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Original Research Article

Fabrication of patient-specific finger joint implants from Ti-6Al-4V using metal binder jetting

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Abstract: Developing personalized medical solutions is crucial for preserving patient comfort and joint mobility. Metal Binder Jetting (MBJ) offers unique advantages for industrializing custom-made and patient-specific implants. This paper discusses the MBJ process, its challenges, and proposed approaches to address them. Specifically, the binder jetting process route used in a research project for finger joint implants is examined. Challenges related to powder flowability, powder reactivity, and the impact of atmosphere during curing are highlighted. The successful manufacturing of implants using MBJ is presented, along with the need for further investigations to optimize powder flowability, reduce waste rates, and enhance material properties. The potential of MBJ in the medical sector and the importance of powder recycling are emphasized as future research directions.

I. Introduction

Developing personalized solutions for medical applications is essential to create new treatments that do not impede the patients comfort and joint movement [1]. Additive Manufacturing (AM) offers many characteristics to successfully industrialize custom made and patient specific implants [2]. This motivation is constantly driving the development of AM processes using biocompatible materials such as titanium. In recent times Metal Binder Jetting (MBJ) has become a promising alternative to other powder-based AM technologies such as laser powder bed fusion (L-PBF) [3,4]. Using only a binder to pre-bond the powder to create green parts for sintering avoids the introduction of residual stresses which is typically seen in laser-based manufacturing methods and also allows for finer details [5], which are often necessary for medicinal applications. Swapping the laser for an inkjet printhead also means lower entry costs for the technology in the future.

To work towards the goal of industrialization of the MBJ process, the procedure itself as well as its benefits and challenges need to be studied. This paper compiles the different steps in the AM process and defines said challenges. Also, necessary or possible approaches to handle said challenges are proposed.

Within the framework of the Fraunhofer-intern research project FingerKIt, a new automated process chain for patient-specific finger joint implants, was developed. The project focuses on optimizing the manufacturing process of certified implants regarding time, cost and level of customization. The manufactured implants are specifically designed to replace finger joints with lost or restricted movement. High demands are especially placed on the comparatively small implants in terms of individual fit and biomechanical stress. X-rays of the finger bones are used to calculate three dimensional models via a new artificial intelligence supported software.

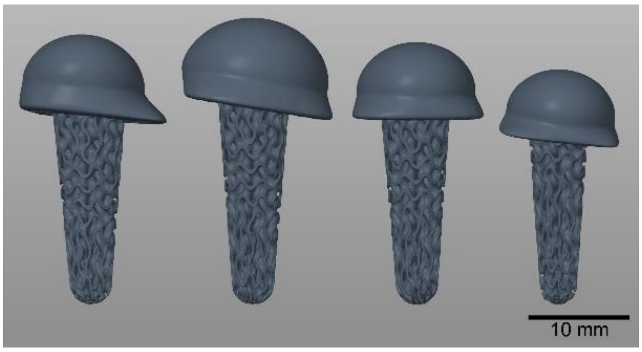

Figure 1: finger joints for metacarpal bone on index finger, middle finger, ring finger, little finger (from left to right)

An example for different finger implants for the metacarpal bones is given in Fig. 1. The size of the implant varies depending on the finger joint and the patient. The depicted joints range from about 22 mm to 27 mm in height.

These models then can be used to create the detailed implants with MBJ. In this publication, the specifics of the binder jetting process route used within the project are discussed in more detail [6].

With MBJ being a sinter-based AM technology, the used powder needs to be finer than those used in other AM processes as L-PBF to uphold a certain level of sinter kinetic. Smaller particles however result in a more cohesive powder which impacts the flowability negatively [7,8]. Determining the impact of the flowability in the process using titanium powder is an important step to fully quantify and assess their influence. Necessary steps or changes in the process should then be discussed.

Ti-6Al-4V is one of the most commonly used titanium alloys because of its good mechanical properties caused by the aluminum as a α-phase stabilizer and vanadium as a β-stabilizer, which is why it is used for this project [9].

The usage of titanium and titanium alloys brings a lot of chances regarding implant technologies, but also creates challenges for the process because of its properties.

One of the downsides when using titanium powder is its reactivity with oxygen which can lead to fires or explosions if improperly handled. The risk of dust explosions, caused by dispersed powder in air, rises the finer the used powder is. Therefor extra steps in terms of work safety should be considered. Implementing those without unnecessarily prolonging the manufacturing process should be discussed. Another challenge is its tendency to absorb different elements like nitrogen, carbon and oxygen at higher temperatures which effect its mechanical properties, especially causing the material to embrittle [10,11]. The temperatures used in the manufacturing process but also during powder conditioning should be documented and kept as low as possible to ensure consistent part quality.

II. Material and methods

The first step in the process chain of MBJ is the preparation of the powder to ensure a consistent part quality. Virgin powder normally does not require any conditioning, however, already used metal powders should be sieved and dried beforehand to optimize the flowability of the particles. Sieving mainly removes agglomerations of powder caused by binder residues or interlocking due to deformed particles. Drying the powder at low temperatures reduces the humidity and therefore the capillary forces in between the particles restricting its flowability.

In this case a gas-atomized titanium alloy powder (Ti-6Al-4V) with a particle size distribution (PSD) between 5 and 25 µm was used (the exact distribution can be found in Table 1). The PSD was determined with the Camsizer X2 using dynamic image analysis.

Table 1: Particle size distribution for the used powder determined by Dynamic Image Analysis (DIA)

D10	D50	D90
9.2 µm	15.3 µm	21.2 µm

The printing process itself, conducted on a Digital Metal DM P2500, consists of dispensing a thin layer of metal powder onto the print bed and afterwards applying the water-based binder via a printer cartridge to the sections that create the implant later on. The layer height for these prints was 36 µm. These steps are repeated until all of the parts are built. The unbound powder in the print bed acts as support material for the parts, which allows for intricate designs with large overhangs and undercuts.

Since it is not bonded with the actual part, it almost can be fully reused. The achievable level of detail is especially relevant in the medical sector because it allows for the manufacturing of optimal surface properties for bone growth to ensure a proper connection of the implant to the bone [12]. An advanced example for such geometries is triply periodic minimal surfaces (TPMS) as shown in Fig. 2 on a test specimen for in-vitro push-out tests.

Figure 2: Example for triply periodic minimal surfaces (TPMS)

In the next step, the applied binder needs to be thermally cured to strengthen the green parts for depowdering and part handling. When moving the print box, it is covered to ensure that none of the powder is being dispersed into the air to avoid the mentioned dust explosions. For curing a Nabertherm oven with a set temperature of 200 °C over a time of 2 hours and a heating ramp of 2.5 hours is used to fully harden the binder. The parts are treated under ambient atmosphere.

The parts are now stable enough to be depowdered, the process in which all of the unbound powder is removed. This process still needs to be done carefully, as the part is only held together by the binder. The utilization of a closed box and a compressed air pistol is commonly used to remove the excess powder especially from small spaces. However, because of its reactive nature titanium should only be depowdered in an inert environment and when possible with a brush as to disperse as little powder as possible and to avoid dust explosions. For this work a glovebox with nitrogen atmosphere was used.

In the next step the cured binder is thermally degraded. By heating the green part to a specific temperature most of the binder breaks down leaving only a carbon component which ensures that the particles are held in place for sintering without interfering with the sintering process. The so-called brown parts are very fragile and need to be handled carefully to avoid damaging them.

Both debinding and sintering took place externally at Element22 GmbH in Kiel. For these specific parts the patented process according to EP 3 231 536 A1 is used. This method is defined by a lower than normal sintering temperature (maximum of 1100 °C) for less than 5 hours under an atmosphere with reduced pressure. To ensure the complete sintering of the parts a PSD <25 µm is required because of the higher sintering kinetics. An additional sinter support, in which the implant can be placed is manufactured to help keep its shape (Fig. 2 on the right). The coating, used to prevent the two parts from bonding, is a ceramic based releasing agent. An example for a sintered implant is given in Fig. 3 on the left.

Figure 3: Sintered finger implant (left) and sinter support (right)

After this step the parts have their final mechanical properties. Due to the MBJ process the parts need minimal reworking, only gliding surfaces like the socket or joint head should be polished afterwards. A pair of joints, finished with electropolishing, is depicted in Fig. 4.

Figure 4: Finished finger joint implant for the proximal phalanx (left) and metacarpal bone (right)

III. Results and discussion

The study was conducted to identify the different steps necessary for the MBJ process and as a proof of concept for its application in the FingerKIt project.

All parts were successfully manufactured using the described methods. MBJ is a promising process for manufacturing personalized implants in the medical industry.

The use of Ti-6Al-4V powders with fine particle size distributions is feasible, however, during the printing process some process fluctuations were detected.

First of all, even though the powder was dried, examination showed a diminished flowability of the powder, most likely caused by the smaller particle size distribution compared to more commonly used powders. A further examination of the drying process could shed light on how to best minimize this effect. Flowability of the powder should be defined by using the rotating drum principle to measure the avalanche angle.

The powder was exposed to air especially during the drying and curing process. The influence of different atmospheres during those steps should be quantified using a mass spectrometer to monitor oxygen, nitrogen and carbon pickup. Works carried out on different MBJ systems and with stainless steels suggest that the atmosphere chosen for curing may have an effect on green part strength [13]. A flexural test can be used to quantify this hypothesis.

The safety measures that were taken when handling open titanium powder, did not slow down the manufacturing process.

During depowdering and sieving a certain amount of powder could not be recycled. An adjustment of the process to reduce waste-rates in manually performed tasks should be examined.

IV. Conclusions

The MBJ process itself is able to produce high quality parts with unique characteristics. Its ability to form intricate surfaces and 3D-models and therefore its application in the medicinal sector should be explored further.

However, more investigations on Ti-6Al-4V are necessary in order to achieve lower waste rates during depowdering. In addition, it should also be investigated to what extent different curing and drying strategies influence the carbon and oxygen pick-up over the entire process chain.

To reduce the cost of manufacturing and to lessen the environmental impact of the process, powder recycling and its effect on green part and finished parts should be studied furthermore. A possible approach would be to cure and dry the parts and powder under inert atmosphere to reduce the absorption of carbon and oxygen, which can influence the material properties negatively. The impact of drying time and temperature can be analyzed by using design of experiments (DoE) to determine the significance of the effects on this process. Furthermore, the influence on PSD during recycling should be studied. The recycling of powder would contribute to a manufacturing process with little to no waste.

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AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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