MM 319 Term Paper: Experimental Verification Of Iso-strain and Iso-stress Failure in Additively Manufactured PLA

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ABSTRACT

This term paper looks at the deformation behaviour of additively manufactured PLA (polyactic acid) parts in the iso-strain, iso-stress and an intermediate configuration. Comparisons have been made between the experiments conducted over a range of temperatures and the behaviour predicted by theory and verified the same via FEM simulations.

Introduction

The concepts of iso-stress and iso-strain loading come from the attempt to compute the strengths of *composite* materials. Composite materials are those which consist of two different phases. In the iso-strain configuration the strains in both phases of the composite are equal and in the iso-stress configuration the stresses in both the phases are equal. In case of additively manufactured parts, the manufacturing process is such that the part is composed of layers. If the part is loaded in a UTM along the length of these layers, then we get an equivalent of an iso-strain configuration and similarly if we load the sample perpendicular to the faces of the various layers then we get an iso-stress configuration. Note that the sample consists only of one phase but different layers.

The authors have performed tensile tests on the additively manufacturing parts in a total of three configurations: iso-stress, iso-strain, and 45° to the loading axis. The deformation behaviour for these modes has been compared with that predicted from theory, this includes the elastic modulus, ductility, and ultimate tensile strength. The samples used for the experiments were 3-D printed with PLA with dimensions 63mm $\times$ 3mm $\times$ 4mm at the Micro-Mechanics of Materials Lab, IIT Bombay.

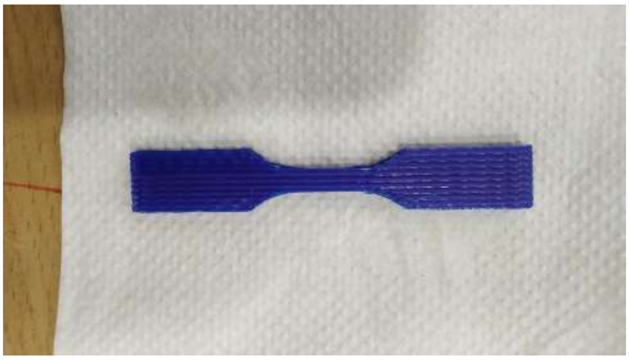

Fig. 2: Iso-strain sample.

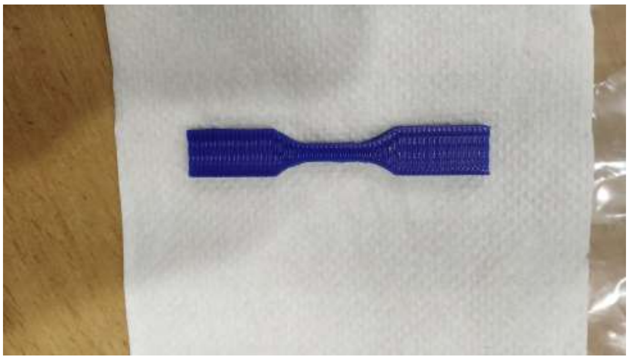

Fig. 3: Iso-stress sample.

Fig. 4: 45 degree sample.

Theory

Consider that a force of F_1 is applied perpendicular to the cross-sections of the composite as shown in the figure below. Let us suppose that all layers in this sample have a cross-sectional area E.

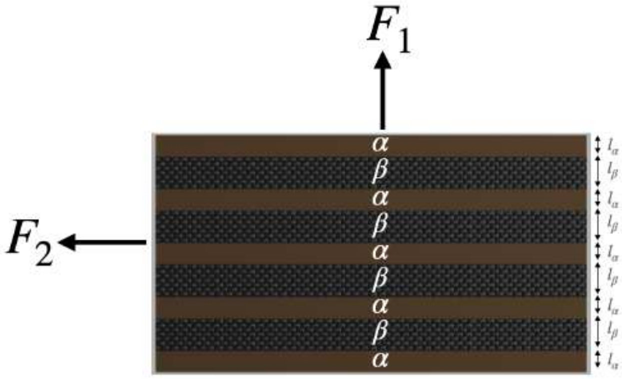

Fig. 1: Iso-strain and iso-stress loading conditions.

Since the force is being applied on the same area, the stress in each layer will be the same. This is the iso-stress configuration. For this arrangement we find that the elastic modulus for the overall composite is as follows.

$$\frac{\sigma}{\epsilon_c} = E_c = \frac{1}{\frac{V_\alpha}{E_\alpha} + \frac{V_\beta}{E_\beta}}$$

Where ϵ_c is the strain, V_α and V_β are the volume fractions of the α and β phase This is called the lower-bound solution. A force F_2 is shown in the figure below is the iso-strain configuration. Here the strain is identical in both the phases. For this configuration the elastic modulus is as follows.

$$\frac{\sigma}{\epsilon_c} = E_c = V_\alpha E_\alpha + V_\beta E_\beta$$

If we plot the elastic modulus as a function of the fraction of the β phase then we get a trend as follows.

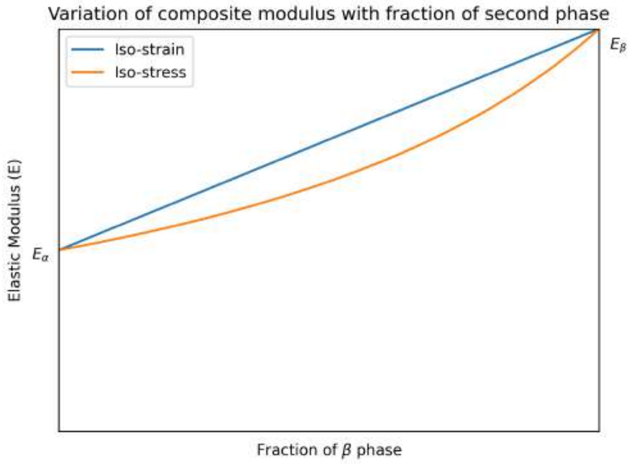

Fig. 5: Variation of elastic modulus with fraction of second phase.

Experimental Setup

For the experiment we prepared 24 samples of dog-bone shaped PLA as specified in [1]. For testing we used the (specify name and model of machine). Out of the 24 samples, one sample was used for *temperature calibration*. The method used for temperature calibration is detailed in the subsequent section. One sample was damaged due to a weak grip in the UTM. In all experiments were conducted on 22 samples of PLA, over a range of temperature. For the low temperature experiments liquid N_2 was used for cooling the samples.

Temperature Calibration

Temperature calibration was required because setting up the sample in the UTM required some time, and during this period the temperature could drop significantly from its temperature in the liq. N_2. The setup used has been shown in the fig. 2. The sample was allowed to equilibriate with the liquid nitrogen at approxiately -190°c. The sample was then removed from the refrigerant and its temperature was recorded at 15s intervals for a total time of 120s. This was repeated thrice and the corelation generated between time outside the bath and temperature of the sample is shown in fig. 3.

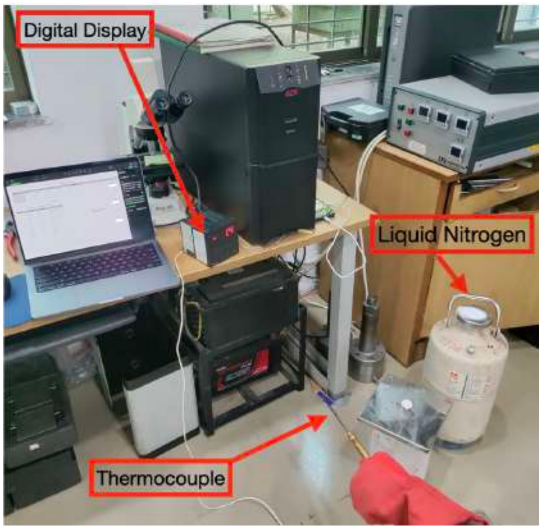

Fig. 2: Temperature calibration setup.

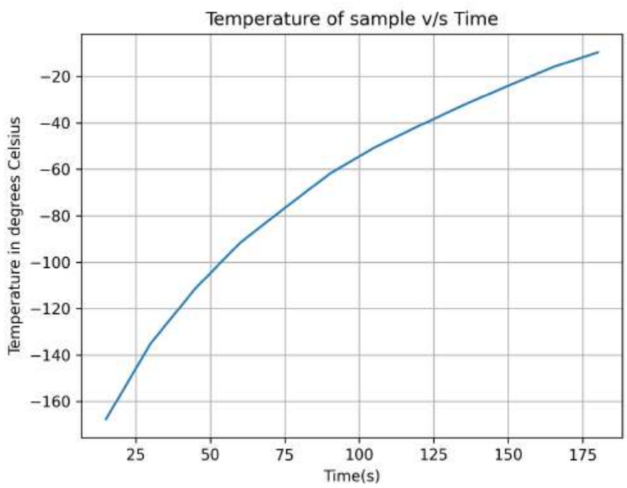

Fig. 3: Temperature of sample versus time outside liq. N_2 bath.

This corelation can be used for arriving at an approximate value for the temperature of the sample before it is put into UTM.

Experimental Procedure

Samples were tested at different temperatures by adjusting the time for which they were kept outside the refrigerant bath. The dependent variables of this experiment are: (i) configuration of the sample and (ii) temperature during the test which is correlated with the time spent outside the liq. N_2 bath.

Analysis of Fractured Samples

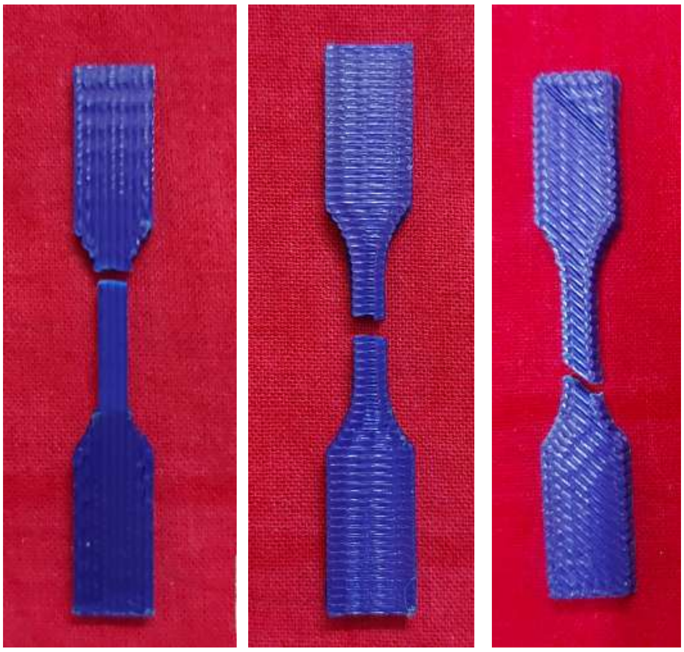

Fig. 4: Fractured samples: (i) isostrain, (ii) isostress, and (iii) intermediate configurations.

We can see that the samples made at 45° and iso-stress fracture along the fibres. The iso-strain sample fails near the grips. The fracture may be easier between fibres than along the fibres. All the samples also have sharp corners near the gauge. These points may serve as locations of stress concetration. In case of isostress and intermediate configurations the fracture is easier along the fibre, in case of the isostress configuration the failure is easier near the point of stress concentration hence the fracture point is closer to the grip.

Results

The tensile tests of the above specimen were performed in a UTM. The data recorded was processed in python. We can see that the yield strength is significantly higher in case of the samples in the iso-strain configuration due to the stress being along the layers of the part. In the iso-stress mode the stress is transferred to the rather thin material holding the PLA layers together. From fundamental elasticity theory one would expect the ductility to reduce i.e the sample to become brittle with decreasing temperature due to an increase in the elastic modulus.

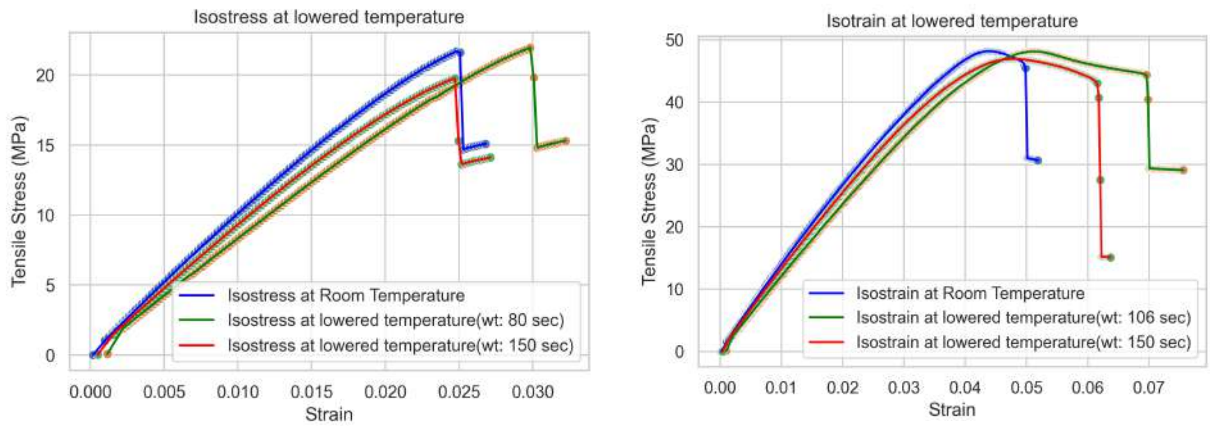

Fig. 5: Stress-strain plots for different configurations and temperatures.

It is observed that the ductility first reduces and then increases with increasing temperature. At high temperatures only the pulling of bonds contributes to the ductility. At lower temperatures along with pulling of bonds the disentaglement of bonds also contributes, leading to increased ductility. The maximum stress oberseved is ~47-50, 19-23, 24-26 MPa for the isostrain, isostress, and intermediate configurations respectively.

FEM Simulation

A dogbone sample was simulated in tensile mode in ANSYS. One end of the sample was set as a fixed support and the other end was a constant displacement rate of $1\mu m/s$. The quadratic Hill yield critetion was used for the simulation. This is a criterion commonly used for anisotropic materials.

$$F\sigma_1^2 + G\sigma_2^2 + H\sigma_3^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{21}^2 = 1$$

Constants F, G, H, L, M, and N have to be calculated experimentally. Below are the safety factor contours for the isostress and isostrain configuration.

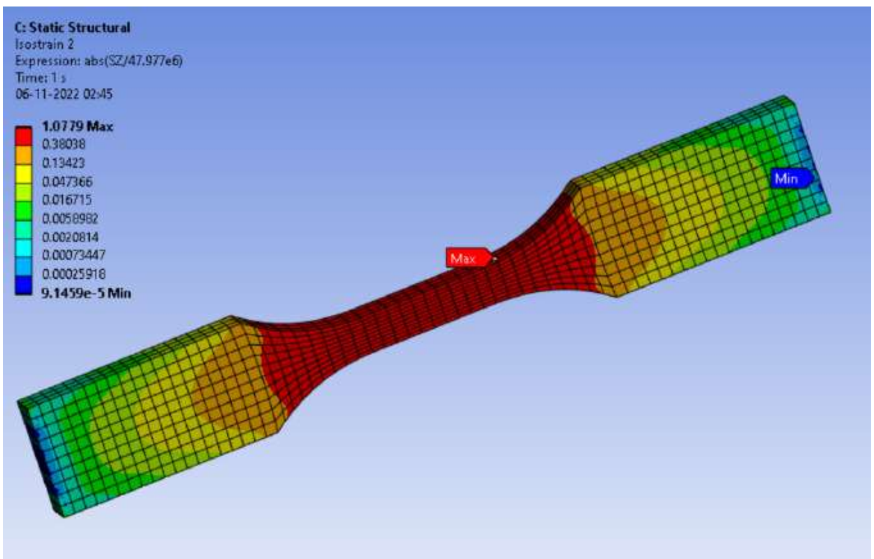

Fig. 6: Safety factor contour in isostrain configuration.

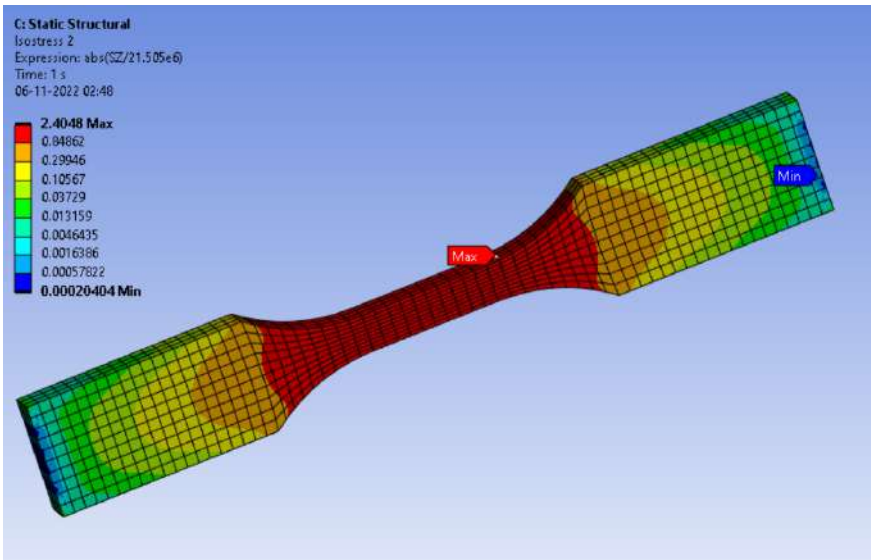

Fig. 7: Safety factor contour in isostress configuration.

References

1. Standard Test Method for Tensile Properties of Plastics.
2. Rafts, Skirts, and Brims.
3. 3-D printing PLA filament.
4. Tensile testing for 3-D printed materials