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Microstructure analysis of additive manufactured CF-PA6 parts under consideration of different consolidation parameters.

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INTRODUCTION

Additive manufacturing is becoming increasingly important in field of component design. In order to enhance the mechanical properties of 3D printed components, load-oriented Continuous Fiber Composite materials (CFC) are used. Previous investigations of 3D-printed CFC have revealed a high degree of cavities in the Carbon Fiber Reinforced Polyamide-6 (CF - PA6) laminate, which lead to a deterioration of the mechanical properties. These imperfections in the laminate can be described as deconsolidation, indicating a poor parameter selection as well as an inadequate consolidation in the 3D printing process [1]. This research presents a first problem analysis and shows possibilities for a significant improvement of the 3D-printed CF-PA6 material.

METHODS

Based on the standard process parameters of Markforged (MF) CF-PA6 manufacturing process and their printing strategy, an own strategy is adopted. Therefore, the MF's CF-PA6 material was subjected to a DSC measurement, to determine the detailed melting and crystallization temperature. For a consolidation study the layer height was varied while other process parameters remained constant (see Table 1). Thus the consolidation pressure increased as the distance between nozzle and printing bed was reduced (see Figure 1). Test specimens (A-D) were printed with fiber orientations of 0° and 90° according to the standard DIN EN ISO 14125 and a microstructural analysis was done. The focus of the microstructural analysis was on the homogeneous distribution of the fiber matrix system as well as the proportion of cavities in the microstructure. For the printing process, the Continuous Filament Fabrication system (CFF) from MF with a self-developed controller board and an open source software was used.

Table 1: Process parameters

Variation	Fiber-orientaion	Layerheight Nozzle distance	Printing-speed	Temperature DSC-MEASUREMENT
A	0° / 90°	0,125 mm	15 mm/s	245 °C
B		0,115 mm		
C		0,135 mm		
D		0, 105 mm		

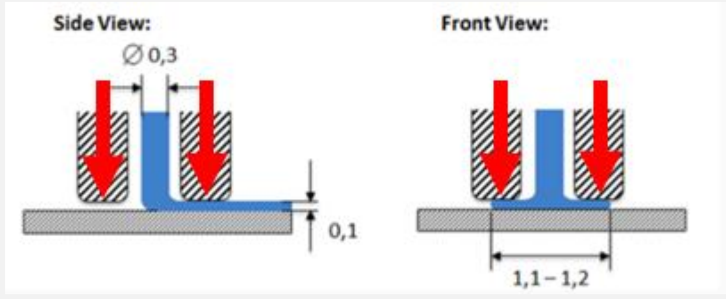


Figure 1: Consolidation concept.

RESULTS

The study showed a stepwise improvement of bending strength of more than 50% as well as an improvement of the flexural modulus over 25% in 0° fiber direction (see Table 2). The specimens with the 90° fiber direction showed only low differences to each other.

Table 2: Results three-point bending test 0°/90° DIN EN ISO 14125

Variation 0°	E_f [GPa]	σ_f [MPa]
VD-0	34	343
VB-0	32	290
VA-0	28	218
VC-0	26	191

Variation 90°	E_f [GPa]	σ_f [MPa]
VD-90	1,4	26
VB-90	1,1	26
VA-90	1	21
VC-90	0,8	19

The reduction of the layer height had a positive effect on the fiber distribution in the matrix and decrease the content of cavities in the composite (see Figure 2). The test sample with the lowest nozzle distance and the highest consolidation pressure, VD-0/90 cross section in fiber direction, provided the best mechanical properties and the most homogeneous microstructure.

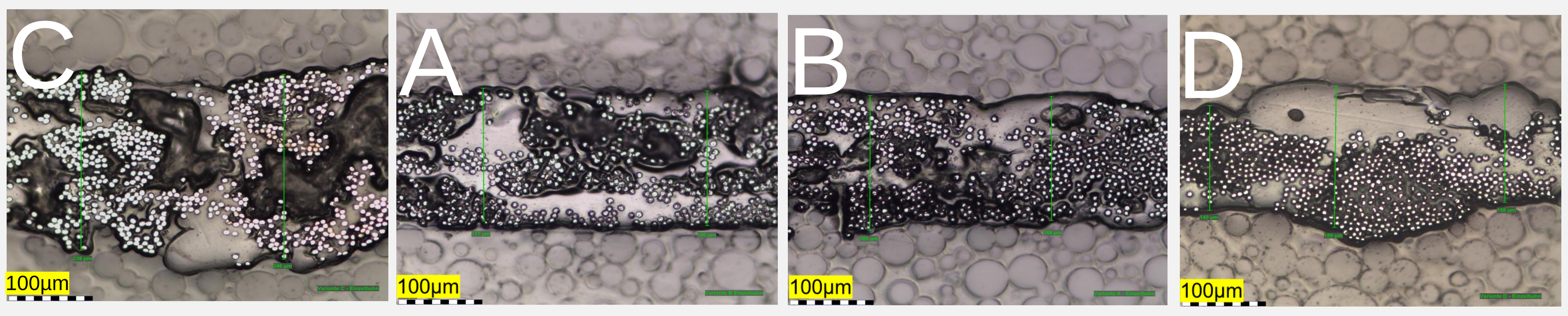


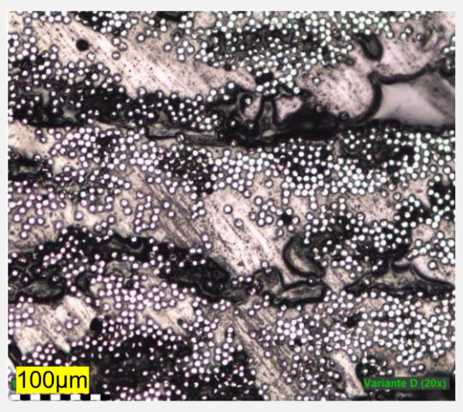
Figure 2: Microstructure in fiber direction of the different consolidation parameters

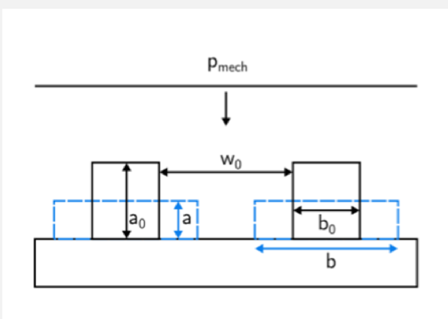
CONCLUSION AND OUTLOOK

The adopted process parameters have shown an improvement of the microstructure. Nevertheless, the layering of the 3D-printed CFC still produces cavities, and the fibers are not homogeneously distributed in the matrix. This leads to a significant reduction of the mechanical properties. A need for further development of the 3D-printed consolidation process and the selection of the process parameters remains. Various consolidation and intimate contact models have already been developed to predict process parameters within conventional manufacturing processes [2]. However, their validity for the 3D-printing process has yet to be proven and, if necessary, new models need to be developed.

Initial calculations based on different consolidation models must be performed. With the first results, tests will be carried out and the results are compared with the theoretical values. Several iterations will be necessary to optimize the microstructure and mechanical properties of the material. In these iteration loops, the consolidation model will be revised and the individual parameters (pressure, temperature, speed, ...) will be optimized (see Figure 3).

Material properties:
Fiber/Matrix



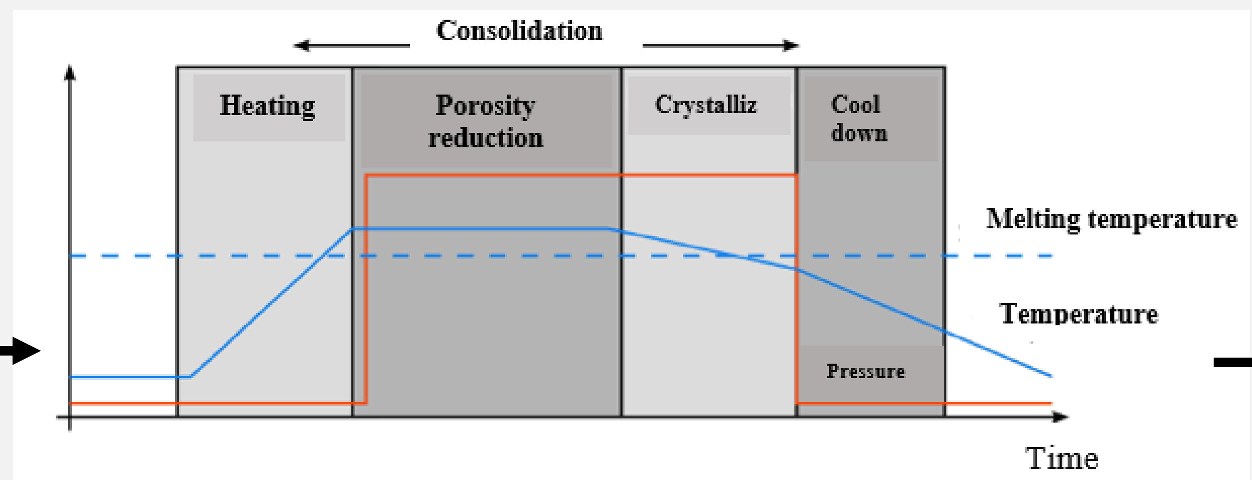


Microscopic geometrical conditions

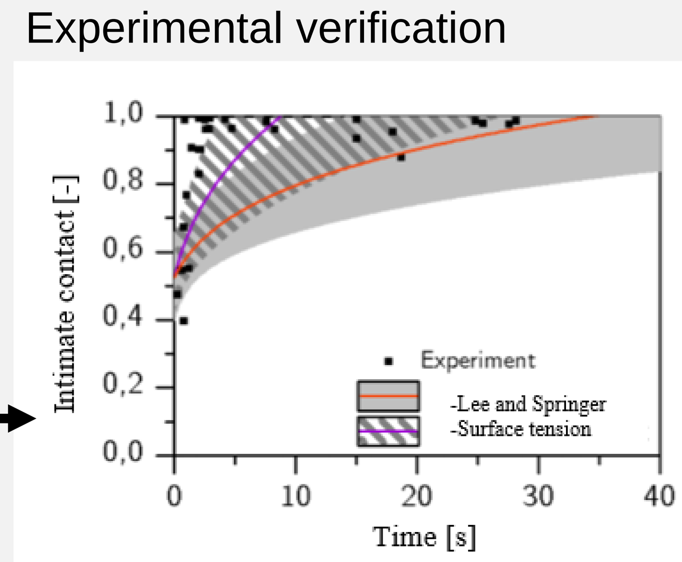
$$D_{ic}\,(t) = \frac{b(t)}{b_0 + w_0} = \frac{\dfrac{a_0}{a(t)}}{1 + \dfrac{w_0}{b_0}}$$

Intimate contact

Consolidation model for transient systems



Experimental verification



Iterative process parameter optimization

Figure 3: Iterative development of a consolidation model for 3D-printed CFC

LITERATURE

[1] Henninger, F. 1998. Deconsolidation behaviour of glass fibrepolyamide 12 composite sheet material during post-processing. *Plastics rubber and composites processing and applications.* 1998, 27.6.

[2] Moser, Marco. 2014. *Konsolidierung thermoplastischer Verbundwerkstoffe – Phänomene, Modellvorstellungen und Vorhersagefähigkeit.* Leoben : Montanuniversität Leoben für Kunststofftechnik, Verarbeitung von Verbundwerkstoffen / Masterarbeit, 2014.