strain contour is relatively constant in the gage section, but the initiation of the crack at the failure location can be observed. Figure 4b shows the strains in the vicinity of the maximum crack right before catastrophic failure. The strains localize around the crack tip. Inspection of the specimens posttest reveal that the failure for all specimens occurs at the point on the specimen where printing began, which was toward the top of the gage section.



(a) (b)

Fig. 4 DIC engineering strain contours at a) maximum applied stress and showing b) point of failure

5. Conclusions

This study tries to quantify the effect of annealing on the tensile properties of an additively manufactured PLA material. Specimens are manufactured in dogbone shapes and subjected to tensile testing in an electromechanical test frame. DIC is used to measure the surface strains experienced during tensile loading. Five specimens are tested without undergoing the annealing process to serve as the baseline for comparison. Five specimens are annealed in an oven at a prescribed temperature and duration. The analysis revealed that the ultimate tensile strength and strain to failure decreased for the anneal samples, while the tensile modulus increases slightly for annealed samples. The failure location on all specimens is consistently at the location where the print initiates in the gage section. It is recommended in the future that the print is started outside the gage section to remove this source of variability from the results.

These results are contradictory to the material data sheet supplied by the material manufacturer. As this study investigated only one temperature and duration for annealing the samples, it is recommended that a more comprehensive study is conducted to determine the annealing parameters necessary to increase the tensile strength of the material beyond what is achievable with an as-printed part.

6. References

1. Advanced PLA data sheet. Fargo (ND): 3D-Fuel; 2019. https://www.fargo3dprinting.com/wp-content/uploads/2016/08/TDS-3DFuel-AdvancedPLA.pdf [accessed 2019 June].

2. 3D-Fuel. How to anneal your 3D print. Fargo (ND): 3D-Fuel; 2019 [accessed 2019 June]. https://www.3dfuel.com/pages/how-to-anneal-your-print.

3. ASTM Standard D638-10. Standard test method for tensile properties of plastics. West Conshohocken (PA): ASTM International; 2019.

4. Correlated Solutions, Inc.; 2019 [accessed 2019 June]. http://www.correlatedsolutions.com.

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