INVESTIGATION OF PROCESS VARIATION EFFECTS VIA A HOMOGENEOUS 3-DIMENSIONAL TENSILE TEST COUPON IN POLYJET 3D ADDITIVE PRINTING

Ravi Pratap Singh. Tomar, Furkan I. Ulu, Dr. Ram V. Mohan, Dr. Ajit kelkar

North Carolina A&T State University
1601 E Market Street
Greensboro, NC 27411

ABSTRACT

PolyJet printing technology is one of few additive manufacturing (AM) techniques capable of making the monolithic, multi-material structure. This paper investigates the Polyjet process variation effects that leads to differences in properties based on how it is built by designing a homogenized 3-dimensional tensile test coupon. Traditional ASTM D638 tensile test coupon's limitation is that one direction is thinner than the other two directions, which may not account for non-uniformity in material deposition in all three directions during printing. Firstly, these test coupons do not represent the real-world material behavior, and secondly, the effect of normal strain, which is a compressive strain in thinner directions, is not effectively captured. To avoid these limitations of the traditional specimen, a homogeneous 3-dimensional tensile test configuration is designed to keep the same cross-section's aspect ratio to form uniform material deposition. Results from tensile behavior of both traditional and homogeneous 3-Dimensional specimen are discussed. Study findings provide insight on the limitation of traditional test coupon and careful evaluations of process variation effect in Polyjet printing. The fracture surface of both PolyJet printed failed specimen are also examined to provide insight into failure characteristic. Findings aid in further understanding the process dependent properties capturing three-dimensional effects of Polyjet printing process.

1. INTRODUCTION

During the use of 3D printed parts for intended applications, the 3D printed parts should withstand various amount of mechanical and environmental stresses. Utilization of 3D printed parts in real-world applications requires its mechanical characteristic in all aspects to be like the part that it will replace, or to those produced by conventional processing methods [1]. Layered processing of polymeric materials, just like encountered in case for 3D printing, has numerous issues that limit its application. Among others, directional dependent properties pose the largest problem in additively manufactured parts. AM processes allow components to be printed in different orientations, offering enhanced design and construction flexibility, but also resulting in nominally identical products with very different properties. While material jetting processes, such as the PolyJet process, offer unique multi-material capabilities, research is still needed to identify the impact that process variations have on the quality of the final manufactured part. This style of layer deposition can introduce build defects and inconsistencies due to how the material droplets are spread and bond.

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Several studies have been conducted to understand the process-induced variation in AM and among the research society; However, these studies are based on traditional ASTM D638 2D test coupons [2][3][4][5]. These traditional 2D test coupons are thinner in one direction, or the cross-section aspect ratio is not same to currently bring out and highlight for manufacturing defects in AM. In AM, both material and structure are built at the same time during the process. Material and structure formation can lead to properties based on how it is built. Any variation during processing can change material configuration and can lead to artifacts. To eliminate these artifacts, present work proposed a homogenized 3-dimensional tensile test configuration with same cross sections aspect ratio for uniform material deposition. This configuration eliminates the limitation of traditional 2D test coupon and helps to understand the process induced variation carefully in AM.

Present paper focusses on the details of the 3D tensile test specimen, CAD design, and tensile testing procedure. In addition, this work studies the effect of process-induced variation comparing the results from traditional 2D test coupons and our present homogenized 3D test coupons.

1.1 Polyjet Printing Process

PolyJet printing is a process of controlled jetting of liquid photopolymers onto a build tray via series of inkjet print heads as shown in figure 1.1. The deposited photopolymers are cured by ultraviolet (UV) lamps that are mounted on the print block in multiple passes. The differentiating functionality of the PolyJet process Stratasys J750 is its ability to simultaneously jet multiple materials with different mechanical properties. A designer can manufacture products with functionally graded material properties such as by simultaneously jetting, for example, an elastomeric material “Tango black” and a rigid polymer “Vero clear”. Therefore, Stratasys J50 offers freedom in specifying both the properties of materials and the placement of materials on a point by point or at voxel level basis. Therefore, AM could be used for mimicking natural and biological structural materials with the capability of using a combination of soft and hard materials[6].

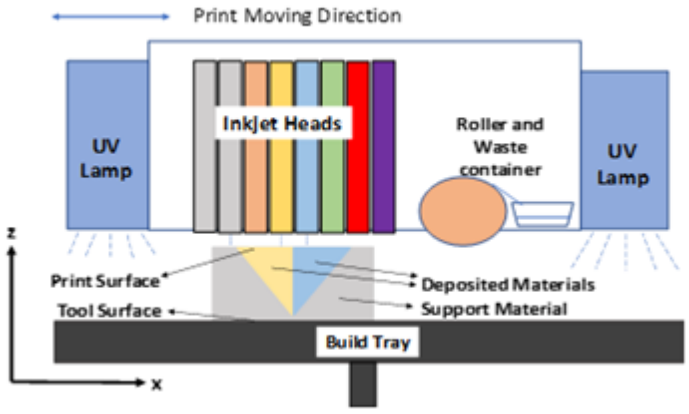


Figure 1.1 Representation of PolyJet printing process [7]

2. EXPERIMENTAL DETAILS

2.1 Design of Experiment (DOE)

Build orientation effect is an important issue in additive manufacturing. In the present study, the following design of experiment is conducted to understand this effect carefully and systematically. This design of experiment is based on printing tensile coupon built along three orientations using Stratasys J750. Parts printed in different orientation appear to be similar physically but could behave very differently under same loading condition. This explains the variation in processing condition in AM, which is called build orientation. To understand the effect of build orientation on printed parts, the test coupons were designed in three principal directions with the coordinate frame *x*, *y*, and *z*. Here *x* and *y* correspond to the orthogonal in layer direction and z corresponds to the layer deposition direction.

2.1.1 CAD model and selection of build orientation of traditional 2D test coupon

ASTM D638 type I tensile test coupon was designed. These test coupons were designed with SolidWorks modeling tool then these designs were exported as an STL file to use in a printer.

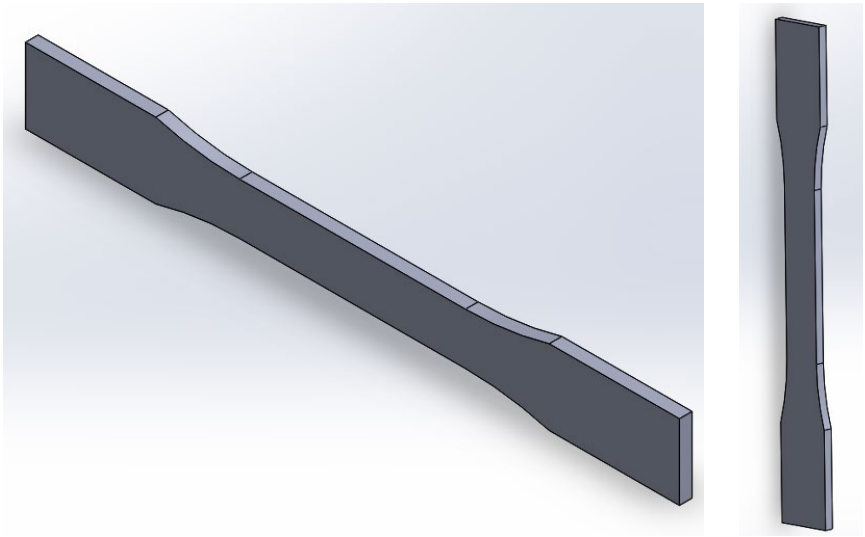


Figure 2.1 CAD model of the 2D tensile test coupon

These three orientations as sown in fig 2.2 were selected to be representative of how each of the longest directions affects mechanical properties. These directions correspond to our standardized principal directions. Parts oriented with their longest direction along the *x*-axis and their second-longest direction along the *y*-axis, which will be referred to as XY-parts (1st Orientation). Parts with the longest dimension along the Y-axis and second-longest along the X-axis referred as YX-parts (2nd Orientation). Parts with the longest dimension along the Z-axis and the second longest along the *x*-axis referred as ZX-parts (3rd Orientation).

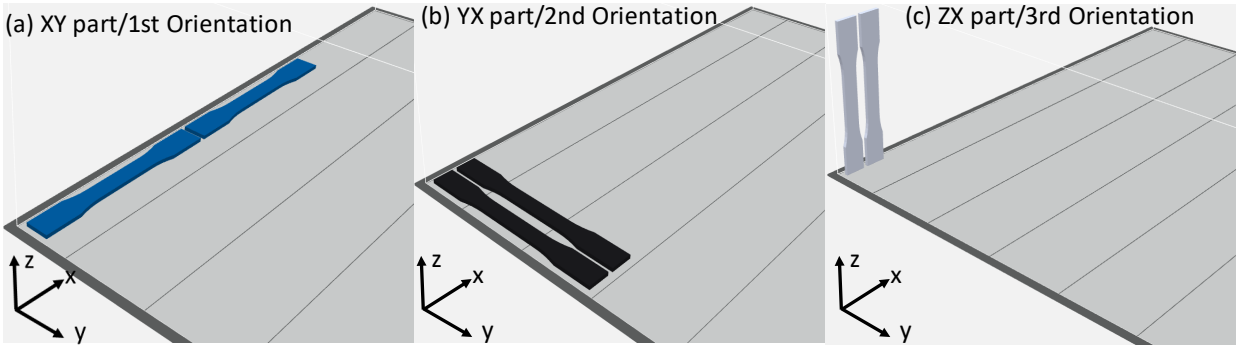


Figure 2.2 Selected build orientation for 2D test coupon

2.2 3-Dimensional test coupon

Since prior test coupons were based on 2D, to understand further whether the process induced variation in the so-called build direction does play role even in case of a homogenous configuration, a 3-Dimensional homogenous test coupon was designed. The limitation of traditional 2D test coupons is that one direction is thinner than the other two directions, which do not count for difference in uniform material deposition in all three directions. Therefore, to eliminate this limitation a 3D test coupon was designed in such a way that cross section has the same aspect ratio as shown in fig 2.3.

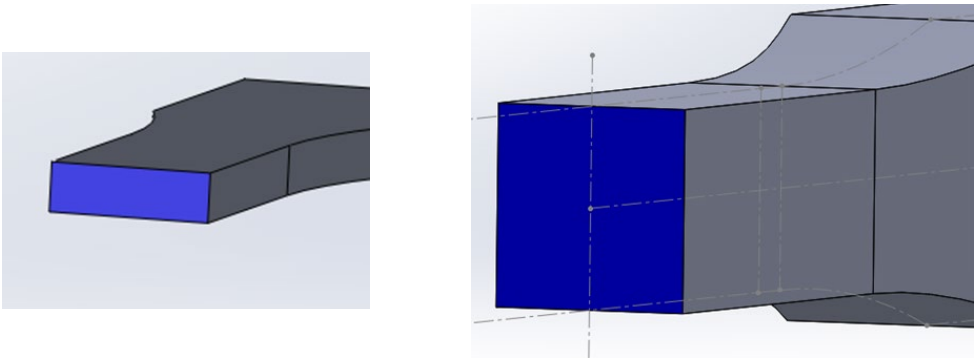


Figure 2.3 Cross-section (a) Traditional 2D test coupon (b) 3D test coupon

2.2.1 CAD model and selection of build orientation for 3D test coupon

A homogenized 3-dimensional tensile test coupon was designed in SolidWorks tool as shown in fig 2.4. The motivation of this design was keeping the same cross-section aspect ratio at each point, while keeping the length similar as in case of traditional 2D test coupon.

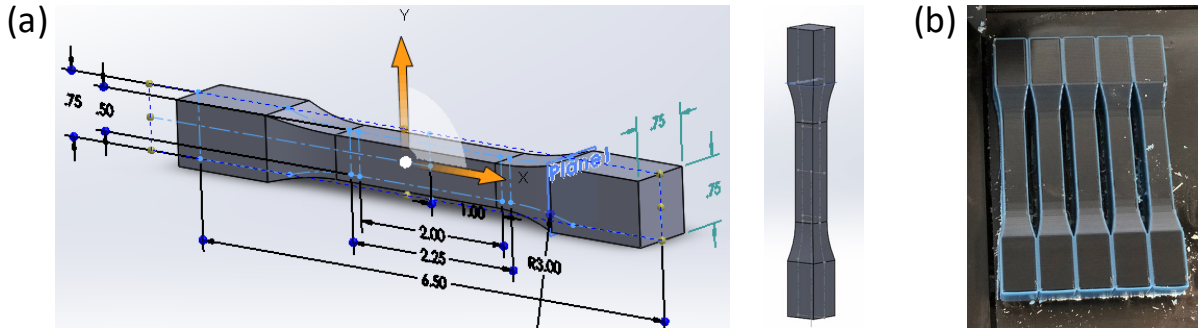


Figure 2.4 3-D tensile test coupon (a) CAD Design (b) Printed parts

These test coupons were printed in three build orientation as shown in fig 2.5, similarly as in case of the traditional 2D coupons to compare our 3D test specimen results with traditional 2D test coupons.

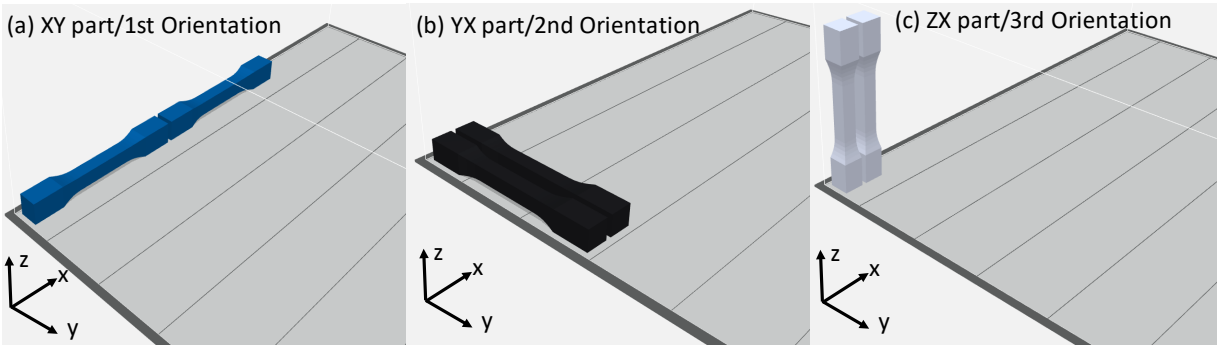


Figure 2.5 Selected build orientation for 3D test coupon

These 3-dimensional test coupons were thicker than the traditional 2D test coupon. Hence, to perform the tension test a different fixture, which has wide grip space between them to clamp the thicker specimen than the standard tensile fixture, was used. This is shown in fig 2.6 and testing was performed following the recommendations of ASTM test standards.

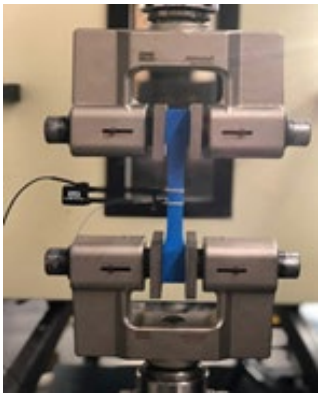


Figure 2.6 3D test coupon during the tensile process

2.3 Material system

The test coupons are printed using Vero family of materials available for Stratasys J750. Vero family material comes in different color and regardless of color, all Vero material has similar mechanical and thermal properties. A different color is used to differentiate the test coupon in each orientation. Vero cyan, Vero black, and Vero clear color are used for coupons printed in X, Y and Z build orientation for both configurations consisting of traditional 2D and 3D coupons.

2.4 Manufacturing process induced defects

From the manufacturing perspective, the quality of printed coupon was analyzed. Traditional 2D test coupon printed in Z direction has some printing defects and was found to be of poor quality. These defects are caused due to machine vibrations or print roller causing the undesired motion in the ZX parts during printing. Due to this undesired motion, the traditional 2D ZX parts wobbled during the build and displayed severe print defects in their upper regions. Moreover, the traditional 2D coupons are thinner which results in the print defects due to the undesired motion, which is not seen in 3D test coupons, as they were much thicker than 2D test coupon and capable to bear the undesirable motion of the machine. Therefore, careful attention should thus be given to manufacturing parts built along in the Z direction.

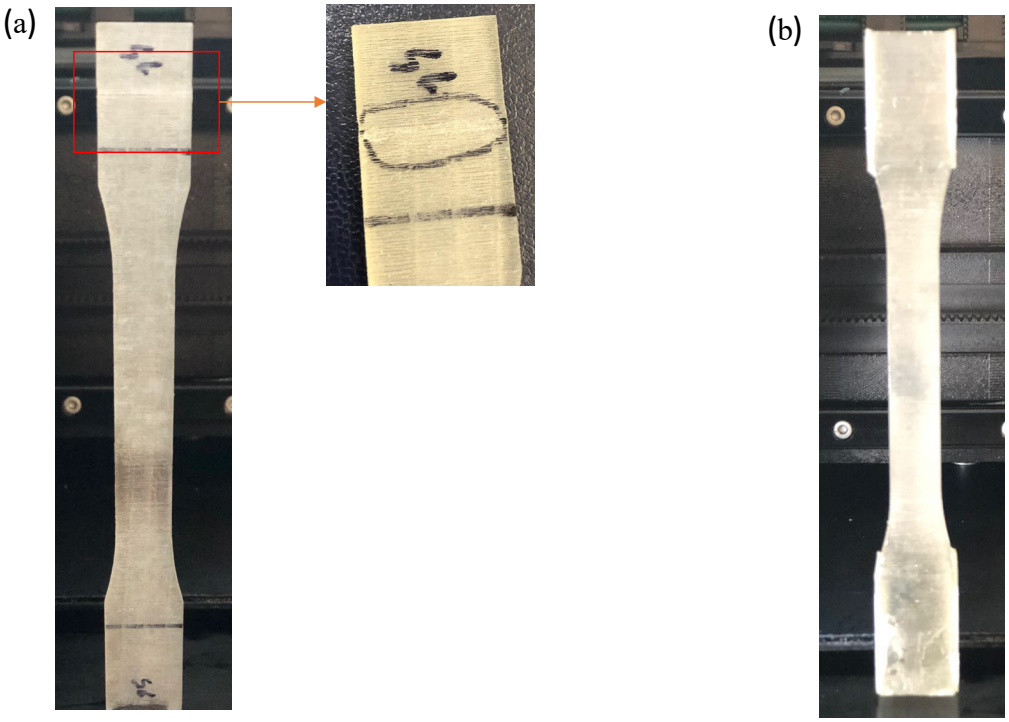


Figure 2.7 ZX parts (a) Defect in top region in traditional 2D test coupon (b) homogenized 3D test coupon

3. RESULTS

3.1 Tension Characterization

To investigate process induced variation and limitation of 2D test coupon discussed earlier, on mechanical properties, ASTM D638 type 1 and homogenized 3-dimensional tension test coupons were printed using three different directions. The tensile deformational behavior of AM printed material test coupons for both cases consisting of traditional 2D and homogenized 3D was performed using an Instron 3384 system following ASTM test Standard [8]. The pull rate was 5 mm/min. The extension was measured using an extensometer. The specimens were tested in batches of three for each build orientation and for both configurations. Test results from tensile characterization are presented in table 1 and table 2.

Table1 Tensile properties of a traditional 2D test coupon for each orientation.

Build Orientation	Tensile Strength (MPa)		Strain at Failure (%)
	Yield point (σ_y)	Breaking Stress (σ_b)	
XY Parts_2D	52.15 ± 0.7	-	9.57 ± 0.69
YX Parts_2D	49.07 ± 0.55	-	11.19 ± 0.64
ZX Parts_2D	-	16.82 ± 2.17	0.68 ± 0.10

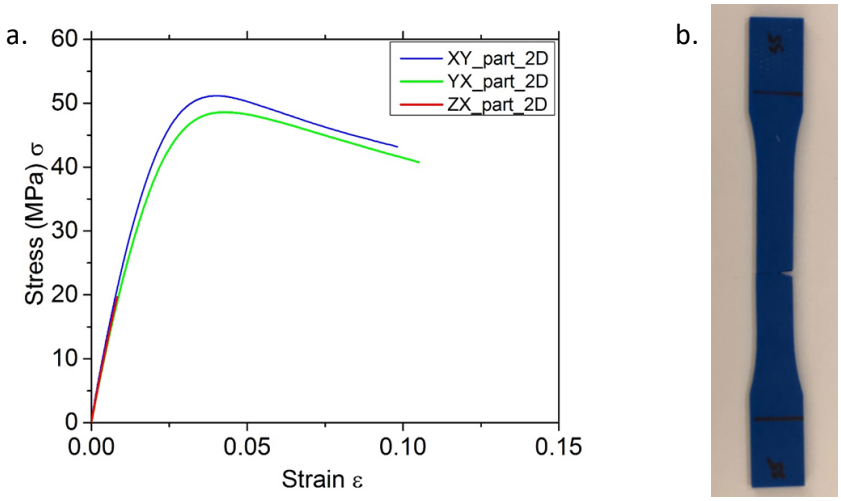


Figure 3.1 Traditional 2D test coupon (a) Stress-Strain curve (b) failed coupon

The stress-strain curves of traditional 2D test coupons printed in three orientation as shown in fig 3.1, concur with previous studies [9][10][3]. Our studies and analysis concur with current literature, where (XY) parts build orientation tend to be strongest, as they are jetted along the direction of the tensile strain (parallel to the loading direction), (ZX) parts build orientation tend to be weakest, as each deposited layer has small cross-sectional areas (perpendicular to the

loading direction), creating the potential for delamination. Thus, it can be assumed that the tensile strength for the XY and YX orientations is defined by the yield point σ_y and for the ZX orientation by the breaking stress σ_B. This shows that process induced variation exit in PolyJet process.

Prior results were based on the traditional 2D specimens, which doesn't have uniform cross-section. Hence, as discussed earlier homogenized 3D test coupon with uniform cross-section was investigated to provide the understanding of process-induced variations that plays role in properties variations in term of manufacturing, without the artifact of geometrical effects seen in 2D coupons. The objective of the 3D test coupon was to capture the processing effect without any manufacturing induced artifacts by AM such as geometrical cross-section variations, different aspect ratio of cross-sectional dimensions. Literature has not considered the 3D configuration specimen configurations that eliminates the geometry effects during build process. Homogenized 3D test coupons built from single material are used to study the effect of process variation in PolyJet process. Prime focus of this work is to evaluate and present data from our 3D tensile test observation as shown in table 2.

Table 2 Tensile properties of a homogenized 3D test coupon for each orientation.

Build Orientation	Tensile Strength (MPa)		Strain at Failure (%)
	Yield point (σ_y)	Breaking Stress (σ_b)	
XY Parts_3D	52.09 ± 4.98	-	2.63 ± 0.35
YX Parts_3D	49.01 ± 1.77	-	2.23 ± 0.08
ZX Parts_3D	-	30.28 ± 1.56	1.31 ± 0.08

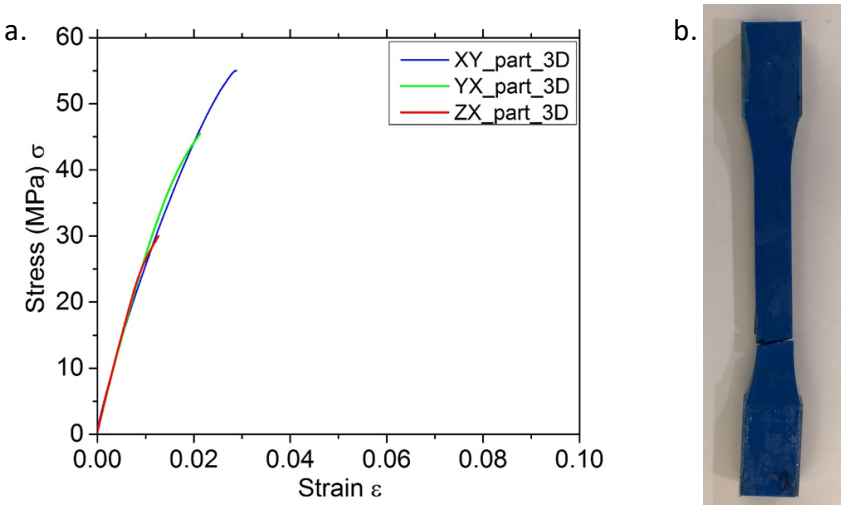


Figure 3.2 Homogenized 3D test coupon (a) stress-strain curve (b) failed coupon

From table 2, in case of 3D test coupons the strain at failure for XY and YX orientation are nearly similar due to same cross section's aspect ratio. This also accounts for uniform material deposition in x and y-direction. In comparison, from table 1, in case of traditional 2D test coupons the strain at failure for XY and YX orientation vary due to its limitation, which is one direction is thinner and does not account for uniform material deposition. Process induced variation are causing the significant difference in XY and YX orientation in traditional 2D test coupon which is not seen significantly in homogenized 3D test coupon. From a manufacturing perspective, it is important to address this processing effect, and capture well its influence on the mechanical performance of part printed in Polyjet process. Reducing the eliminating the geometry cross-sectional effects, it can be inferred that our proposed homogenized 3D test coupons provide an effective method to evaluate AM without geometrical difference artifacts in the build process.

Table 3. Tensile properties comparison for traditional 2D and homogenized 3D configuration

Build Orientation	Strain at Failure (%)	
	Traditional 2D test coupon	Homogenized 3D test coupon
XY Parts	9.57 ± 0.69	2.63 ± 0.35
YX Parts	11.19 ± 0.64	2.23 ± 0.08
ZX Parts	0.68 ± 0.10	1.31 ± 0.08

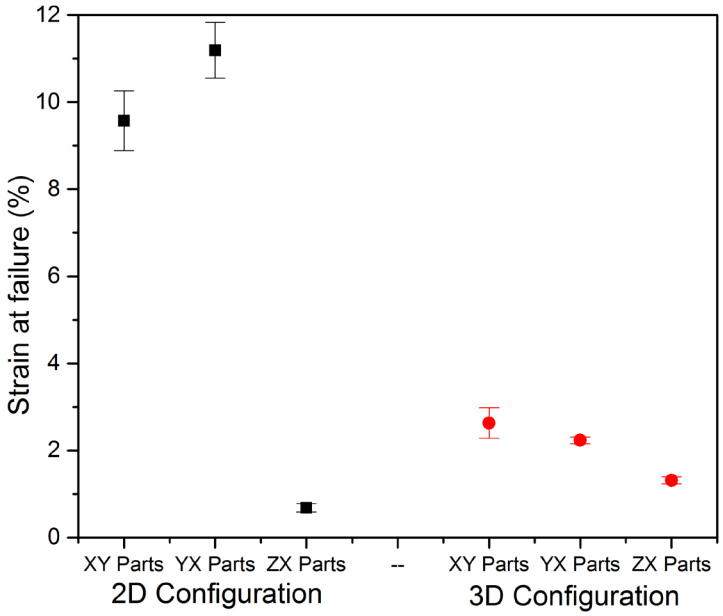


Figure 3.3 Strain at failure for each orientation for 2D and 3D configuration.

In addition to that, in case of homogenized 3D test coupons, the ZX orientation result shows stronger mechanical characteristic and higher failure strain compared to ZX orientation of traditional 2D test coupons. Traditional 2D test coupon was thinner and the machine ‘s vibration or the print roller caused undesired motion in ZX part during printing and caused ZX part to wobble during printing and displayed a severe print defect in their upper regions, which was not seen in homogenized 3D test coupon as these coupons were thicker. In addition, the strain at failure in case of homogenized 3D configuration seems to be more consistent (the strain at failure ranges from 1.31% to 2.63%) in all three orientation, which was not seen in case of traditional 2D test coupon (the strain at failure ranges from 0.68% to 11.19%). These results show that homogenized design of 3D test coupons eliminate the possible processing induced effect in AM.

From the graph, as shown in fig 3.3, it was noticed that the failure strain value range has a wider distribution in case of traditional 2D test coupon than in case of homogenized 3D test coupon. In traditional 2D test coupon configuration, one direction is thinner than other two, directions, which can be considered as a thin plate with stresses acting along its plane, and there is no stress acting perpendicular to the plane. Due to a negligible thickness in one direction, the strain component is also negligible in that direction, which results in all the stress components (normal and shear stress) to be nearly zero in that direction. So, the effect of normal strain from other direction was ignored in traditional 2D test coupons due to its negligible thickness, while the homogenized 3D configuration eliminates such errors that could result in process-induced error from AM. Homogenized 3D configuration eliminates some of the artifacts that could be present in traditional 2D configuration while testing AM parts. Therefore, the homogenized 3D configuration captures the effect of normal strain from another side due to same cross section’s aspect ratio, which was ignored in traditional 2D test coupon. From fig 3.3, results show that for 3D configuration mechanical properties in three orientation do not have a significant variation as in case of traditional 2D configuration. In summary, our proposed 3D test specimen configuration provides the effective method without worrying the build orientation or process-induced variation influencing the results.

4. CONCLUSIONS

Processing-induced variation affects the performance of parts in AM, as the way AM forms part are formed is different from the traditional manufacturing that leads to many artifacts. Present work shows that traditional 2D test coupon has significant process induced variations such as ignoring normal strain effect from another side. To understand the process induced variation and to capture the normal strain effect, this work proposed and evaluated a homogenized 3D configuration test coupon, which reduces the process, induced artifacts. These artifacts affect the mechanical properties of final parts formed in AM. Results from tensile characterization using traditional ASTM tensile test coupon and homogenized 3D tensile test coupon were presented. Mechanical characterization data from printed traditional 2D test coupon showed significant variations in properties in three different orientation, whereas homogenized 3D configuration showed better agreement in properties in three different build orientation. 3D test specimen configuration as proposed in this work is an effective test and evaluation method for AM, while removing process induced variations due to geometrical effects during building. Further tests and evaluations are needed to fine-tune this proposed 3D test coupon methodology.

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