COMPARISON OF SELECTIVE LASER CENTRIFUGAL CASTING AND SINTERING TECHNOLOGIES IN MANUFACTURING OF PERSONALIZED JAWBONES FIXATION PLATES

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Abstract: Personalized bone fixation plates would shorten maxillofacial surgery time. However pre-clinical assessments of manufacturing deviation and quality of materials are required. The hypothesis was that the use of titanium or cobalt alloys or zirconium ceramics affects the personalized bone plate technological inaccuracies. Individual bone plates were designed. The wax plate was milled in CNC and casted with Co-Cr alloy (Remanium 2000+). Second plate was made with SLM of Ti6Al4V alloy powder with granulation of 15-45 μm with a 1070 nm ytterbium-fiber laser (AM125, Renishaw). Third plate was sintered from Y-stabilized tetragonal zirconia. Manufacturing accuracy was found on sufficient level and satisfactory typical microstructures with correct grains and phases were showed. Zirconia plates showed slightly better accuracy.
Key words: personalized bone plate, titanium alloy, casted cobalt, selective laser melted (SLM)

1. INTRODUCTION

Computer aided design (CAD) of implants together with computer aided manufacturing (CAM, 3D-printing) allow a patients to have personalized implants which reveal features more favorable than implants produced serially [1,2]. However, many areas of reconstructive engineering expect verification and rationalization of available treatment methods, as well as improvements in traditional surgical management. Such area may be the use of personalized bone fixation plates for maxillofacial and skull surgery, especially during orthognathion osteotomy [3-5]. During a few hours of surgery, a significant amount of time is taken up by bending a prefabricated plates and fitting to the bone shape, and then positioning the bones in a new position. The introduction of rapid prototyping into the clinical practice is associated with the analysis and evaluation of widely available CAD/CAM systems and the selection of materials and adequate favorable technology. In addition to metal materials that have sufficient biocompatibility [6,7], yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) [8-10], especially for dentures has gained considerable popularity due to the ease of machining of the personalized shapes before sintering process, but also for implants [11-13]. The different processes and material phenomena accompanying the technology determine the manufacturing deviations, which are presented by the technology suppliers. However, in the case of jaw fixation plates, the design, technologic and load bearing conditions differ from standard dental applications. Recently, only in the one work [5] was shown pre-clinical verification of strength of ceramic materials in application to fixation of maxillary osteotomy only during the transfer of bilateral symmetrical and vertical occlusion loads [5]. Meanwhile, unilateral and oblique forces are generated with mandibular muscles [14-16], which together with tissue/implant contact and tribological phenomena determine selection of materials [17,18] for appliances that are working in oral cavity [19,20].

The aim of the work was to assess the dimensional accuracy of individual jaw fixation plates made with three variable technologies and materials: casted cobalt alloy, sintered YTZP and selective laser melted (SLM) titanium alloy. The hypothesis was that the use of titanium or cobalt alloys or zirconium ceramics affects the personalized bone plate technological inaccuracies.

2. EXPERIMENTAL

2.1 Design of bone fixation plates and osteotomy

Assessment of the dimensional accuracy of different technologies and strength analysis of the individual bone fixation plates required the development of the CAD design of the assembly of plates and osteotomy. In the initial stage it was necessary to perform a 3D model of the maxilla (Mimics, Materialise) of the patient with a planned orthognathic surgery based on computed tomography (CT). The next stage was the performance of the planned maxillary osteotomy in cooperation with the surgeon and reposition of the jawbones relative to the rest of the skull - Figure 1. The model of the re-positioned bones in the form of a surface triangle mesh (STL) was imported into the CAD engineering software (Solidworks), in which the plates were designed.

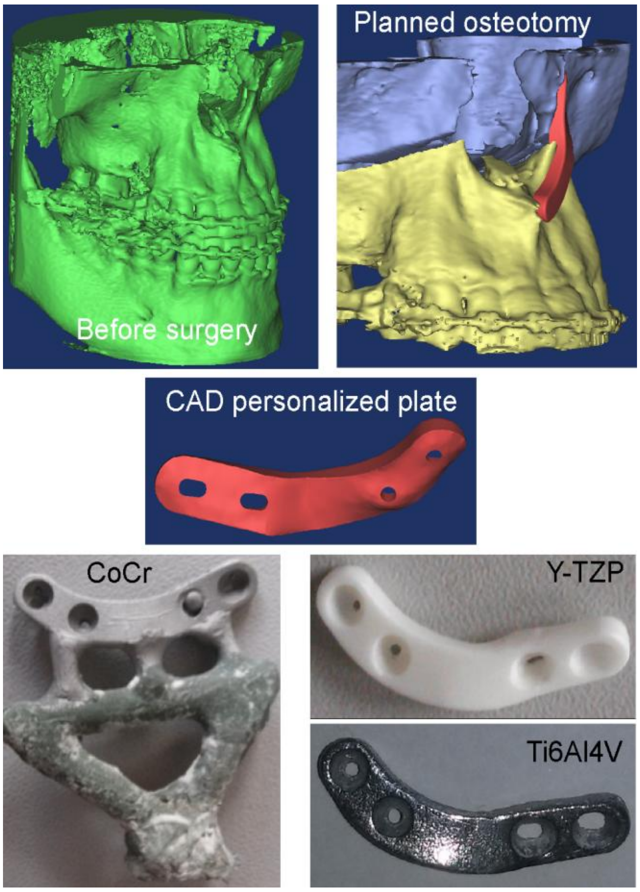

Fig. 1. View of the skull model with a designed bone fixation plate subjected to dimensional analysis of three materials and technologies: lost wax casted Co-Cr alloy, sintered Y-TZP, SLM Ti6Al4V alloy

2.2 Cobalt-chromium alloy bone fixation plate manufactured by lost-wax casting

The bone fixation plate STL model was positioned inside the wax plate model in CAM dental software (3M - Lava Desgin CAM 7 Module) to generate CNC codes. After the milling, the wax model of fixation plate was provided with a system of casting channels (2 and 4 mm in diameter) and fixed into the casting ring, which was lined with ceramic facing. Before casting, the model was sprayed with a preparation preventing the formation of air bubbles within the model. The prepared ring with the model was covered with a covering mass (Bellavest SH by BEGO) 320g mass / 72ml mixing fluid (BegoSol HE, BEGO) / 8ml distilled water / vacuum stirrer (Renfert). After 20 min, the rubber stand was removed so that the liquid wax could spill out. For the next 10 minutes the form was allowed to complete the binding reaction. The mold was placed for 40 minutes in a furnace preheated to 900°C. After firing the mass, the model was cast using centrifugal casting. The Co-Cr (Remanium 2000+, Dentaurum) alloy in an amount of 20 g was inductively melted and the liquid metal was injected by centrifugal force (Formax, BEGO) into the mold. The cast was allowed to cool in air at ambient temperature. After the mold casting was released (Figure 1), the casting channels were cut and the fixation plate was sandblasted with 50 μm alumina (Duostar, BEGO) and polished.

2.3 SLM Ti6Al4V alloy fixation plate

Ti6Al4V alloy powder with granulation of 15-45 μm was used. SLM of the bone fixation plate was made with a 1070 nm ytterbium-fiber laser (AM125, Renishaw) under an argon atmosphere. The bone fixation plate STL model was planned (AutoFab) in the working area in a position on the side wall, in order to obtain the best quality of the upper and lower surface of the plate. The melting parameters were: laser power of 150 W, powder diameter of 20 μm, fused layer thickness of 30 μm. In the subsequent stages, the bone fixation plate was grinded and polished (Figure 1). After the selective laser melting process was completed, the finished element was subjected to appropriate heat treatment - in this case it was stress relief annealing. The process was conducted in a high temperature furnace (HT-2100-G-Vac-Graphit-Special, Linn), a two-chamber vacuum furnace with a system of hardening to remove stress may arise as a result of sample preparation.

Parameters of heat treatment process: 1. Draining the oven for 30 minutes. 2. Heating in an Argon 60 atmosphere for 2 hours. 3. Soaking in Argon 60 atmosphere for another 2 hours. 4. Free cooling in an argon 60 atmosphere for 1h. Vacuum generation in a subsequent cooling stage (vacuum value $6.8 \cdot 10^{-3}$ [bar]).

2.4 Sintered Y-TZP bone fixation plate

The bone fixation plate STL model was in CAM (3M - Lava Desgin CAM 7) software increased by the size of the predicted contraction during sintering. After milling from a block (3M - Lava

CNC 240, 3M) the connectors were cut off from the bone fixation plate and the places were smoothed. The bone fixation plate in the next step was subjected to sintering (3M -Lava ESPE Furnace 200) with a heating rate of 720°C/h and sintering 1470°C/2.5 h. After cooling (Figure 1), the plate was subjected to standard sandblasting with 50 µm/3.5 bar alumina to induce the strain-induced transformation of the tetragonal to monoclinic phase in order to hinder the propagation of microcracks on the surface, thereby strengthening its structure.

2.5 Dimensional deviations and microstructures of the bone fixation plates

Dimensional deviations were investigated with optical scanner (3D Comet 6, Zeiss) characterized by a scanning resolution of 16 million pixels, which allows to obtain a digital model with an accuracy of 6 µm at a working area of 15 by 15 cm. The patches created during scanning were combined together until the complete model was obtained. Measurement data was compared to the primary CAD model. Samples for microstructural study were cut from plates and hot-included in resin (Condufast Black, Streues/CitoPress-20, Struers). The sections were obtained by grinding (120, 500, 1200 and 4000) and polishing with 9, 3 and 1 µm diamond suspensions. Royal water was used to reveal the structure of Co-Cr alloy (etching time 5s) and 3% HF+65% HNO3 solution reagent to titanium alloy structure (etching time 15 s). The Y-TZP structure is revealed by temperature etching (6 min) at 100°C below sintering temperature [21,22] (Figure 2).

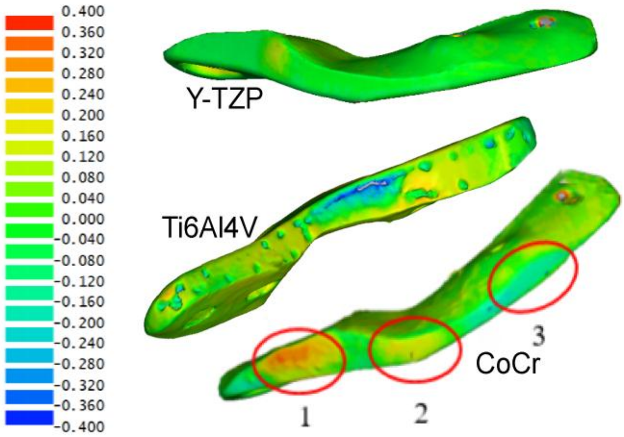

Fig. 2. Distribution of dimensional deviations in plates: sintered Y-TZP, casted Co-Cr alloy and SLM Ti6Al4V alloy

3. RESULTS

Dimensional deviations of bone fixation plates made from variable materials and technologies are presented as maps on Figure 3. Deviations at the control points on the upper, lateral and lower surface of the plate were also determined. Dimensional analysis of the casted Co-Cr plate showed deviations for the lower surface to 0.137 mm, while for the upper surface it was 0.026-0.115 mm. The SLM plate characterized by good surface quality, except the supporting wall, on which unevenness remained after the supports. Dimensional deviations of the SLM plate were 0.036-0.116 mm on the upper surface and 0.020-0.123 mm on the lower surface. Dimensional deviations of the holes between the STL model and the scanned SLM plate was 0.05-0.11 mm. Dimensional deviations of the Y-TZP plate were 0.005-0.046 mm on surfaces and at the limit of measurement error on the holes. In case of plate of 3 mm nominal thickness the dimensional accuracies there were at the level adequate for the 10 class of machining only for Y-TZP while there were at the worse classes in the metallic plates. In the presented structure of the casted Co-Cr alloy (Figure 3), the carbides showed a continuous form and were placed on the grain boundaries. The structure of this type is obtained when the casting process occurs quickly and without overheating. Microstructure of Ti6Al4V (Figure 4) was different from ones obtained under the slow cooled conditions via powder metallurgy (Figure 5) [25,26]. Texture in growth direction was visible and bimodal (alfa+beta) microstructure together with lamerall martensite phase in longitudinal and transversal cross-sections.

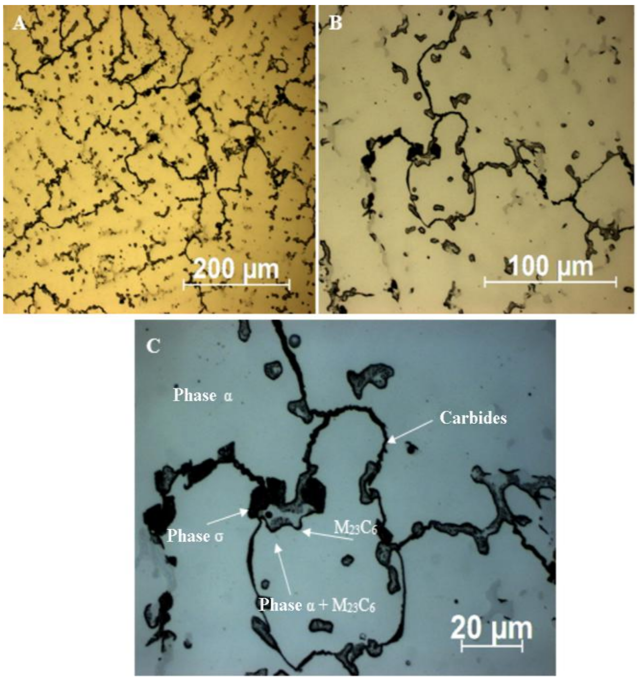

Fig. 3. Microstructure of casted Co-Cr (Remanium 2000+)

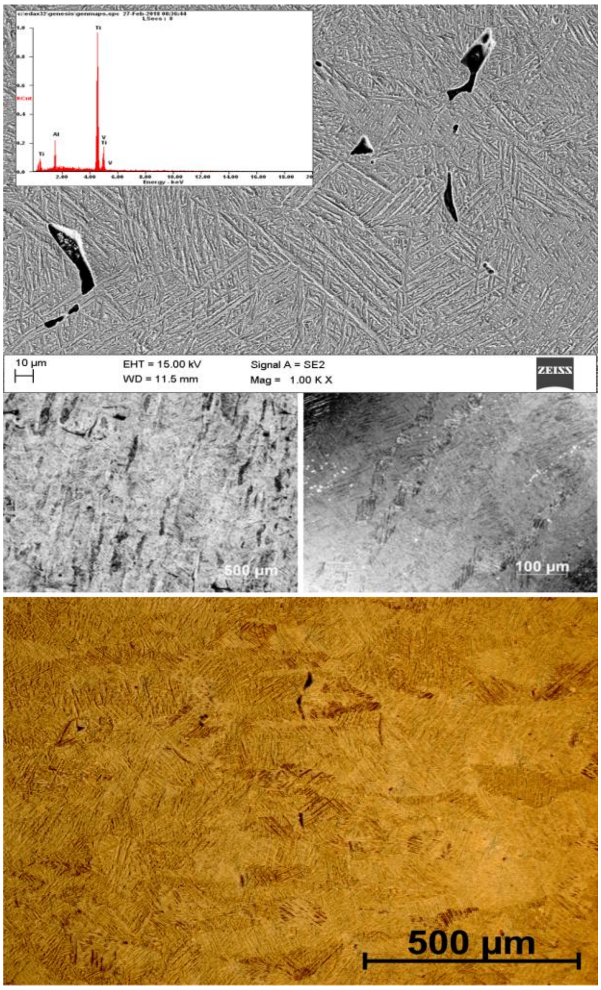

Fig. 4. Microstructure of SLM Ti6Al4V.

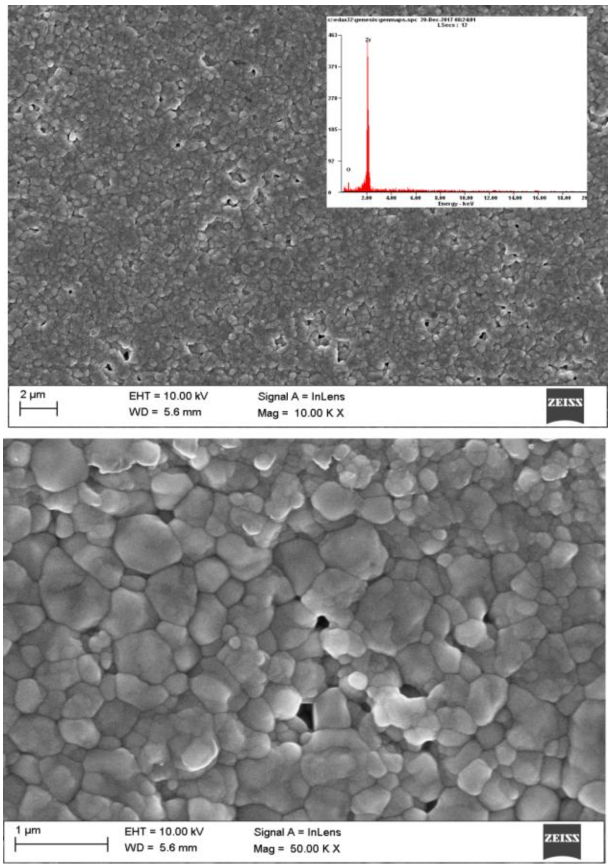

Fig. 5. Microstructure of sintered Y-TZP

4. DISCUSSION

The development of the methodology for the implementation of personalized plates for bone fixations is dictated by the need to simplify and shorten the duration of planned operations. The study presented so far focuses mainly on the aspects of improving virtual surgical planning (CAD) [2], plates design and the transmission of occlusal loads [3,5]. Meanwhile, the advantage of using miniplates osteosynthesis is elimination the necessity to use jaws immobilization what favors better eating in rehabilitation and hygiene, especially important in oral cavity [27,28]. Intermaxillary mobility is permissible only if the fixation plate provides good stability, which is guaranteed by sufficient dimensional accuracy and mechanical properties of the material. Dimensional deviations of plates which introduce occlusal disorders are unacceptable, because in clinical practice they may result in pathologic muscular activity and overloading of temporo-mandibular joints together with serious and difficult to cure pain [29,30].

Detection of occlusal discrepancies in dental practice is usually about of dozen micrometers. Plates which are bended manually by surgeons does not seem to fit better. Therefore achieved in the study accuracy of surfaces adhering to bones was on satisfactory level albeit Y-TZP showed lower values of deviation despite of sintering shrinkage. The holes in metallic plates required further machining for achieve adequate tolerance when holes in YTZP plate was on level about 5 machining class adequate for achieve fit with bone screw. Microscopic examination of both metal and ceramic plates revealed typical correct microstructures which confirmed correctness of technological processes. Microstructures have been tested to ensure the material quality and their strength, instead of time-consuming and costly mechanical tests. Y-TZP is bioinert ceramic [31,32] what is favorable in fixation plates because of problems during its removal when bone has grown to plate. Metallic plates can be also bioinert after coating with layer of aluminum or zirconium oxide with use atomic layer deposition [33,34] or sol–gel [35] technology. However coating behavior under tension and during contact friction with cortical bone must be still investigated, especially that the significant influence of medical sterilization on the physical and chemical properties of oxide layers is shown [36]. Manufacturing a personalized plate from Y-TZP in the entire volume does not extend the waiting time required for additional coating process. Y-TZP is controversial due to the decrease in strength in wet environment and human body temperature [8]. Strength decreases together with aging in human body as a result of transformation of metastable tetragonal phase to monoclinic. However, this problem does not apply to short-term use of fixation plates, hence Y-TZP is favorable due to its initial high strength and was chosen in our study as material clinically tested and commonly available [8,9,11]. On the other hand, metallic plates are categorized as standard [3,4,37] for bone fixation in regard of their strength. The study indicates that further pre-clinical investigation of realistic technologic fit between screw and hole is required because of fracture behavior of ceramic materials while plasticity of metals allows equalization of a local overloads.

5. CONCLUSIONS

Cobalt and titanium plates showed correct microstructures albeit dimensional accuracy was best for Y-TZP plate, especially for the holes. Among metallic plates the SLM technology showed better robustness before casting plate where was required further machining because of the foundry defect in a bone screw hole. Bioinert Y-TZP was selected as surgically unproblematic material during bone plate removal due to lack of osteointegration. However the Y-TZP bone plate strength verification is required in the future.

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