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Powder-bed 3D printing meets orthopedic rehabilitation devices

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Abstract: In order to assist or restore the missing mobility, orthoses must be produced based on the specific anatomy and therapeutic needs of a particular patient. Powder-bed 3D printing technologies allow rapid and detailed manufacturing of complex structures. Application of powder-bed 3D printing technologies for orthopedic manufacturing makes it possible to produce lightweight, tailorable and reproducible rehabilitation devices. This promising manufacturing technique brings its uncertainties which must be answered before being used. Hence, it is very important to monitor the manufacturing quality and investigate the material behavior of the finished products.

I. Introduction

Manufacturing a perfect orthosis which supports a patient until a desired level is a key skill that orthopedic technicians learn in a special training course. This manufacturing process is mainly manual and requires repetitive adaptation and constant control. An important challenge is posed by foot orthoses, which are commonly called orthotics. Orthotics are considered as a substitution for muscular strength (permanent or temporary) and are used by the patients who suffer from spastic paralysis of the leg muscles, or shortening of the leg muscles. There are various types of orthotics to assist different patients with their needs. However, all the orthotics share some primary requirements. An orthotic must be flexible enough to not (fully) restrict dorsiflexion and plantarflexion movements. It needs to be comfortable for long-term usage. Hygienic issues such as sufficient ventilation of the skin under the orthotics are also important necessities. Also, its external geometry must be designed in such a way that the patient can wear a shoe on it [1,2].

Recently, 3D printing technologies have attracted a large amount of attention for the manufacturing of orthoses. 3D foot shape files including foot size, texture and shape information can be created by 3D scanning of the foot. Afterwards, these data are converted into stereolithography (STL) files and can be printed by any 3D printer. Clearly, this is a continuous and closed-loop manufacturing process which can also become automated. Comparing this process with the traditional manufacturing of orthotics, this new method produces patient-specific and reproducible orthotics within less time and human effort [3,4]. Along with a precise design and rapid manufacturing, functionality of the final products must be evaluated before any use cases.

Selective laser sintering (SLS) is a precise powder-bed 3D printing technology for polymer manufacturing. At the same time, polyamide 12 is a biocompatible thermoplastic with low sensitivity towards chemicals and humidity. SLS 3D printers can use a powder version of polyamide 12 which is called PA 2200 [5,6]. Thus, personalized PA 2200-orthotics which are 3D printed with SLS are among very probable future orthopedic devices. Therefore, studying properties and behavior of some initial prototypes is essential. Within this manuscript, mechanical response of the specimens under tensile loads has been studied.

II. Material and methods

The specimens were 3D printed by a SLS-EOS P-396 machine. To perform and interpret tensile test results, the standard ISO 527 and sample type 1A [7] were used. In order for studying the mechanical structure, the same STL file was printed in 3 orthogonal orientations.

Table 1: Information about the applied 3D printer in this work, according to the reference [8]

Build volume	Maximum printing speed	Minimum layer thickness	Mixing ratio of fresh/recycled powder
340×340×600 mm^3	3.0 L/hr	0.06 mm	50/50

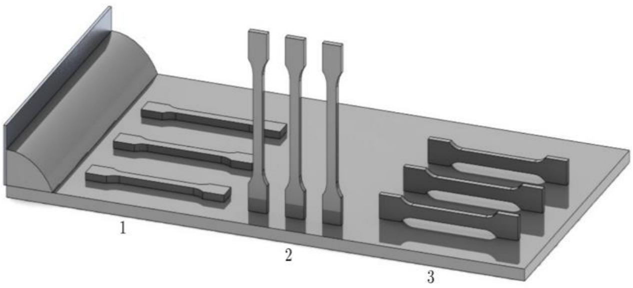

Figure 1: Print orientations are: 1- flatwise, 2-upright, and 3-edgewise.

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II.I. Density Measurements

Density measurements have been done by following the Archimedes principle and using water as the liquid. The measured values show no dependency between density and the print orientation.

Table 2: Measured densities ($\frac{gr}{cm^3}$) for each print orientation. Each number in this table represents an average value for 10 specimens. The right column has been taken from the mentioned reference.

Flatwise	Edgewise	Upright	Data-sheet [5]
0.996	0.977	0.990	0.93

III. Results and discussion

The measured densities and mechanical characteristics of SLS printed PA 2200 specimens under quasi-static tensile loads at two cross-head speeds of 5 and 50 $\frac{mm}{min}$ have been explained.

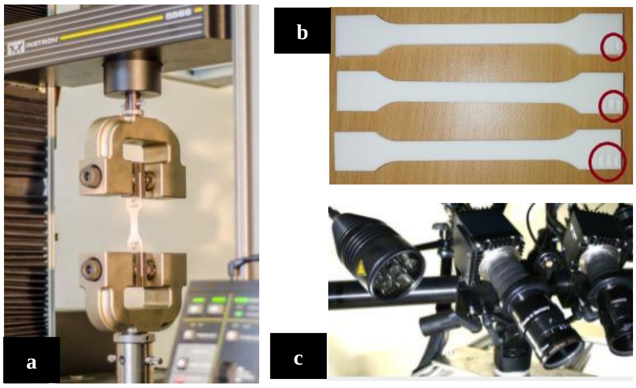

Figure 2: a) INSTRON 5566 universal testing machine. b) Specimens printed in 1- flatwise, 2-upright, and 3-edgewise orientations. c) Digital Image Correlation (DIC) for non-contact optical measurement of strain and displacement values.

III.I. Tensile Test Results

Obviously, a non-linear mechanical behavior is explainable for SLS specimens (which undergo tensile loads) by looking at the stress-strain curves shown in the Figures 3-4. The deformation behavior is approximately linear up to the stresses of about 30 MPa and 35 MPa for the test speeds of 5 and 50 $\frac{mm}{min}$, respectively.

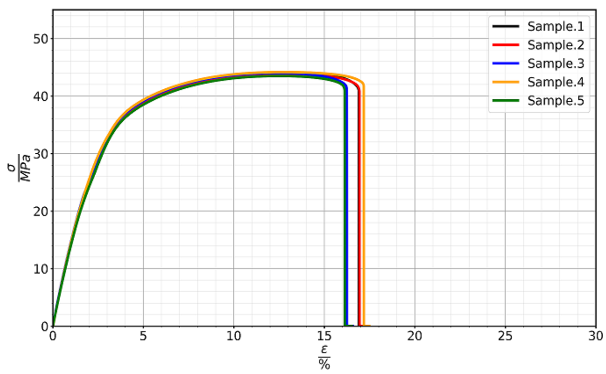

Figure 3: Engineering stress-strain curve showing the mechanical performance flatwise specimens. A displacement rate of 5 mm/min has been used.

Within the elastic region, a more-or-less isotropic and rate-independent mechanical behavior can be explained for the SLS specimens. However, when the deformation increases and the behavior is not elastic and rate-independent anymore; the scenario changes. For instance, final elongations are considerably changing due to the print orientation (Figure 4).

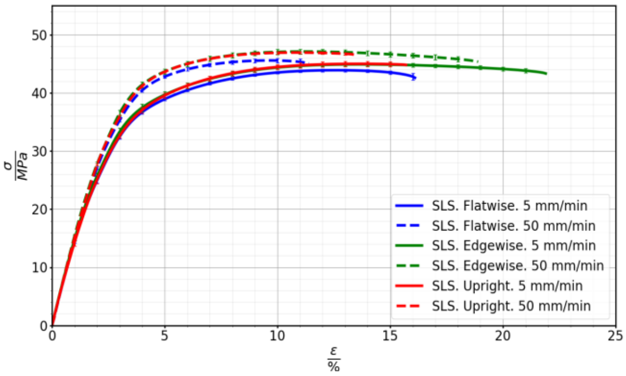

Figure 4: Averaged engineering stress-strain curves for SLS 3D printed samples under tensile loads. Here, all the three print orientations are included (refer to Figure 1). Solid lines correspond to the displacement rate of 5 mm/min and dashed lines illustrate the results from tensile testing at a displacement rate of 50 mm/min. Furthermore, error bars show the scattering of the experimental results. Different colors are used to show different print orientations.

IV. Conclusions

Anisotropy and rate dependent mechanical behavior of SLS 3D printed polyamide 12 under tensile loads have been studied. Deformation behavior of the specimens shows non-linear and rate-dependent mechanical characteristics. Print orientation had a small influence on the material parameters unless on the elongation at break values. There, significant deviations were observed.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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