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# Scale effect on the mechanical behavior of PLA specimens fabricated via Fused Deposition Modeling

Zhuo Xu[a], Rakel Fostervold[a], Seyed Mohammad Javad Razavi[a*]

[a]*Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Richard Birkeland vei 2B, 7491, Trondheim, Norway*

**Abstract**

Fused Deposition Modeling (FDM) is one of the most widely used additive manufacturing processes in the world. It is also a rapid prototyping process that can fabricate the physical model generated from the CAD model automatically without the usage of any tooling or fixture. In general, the mechanical properties of components produced with additive manufacturing are dependent on the geometry and the scale of the fabricated part. Any change in the geometry of the parts will influence the underlying fabrication process and inherent characteristics of the parts such as internal porosity, residual stress, etc. Therefore, it is important to understand the connection between the mechanical properties of these components and their geometry and scale of the produced parts in order to improve the design technique and applicability of the manufacturing technique. In this study, the scale effect on the mechanical performance of PLA (Polylactic Acid) specimens fabricated via FDM technology has been investigated. A total number of 15 test specimens were fabricated with three different scales, including 30%, 50%, and 100% of the size suggested in ASTM standard for tensile testing of polymers. The mechanical properties, including yield stress, ultimate tensile strength, Young's modulus, Poisson's ratio and elongation at failure were determined, compared, and analyzed from uniaxial tensile tests. In addition, 2D digital image correlation (DIC) method was also used to track the full-field displacement and strains on the surface of specimens. Moreover, the fracture surfaces were analyzed with the use of an optical microscope to evaluate the failure mechanisms of the tested specimens. The experimental results revealed that specimens with downscaling experience both lower ultimate tensile strength and elongation at failure. Furthermore, the standard deviation of elongation at failure increases when downscaling. This is due to the fact that first layer quality and residual stress will have more influence on the data uncertainty when the scale is lower.

* Corresponding author.
*E-mail address:* javad.razavi@ntnu.no

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## 1. Introduction

Additive Manufacturing (AM) allows the creation of complex geometries that are not possibly fabricated with conventional manufacturing methods. This technique enables the fabrication of components with fully customizable geometries as well as mechanical properties. The usage of AM technology for the fabrication of personal and industrial products has grown dramatically during the past decade. When compared to the conventional fabrication techniques such as CNC or milling, AM technologies provide considerable benefits, including a high degree of freedom, quick production periods, flexibility to produce customized components, and the ability to manufacture small batches at a lower cost (Sardinha et al. 2021),(Seibert et al. 2020). Therefore, due to the inherent technological advantages and disruptive nature of AM technologies, it is reasonable to anticipate that the application will continue to grow in the future.

Fused deposition modeling (FDM) or fused filament fabrication (FFF) is one of the most frequently utilized manufacturing methods for fast prototyping because of its simplicity in operation, low cost, and high speed. It is an AM technique based on material extrusion that was developed in the 1980s, which the method utilizes heated feedstock thermoplastic filaments extruded via a nozzle tip to deposit layers onto a platform, allowing for the layer-by-layer construction of components directly from a digital CAD model (Ayatollahi et al. 2020).

Numerous literature studies have already been reported on the scale effect of several conventionally manufactured materials such as concrete (Van Mier and Van Vliet 2003), fiber-reinforced-plastic (FRP) composite materials and structures (Sutherland, Shenoi, and Lewis 1999), continuous fiber-reinforced composites (Wisnom 1999), and carbon fibers (Tagawa and Miyata 1997). For instance, (Van Mier and Van Vliet 2003) has investigated the influence of the microstructure of concrete on the scale effect of tensile fracture. The experimental studies on the dog-bone-shaped concrete specimens demonstrated a reduction in nominal strength as specimen size increased. A similar trend was also observed for the fiber-composite materials as well (Wisnom 1999). The results indicated that the ultimate tensile strength decreases as the specimen volume increases. In addition, although some researchers have attempted to investigate the scale effect of the specimens on fracture behavior (Chen et al. 2020),(Nurizada and Kirane 2020),(Razavi, Van Hooreweder, and Berto 2020), however, there is a lack of research on the scale influence on mechanical properties of PLA parts fabricated via FDM.

**Nomenclature**

| | |
|---|---|
| AM | additive manufacturing |
| CAD | computer-aided design |
| CNC | computer numerical control |
| DIC | digital image correlation |
| FDM | fused deposition modeling |
| FFF | fused filament fabrication |
| FRP | fiber-reinforced-plastic |
| PLA | polylactic acid |
| UTS | ultimate tensile strength |

### *1.1. Materials and fabrication process*

Transparent PLA filament manufactured by a company called 3DNet was selected as a feedstock for fabricating the test specimens. All the specimens were fabricated via FDM process by using an Original Prusa i3 MK3. A slicing software Ultimaker Cura 4.8.0 was used to slice the model and generate G-codes. All the specimens were attempted to be fabricated with 100% infill density in order to approach the optimal mechanical properties of fully dense material as close as possible (Torres et al. 2016). Moreover, 0.4 mm nozzle diameter was selected for this research, and all other detailed important parameters were demonstrated in Table 1. These printing process parameters were determined based on the experimental results, with the objective of fabricating satisfactory specimens with the fewest feasible voids while retaining precise measurements and smooth layers. Initial gauge length and cross-sectional area for each scale are presented in Table 2.

Table 1: Printing process parameters for all the specimens.

| Building parameters | Parameter value | Building parameters | Parameter value |
|---|---|---|---|
| Layer height | 0.1mm | Build plate temperature | 75 °C |
| Infill line distance | 0.4mm | Printing speed | 45mm/s |
| Wall thickness | 0.8mm | Initial layer printing speed | 30mm/s |
| Wall line count | 2 | Raster angles | ± 45 degrees |
| Infill density | 100% | Nozzle temperature | 215 °C |

Table 2: Cross-section and initial gauge length for each type.

| Property: thickness | II-0.3 | II-0.5 | II-1 |
|---|---|---|---|
| $A_0$ [$mm^2$] | 3.51 | 9.75 | 39 |
| $L_0$ [mm] | 17.1 | 28.5 | 57 |

### *1.2. Tensile tests*

Three different geometries of testing specimens with a scale of 100%, 50%, and 30% were fabricated where the scale of 100% with the thickness of 3mm is the value recommended in ASTM standard for tensile testing as polymers as illustrated in Fig. 1. Five specimens were fabricated all at once with a parallel printing sequence for each case as illustrated in Fig. 2. All the tensile tests were performed in a universal tensile testing machine called MTS Criterion Model 42 with a maximum cell load capacity of 5kN. Besides, it is also worth mentioning that additional specimens were also printed and examined in cases where the data for a particular configuration was ambiguous, as indicated by a significant data discrepancy. The tensile displacement was set to be 2mm/s until failure and the actual thickness of each specimen was measured using a caliper in order to get more accurate results of stress prior to testing.

DIC was utilized in the tensile tests, which is an optical measuring method that enables comprehensive field study of a materials or structure's deformation, displacement, and strain. This method is gaining popularity, especially in the aerospace and automotive sectors, where it is used to determine the strength and load response of various components and materials (Motamedi 2019). A high-speed fixed camera system was also utilized to record frames with a specified sampling frequency. Additionally, a specialized software package named Vic 2D was used to evaluate and monitor subsequent changes in images by using cross-correlation algorithms (Caporossi, Mazzanti, and Bozzano 2018). Test specimens from each scale were painted with a white background and speckled with black dots to make a distinct contrast. Vic 2D monitored the speckle's movement in the X and Y directions and computed the corresponding strains. Moreover, the sampling frequency of the camera was set at 200ms, which is capturing 5 images per second.

Furthermore, Hirox RH-2000 digital microscope was utilized to analyze the fracture surfaces of the specimens. The specimens were photographed from the fracture surfaces as well as the sides.

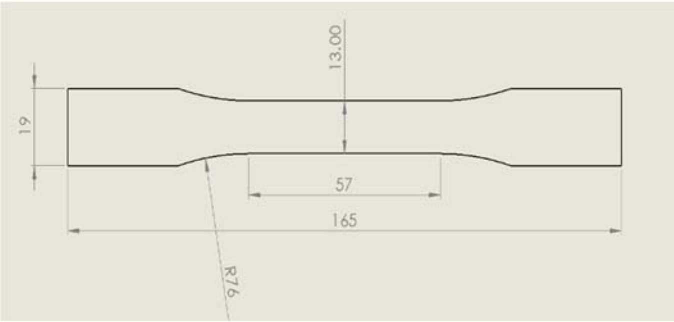



Fig. 1. Standard dimensions of test specimen ASTM D638 type

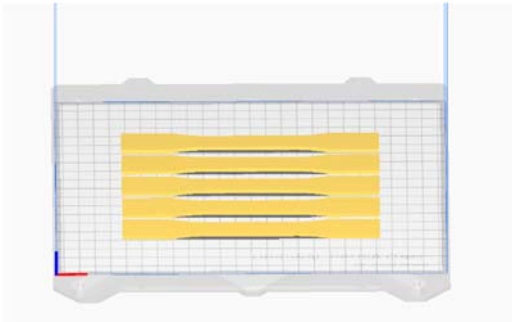
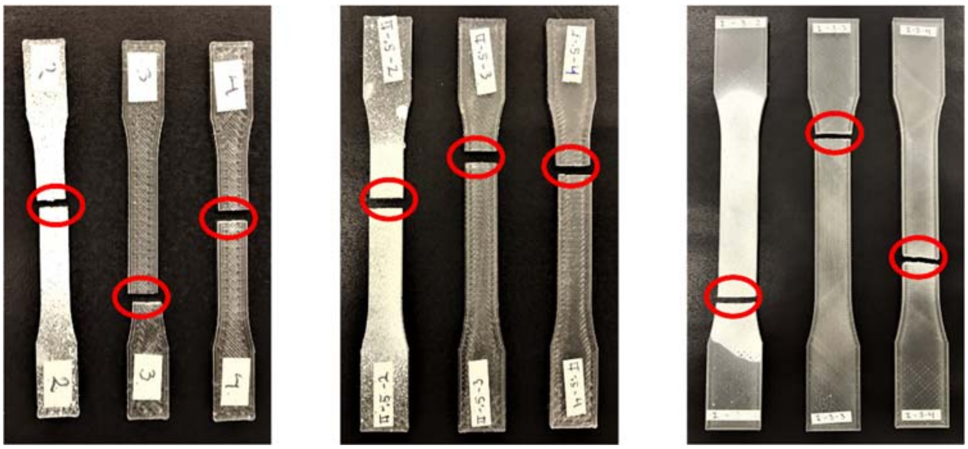


Fig. 2. Specimens printing orientations on a building platform

## 2. Results and Discussions

As stated earlier, the main purpose of these tensile tests is to investigate the scale effect of the mechanical properties. Three out of five specimens were selected as representatives to examine the failure pattern as demonstrated in Fig. 3. It is worth mentioning the major fracture location occurred within the edge of the gauge section of the specimens. One of the possible reasons could attribute to the printer settings. It can be observed that each new layer was initiated at the junction of the gripping region and the gauge part as illustrated in Fig. 4 (a). The printing proceeds in the direction indicated by the red arrow. Finally, the gripping region on the other side as well as the gauge part in the center begin to print. As a result, this printing sequence could lead to a potential weak spot in the specimens.



(a) (b) (c)

Fig. 3. Specimens after fracture with different scale: (a) 30%, (b) 50%, (c) 100%

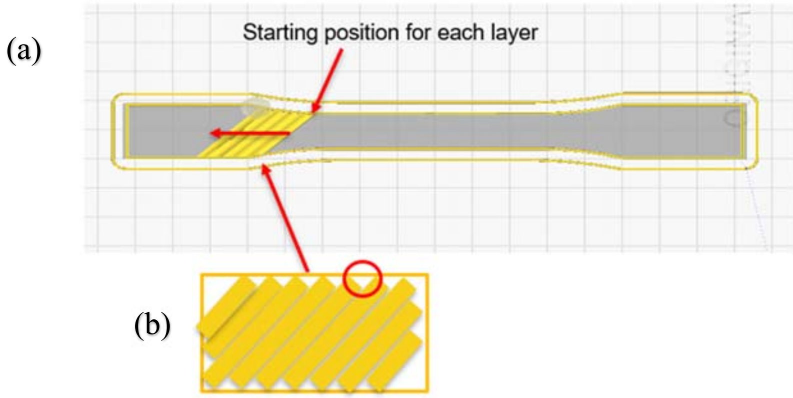



Fig. 4. (a) Printing procedure for each layer during 3D printing, (b) Detailed schematic illustration of printing defects

DIC was used to determine the full-field strain distributions of the specimens as illustrated in Fig. 5 with 30% and 50% of the scale displayed. Stress-strain curves for different scales were obtained as well as illustrated in Fig. 6. Additionally, the ultimate tensile strength, yield stress, elongation at failure, Poisson's ratio, and Young's modulus were computed and reported in Table 3, accompanied by the standard deviation for relevant values.

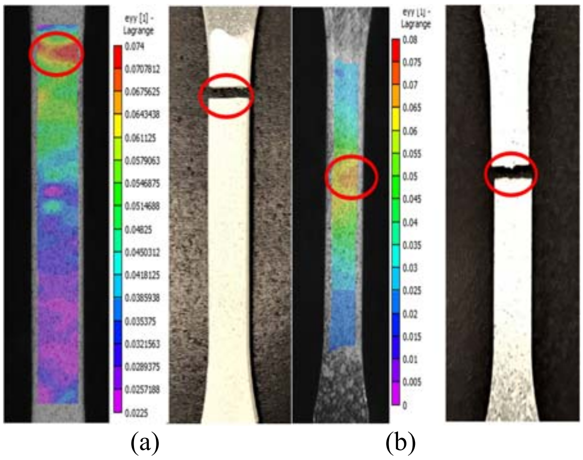



Fig. 5. Strain in Y-direction of DIC compared with tensile tests of scale: (a) 30%, (b) 50%

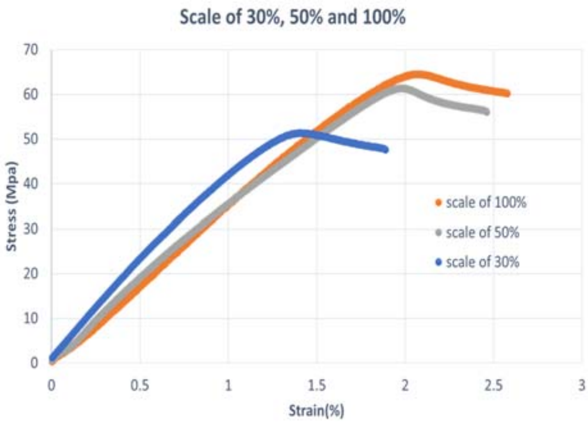



Fig. 6. Representative stress-strain curves for each scale

It can be discovered that specimens with downscaling experience both smaller ultimate tensile strength (UTS) and lower elongation at failure, as well as the yield stress. One of the reasons can be attributed to the first layer quality influence. In this project, as displayed in the table of printing process parameters, the initial layer was printed at a speed of 30mm/s in order to achieve a better bonding adhesion between the layer and the building platform, which was relatively smaller than the rest of the layers (45mm/s). Consequently, the actual thickness of the first layer is slightly higher than the rest layers (0.1mm). A literature study has reported that the ultimate tensile strength decreases monotonously when the thickness increases from 0.1mm to 0.3mm with +/- degrees raster angles (Yao et al. 2019).

Therefore, it can be concluded that the ultimate tensile strength for thickness of 0.15mm is slightly lower than that of 0.1mm. Consequently, the first layer quality will have a more dominant effect because of the larger percentage of the volume fraction when downscaling, which results in lower ultimate tensile strength. The other reason is due to the fact that defects such as voids on the edge of the specimens occurred during the fabrication process as illustrated in Fig. 4 (b). Voids dimensions are assumed to be the same because the identical printing process parameters were used when fabrication. Therefore, the proportion of the voids with respect to the entire volume increases when downscaling, which results in lower ultimate tensile strength. Another conclusion discovered from a literature study matches with the experimental results as well. it was also reported that a higher number of layers can result in a greater temperature gradient between the layers, which accelerates the diffusion process between adjacent rasters, thus lowers the void ratio and increase the bond's strength (Garzon-Hernandez et al. 2020).

Table 3. The calculated value of ultimate tensile strength (UTS), yield stress, elongation at failure, Poisson's ratio, and Young's modulus for various scales

| Property | 30% scale | 50% scale | 100% scale |
|---|---|---|---|
| UTS (Mpa) | 52.03±5.64 | 61.45±2.47 | 64.50±0.62 |
| Yield stress (Mpa) | 48±5.28 | 61±4.39 | 63±0.58 |
| %EL | 1.89±1.04 | 2.37±0.42 | 2.58±0.31 |
| Poisson's ratio | 0.273 | 0.233 | 0.316 |
| E (Gpa) | 3.1 | 3.3 | 3.1 |

## 3. Conclusions

Overall, the scale effect of PLA specimens fabricated via FDM technology on their mechanical properties has been investigated in this research. Tensile tests were performed under uniaxial static loading at a constant rate of 2mm/min, and DIC was used to calculate the strain distributions of the specimens. Then the specimens were examined under a digital microscope and discovered to have high density with few voids.

The experimental results revealed a high degree of association between tensile properties and the scale of the specimens. Specimens with downscaling experience both smaller ultimate tensile strength and lower elongation at failure, as well as the yield stress. One of the reasons is the influence of first layer quality. Another reason is due to the fact that defects such as voids on the edge of the specimens that occurred during the fabrication process were dimensionally fixed, which resulted in various proportions of voids volume. Moreover, it was discovered that a higher number of layers can cause a greater temperature gradient between the layers, which accelerates the diffusion process between the neighboring rasters, thus lowers the void ratio and increase the bond's strength. In addition, the standard deviation of mechanical properties (elongation at failure, yield stress, and ultimate tensile strength) has a tendency to increase when downscaling due to the mentioned reasons.

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