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The Effect of Geometry on Mechanical Properties of Biodegradable Polylactic-Acid Tensile-Test Specimens by Material Extrusion

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ABSTRACT

Additive manufactured biomedical devices have been widely used in the biomedical fields due to the development of biomaterials and manufacturing techniques. Biodegradable Polylactic Acid-based polymers are the most common material that can be manufactured using material extrusion, one of the most widely known additive manufacturing methods. However, medical grade polymers are too expensive for degradation studies with common tensile specimens. Therefore, this paper aims to reduce the volume of the material used for manufacturing tensile specimen by introducing a new tensile specimen, micro-X tensile specimen, developed for steel. Young's Modulus and Ultimate Tensile Strength of micro-X tensile specimens were compared with the ASTM D1708 standard specimens. The experimental results showed that there is no significant difference in terms of mechanical properties. Furthermore, the micro-X tensile specimen was reduced the volume and as well as the cost by approximately 91% in comparison to ASTM D1708 standard tensile specimen.

KEYWORDS: Additive Manufacturing; Material Extrusion; Mechanical Properties; Biodegradable PLA; Micro Tensile Test

1. INTRODUCTION

Additive Manufacturing (AM) is a manufacturing process that joins material layer by layer to make objects from the 3-dimensional digital data [1]. Developments in AM process technology has led to improved quality and production speeds whilst typically reducing costs, coupled with and increased range of polymer, metal, and ceramic materials [2].

Biodegradable polymers produced via AM and conventional manufacturing methods are extensively applied in the field of orthopaedics, drug carriers, facial fracture repair, tissue engineering, and ureteral stents [3]. Of all the biodegradable polymers, Polylactic Acid (PLA) is one of the most commonly used polymer due to their biocompatible, biodegradable and non-toxic properties. PLA is also the most extensive materials to be manufactured by Material Extrusion (ME) [4] . ME is a cost effective, fast and customised AM technology [5]. However, the use of medical grade PLA-based polymers can typically range between \$3000 to \$5000 per kg - too expensive to implement for degradation studies [6]. Degradation studies require a large number of test specimens, therefore reducing the material cost can be achieved by decreasing the volume of the material for AM.

In addition to the utilisation of PLA-based polymers as an alternative to medical grade polymers, studies have been undertaken to optimise the volumetric size of test specimens, whilst maintaining experimental rigor. For example, a dog bone tensile specimen, named Interfacial Micro Tensile-Testing (IMTT), was developed and printed vertically to a horizontal bed in order to reduce the volume of the specimen [7]. Results from this study demonstrated that the volume of printed specimens reduced by approximately 25% in comparison to ASTM D1708 micro-tensile specimen with the same thickness. In a further study, a micro tensile specimen developed and tested in S235JR, S355JR and 1.4301 steel demonstrated tensile test results comparable to the commonly used standard tensile specimen [8]. Within the outline study, this newly developed and tested micro tensile specimen that was not used in any other studies using AM or conventional methods for polymers will be referred to as micro-X tensile test specimen. The dimension of micro-X tensile specimen is 0.5 mm thickness, 1.5 mm width and 2.6 mm gauge length.

With a view to further optimise resources in the development of tensile test specimens manufactured from typically expensive biodegradable polymers, this study compares the tensile performance and volume of ASTM D1708 micro-tensile and micro-X tensile specimens.

2. EXPERIMENTAL PROCEDURES

The design and dimension of the ASTM D1708 micro-tensile and the micro-X tensile specimen are shown in Figure 1A and 1B, respectively. They were manufactured using biodegradable PLA (3D Printlife Pure PLA) using an Ultimaker 2 Material Extrusion system.

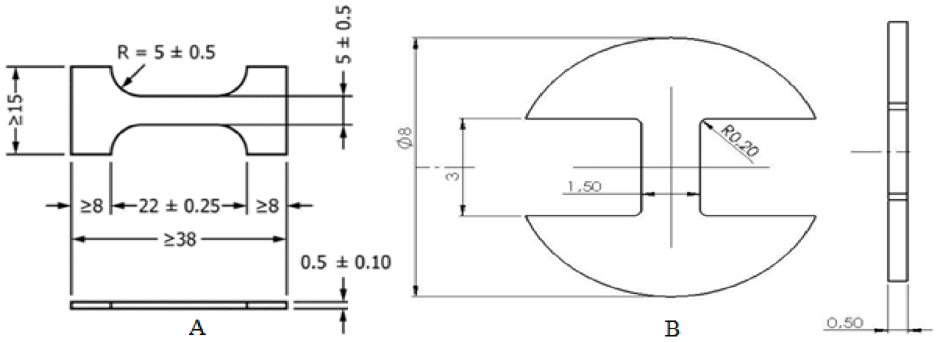

Figure 1: (A) Dimension of ASTM D1708 micro-tensile specimen [9]; (B) Dimension of micro-X tensile specimens [8] (all dimensions are in mm)

Specimens were printed with a 0.1 mm line width, 0.1 mm layer height, and were extruded in a longitudinal direction and zigzag pattern. In total 40 tensile specimens, 20 ASTM D1708 micro-tensile and 20 micro-X tensile specimens were manufactured in the centre of the build plate. The extrusion and bed temperatures were maintained at 210°C and 60°C respectively, and, the extrusion speed was set at 15 mm/sec.

For experimental testing, mechanical properties of the tensile test specimens were identified using an Instron 3343 machine equipped with 1 kN load cell for the ASTM D1708 micro-tensile specimens and a side action screw pin joint grip for micro-X tensile specimens respectively. Strain rate was maintained at 1 mm/min for both micro and micro-x tensile specimens.

3. RESULTS and DISCUSSION

Results from experimental testing are presented in two stages: mechanical properties of the AM tensile test specimens in the first stage while the second stage presents a comparison between the volumetric results from the two tensile test specimens used within this study as well as a number of common alternatives.

3.1 Mechanical properties

The mechanical properties, including the Young's Modulus (E) and the Ultimate Tensile Strength (UTS) of 20 ASTM D1708 micro-tensile and micro-X tensile specimens, were calculated from the load-extension curves.

A selection of tensile specimens as demonstrated in Figure 2A and 2B did not fail between the gauge length; however, their UTS values were still comparable.

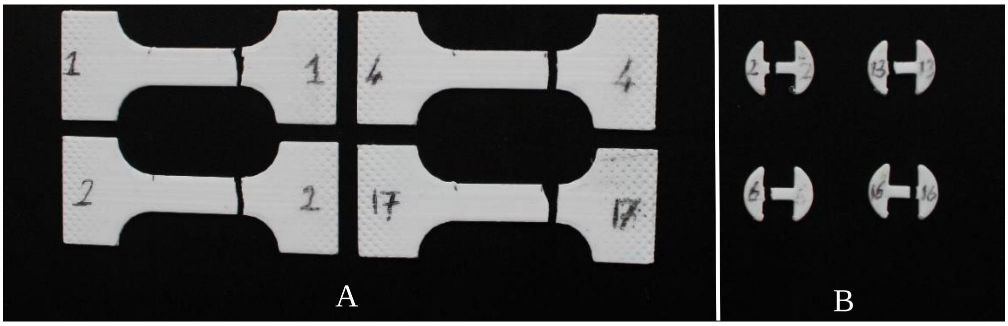

Figure 2: (A) Broken ASTM D1708 micro tensile specimens, (B) Broken micro-X tensile specimens

In this study, the UTS shown in Figure 3 was 46.17±4.3 MPa for ASTM D1708 micro-tensile (ranged from 39 to 54 MPa) and 48.31±4.5 MPa for micro-X (ranged from 39 to 57 MPa) tensile specimens. The difference between the UTS values for both tensile specimens did not exceed 5%. Young's Modulus demonstrated in Figure 4 was calculated at 1.44 GPa and 1.43 GPa for ASTM D1708 micro-tensile and micro-X tensile specimens respectively. As such, there was almost no significant difference between ASTM D1708 micro-tensile and micro-X tensile specimens in terms of their mechanical properties. The average UTS of ME printed PLA found in the literature was 49.29 MPa with almost the same process parameters used in this study [10].

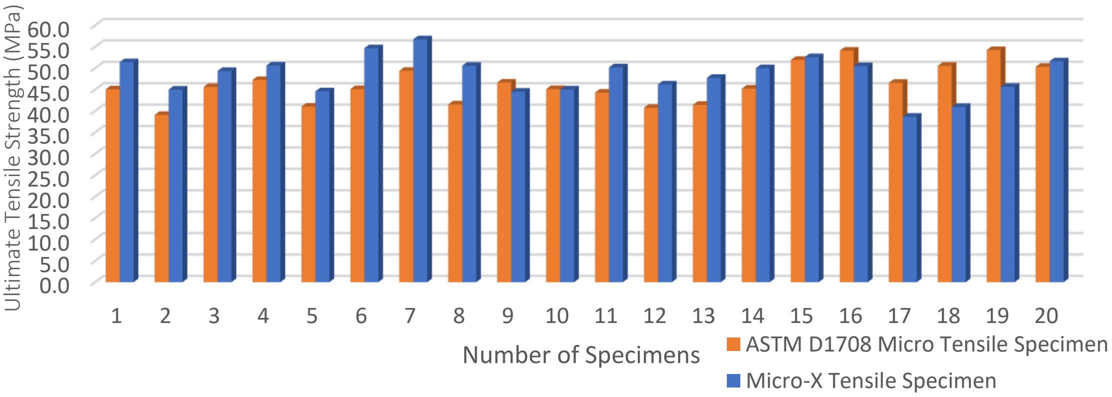

Figure 3: UTS of ASTM D1708 micro-tensile and micro-X tensile specimens

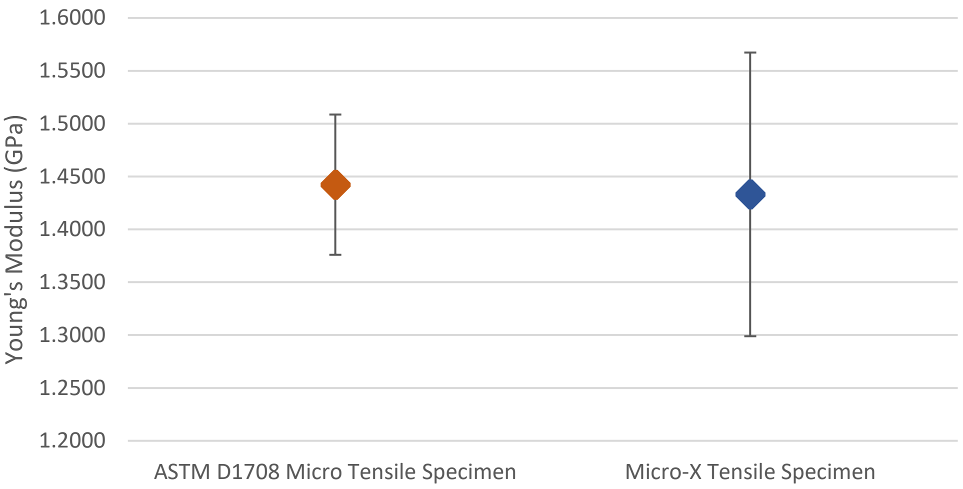

Figure 4: Young's modulus of ASTM D1708 micro-tensile and micro-X tensile specimens

One reason failure close to the neck occurred may be due to the printing and travelling path for the ASTM D1708 micro-tensile and identified pores for micro-X tensile specimens as shown within the Figure 5 and Figure 6 respectively. The travelling path of micro-tensile specimen shown in Figure 5 with blue line may have caused failure in the neck due to excess material stringing across the printed layers whilst travelling. In relation to the micro-tensile specimen, the selected process parameters were specified carefully to manufacture proper micro-X tensile specimens along with good mechanical properties due to small dimension. The infill line width was kept at 0.1 mm to reduce the number and dimension of pores occurred during printing and to get better surface quality even though it increased the number of joints which reduce the mechanical properties [11]. Following that, the layer thickness was also maintained at 0.1 mm due to the mechanical results of material extruded PLA with layer thickness of 0.1, 0.12, 0.15, 0.18 and 0.2 mm. The results from this study outlined that 0.1 mm layer thickness had the highest mechanical properties in terms of E and UTS [10]. In the same study, the effect of layer orientation was also studied, and longitudinal direction of layer orientation showed the highest mechanical properties in comparison to other raster angles [10]. Therefore, longitudinal direction was used to obtain the highest mechanical properties.

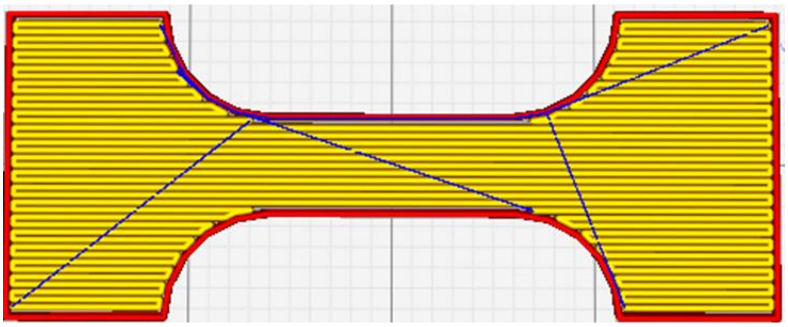

Figure 5: Printing and travelling path of ASTM D1708 micro-tensile specimen

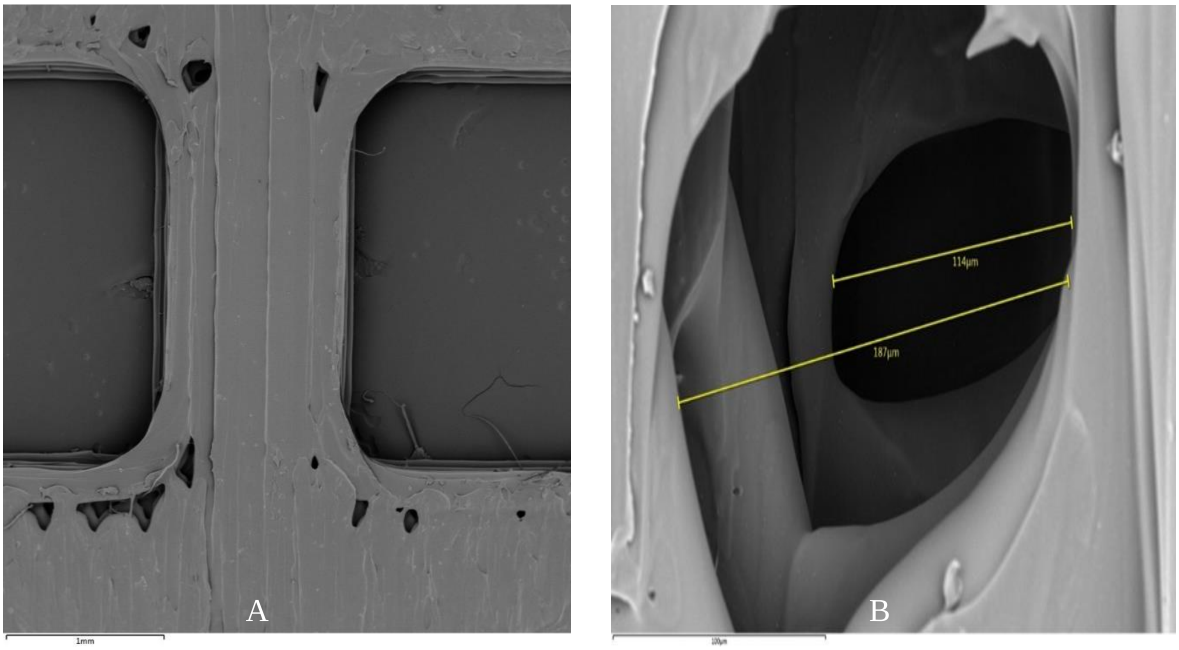

Figure 6: (A) SEM illustration of micro-X tensile specimen (B) Dimension of pores for micro-X tensile specimen

The occurrence of pores shown in Figure 6A and Figure 6B reduced by using selected process parameters and identified pores ranged between 100 -200 µm in the neck point as measured using Scanning Electron Microscope (SEM). The pores occurred during neck caused weakness in the neck; therefore, the samples were broken in the neck during tensile testing.

3.2 Volume reduction

Degradation studies need multiple samples and medical grade polymers that can typically be expensive. Therefore, reducing the volume of the specimens are likely to reduce the material cost. A comparison of two tensile specimens used within the studies coupled with other commonly used tensile specimens is presented in

.

The volume of ASTM D638 type V which has the smallest volume among other types is 1580 mm^3 [12]. Besides, the volume of IMTT is 446 mm^3. The volume of ASTM D1708 micro-tensile and micro-X tensile specimen printed with 0.5 mm thickness are 185.73 and 15.68 mm^3 respectively.

Table 1: The tensile specimens, their volumes and compared volume reductions

Tensile Specimens	Volume	Volume Reduction
Micro-X tensile specimen	15.68 mm^3	-
ASTM D1708 micro-tensile specimen	185.73 mm^3	91%
Interfacial Micro Tensile-Testing	446 mm^3	96%
ASTM D638 type V tensile specimen	1580 mm^3	99%

By comparing these specimens, micro-X tensile specimen’s volume is 91%, 96% and 99% smaller than ASTM D1708 micro, IMTT and ASTM D638 type V tensile specimens. This result demonstrates that the use of micro-X tensile specimen can reduce the material cost excessively.

4. CONCLUSIONS

The ASTM D1708 micro-tensile and the micro-X tensile specimens were printed using biodegradable PLA via ME technology with five layers of single filament with 0.1 mm layer height with the total thickness of 0.5 mm. During testing, the tensile specimens did not break between the gauge lengths potentially due to the occurrence of pores located close to the neck. Although the specimens did not break in the middle, the UTS data is comparable. The E and UTS of ASTM D1708 micro-tensile and micro-X tensile specimens are not significantly different, and they are also comparable with other studies. The average UTS is identified as 46.2 MPa and 48.3 MPa, with a Young’s Modulus of 1.44 GPa and 1.43 GPa for ASTM D1708 micro-tensile and micro-X tensile specimens, respectively.

Material used is reduced by approximately 99% compared to ASTM D638 type V by using micro-X tensile. Therefore, based on the results from the outlined mechanical testing coupled with significant potential savings in key resources future degradation studies along with finding thermal and molecular weight properties using medical grade polymers may benefit from the use of micro-X tensile test specimens.

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