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Using X-ray computed tomography to improve the porosity level of polyamide-12 laser sintered parts

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ABSTRACT

Porosity is a key parameter determining the functional application limits of polymeric parts produced by laser sintering (LS). In this paper, X-ray computed tomography (CT) is used to investigate the influence of the LS scanning parameters (laser power, hatch spacing, and scan speed) and part or feature size on the distribution and size of pores within polyamide-12 (PA12) laser sintered parts. CT model slices are created parallel to the original LS manufacturing layers in order to determine the porosity distribution and variation within each layer as well as along subsequent layers. Mapping the porosity distribution within these slices onto the laser scanning trajectory moreover allows investigating the influence of LS scanning parameters. Correlation of these porosity data with results from mechanical testing allows identifying optimal LS scanning parameters.

1. Introduction

Lasersintering (LS) of polymeric parts has evolved from a mere rapid prototyping technology into a genuine manufacturing technology used for the toolless production of functional parts. Sufficiently high and consistent mechanical properties of the produced parts are essential for a further market expansion of the technology towards e.g. the aerospace industry [1]. Literature provides ample evidence that multiple factors, such as laser energy density, powder bed temperature, delay time between layers, as well as the place of the part in the build, significantly affect the mechanical properties, since all influence both the degree of crystallinity as well as the porosity of the parts [2–5]. Even for PA12, which counts as the most investigated and applied LS material, problems of ensuring low porosity levels and isotropic mechanical properties persist [1,5].

Due to its capabilities to non-destructively inspect internal structures, computed tomography (CT) is a very suitable tool to investigate the influence of LS scanning parameters and geometric feature parameters on the distribution and size of pores within LS parts [6]. In this paper, X-ray computed tomography (CT) is used to investigate the influence of the LS scanning parameters (laser power, hatch spacing, and scan speed) as well as scanning strategy on the distribution and size of pores within polyamide-12 (PA12) laser sintered parts.

2. Materials and methods

2.1. Samples

Samples have been produced using a P396 machine from EOS GmbH using an alternate *x*–*y* scanning pattern and a PA2200 PA12 powder with a mixing ratio 50/50 between virgin and recycled powder; the latter securing industrial representativeness of the test conditions. It concerns 10 × 10 × 10 mm^3 cubes (Section 3.1), tensile test bars (Section 3.2), and cylindrical pins (Section 4) manufactured with an average sintered layer thickness of 120 μm and a hatching distance of 0.3 mm.

2.2. X-ray CT scanning and pores volume distribution

The CT scans have been performed using a 225 kV CT machine from Nikon Metrology using a molybdenum target without metal hardware filter. Additional CT settings are reported in Table 1.The combination of settings has been selected by optimizing signal-to-noise and contrast-to-noise ratios of the reconstructed CT-slices of different datasets. The reconstruction of the projections into the 3D voxel volume is performed using *CT-Pro* software from Nikon Metrology. The datasets are analyzed using *VGStudio MAX 2.2* from Volume Graphics GmbH, where the closed porosity is calculated using the "defect detection" module. The data are further analyzed using a Matlab code, in order to derive information about the pores volume distribution.

Fig. 1 shows the contribution of pores with increasing size to the total number of pores as well as to the total porosity volume for a cubic PA12 sample with 10 mm side. Despite the high count, pores with diameter smaller than 90 μm have a limited contribution to

Table 1
CT scanning parameters used for the different samples.

Sample	Voltage (kV)	Current (μA)	Voxel size (μm)	Projections
Cubes/tensile bars	70	200	10	1500
Cylindrical pins	110	127	20	3000

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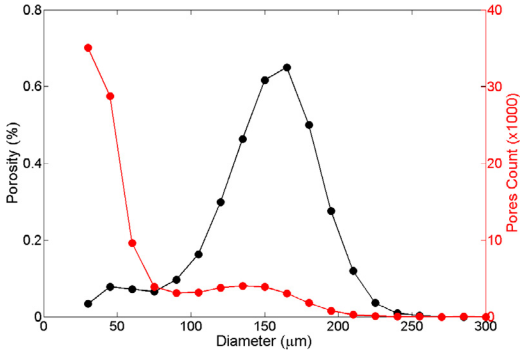

Fig. 1. Pores count distribution (a) and pores volume distribution (b) of a PA12 cube with 10 mm side obtained with a magnification of ×20 (voxel size: 10 μm).

the total voids' volume. CT voxel sizes ranging from 10 μm to 30 μm are adequate for the intended analyses.

2.3. Porosity distribution along the printing direction

To allow further analysis of the distribution of the pores throughout the sample volume, each 3D voxel volume acquired via CT is re-aligned to the original STL-files and to the X–Y–Z axis of the LS machine. This allows slicing the CT-models parallel to the LS layers (LS slices). Subsequently, all CT slices are binarized in Matlab using Otsu's thresholding algorithm [7] to calculate an average porosity per slice. Fig. 2 hence depicts the porosity for all CT slices from bottom to top for a cube sample. The graph evidences porosity variations with a wavelength corresponding to the layer thickness of 120 μm.

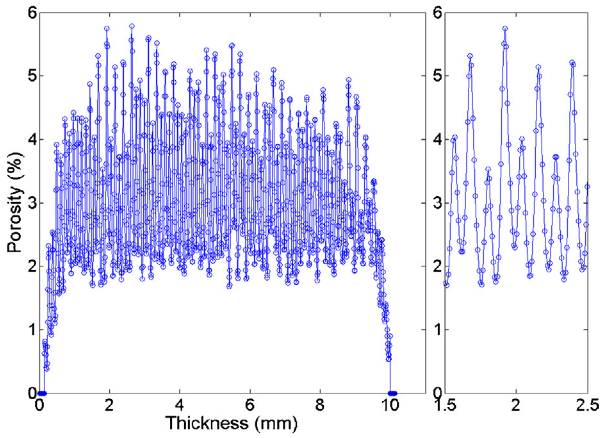

Fig. 2. Porosity distribution along the printing direction (left) and detail (right).

2.4. Cumulative porosity maps

The porosity information of the CT-slices also allows creating 2D cumulative porosity maps of the specimens (Fig. 3) following an approach proposed by Reh et al. [8]. Each pixel of a porosity map represents the cumulative porosity of the corresponding pixels of the entire stack of CT slices. Porosity maps based on CT slices parallel to the LS layers (Fig. 3, left) allow correlating porosity concentrations with the X and Y scanning strategy, whereas porosity maps based on CT slices orthogonal to the LS layers (Fig. 3, right) represent the porosity variations along the build height or the successive LS layers, as already evidenced by Fig. 2.

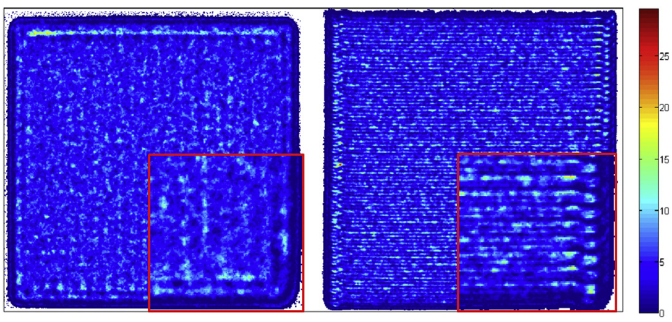

Fig. 3. Porosity maps based on CT slices parallel to the LS layers (left) and based on CT slices orthogonal to the LS layers (right).

3. Influence of LS energy density parameters

3.1. Influence of LS energy density parameters on porosity

The influence of the LS energy density (ED) on the mechanical properties of LS parts has been recognized in literature [9–12]. However the ED is determined by three main process parameters: laser power (LP), scanning speed (SS), and hatching distance (HD), as evidenced by Eq. (1):

$$\mathrm{ED}\ [\mathrm{J/mm^2}] = \frac{\mathrm{LP}\ [\mathrm{W}]}{\mathrm{SS}\ [\mathrm{mm/s}] * \mathrm{HD}\ [\mathrm{mm}]} \tag{1}$$

In order to investigate the influence of these individual parameters on the porosity, 13 cube samples of 10 × 10 × 10 mm^3 have been manufactured using different combinations of settings. Starting from a reference parameter set yielding an ED of 35 mJ/mm^2, the other parameter sets were chosen to yield one of four additional levels of ED, by always changing just one out of three contributing parameters (Table 2).

Table 2
Settings for cube samples to assess the influence of energy density (ED): laser power (LP), hatching distance (HD), and scanning speed (SS).

Sample ID	LP [W]	HD [mm]	SS [mm/s]	ED [mJ/mm^2]
REF	44	0.3	4190	35
P1	30.8	0.3	4190	24.5
P2	37.4	0.3	4190	29.8
P3	48.4	0.3	4190	38.5
P4	52.8	0.3	4190	42
SS1	44	0.3	5986	24.5
SS2	44	0.3	4929	29.8
SS3	44	0.3	3809	38.5
SS4	44	0.3	3492	42
HD1	44	0.43	4190	24.5
HD2	44	0.35	4190	29.8
HD3	44	0.27	4190	38.5
HD4	44	0.25	4190	42

Fig. 4 shows that both laser power and scanning speed have a similar effect on the porosity content, leading to a minimum porosity near 35 mJ/mm^2. This complies with earlier findings by e.g. [13], who reports density to be increasing with laser power due to better fusion of powder particles, and formulate the hypothesis that excessive energy density will lead to polymer degradation, hence increased porosity by trapped gases. Fig. 5 shows that

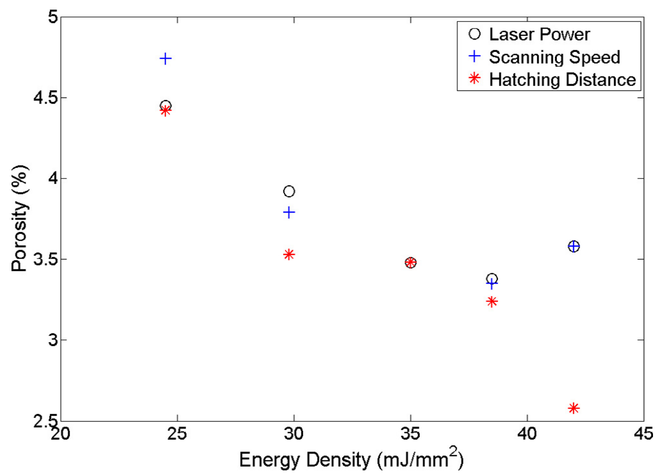

Fig. 4. Porosity content for different ED levels obtained by changing one parameter among laser power, scanning speed and hatching distance, while maintaining the other two constant.