Additive manufacturing of Ti6Al4V parts via Fused Filament Fabrication

Ralf Eickhoff[1*], Dorit Nötzel[1], Steffen Antusch[1] and Thomas Hanemann[1,2]

[1]Karlsruhe Institute of Technology, Karlsruhe, Germany

[2]University of Freiburg, Freiburg, Germany

*Corresponding author email: ralf.eickhoff@kit.edu

Abstract – In this work, the development of a process chain to produce titanium components via Fused Filament Fabrication (FFF) will be introduced applying eco-friendly partially water-soluble binder systems. The focus of this study was the influence of different thermoplastic binder components on the properties of the feedstocks. It was found that short-chain fatty acids decrease the viscosity of the feedstocks and extraordinarily increase the flexibility of the filaments at the expense of hardness. Printing of the feedstocks showed promising results, even complex geometries could be achieved with a high level of detail. After subsequent debinding and thermal densification, titanium components were produced with a density of more than 99.9 % of the theoretical value.

Key Words – titanium, 3D printing, FFF

I. INTRODUCTION

Common equipment and operation of Additive Manufacturing (AM) of titanium is usually cost-intensive due to advanced machines [1]. Extrusion Additive Manufacturing (EAM), for instance Fused Filament Fabrication (FFF), offers the fabrication of titanium components with complex geometries and a high level of detail at low costs [2]. This can be achieved by the low waste of titanium powder and by using cost-effective, commercial FFF printers. These printers are fed with feedstocks containing titanium powder and thermoplastic polymers (binders), which enable the mixture to be shaped at moderate temperatures. After shaping, the binder must be removed by dissolving in water and subsequently pyrolyzing. A final sintering step densifies the metal and controls its structure and mechanical properties. With respect to the requirements of the printing process, a process chain to fabricate dense and defect-free Ti6Al4V parts via FFF was established and optimized.

II. MATERIALS AND METHODS

The titanium alloy Ti6Al4V (Grade 23FE) was selected as the powder, which has a particle diameter (d_{50}) of 29.9 µm and is characterized by low oxygen and carbon content. The binder consists of polyethylene glycol (PEG), fatty acids, poly(methyl methacrylate) (PMMA) and poly(vinyl butyral) (PVB). At first, the powder and the polymeric components were mixed for one hour in a mixer-kneader and subsequently characterized by shear and oscillation rheology. The second step included on the one hand the extrusion of filaments and on the other hand the printing of green parts. A matter of interest were the printing parameters, such as the printing temperature or the nozzle size, and their influence on the properties of the green parts. At last, the debinding behavior of the green parts in water and the sintering parameters (temperature, time, and atmosphere) were investigated and optimized.

III. RESULTS AND DISCUSSION

Feedstock preparation and characterization

Feedstocks with PVB and a high content of short-chain fatty acids showed an interesting behavior: Beside the expected decrease of the viscosity (Figure 1), they became very flexible and soft.

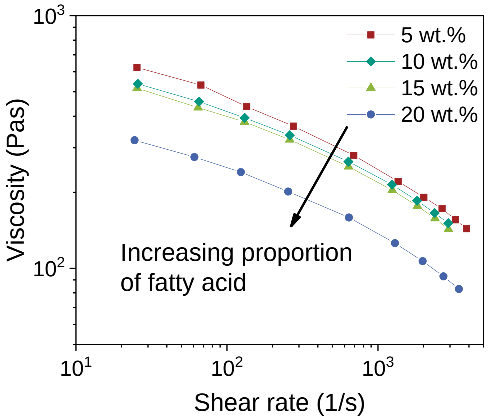

Figure 1. Shear rate dependent melt viscosity at 160 °C at a solid load of 60 vol.% titanium. The proportion of the fatty acid is given in wt.% of the binder.

Although a certain flexibility of the filaments is desirable, too soft filaments can cause problems during printing [3]. A possible solution to this problem could be the addition of a small amount of the brittle PMMA to the binder to increase the hardness of the filaments. Pretests showed promising results.

Extrusion and printing

Filaments were produced on a single-screw extruder, equipped with a 2.8 mm nozzle, and subsequently winded. Due to the high solid load, swelling of the extrudate was almost completely suppressed. During printing, the feedstocks showed good processing properties. As can be seen in Figure 2, parts with complex geometry could be printed with a high level of detail.

Figure 2. Printed chess figures in green state

Debinding and Sintering

Solvent debinding in water showed no abnormalities, and over 85 % of the PEG was removed. However, a higher content of fatty acids seems to inhibit the debinding of PEG to some extent.

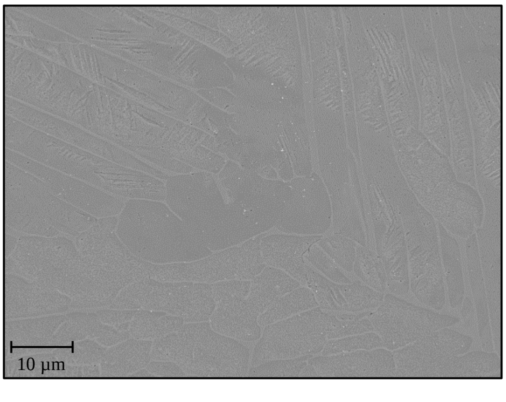

Figure 3. SEM image of sintered and additional HIPed microstructure (density 99.9 %, etched with ammonium hydrogen fluoride)

Due to the high reactivity of titanium with oxygen, thermal debinding (at 550 °C) and sintering (at 1350 °C) were performed under argon atmosphere to avoid contamination. After sintering, a density over 96 % of theoretical value was achieved. For enhanced density values (≥ 99.9 % of theoretical density) an additional hot isostatic pressing (HIP) can be applied. Figure 3 shows a SEM image of the microstructure of Ti6Al4V, where the typical α/β texture of this alloy is present [4].

IV. CONCLUSION

In this work, a process chain for the fabrication of dense titanium components using FFF with partially water-soluble binder systems was established and validated. It was possible to produce parts with a high level of detail, density above 99.9 % of theoretical density, and low carbon and oxygen content. Future research will focus on the mechanical properties of printed components as a function of the binder systems, printing parameters and sintering parameters used. In addition, it is planned to transfer the knowledge gained to another metal powders.

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