SLS NYLON 12 CHARACTERIZATION THROUGH TENSILE TESTING AND DIGITAL IMAGE CORRELATION FOR FINITE ELEMENT MODELLING OF FOOT AND ANKLE-FOOT ORTHOSES

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1. ABSTRACT

Selective Laser Sintering has been recently proposed as a feasible engineering technique for manufacturing of customized ankle-foot orthoses (AFOs). Development of computer-aided design (CAD) models and virtual evaluation of the orthotic devices are important steps in the engineering design process. This paper will describe a method for accurate characterization of SLS Nylon 12 mechanical properties to be implemented in the finite element models (FEM) of AFOs. Elastic mechanical properties were determined for principal and perpendicular building directions.

2. BACKGROUND

Ankle-foot orthotic devices are widely prescribed to patients with various lower limb muscle and joint weaknesses and instabilities (Halar and Cardenas, 1987). Depending on the clinical application, AFOs may have variable sizes, designs and thicknesses. In the current practice, determination of the functional characteristics of the needed orthosis is primarily based on the experience and craftsmanship of the orthopaedic technician, e.g. the shape of the device is adjusted until the orthosis meets the functional criterion following a trial and error procedure.

Recent studies have proved the feasibility of Selective Laser Sintering (SLS) for manufacturing of customized prosthetics (South *et al.,* 2010), foot orthoses (Pallari *et al.,* 2010) and ankle-foot orthoses (Faustini *et al.,* 2008). Due to the small number of manufacturing constraints, the SLS process can be efficiently used to fabricate tailored, patient-specific orthotics with a predefined optimal stiffness level. The finite element method was successfully integrated in the framework of ankle-foot orthotic (Faustini *et al.*, 2008) and prosthetic sockets (Faustini *et al.*, 2006) design, analysis and manufacturing. In this way, the assessment of device structural integrity and mechanical performance is possible prior to manufacturing. Predictions through such analysis highly rely on the geometrical accuracy of the model and on the consistency of material properties implementation: different material parameters will lead to different estimates for the same product and in the same conditions.
For example, rotational stiffness (and consequently the dorsiflexion deflection) of an ankle-foot orthosis calculated by FE simulations will vary if the material is considered isotropic or transversely isotropic (Muraru *et al.*, 2010).

Although the multi-layered structure of sintered Nylon was evidenced by scanning electron microscopy (Caulfield et al. 2007; Amando-Beker *et al.,* 2008), published mechanical properties from the SLS machine manufacturers do not consider this aspect (Zarringhalam *et al.*, 2006) but refer to as isotropic material. Moreover, recent studies have shown the dependence of mechanical properties on the building parameters (Caulfield *et al.*, 2007) as well as a discrepancy between measured mechanical properties and those provided by the data-sheets (Majewski *et al.,* 2009). However, in the studies integrating FEM in the framework for orthotic/prosthetic design, analysis and SLS manufacturing, SLS materials were characterized according to properties from data sheets and were considered elastic isotropic materials.

The objective of this paper was to determine mechanical properties of SLS Nylon 12 to be implemented in the finite element models of AFOs. Elastic mechanical properties were determined for principal and perpendicular building directions.

3. MATERIALS AND METHODS

3.1 Tensile test

In order to determine mechanical characteristics of SLS Nylon 12 material a series of uniaxial tensile tests were conducted on a INSTRON 4467 machine at 1mm/min.
Standard tensile test specimens were manufactured according to ISO 527-2. The most important dimensions of the "dogbone" specimens are summarized in Figure 1 A. Two different build orientations were considered: (i) 0° orientation when the part thickness is along the build direction (Figure 1B) and (ii) 90° orientation when the part long axis is along the build direction (Figure 1C). Five test specimens were produced for each orientation.

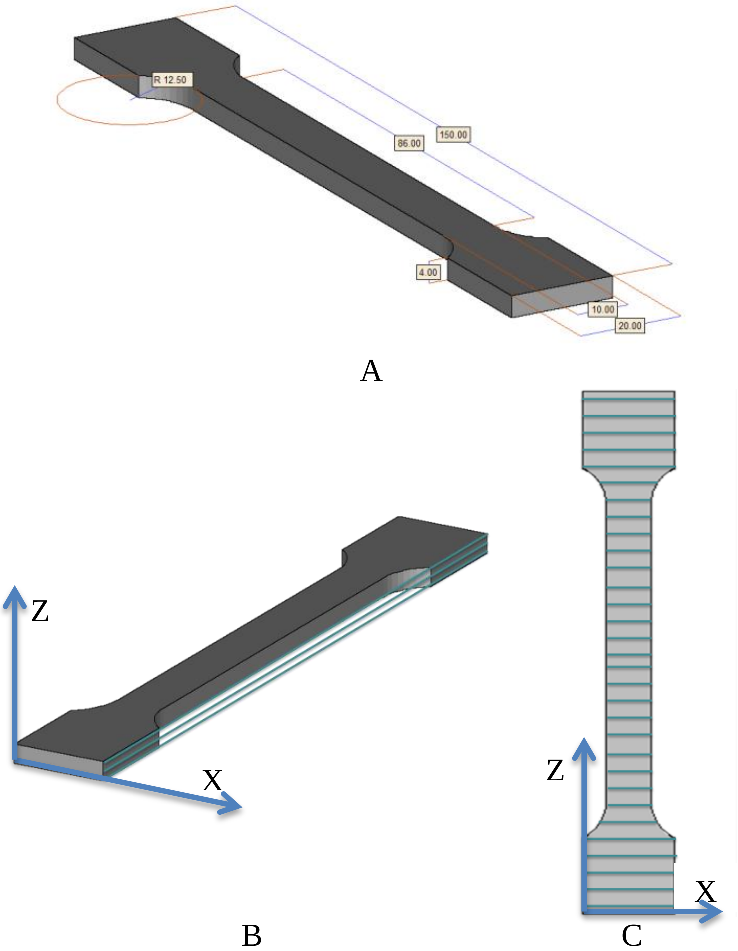


Figure 1: A – "dogbone" test specimen, B – 0° orientation: the part is laying in the X-Y plane while its thickness is along the building direction; C – 90° orientation: longitudinal axis of the part is along the building direction

3.2 Digital image correlation

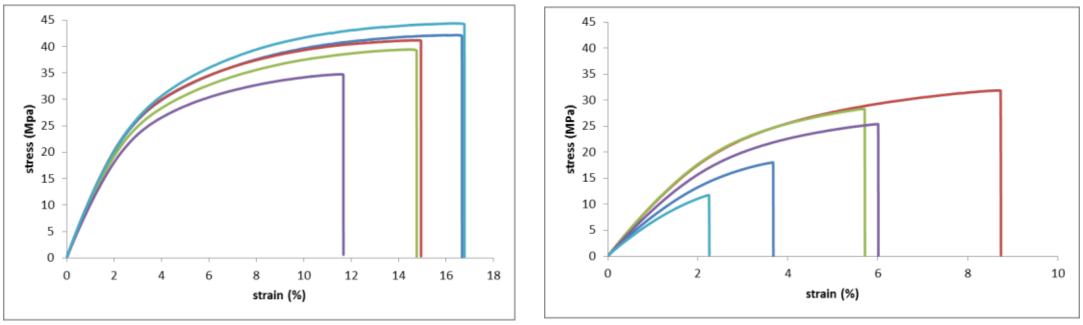
The digital image correlation is an optical method that uses a mathematical correlation analysis to examine digital image data taken while for example, samples are in mechanical tests. This technique was recently used to assess mechanical properties of bovine dura mater (Person *et al.*, 2010) or of human soft tissue (Moerman *et al.*, 2009). Ivanov and colleagues (Ivanov *et al.*, 2009) used digital image correlation to study the experimental behavior of textile composites and for numerical validation of corresponding finite element models.

Tensile tests performed on INSTRON 4467 were recorded at 0.2 Hz with a Correlated Solutions digital image correlation system (Limess GmbH, Pforzheim, Germany). Images recorded during tensile tests were processed with VIC 2D software (Limess GmbH, Pforzheim, Germany). Lateral and axial deformation were computed and used to calculate Poisson's ratio:

$$\vartheta = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}}$$

4. RESULTS AND DISCUSSION

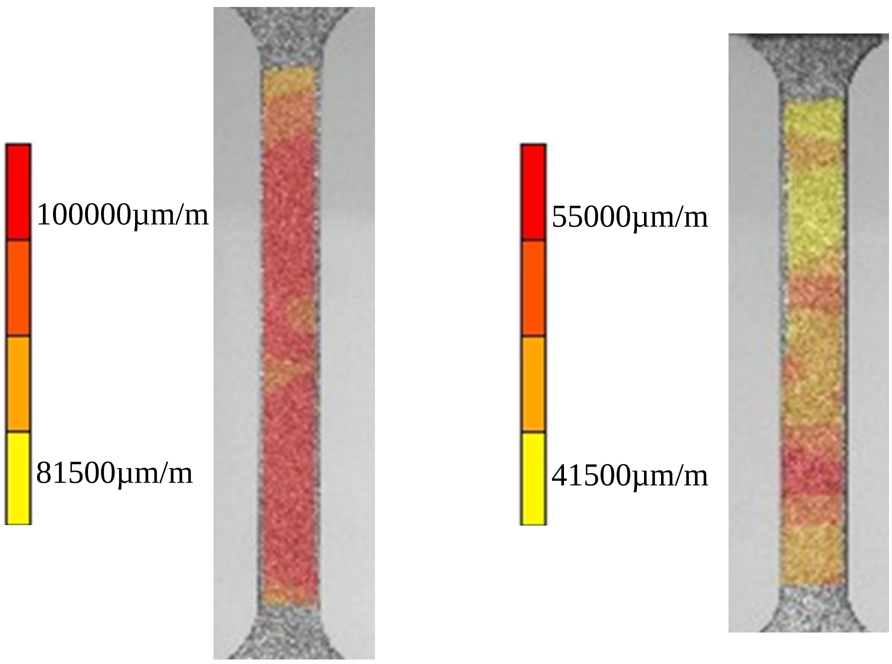
Typical stress strain curves from the tensile tests are shown in Figure 2.



0° orientation 90° orientation

Figure 2: Stress-strain diagrams for each of the tested specimens having 0° orientation (left) or 90° orientation (right).

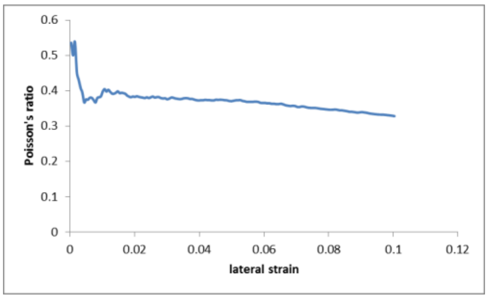
Young's modulus was calculated as the tangent of the slope in the elastic region. Averaged values over each set of 5 measurements for 0° and 90° orientation were calculated: $E_{0^\circ} = 1353\ MPa$ and $E_{90^\circ} = 1145\ MPa$. Young's modulus of 90°orientated parts was lower than Young's modulus of 0°orientated parts. The same is valid for ultimate tensile strength (Figure 2) and in agreement with maximum tensile strain values (Figure 3) calculated by digital image correlation on samples surfaces. For the 0° parts the stress is distributed to all layers and will increase along the layers while for the 90° parts the stress is perpendicular to the layers orientation. For the 0° parts, strain on the surface is uniform (Figure 3A); the fracture will probably be initiated by one of the pores which represents in this case a discontinuity. For the 90° parts the strain on the surface has a "stepped-like" aspect (Figure 3B) clearly predicting possible fracture places.



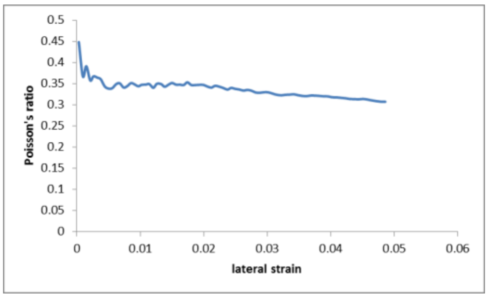
A B

Figure 3: Maximum tensile strain on one sample surface estimated by digital image correlation for one of the samples with 0° orientation (A) and for other sample with 90° orientation (B)

Poisson's ratio for 0° and 90° samples are comparable although those for 0° orientation are slightly higher in the tested samples (Figure 4). Further research should show if this is significant.



0° orientation



90° orientation

Figure 4: Poisson’s ratio for one of the 0° (left) and 90° parts (right).

5. CONCLUSIONS

Young’s modulus and Poisson’s ratio were determined for SLS Nylon 12 for principal and perpendicular building directions. Having determined these parameters, a transversely isotropic definition of SLS Nylon 12 can be implemented in the FE models of foot or ankle-foot orthotics. Further validation of these numerical models is currently undertaken. This will increase the confidence of the designer and give more reliability of the results predicted by numerical simulation.

6. ACKNOWLEDGMENTS

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