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Experimental verification of the influence of thickness on 3D printed samples on fracture toughness parameters

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Abstract: Currently, additive manufacturing technologies are widely used in biomedicinal applications. 3D printing technology brings great benefits to this industry as it can produce complex and diverse shapes. The problem then arises with very thin samples, where this technology is still not perfect and shows relatively large uncertainty and manufacturing defects. The main aspect of this research is to test the fracture toughness of very thin polyamide specimens fabricated by 3D printing using SLS technology. The geometry, experimental procedure and evaluation of the results were designed according to EN ISO 12737. The experiment took into account the orthotropy of the print by using different printing directions. Then the resulting data from the experiments were compared with the data from the numerical analysis.

Keywords: fracture mechanics; 3D printing; polyamide PA12; digital image correlation; numerical analysis

1 Introduction

In today's era of rapidly advancing technology and innovation, 3D printing has an indispensable place in manufacturing and scientific research across engineering disciplines. Material engineering and biomedicinal application are one of the key areas where this technology is being used. Titanium alloy 3D printing technology enables to creation of any shape of future implant, the design of an optimized surface and the fast individual manufacture of a specific replacement for a specific patient.

For the purposes of implants and their surfaces, it is necessary to create very thin structures with thicknesses ranging from 150 to 600 μm. This pushes the limits of current 3D printing capabilities, and the resulting mechanical properties do not align with theoretical expectations [1]. Current research often focuses on conventional mechanical parameters, but for obtaining a broader range of characteristics, it is necessary to expand experimental efforts [2, 3, 4]. This expansion is motivated by the subsequent development of a material model that corresponds to the reality of 3D printing. In clinical practice, metallic materials are primarily used for implants but are expensive to produce, and as this research is a pilot study it will investigate polymer samples (PA12 material) produced by 3D printing SLS technology. One of the main motivation for this research is to test fracture toughness, which is a key parameter for assessing the material resistance to accidental loading and crack propagation. The research addresses not only the deep significance of fracture toughness methodologies, but also the design and optimization of methods and procedures for testing, evaluation and applying this knowledge to metallic specimens.

2 Fracture toughness results for PA12 material

Fracture mechanic is the study of engineering mechanical where the resistance of a material to crack propagation is measured and is called fracture toughness. Fracture toughness values can serve as one the main material properties and quality for typical engineering structure [5]. Fracturing of material is cased by the finite strength of atomic bonds. When a material begins to fail, cracks are responsible for amplifying local stress states that lead to fracture [6].

In fracture mechanics studies, two main parameters called fracture energy G and stress intensity factor K are often determined and presented [7]. The fracture energy is defined as the amount of energy needed to create one unit area of a continuous crack and is the fundamental quantity that governs crack propagation [8]. While stress intensity factor is based on three different modes (mode I, mode II, mode III) and can specify the mechanical behaviour of material with crack [9].

2.1 Geometry and pre-test

The geometry of the sample and the calculation of the fracture toughness values was designed according to EN ISO 12737 Metallic materials - Determination of plane-strain fracture toughness. The thickness condition according to the standard was not included in the geometry because investigation of fracture toughness of very thin specimens. The calculation of the fracture toughness value K_Q is given in the Equation 1.

$$K_Q = \frac{F_Q}{B\sqrt{W}} * f(a/W) \tag{1}$$

where F_Q is determined force from the load-distance diagram given in kilonewtons, B is specimen thickness and W is length of a ligament, both given in centimeters. Last parameter in calculation is geometry factor $f(a/W)$ (Eq. 2) which is dimensionless fuction of a/W.

$$f(a/W) = (2 + a/W) * \frac{0,886 + 4,64(a/W) - 13,32(a/W)^2 + 14,72(a/W)^3 - 5,6(a/W)^4}{(1 - a/W)^{\frac{2}{3}}} \tag{2}$$

The 3D models geometry was created in ARCHICAD 25 software using the Profile Manager and were utilized to create 4 different geometries (31.25x30; 37.5x36; 43.75x42; 50x48 mm) with 6 different thicknesses (0.50; 0.75; 1.00; 1.25; 1.50; 2.00 mm). These 3D models were saved as .stl files and exported to Synterit studio, which created S-code for SLS 3D printing. After printing, the specimens were cleaned and prepared for the pre-test experiment. For the pre-test experiment, 96 specimens were printed and a MARK 10 load press was used for testing. For consistency of results, the crack length a was determined as a constant at this stage of research as $a = 0.5 * W$. For the further experiment, 2 specimen geometry were selected which had the most linear increase in fracture toughness values with varying specimen thickness and were best to handle in experiment. Figure 2 shows a diagram of fracture toughness versus thickness of each specimen geometry on the left and the 2 selected specimens SAMPLE 2 and SAMPLE 3 for the following experiment are shown on the right. Figure 1 show the geometry of selected SAMPLE 2 and SAMPLE 3.

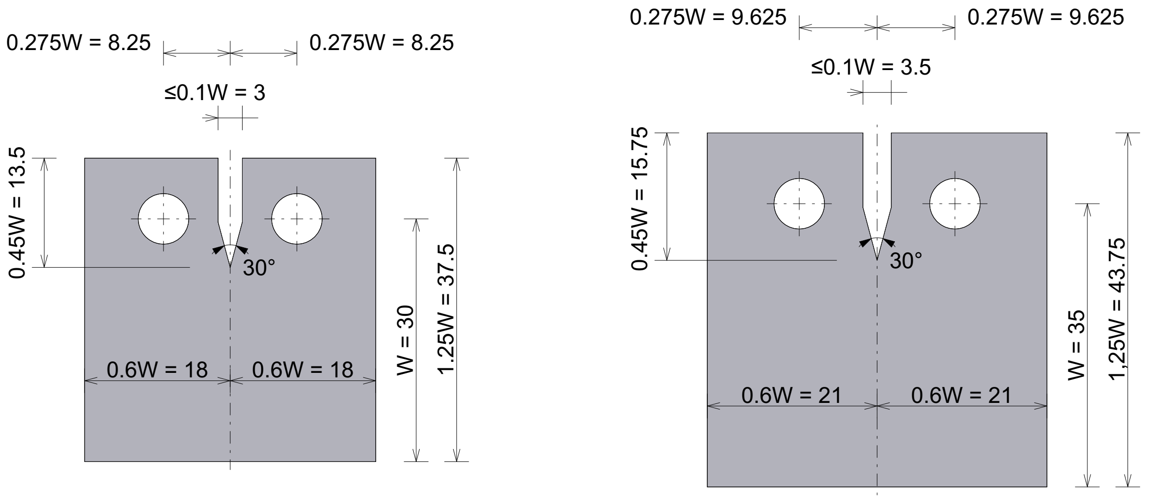

Fig. 1: Example of selected samples geometry according to EN ISO 12 373 designed in ARCHICAD 25 software, SAMPLE 2 on the right, SAMPLE 3 on the left [10].

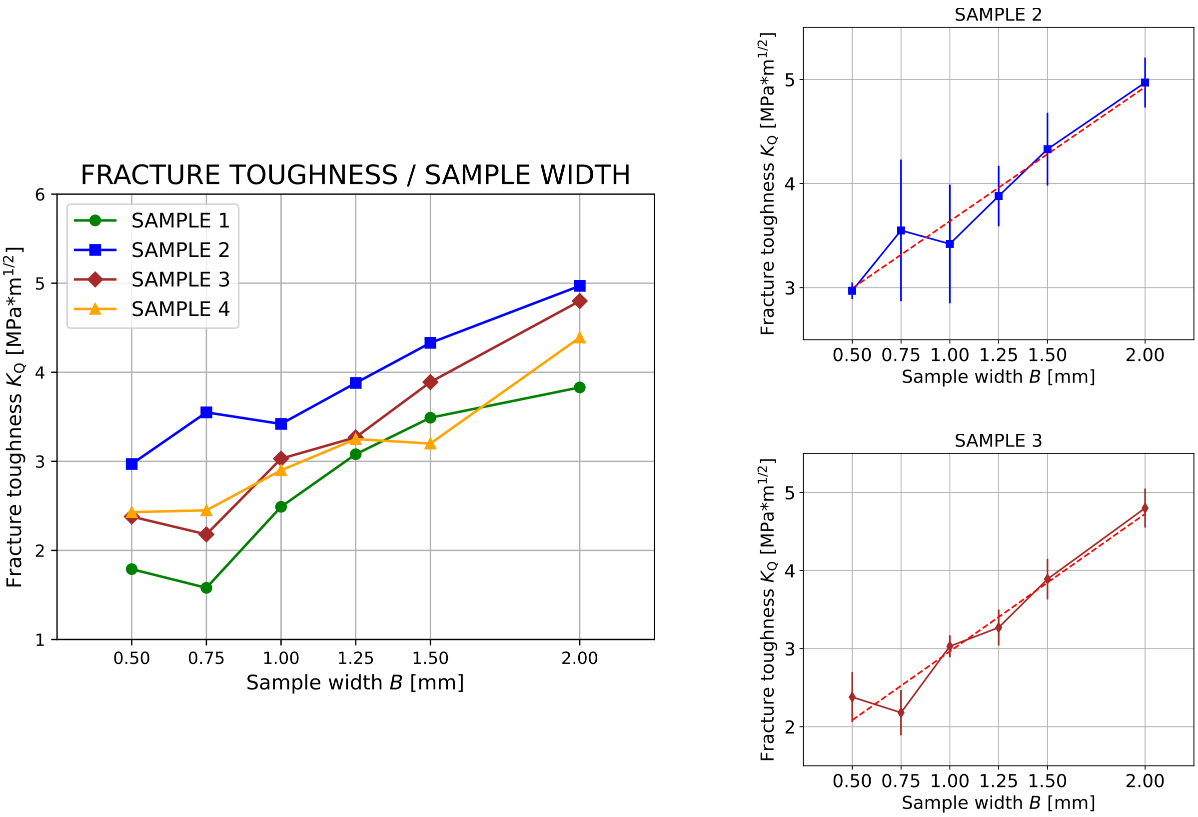

Fig. 2: Fracture toughness results from the pre-test experiment. Summary of fracture toughness values versus width of each specimen geometry (left) and values for selected geometry to the following experiment (right) [10].

2.2 Experimental analysis

In the next step of my research, I proposed to take into account the orientation of printing. The specimens were printed in horizontal (H) and vertical (V) direction which is shown on Figure 3. For both print orientation, 6 pieces were printed for each thickness (0.50 – 2.00 mm), giving a total of 140 printed specimens.

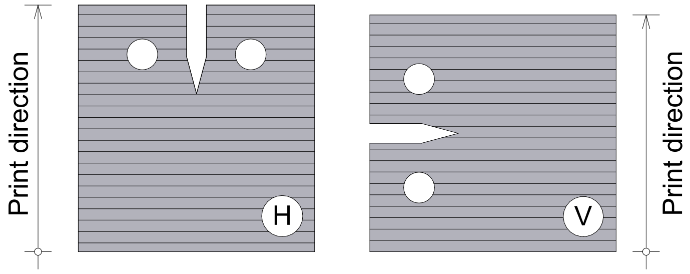

Fig. 3: Demonstration of the two types of different sample printing orientations [10].

This experiment involved a MARK 10 load press where the loading rate was set at 4 mm/s. The experiment was supplemented with 3D DIC, which led to provide the sample with a speckled pattern, where I used combination of white and black color. This pattern is used to mark points from which the displacement of the specimen can be monitored and subsequently the stress and strains values can be calculated [11]. In some cases, especially for thicker specimens, the crack has destroyed the specimen along its entire length. 3D DIC was used to determine the length of the crack a before the specimens were fully ruptured.

2.3 Numerical analysis

For the two specimen geometries (SAMPLE 2, SAMPLE 3), only numerical models for widths of 0.50, 1.25 and 2.00 mm were created. First, I determined the material model of PA12 material. Only the Young's modulus E and the Tension strength f_t are given in the technical datasheet. For the other material properties, I had to do a search of other experiments and determine the values from them, where mainly looked for the values of Poisson's ration μ, Compression strength f_c and Fracture energy G_f.

The numerical model was created in GiD 16.0.6. and the calculation was performed using ATENA studio. A mesh with and element size of 0.25x0.25 mm was used in the most important region below the tip. For all 6 models, the calculation was performed with a linear and quadratic element mesh. Model was loaded with displacement and the Newton-Raphson method was used in calculation.

3 Conclusion

This section summarizes the results form the experiment and numerical analysis. Table 1 shows the summary of fracture toughness values from the experiment calculated according to EN ISO 12 737. The results show a consistent increase for the horizontally printed samples from a certain width and very inconsistent result for thinner widths. The values for vertically printed samples are around 1.00 $\mathrm{MPa}\sqrt{\mathrm{m}}$ independent of the specimen width.

Tab. 1: Summary of experiment results of K_Q for PA12 material printed in horizontal and vertical directions with their deviation of results (H - horizontal print orientation, V - horizontal print orientation) [10].

Thickness [mm]	0.50	0.75	1.00	1.25	1.50	2.00
SAMPLE 2 - H	2.0 ± 0.6	2.64 ± 1.12	1.65 ± 0.23	1.87 ± 0.09	2.16 ± 0.45	2.37 ± 0.31
SAMPLE 2 - V	0.99 ± 0.37	0.91 ± 0.38	0.93 ± 0.11	1.35 ± 0.35	0.94 ± 0.07	1.09 ± 0.15
SAMPLE 3 - H	1.54 ± 0.22	1.33 ± 0.48	1.5 ± 0.15	1.73 ± 0.38	2.01 ± 0.33	2.2 ± 0.36
SAMPLE 3 - V	1.2 ± 0.41	0.72 ± 0.11	1.3 ± 0.42	1.03 ± 0.06	1.21 ± 0.15	1.09 ± 0.15

Figure 4 shows a comparison of experimental data and numerical analysis for SAMPLE 2 with widths of 0.50 and 2.00 mm. Agreement between experimental and numerical analysis was not expected. One of the main reasons for discrepancies in results is the imperfect numerical material and geometric model that fails to account for imperfections in 3D printing (such as porosity) and the orthotropic properties of oriented 3D printing. The problem of 3D printing is that the technology is not yet good enough for the individual powder beads on the surface of the sample to melt together sufficiently. These powder beads can then "fall off" when the sample is handled, which weakens the thickness of the sample. This aspect is then fatal for very thin samples.

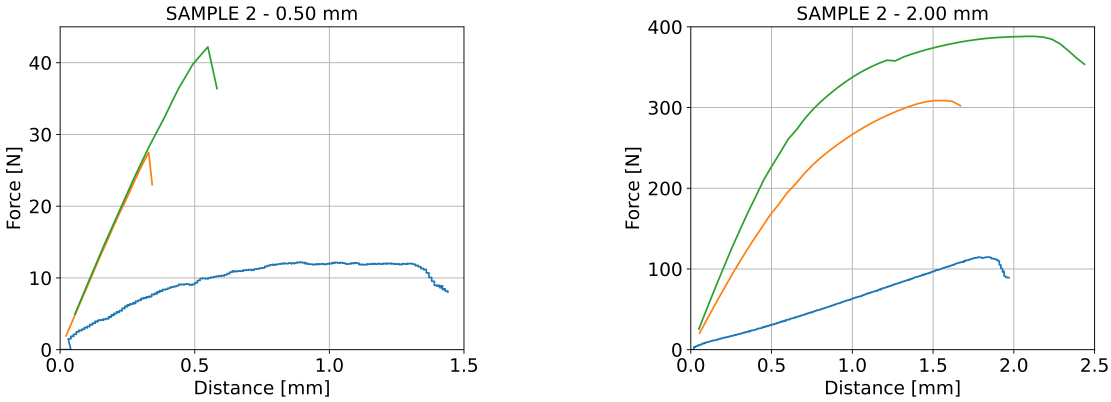

Fig. 4: Load-displacement graphs for one selected sample from the experiment and 2 types numerical models, where the orange line is the numerical model with linear elements, the green line is the numerical model with quadratic elements and the blue line is the experimental data [10].

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