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Thickness dependency of mechanical properties of laser-sintered polyamide lightweight structures

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ABSTRACT

Laser sintering (LS), as an additive manufacturing process for production of polymer structures, provides the possibility of directly manufacturing personalized, structural motorcycle components for motor sports. To create such lightweight structures, the wall thickness and position limits of the LS systems need to be investigated in detail. Appearing process-related flaws such as different amounts of crystallinity, surface roughness, and defects such as pores exhibit dimensions similar to the wall thickness. To study the process-related effects on the mechanical properties of 450 tensile test specimens in *z*-direction, the build areas of two LS systems were screened and a detailed wall thickness investigation was conducted. In addition, dynamic mechanical analysis, differential scanning calorimetry, and scanning electron microscopy for several wall thicknesses similar to the spot size were conducted. The investigations showed that the Young's moduli and ultimate tensile strengths of the produced specimens of the two commercial EOS systems, P396 and P770, are similar and evenly distributed. However, distinct differences were found in elongation at break. The scattering of mechanical properties is more in the specimens produced by P770 than in those produced by P396. The Poisson's ratio does not vary between thin- and thick-walled structures. Furthermore, structures with a thickness below 1 mm showed distinctive losses in stiffness, ultimate tensile strength, and elongation at break.

1. Introduction

For analysis of lightweight motor sport structures (Fig. 1a), mechanical properties such as tensile Young's modulus (E_T), yield or ultimate tensile strength (UTS), Poisson's ratio, and especially the elongation at break (EaB) are of interest. Breuringer et al. [1] showed that Young's modulus depends on thickness, whereby the investigated dimensions were 1, 5, and 8 mm. Türk et al. [2] designed an additively manufactured lightweight honeycomb for composite sandwich structures. The minimum wall thicknesses of the honeycomb was 0.4 mm but test specimens for creep tests had a thickness of 4 mm. Because of different types of commercial systems [3] and different powder qualities with a reuse factor [4], the mechanical properties differ. Goodridge et al. [5,6] showed non-homogeneous distribution of mechanical properties in the build area and the dependency of part placement in *z*-direction, which is considered the worst building direction [7], using only virgin powder in their investigation.

System-specific Young's modulus and material properties are essential for enabling personalized small-scale motor sport production, where the stiffness and shape meet the rider's demands. The possibility of creating a diamond lattice structure with different effective thickness-compensated stiffness values and densities was presented by Neff et al. [8]. A nearly 1000 mm long motocross seat, illustrated in Fig. 1a, with such a lattice structure or a thin-walled substructure (see Fig. 1b) could be manufactured in a P770 LS system (see Fig. 1c). The mounting points at the front, bottom, and back-end of the seat would be widely distributed through the build area.

The Young's moduli of test specimens with wall thicknesses of 3 mm [4,9,10] and 4 mm [5,11–15] are related to process parameters [16]. The laser process parameters affect the outcome of the produced parts significantly in terms of density and mechanical properties [5,9,12,13,17]. Determination of mechanical properties near the spot size and detailed screening of mechanical properties of thin-walled structures has not been reported so far to the best of authors'

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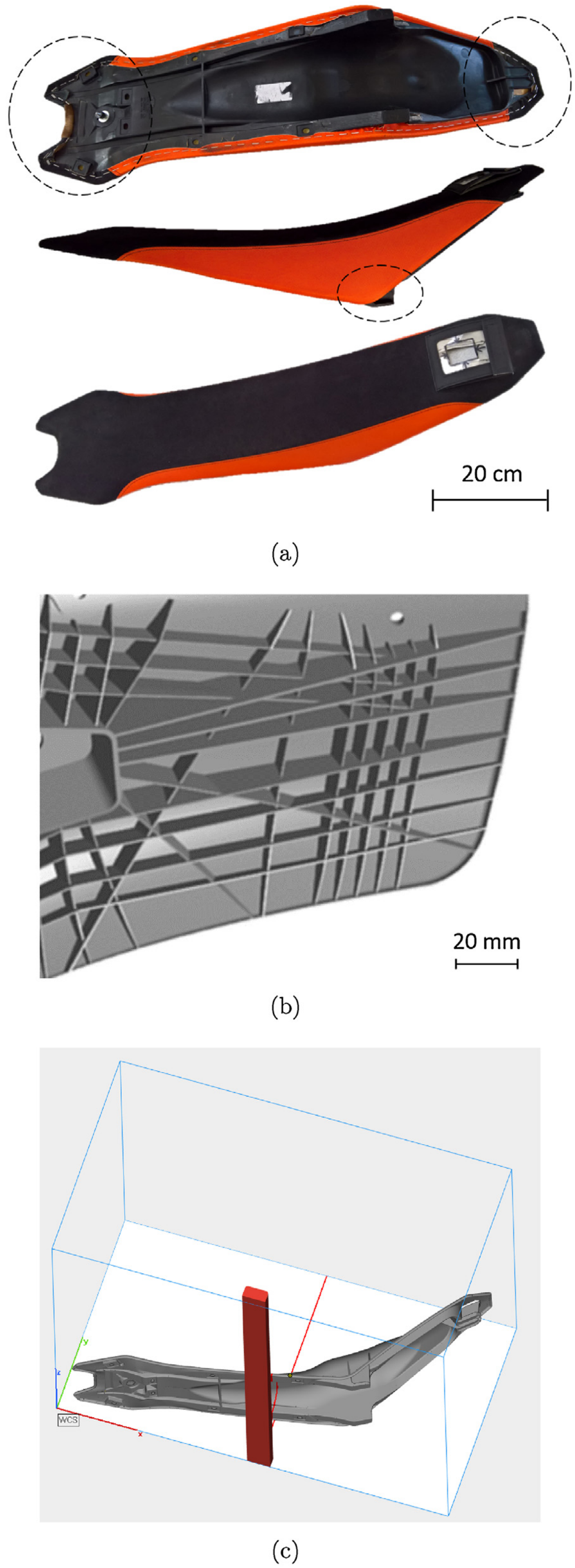

Fig. 1. (a) Motocross seat of a KTM 450 Rally with mounting points (dashed circles); (b) Double curved surface with a surface perpendicular thin-walled substructure; (c) Motocross seat in the build area of P770.

knowledge.

Caulfield et al. [9] investigated the relationship between energy density and thickness, wherein the test specimen thickness increased from 3 mm to 3.5 mm with an increase in energy density. Further, the influence of energy density on E_T, UTS, and EaB was shown for PA 12 by Caulfield et al. [9] and for carbon nanotubes reinforced PA 12 by Yuan et al. [18]. Scan spacing, laser power, and speed influence the energy density [9]. The use of a hatch grid 3 to 6 times lower than the laser beam diameter [5] is recommended by system suppliers. The more comparable the structure thickness to the spot size, the more the suggestions from system producers remain unfulfilled. Further, mechanical properties for wall thicknesses near the production limits of the systems were investigated. The reliability of mechanical properties and their dependence on laser energy and process-induced influences were shown by Pavan et al. [19]. To investigate the progress in system technologies regarding the inhomogeneous behavior within the build area, two commercial LS systems were filled with *z*-direction specimens and compared. Additionally, the Young's moduli of test specimens with the thickness varying from 0.6 mm to 2 mm and a thickness of 4 mm were investigated.

Amel et al. [20] determined the glass transition temperature and storage modulus by performing dynamic mechanical analysis (DMA) at different frequencies. They found that the glass transition temperature shifted to higher temperatures and the Young's modulus increased with increasing frequency. Salmoria et al. [21] compared the elastic moduli of different PA 6/PA 12 blends, showing that a higher proportion of PA 12 increases the Young's modulus. To examine the influences of different wall thicknesses and the resulting crystallinity on the inner friction and flexural dynamic Young's modulus, DMA was conducted.

Dadbakhsh et al. [4] described the thermal behavior of PA 12 powder. Through differential scanning calorimetry (DSC), they compared the melting peaks of virgin, aged, and mixed powders, and discovered a higher melting peak and a lower crystallization peak of the aged powder compared to the virgin powder. Drummer et al. [13] showed the behavior of the powders during the sintering process. Due to the low crystallization temperature, the powder was melted by the laser beam and stayed as a liquid until the entire powder bed cooled down. Schmid et al. [22] investigated the difference in thermal behaviors of PA 12 obtained from two different suppliers and compared the thermal behavior with the powder size distribution. Verbelen et al. [23] studied the influence of maximum temperature after melting on the recrystallization temperature using samples produced with different laser energies. Therefore, DSC can be used to investigate the crystallinity along with wall thickness investigation.

Guo et al. [24] presented an as-built surface with an unmelted powder layer on a thick block specimen. The arithmetic average roughness, Ra, was around 16 µm. This value was confirmed by Bai et al. [25] in their investigations on wear properties and by Pavan et al. [19]. However, no relationship with the strength of the thin-walled parts was deduced. Surface investigations for metallization purpose were carried out by Amend et al. [26] on test specimens thicker than 4 mm. The untreated, fused particle surface and the influence of glass bead and corundum blasting on the surface roughness depth (Rz) were presented for PA 12. Untreated, the Rz was around 125 µm. Dadbakhsh et al. [4] studied the microstructure and surface morphology of single-layer LS parts of different powders (virgin, aged, and mixed) by scanning electron microscopy (SEM). The influence of specimen size on the porosity was investigated by Pavan et al. [27]. It was found that the porosity decreased in number and size with decrease in sample diameter. The present study investigates the fracture of residual cross section by considering the surface layer and pores on the residual cross section of the break plane by SEM.

2. Methodology

2.1. LS systems

To gain insight into the LS systems, P396 ($W \times D \times H$ in mm/ 340 × 340 × 600) and P770 (700 × 380 × 580) LS systems from EOS (Munich, Germany) were used to produce the test specimens. The PA 12