The Performance of Laser Micro Sintering with Different Material Classes

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The generative freeform fabrication technology 'Laser Micro Sintering' was developed as a modification of Selective Laser Sintering in 2002. It owes its unique features mainly to the low grain size of the powder feedstock and a special laser regime. It has proved suitable for the production of solid components with structural features down to 30µm. The mechanism of the process differs slightly depending on the respective material. According to their process behavior the up to date employed powder materials are divided into three classes: metals, oxide ceramics and non-oxide ceramics. The essentials of the hypothesized specific process mechanisms are briefly explained and evidence is given of the technology's performance and the state of the art.

Keywords : laser micro sintering, shield effect, q-switched pulses, oxide-ceramics, non-oxide ceramics

1. INTRODUCTION

1-1. Selective Laser Sintering:

The principle of selective laser sintering is the repeated coating and selective densification (sintering) of powders or pasty materials with the ends of generating a three-dimensional body layer by layer. In accordance with the name, the sintering process is achieved by scanning a laser beam across the entire admeasurements of the intended object's cross-section **[Fig. 1]**.Since its invention by Carl Deckard & colleagues (Deckard 1986, Bourell et al. 1990) Selective Laser Sintering has been upgraded continuously to meet the requirements for the production of functional components (Shellabear & Nirhylä 2004).

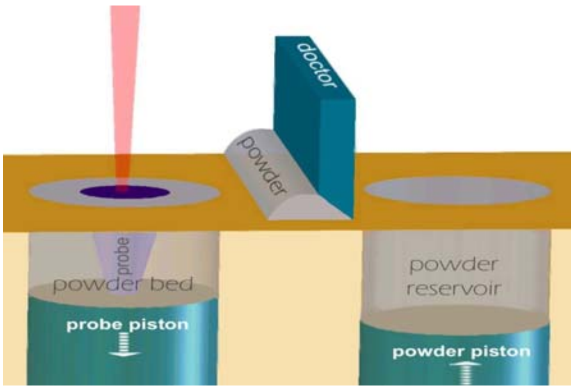


Fig. 1: *Schematic of selective laser sintering.*

1-2. Laser Micro Sintering - a Step Towards Higher Resolution:

A few years ago the improvement of the resolution for a while seemed to have reached its limit at about 100µm (Castle Island 2004). In early 2003 Laserinstitut Mittelsachsen e.V. (LIM) demonstrated that by a newly developed modification the resolution of selective laser sintering could be shifted considerably below the limits commercial SLS devices had been confined to (Regenfuss et al. 2003). The obtained structures show a resolution of less than 30 µm for overall resolution, of 20µm for ligaments and of 10µm for notches at aspect ratios of 12 and above, and presently a minimal roughness R_a of 1.5µm.

1-3. Laser Micro Sintering - the Technique and the Equipment:

The early source of the laser pulses was a Q-switched Nd:YAG – laser (λ = 1064nm) in TEM00 mode (Regenfuss et al. 2003), lately multimode pulses and other lasers with various wavelengths are used. A beam scanner with a scan field of 25mm x 25mm steers the pulses across the powder coating **[Fig. 1].** Q-switched pulses were finally chosen because of their special effects on the powder material (Regenfuss et al. 2004 & 2006). The first patent a device for laser sintering under vacuum was applied in 1999 (Ebert & Exner 1999). Since 2001 sinter machines were developed for the specific requirements of laser micro sintering: The powder coating mechanism consists of a cylindrical ring that carries a small amount of powder (around 10 cm^3), which is swept across the powder bed by the circular motion of a lever, leaving a thin powder layer that is sintered according to the respective cross section of the projected body. The powder coating device is enclosed in a vacuum tight casket with a window in the lid for the incident radiation. Within this casket the process can be conducted under a controlled and pure atmosphere which is sometimes appropriate.

2. LASER MICRO SINTERING OF METAL POWDERS

2-1. Mechanism:

The main properties of Q-switched laser pulses are that they can deliver a high pulse energies at comparably short pulse lengths, this means that high peak intensities can be achieved for a very short time.

It is meanwhile generally agreed that in the powder material the following steps occur upon the incidence of the laser pulse: Material is heated by the laser pulse and limited emanation of vapor occurs. The vapor or plasma from the emanating material and the process atmosphere in contact with the heated spot expands rapidly. This exerts a pressure on the remaining material below, forces it downward and prevents the boiling of the microscopic melt pool in the early phase of the pulse. This is observed as the 'condensing effect' of the laser pulse upon the powder layer which initially has a very low density. After the break-down of the vapor/plasma bulb spontaneous boiling occurs. These dynamic effects of the plasma and the boiling incidents cause the typical texture of a laser micro sintered metal surface and also the 'shield effect' (Regenfuss 2006) that makes it possible under certain conditions to perform the process under normal atmosphere.

Prerequisite for unwanted oxidation of the powder or the sintered material during laser sintering are firstly the availability of oxygen and secondly sufficient caloric energy for a considerable amount of material to exceed the activation enthalpy. Throughout the vapor expansion phase of the pulse event, oxidation is very improbable. There is one chance for oxidation at the beginning of the pulse when the material is heated and another one after the breakdown of the vapor bulb, as long as the temperature is high enough.

It is perspicuous that fine grained powders that usually have a very fluffy packing, are much more susceptible towards oxidation, when processed in air, than coarser grained materials with a denser packing.

2-2. Submicron Metal Powders:

Because of their higher affinity for oxidation submicron sized powders are usually laser sintered under an

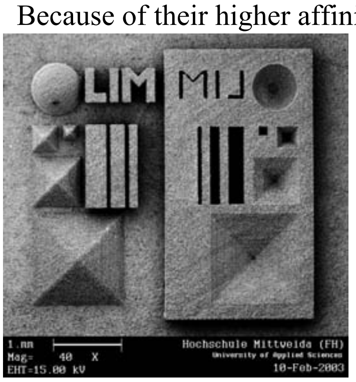
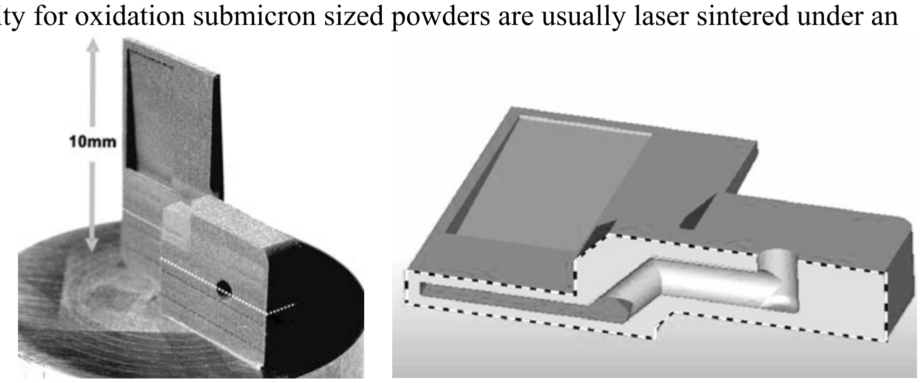


Fig. 2a: *Multi shape test structure from 0.3 micron tungsten powder.*



Figs. 2b: *First functional part (wafer positioner) from.3 micron tungsten powder. The drawing on the right shows a cross section along the dotted line in the photograph on the left. The hidden channel is visible.*

inert gas atmosphere.

Fig. 2a shows the first test structures from 0.3 micron tungsten powder. The structure was 400 µm high, maximal aspect ratios were around 10 and the minimal roughness of horizontal surfaces was in the range of $r_a \approx 10 \mu m$. The first functional part **[Fig. 2b]** was a positioning tool for a micro-manipulator. The shape and the run of the internal channel are visible in the cross sectional view.

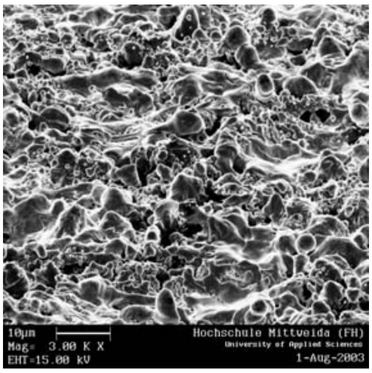


***Fig. 3a:** Surface of a laser micro sintered specimen. Minimal roughness r_a=1.5 µm.*

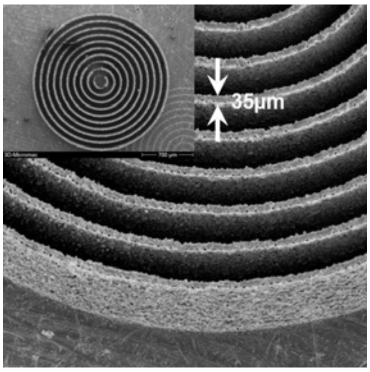


***Fig. 3b:** Top view of tungsten ligaments showing the cut-ins from the pulses.*

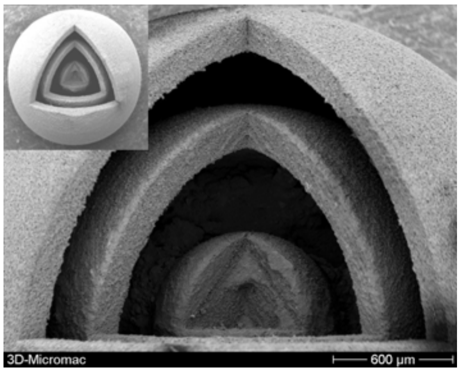


***Fig. 3c:** Blow up view of a specimen consisting of three nested spheres.*

The typical texture of a laser micro sintered metal surface is illustrated in **Fig. 3a**. Presently the minimal achievable roughness is $r_a \approx 1{,}5 \mu m$. The circular ligaments in **Fig. 3b** have a thickness of 35µm and a height of 400µm. Undercuts were realized without support structures up to an angle of 70° (20° between specimen surface and the horizontal level). The specimens in **Figs. 3c** and **4a** – three nested spheres and a double helix

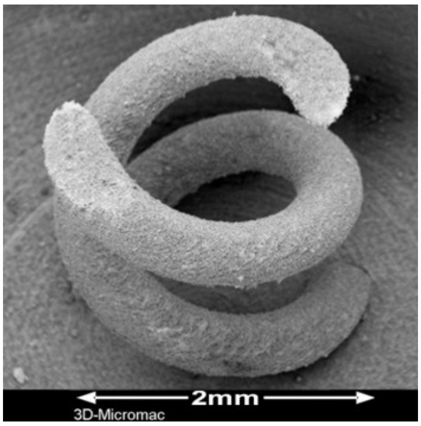


***Fig. 4a:** Double helix from 0.3 micron tungsten powder.*

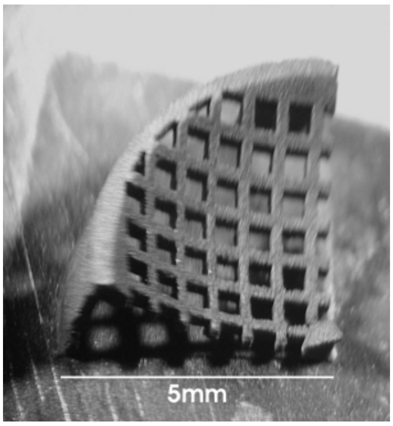


***Fig. 4b:** Tungsten grid generated with unlimited undercuts.*

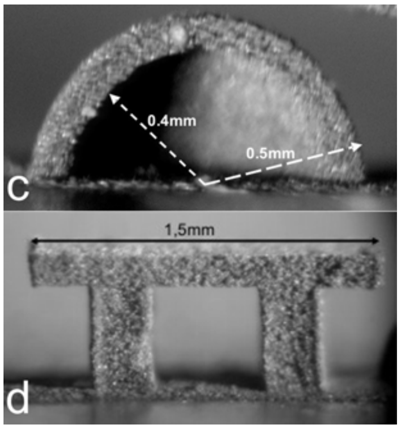


***Fig. 4c,d:** Quarter-sphere shell and traverse structure.*

- were designed to stay within these limitations.

Unlimited undercuts were realized in a partially solidified powder bed. It forms a removable matrix for the generation of solid bodies with undercuts. The samples in **Figs. 4b, c** and **d** were generated with this regime.

2-3. 1-10 µm Metal Powders:

The employment of powders with grain diameters of 1µm and above was introduced into laser micro sintering as a result of the increasing demand for microparts with highly specific material properties. As there are still a number of materials not available in smaller grains sizes, the necessary diversification of the feedstock advanced the use of powders with grain diameters of 1µm and above. Compared to the processing of finer grained materials higher sintering rates can be attained but the achievable resolution and surface roughness are coarser (Regenfuss et al. 2005). One important observation, however, was also that due to the aforementioned “shield effect” (2-1) in many cases laser micro sintering with 1-10 micron metal powders can be conducted under normal atmosphere without a noticeable content of oxide in the sintered solid.

Fig. 5a shows a triple helical structure that was sintered from 1µm grained 1.4404 steel powder. The required process time was 30 minutes. The molybdenum coil **[Fig. 5b]** was generated from 1µm sized powder. Both specimens were produced without a shield gas. The cogged wheel **[Fig. 5c]** was sintered from 2 micron sized silver powder. Its destination was functional prototype for a stent positioning device. Silver

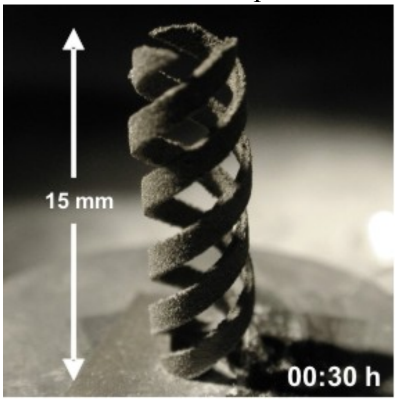


Fig. 5a: *Triple helix (10 micron stainless steel powder; normal atmosphere; 30 min process).*

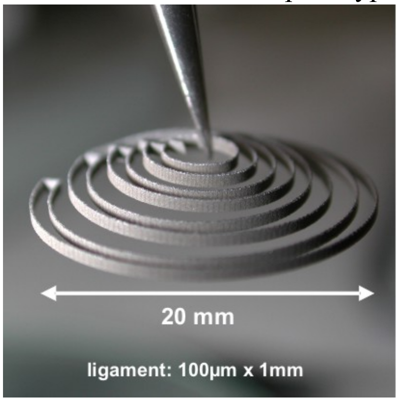


Fig. 5b: *Elastic coil (7 micron molybdenum powder; normal atmosphere).*

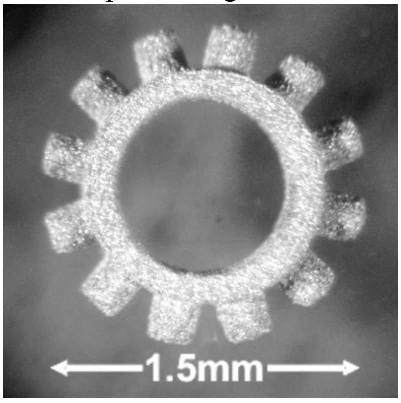


Fig. 5c: *Cogged wheel; (2 micron silver powder; normal atmosphere). Courtesy of JOTEC GmbH, Stuttgart*

yielded the highest density (87%) so far achieved with mono component powders >1µm.

2-4. Lamination Sintering:

One of the special features of the sintering machine is the option to switch between two different materials during the generation of a micro body **[Fig. 6a]**. As a demonstration a cylinder was generated from 1µm

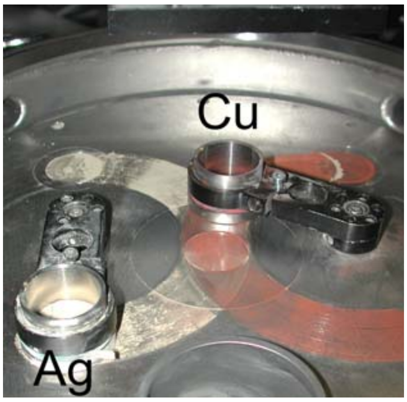


Fig. 6a: *Automatic change of powders during laser micro sintering.*

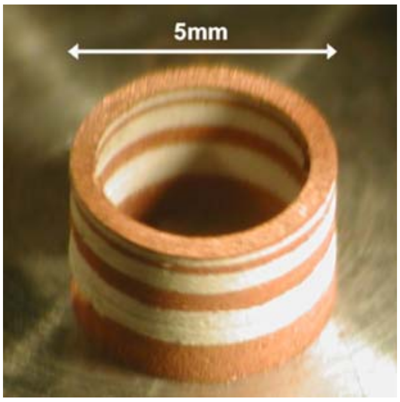


Fig. 6b: *Cylinder with alternating segments of copper and silver.*

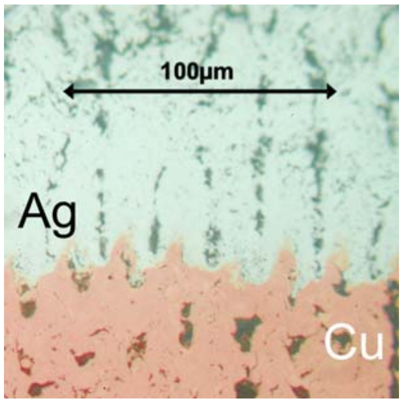


Fig. 6c: *Fusion zone between a sintered copper and the succeeding silver segment.*

grained powders of silver and copper respectively **[Fig. 6b]**. If the materials are compatible with each other, the interface between the two components will become tight enough for a firm connection [Fig. 6c].

3. LASER MICRO SINTERING OF OXIDE CERAMICS

3-1. Mechanism:

Laser micro sintering of oxide ceramics involves material processes that differ somewhat from the corresponding processing of metal. Radiation from near IR and the VIS region that allow for sufficiently sharp focusing in order to reach the intended resolution of 50µm, is only poorly absorbed by these materials at room temperature due to their dielectric properties with a band-gap that is too large for the photon energy. The non-linear effects and the short duration of q-switched pulses have been used to overcome this problem and avoid overheating due to avalanche effects (Regenfuss et al. 2006). Meanwhile, after further development, it is possible to generate micro bodies from oxide ceramic powders (Exner et al. 2006). **Fig. 7a** shows two samples of laser micro sintered oxide ceramics the left one of which with the partially hidden channel is a functional component. **Fig. 7b** shows the high density of an alumina ceramic cylinder from a special process with laser micro sintering. The impellers in **Figs. 8a** and **b** illustrate the present state of the art.

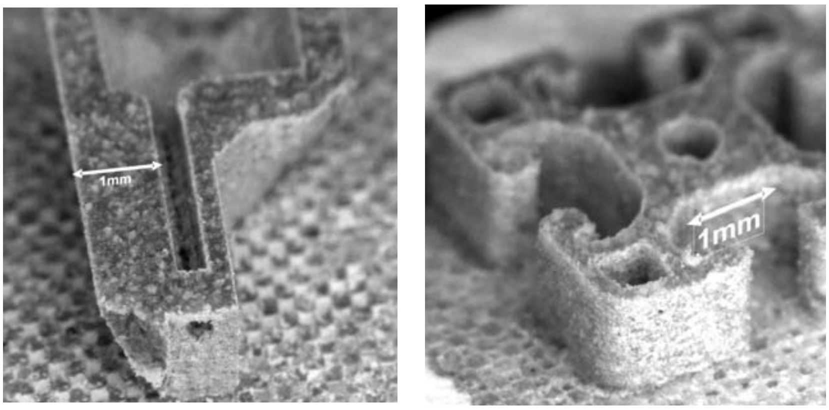


__Fig. 7a:__ Functional component (left), demonstrator part (right) generated by laser micro sintering from oxide ceramic powders.

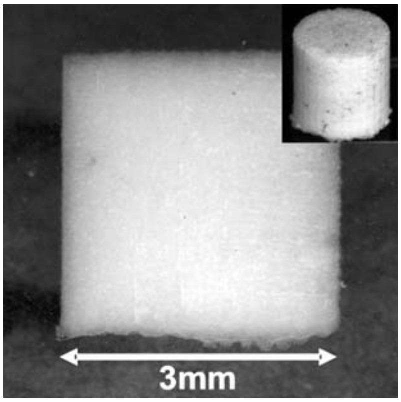


__Fig. 7b:__ Cross section through an alumina ceramic cylinder produced by a special process with laser micro sintering.

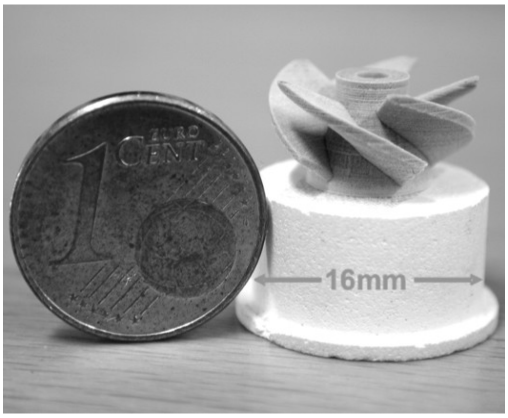


__Fig. 8a:__ Laser micro sintered miniature impeller from alumina-ceramics.
Courtesy of EOS GmbH, Munich

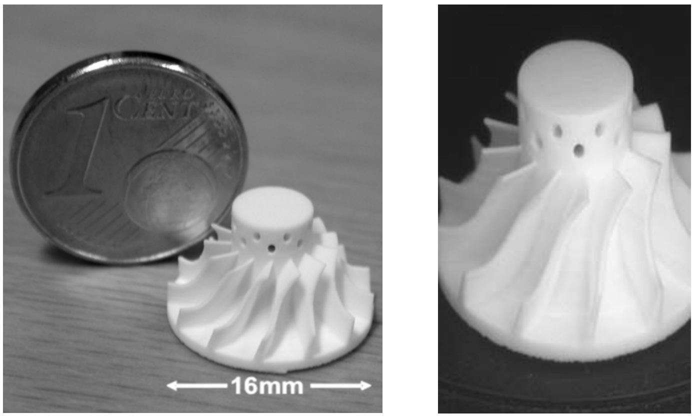


__Fig. 8b:__ Laser micro sintered miniature impeller from alumina-ceramics.
Courtesy of EOS GmbH, Munich

4. LASER MICRO SINTERING OF NON-OXIDE CERAMICS

4-1. Mechanism:

Further complications arise with laser micro sintering of non-oxide ceramics. In the case of siliconoxide the absorption and sintering mechanisms depend considerably on the composition of the powder materials (Streek et al. 2006). SiSiC powder can be sintered with a q-switched Nd:Yag laser under normal atmosphere, taking advantage of the absorption and the shield effect by the silicon content of this material. Sintered probes from SiSiC are shown in **Figs. 9a** and **b**. Technically pure SiC has to be processed under shield gas

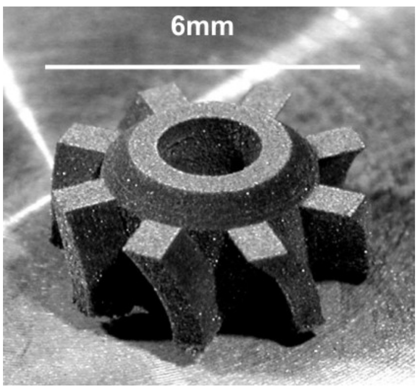


__Fig. 9a:__ Laser sintered gear wheel from SiSiC without infiltration (normal atmosphere).

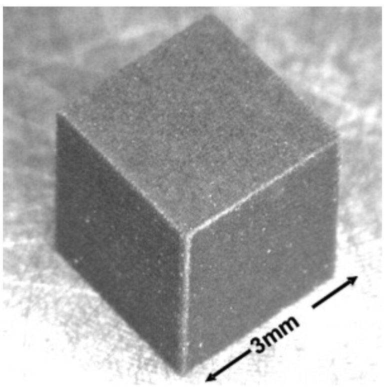


__Fig. 9b:__ Cube from SiSiC (normal atmosphere).

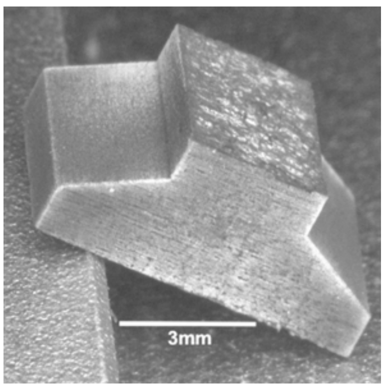


__Fig. 9c:__ Miniature from SiC powder (sintered under shield gas).

and with considerably lower intensities. A mechanistic explanation for this material behavior has been published in the work of Streek et al. (2006).

5. SUMMARY

Laser micro sintering is a suitable method for direct freeform fabrication of metal and ceramic components with structural features down to 30µm for metal and 50-80µm for ceramics. This resolution of the generated structures is presently the best that can be achieved with any laser sintering method. Due to differences in the process behavior the sinter regimes and the results vary according to the respective material classes: metals, oxide ceramics and non-oxide ceramics. The coating mechanism provides the option to alternate the material along the vertical axis or to realize vertical material gradients in the generated products. Components produced by laser micro sintering have already been implemented as functional prototypes and as micro tools in various technical and instrumental applications.

6. ACKNOWLEDGEMENTS

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