Comparison of SLM and conventionally produced implants using dynamic biomechanical loading

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Abstract

Conventionally produced titanium grade 2 medical implants were compared to replicas made by Selective Laser Melting (SLM); a biomechanical test set-up was used to determine fatigue performance. SLM production parameters, building direction of the implants and post-processing heat-treatment were optimized with respect to tensile strength. These optimized settings were used to manufacture the implants for biomechanical fatigue testing. Additionally, dimensional accuracy of these parts was measured and compared to the CAD models.

Keywords: Additive Manufacturing, Selective Laser Melting SLM, cp titanium grade 2, comparison, dynamic load, wrist arthrodesis plate

Introduction

Selective Laser Melting (SLM) is becoming increasingly relevant for medical implant applications [1]. SLM is an additive process that allows generation of complex 3D parts. A laser beam's thermal energy is used to selectively melt metallic powder particles arranged in a thin layer onto a building stage; after formation of a complete layer, the building stage is descended, a new layer of powder is deposited and the laser passes again, selectively melting another layer onto the previous one. The beam path is computer-controlled and follows previously defined cross sections derived from CAD designed volumetric data.

While SLM is already used for manufacturing of some implants, there are still concerns regarding processing accuracy and fatigue performance of the finished parts. The present study investigates these geometrical and mechanical aspects with comparing conventionally (subtractive) machined and SLM (additive) generated parts; the design corresponds to a commercially available wrist arthrodesis bone plate (Fig. 1).

Fig. 1: Left: Medartis wrist fusion plate spanning the radio-carpal and mid-carpal joint. Right: SLM replica.

Total wrist arthrodesis is a reliable treatment for painful wrist conditions, caused e.g. by arthritic or post-traumatic joint degradation [2]. Depending on the medical condition, wrist arthrodesis may include the mid-carpal joints including or excluding the carpometacarpal (CMC) joints [3]. The plate used for testing is intended for fusion of the radio-carpal and carpal bones, sparing the CMC joints and is supposed to provide stable fixation until bony union has occurred which can typically be expected 4 – 6 weeks post-operatively.

Materials & Methods

Initially, the influence of SLM building direction and the post-processing heat-treatments were optimized with respect to maximized ductility and tensile strength. Tensile probes (acc. DIN 50125 - C 5 x 25) were produced at 0°, 45° and 90° (angle between probe's longitudinal axis and the building platform). To increase ductility, all probes were heat treated under inert atmosphere in a chamber furnace (Nabertherm N60/85, Lilienthal, Germany).

Even though the wrist fusion plate tested (Medartis APTUS 2.5, A-4760.01) can be used with locking screws (TriLock) we decided to only use non-locking screws due to simpler screw hole design required. An appropriately prepared CAD model was used to reproduce the plate with SLM (SLM 250HL, SLM-Solutions, Lübeck, Germany). Cp titanium grade 2 (acc. ASTM F67) was used for all plates (SLM: SLM-Solutions; conventionally machined: Signer Titanium, Freienbach, Switzerland).

The Medartis plates, hereinafter referred to as "commercial", were produced using standard milling and drilling procedures followed by mass finishing, electropolishing and anodization. SLM plates were manufactured using two different approaches: SLM plates designated "native" were tested "as is", i.e. without mechanical post-machining. SLM plates designated "hybrid" were CAD designed for mechanical post-machining of the screw holes: screw holes were reduced in size by 0.3 mm in the CAD model and machined free-handedly to remove the allowance of 0.3 mm.

This distinction in screw hole manufacturing was made in order to test its influence on fatigue. Furthermore, the usability of native SLM parts without mechanical post-processing steps should be verified with the goal of easy and affordable implant production

Since it is known that the building direction of SLM has an influence on mechanical properties [4] and that vertically (z-axis) built tensile probes are less tensile than probes produced horizontally, all plates in this study were produced vertically ("worst case" direction) in layers of 30 µm.

To achieve thermal stress relief after SLM, implants were heat treated (while still on the platform) under inert gas atmosphere according to above described process. All SLM plates were subsequently mass finished according to Medartis' internal specifications.

Dimensional accuracy was measured using optical 3D scanning methods (Atos I, GOM, Braunschweig, Germany).

A simplified wrist model approximating the anatomical situation was used for biomechanical testing; fixtures were produced from glass-fiber reinforced polyamide (PA) using Selective Laser Sintering (EOS GmbH Electro Optical Systems, Krailing, Germany) (Fig. 2).

Fig. 2: Wrist fusion plate mounted on the simplified wrist model for dynamic load (arrow) testing.

Implants were mounted to the substrate using Ti6Al4V non-locking implant screws (APTUS A-5700.xx). The axial load was transferred at a defined distance from the radiocarpal joint through a bearing onto the PA fixture (Fig. 2, left). A parallel bearing was used to inhibit shear forces.

Fatigue testing was performed using a servohydraulic dynamic testing machine (LFV 5–PA/EDC 120, Walter & Bai, Löhningen, Switzerland) following a modified Locati approach [5,6]. Load was increased after an initial 50’000 cycles and again after every subsequent 10’000 cycles, until failure (fracture or deformation, d_{max}, ≥ ±10 mm). Initial load was 70 N, subsequent load increases were 15% each. Sinusoidal loading was carried out at 4 Hz and the ratio ($R=F_{min}/F_{max}$) was 0.1. Maximal loads and deformations were recorded.

Results and Discussion

As expected, SLM tensile probes produced horizontally showed better mechanical properties; compared to vertically built samples an 8% improvement in yield strength was observed. Heat treatment at 550°C for 1h resulted in samples with an ultimate tensile strength of 680 MPa and an elongation at fracture of 22%. As defined previously and to cover "worst case" conditions for implant manufacturing, we decided to use vertically produced SLM implants throughout this study; during manufacturing plates therefore needed minimal support on the palmar side (contact surface with carpal bones) only.

Subsequent 3D scanning showed this area to be bent slightly upwards (max. +0.12 mm) while the remainder of the surfaces had a geometrical deviation of roughly ± 0.08; heat treatment seemed to slightly decrease geometrical accuracy compared to the CAD file (Fig. 3).

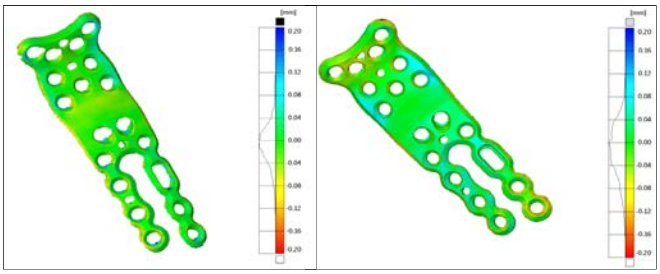

Fig. 3: Geometrical accuracy check. Left: before heat treatment. Right: after heat treatment.

Fatigue tests showed a diverse picture: while no production method seemed to perform better in terms of fatigue life and fatigue strength (Fig 4, top and middle), SLM produced parts are stiffer and less ductile than the conventionally produced parts (Fig 4, bottom): while the maximum deformation of the conventionally produced parts lies around 5 mm, the SLM parts (both hybrid and native) had maximum deformations of roughly 2.5 mm. This proved to be the case not only at fracture but throughout the load profile, i.e. the higher ductility was apparent even at low loads. Also, parts produced with the hybrid method show a narrower distribution of fatigue life and strength, indicating that the better surface quality in the screw holes may indeed postpone crack initiation.

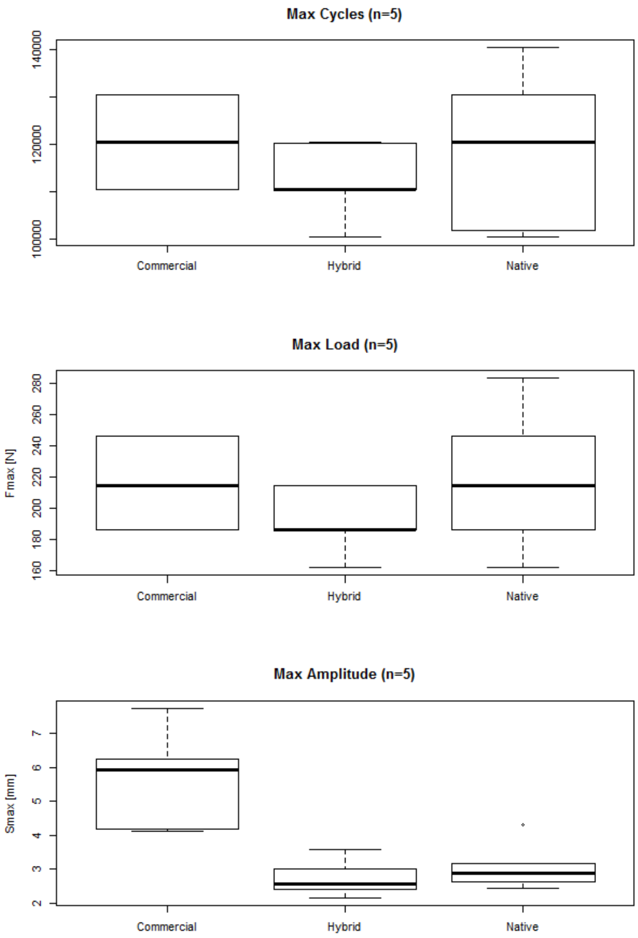

Fig. 4: Results of fatigue test. A comparison between commercially machined plates (Medartis), SLM hybrid plates (machined screw head cavities) and SLM native plates.

Conclusion

Ideal and worst case production processes for cp titanium grade 2 SLM parts were established using tensile test samples. Fatigue performance of wrist fusion plates manufactured conventionally and using SLM was compared in a biomechanical test set-up that simulates typical loading scenarios after wrist arthrodesis surgery. SLM plates were used "as is" ("native") and after mechanical post-processing ("hybrid").

We found that all three groups had comparable fatigue life (number of cycles until fracture) and strength (load at failure) indicating that the surface quality may not have a large influence under the load case used. The tests also showed that the SLM manufactured plates were stiffer and less ductile (i.e. showed less deformation) than the conventionally machined parts. Whether this is due to the base material used or a result of the SLM process or the subsequent heat treatment could not be determined and needs to be investigated throughout further post-processing steps such as heat-treatment with higher temperatures or hot isostatic pressing (hip) processes.

References

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