

# Rapid Manufacturing of Ceramic Components for Medical and Technical Applications via Selective Laser Melting

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## Abstract

The recent activities at Fraunhofer ILT to develop the Selective Laser Melting (SLM) process for the direct manufacture of ceramic components are presented.

The work focuses on two different materials: Zirconia ceramics and tricalcium-phosphate (TCP) ceramics.

Applications for a rapid manufacturing process for zirconia are e.g. the manufacture of customized dental restorations or technical applications where high strength, wear resistance and heat resistance are required. The zirconia is processed by direct laser melting. The ceramic powder is completely melted and thus a very high density of the created part is achieved, without any post-processing. A problem to be solved is the limited strength of the parts due to micro-cracks in the material.

The development of the SLM process for TCP ceramics is aiming at the rapid manufacture of customized bioresorbable bone substitute implants. Such implants gradually degrade during service in vivo and are simultaneously replaced by native bone material. The SLM process uses a composite material of TCP and a glass, which is melted by the laser beam and acts as a binder.

Both processes are still in a development stage. Demonstrator parts have been built and are presented.

## 1 Introduction

Laser-based additive Rapid Manufacturing (RM) systems for metallic materials have become commercially available and are used in industry. Especially the direct laser melting techniques that do not require any post-processing steps provide high part

quality out of standard materials.

Comparable techniques and systems for the processing of accepted ceramic materials are not yet available.

At the same time there are important fields of application for such RM techniques for ceramics. Generally speaking the use for the production of small quantities or single

units of a certain geometry is attractive from an economic point of view. Examples are customized products in the field of medicine such as implants or all-ceramic dental restorations, as well as prototypes or tools in technical fields.

Next to the potential economic benefit in certain cases, additive RM offers new design possibilities: The complexity of the part geometry including internal structures is almost unlimited. Compared to conventional manufacturing techniques in particular for ceramic materials, this is a notable gain.

The following article describes the state of development of two RM techniques that are currently investigated at Fraunhofer ILT. The article is subdivided into two main parts. The first describes the work and results related to zirconia ceramics, the second deals with the manufacture of implants made of bioresorbable material.

## **2 Rapid Manufacturing of ZrO<sub>2</sub>-based Ceramics**

### **2.1 Potential Applications and State of the Art**

Within the group of oxide ceramics, zirconia (ZrO<sub>2</sub>) offers the highest mechanical strength and fracture toughness as well as a very high wear resistance.

Applications include all-ceramic dental restorations, components for hip joint prostheses, wear resistant parts for the textile industry such as thread guides, cutting inserts for machining of steel and casting shells for precision casting. Existing additive RM techniques for high strength ceramic materials such as 3D printing, stereolithography or selective laser sintering require sintering post-processing steps. In many cases also a debinding step to remove a polymer binder is necessary [CIMA01], [BERT04]. The company Phenix Systems offers a selective laser sintering system that is also suitable for binderless processing of

zirconia [PHEN06]. However, information about the properties of the created parts such as mechanical strength is not available. The manufactured parts are porous and require sintering post processing.

Sintering post-processing for densification always results in shrinkage of the part. In addition, due to the layer-wise manufacturing process this shrinkage is often non-isotropic and limits the dimensional accuracy of the part.

### **2.2 New Approach: Direct Melting**

The new approach that is currently being developed at Fraunhofer ILT is based on direct and complete melting of a ceramic powder material by means of a laser beam. The powder material used consists of zirconia with small additions of other oxide ceramic materials. It does not contain any glass nor any metallic component.

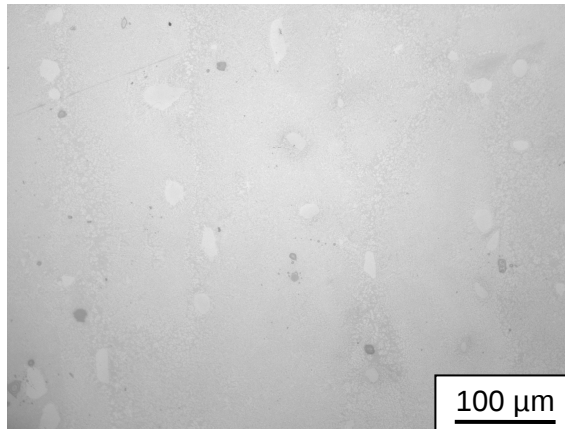
The SLM technique is a powderbed-based additive Rapid Prototyping or Rapid Manufacturing technique. Parts are built layer by layer according to CAD data. The SLM manufacturing process comprises the following steps:

1. The CAD data are pre-processed (slicing, generation of scan vector data for each layer).
2. A thin layer of powder material is deposited on the build platform.
3. The appropriate areas of the powder layer are selectively heated and melted by means of a focused laser beam. For this purpose the laser beam is deflected by a scanning head with two galvanometer driven reflectors.
4. The build platform is lowered by a distance corresponding to the layer thickness.
5. Steps 2 to 4 are repeated until all layers have been built up. The surrounding loose powder can then be removed and the part can be separated from the build platform.

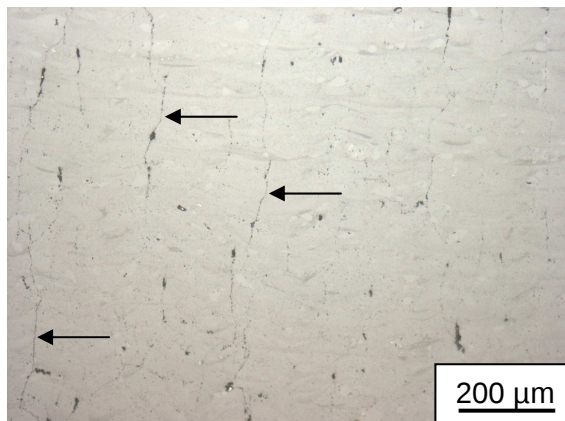
Manufactured parts have a very high density. The cross section in Figure 1 demonstrates that there is almost no

porosity in the part. The high density results from the complete melting of the powder material and is achieved without any post-processing.

However, all manufactured parts contain a large number of micro-cracks as shown in Figure 2 (see arrows). The cracking occurs during the build process and is caused by thermal stresses.

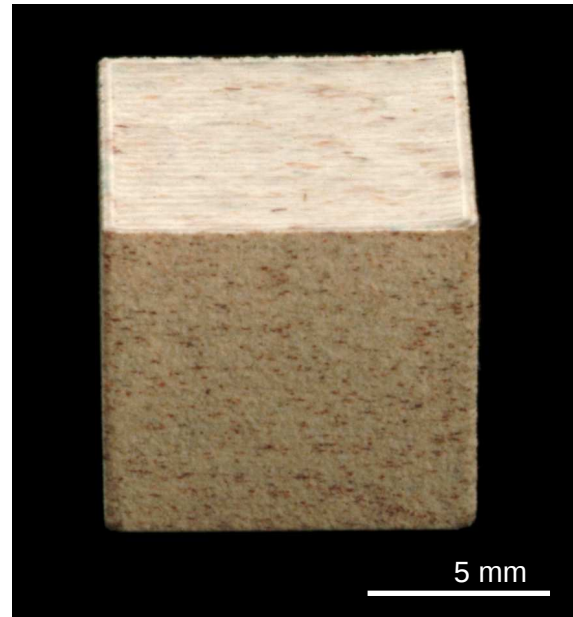


**Figure 1:** Cross section through an SLM-manufactured ceramic specimen (image: optical microscope) showing the very high density

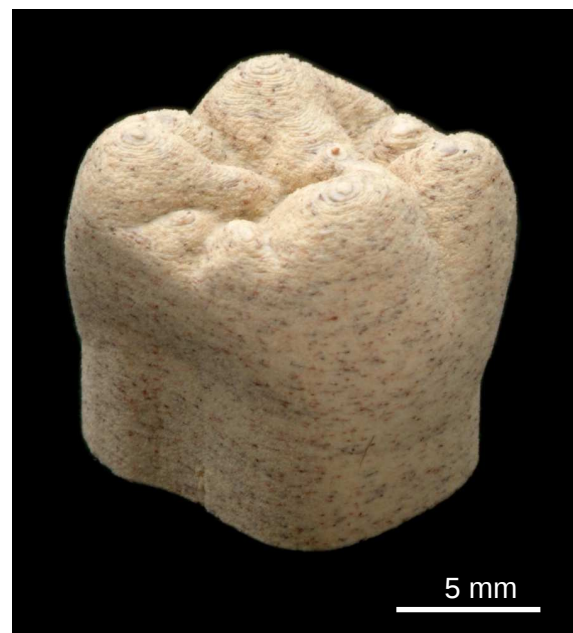


**Figure 2:** Cross section through an SLM-manufactured ceramic specimen (image: optical microscope). The arrows point at cracks in the material.

Demonstrator parts have been built and are shown in Figure 3 and Figure 4. The darker spots on the surface are believed to result from impurities in the raw material. The parts have a good surface quality and show a high geometric resolution.



**Figure 3:** Cube created by SLM out of zirconia-based ceramic material



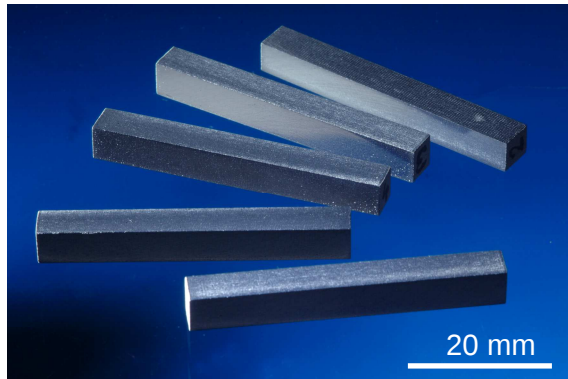
**Figure 4:** Demonstrator for an all-ceramic dental restoration made by SLM

## 2.3 Mechanical Properties

The mechanical strength of specimens created by SLM was tested using the four-point-bending method. Five specimens (Figure 5) were tested and an average bending strength of 9.79 MPa was measured.

This value is very low compared to a strength of more than 1000 MPa achieved

with this material using conventional manufacturing techniques. The low strength is due to the large number of micro-cracks that are fairly evenly distributed throughout the specimens.



**Figure 5:** Test specimens made by SLM for measurement of bending strength (surfaces are grinded)

The dark color of the specimens in Figure 5 results from a lack of oxygen in the crystalline structure. By means of an appropriate heat treatment the color can be easily turned into the bright color visible in Figure 4.

To improve the mechanical strength, current work is focusing on avoiding crack formation during the manufacturing process. It is expected that the cracking can be avoided by heating the build chamber to a sufficiently high temperature during the build process.

For this purpose a high temperature processing chamber will be designed and built up at Fraunhofer ILT.

### **3 Rapid Manufacturing of Bioresorbable Ceramic Implants**

#### **3.1 Potential Applications and State of the Art**

Bone substitute implants made of bioresorbable tricalcium-phosphate (TCP) ceramics offer significant advantages compared to metallic implants in various cases. Bioresorbable materials stimulate the self-healing process of the native bone and therefore support the clinically

preferable strategy of regenerative therapy. The implant gradually degrades during service in vivo and is simultaneously replaced by native bone material. This means that no artificial material will remain in the body of the patient. Additional surgeries for size adaptation of an implant for a child can be avoided. Metallic craniofacial implants can cause pain at elevated temperatures. This problem can be eliminated by using bioresorbable material.

Implants for the therapy of bone defects may be required in the case of congenital bone defects or due to the incidents cancer, inflammation and trauma of hard tissue structures.

Some approaches for the additive manufacturing of implants made of the calcium phosphate phase hydroxyapatite are reported in the literature. E.g. Cruz et al. describe a Selective Laser Sintering technique for the manufacture of implants from poly(L-lactide) / hydroxyapatite composites [CRUZ02]. However, hydroxyapatite does not have the excellent resorption characteristics that TCP has. It has been shown that 3D printing can be used to create hydroxyapatite bone tissue scaffolds [LEUK05]. This technique requires debinding and post-sintering, which is associated with shrinkage.

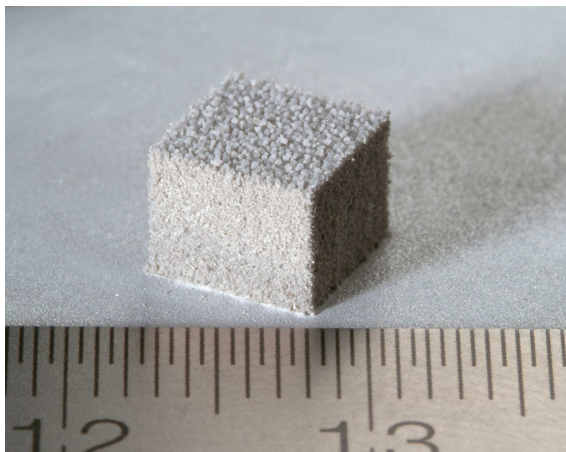
#### **3.2 Selective Laser Melting using a TCP/Glass Composite**

The laser melting approach described here does not need any sintering post-processing and thus a high accuracy and a short manufacturing time can be achieved. TCP itself is temperature sensitive and can not be heated to melting temperature without chemical phase conversion and decomposition. Therefore a composite material of TCP and a glass is used in the SLM process in a way that the glass is completely melted by the laser energy and acts as an inorganic binder. The temperature is kept significantly below the decomposition temperature of the TCP.  $\beta$ -TCP was synthesized by scientists at the Institute of Mineral Engineering (GHI),

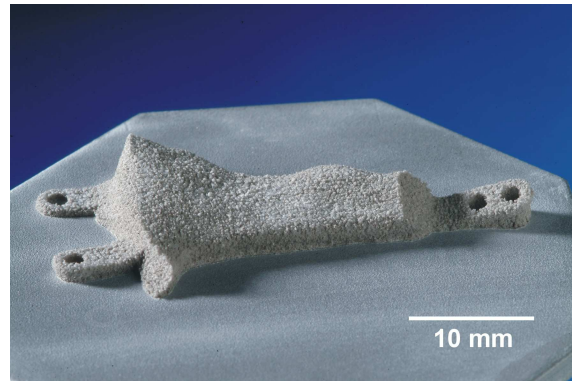
RWTH Aachen University. The  $\beta$ -TCP was mixed with an alkaline borosilicate glass at a ratio of 70%  $\beta$ -TCP and 30% glass and subsequently granulated in a spray dryer (GHI). The resulting spherical granules show a mean granule size of approx. 25  $\mu$ m.

An experimental SLM system developed at Fraunhofer ILT was employed to create three-dimensional parts from the composite powder. A comparison of experiments with different types of lasers revealed a higher absorption of the powder material at a laser radiation wavelength of 10.6  $\mu$ m ( $\text{CO}_2$  Laser) than at a wavelength of 1.064  $\mu$ m (Nd:YAG Laser). Therefore a  $\text{CO}_2$  Laser was selected as the beam source, operating in continuous wave (cw) mode. The powder layers were prepared by an automatic levelling system using a brush. For all experiments a layer thickness of 50  $\mu$ m was used.

The created demonstration parts (Figure 6 and Figure 7) show the capability of the technique to resolve small geometric features and to manufacture freeform parts. The part shown in Figure 7 is a replication of an authentic implant which was manufactured at Fraunhofer ILT out of titanium in an earlier study using the SLM technique (Figure 8).



**Figure 6:** Cuboid made from  $\beta$ -TCP/glass material by SLM



**Figure 7:** Demonstration implant created from  $\beta$ -TCP/glass material by SLM



**Figure 8:** Titanium implant of the same geometry manufactured by SLM at Fraunhofer ILT in an earlier study

The porosity of the parts is high, which makes the technique well suited for the manufacture of bone tissue scaffolds. The compressive strength of the material was determined to 0.8 MPa. To improve the mechanical strength it is intended to compact each powder layer before laser beam exposure and further adapt the process parameters.

XRD analysis of a manufactured specimen confirmed that TCP is still the dominant phase. That means that it is possible to keep the temperature during the process low enough to prevent at least the majority of the TCP from phase conversion.

Within the scope of a recently started joint project (in cooperation with GHI, RWTH Aachen and other partners) the technique will be further developed. The work will focus on an improvement of the mechanical properties and the development of a bioresorbable glass with a made-to-measure resorption capability.

## 4 Conclusion

The Selective Laser Melting technique can be used to create highly dense ceramic parts from a zirconia-based material. The high density is achieved by complete melting of the ceramic powder material. The created parts have a good surface quality, accuracy and geometric resolution. However, the parts have a low strength due to micro-cracks in the material. This problem will be addressed by heating the SLM build chamber to a high temperature during the manufacturing process. If a sufficiently high mechanical strength can be achieved, the technique can be used e.g. for the rapid manufacture of all-ceramic dental restorations. Several units could be manufactured simultaneously in one machine run and thus a cost-effective production could be realised.

It has been shown that the SLM technique is suitable to manufacture three-dimensional freeform parts from a  $\beta$ -TCP / glass composite material. The resulting parts have a good resolution and accuracy as well as a high content of the bioresorbable TCP phase. Within a current project the mechanical strength will be improved and a glass with the appropriate resorption characteristics will be developed. The technique then has a good potential for a cost-effective manufacture of customized bioresorbable implants.

## 5 Acknowledgements

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