Microsintering of Miniature and Precise Components and Tools

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Abstract

Mechanical enineering industry encounters a growing demand of µm-sized or µm-structured components and tools for an increasing field of applications. The Laser Institut Mittelsachsen e.V. in Mittweida, Germany, has developed a procedure and a device /1/ which makes feasible the generation of solid and structured parts out of metals and ceramics by a freeform method, thus allowing the fabrication of not only prismatic or tapered microstructures which can be applied as electrodes for electro erosion, as tools for direct shaping of plastic materials or as molds for injection molding but also micro-bodies with undercuts and hollows. The obtained structures show a resolution of less than 30 µm and a minimal roughness of 3.5µm can be achieved.

Microtools can be built by selective laser sintering

Miniaturization is presently ranking among the most important goals in product and tool development. Selective laser sintering (SLS), a familiar technique in rapid prototyping and rapid tooling, was heretofore preferentially applied for the generation of macroscopic freeforms. Commercial devices with a laser focus diameter of 40-500µm still do not allow generation of microparts smaller than 100µm. Therefore since its first application, efforts have not ceased to increase the resolving power of SLS, aiming for dimensions in the range of 20µm. This is beyond the bounds of classical chip removing or milling processes.Compared to still higher resolving techniques, selective laser (SLS) still bears the advantages of relatively low production costs and short processing times, if uniques or small sample numbers are needed. Furthermore freeform - meaning "tool-independent" - undercuts and hollows can be realized easily, allowing e.g. the fabrication of miniature tools and components with hydrodynamic functions.

Microparts with a structural resolution of <30µm and aspect ratios of >12 have been generated by selective laser sintering on the basis of previous developments at the Laserinstitut Mittelsachsen e.V.. The established process had to be modified and a device had to be constructed that eventually turned out a prototype for a commercial machine perspectively to be offered for

sale in early 2004. Procedure and machine are filed for patents.
The technique includes sintering under conditions of vacuum or reduced shield gas pressures /2,3,7/. In a novel set-up the material is processed by a Q-switched 1064nm Nd-YAG laser after a special raking procedure. The procedure allows the work pieces to be generated from powders of high melting metals like tungsten as well as lower melting metals like aluminium and copper.
Contingent on the parameters, the generated bodies are either firmly attached to the substrate or can be dissevered by a non-destructive method.

Processing µm or sub-µm powders requires special equipment

The process assembly consists of the sinter chamber (SC), an attached turbo molecular vacuum pump, a ScanLab beam scanner with a scan field of 25x25mm, a Q-switched Nd:YAG – laser (? = 1064nm), the mounting and gate valves for various shielding and reaction gases as well as the power supply and the control unit for the coating and positioning bench (CPB).
The CPB - the core of the SC, where the sintering takes place - is mounted inside a vacuum tight stainless steel casket, the lid of which has an integrated quartz glass window with transmission for the laser radiation. The casket has electrical feed throughs for the sintering platform and an internal process observation camera.
The CPB has an aluminium frame, holding three piezzo ceramic drives (a,b and x.axes in Fig.1) with a resolution of 0.1µm, and the sintering platform. The platform is positioned horizontally and has two vertical cylindrical bores for the powder piston and the probe piston. Each of it has its separate drive. With the third drive a specially designed rake, sweeps the powder from the reservoir onto the probe piston and generates a powder layer on the substrate by a well defined procedure. The rake is supposed to run as low over the platform surface as possible. The pistons are tight for powders and liquids which allows to process also emulsions and ceramic slurries.
The SC can be evacuated by the attached turbo molecular pump down to pressures of 10^{-3}Pa and it can be charged with shielding gases or reaction gases at any pressure in the range between and 10^{-3}Pa up to $4x10^{5}$Pa. A second – chemically resistant – pump can be connected to the chamber and, with a system of flow controls and pressure reducers, reaction gases can be flushed through at pressures of =1Pa, which makes the SC applicable for laser chemical vapour deposition (laser CVD).

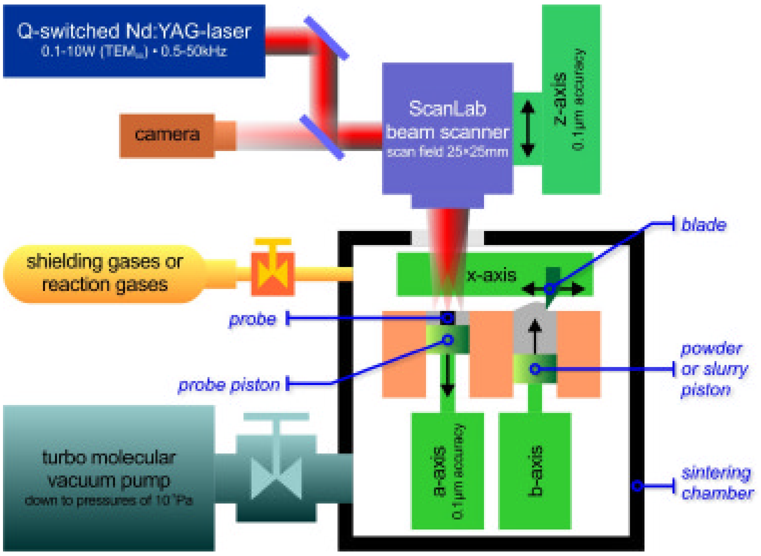


Fig. 1: Schematic set-up for laser microsintering

Processing µm or sub-µm powders requires special materials

For the generation of metallic free forms single component powders were used (Table 1), in addition, metal sintering was performed with mixtures of copper / tungsten, aluminum / tungsten and aluminum / molybdenum.

All metals are relatively inert materials at low and normal temperatures. When

Table 1: Processed Metal Powders and their Grain Sizes

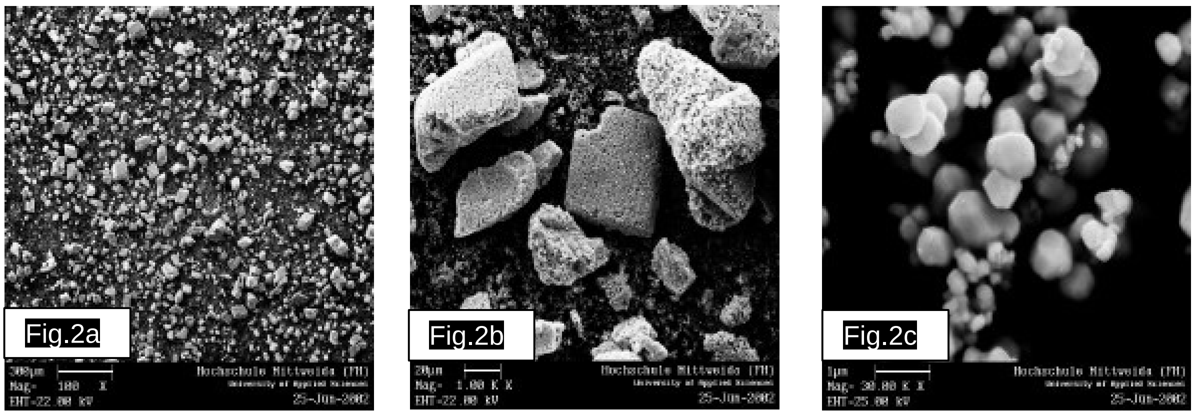
Metal	Tungsten	Aluminium	Copper	Silver
Grain Sizes	300nm, 1-5µm, 10µm	3µm	10µm	2µm

processed with laser radiation under a normal atmosphere, however, most of them show considerable oxidation.
Presently direct sintering of ceramics is probed with aluminium nitride powder and a porcelain raw material as a nonoxide ceramic and an oxide ceramic with a glassy component respectively.
Selective reaction sintering is being done with aluminium powder under nitrogen.
The results presented further on in this article confine to selective sintering of metal powders, especially tungsten.

Gas environment, powder layer and sintering regime are crucial for SLS on a µm-scale

The process atmosphere:
To provide the proper atmosphere for the process, the sinter chamber is evacuated to 10-3Pa. Depending on the condition of the powder the vacuum is applied for several hours to allow desorption of water. Subsequently, the chamber is charged with the shielding gas at the appropriate pressure between 10^4 and 10^5 Pa. Usually the gas does not need flushing or exchange in the course of a process even if this extends over more than one day.

The raking procedure:
As mentioned above, the raking of a thin layer of fine grained powder causes problems, because the material does not sediment in a dense packing but – partly supported by the raking –forms agglomerates which in the case of a sub micrometer tungsten powder often occur in the shape of polyhedrons with a preference for certain angles [Figs.2] The agglomerates, which are approximately an order of magnitude larger than the grain size, do not pack densely either. The mass of the particles is too low for gravity to suffice for a dense sedimentation. To overcome this drawback a special raking regime was developed to generate a thin layer by first applying a thicker one which is sheared off by successive raking from opposite directions. The nature of the interparticular forces is not quite clear, but obviously the amount of absorbed water plays a certain role, as exposition of the powder to a vacuum of 10^{-3}Pa for several hours improves the result of the raking procedure. The raking speed was 50mms^{-1}.



Figs. 2: SEM views of tungsten powder with an average grain size of 0.3µm at different magnifications.

Still, however, the density of the resulting layer is very poor, estimations are in the range of 15%, so that further condensation has to be achieved during sintering.

Sinter process:
Laser pulses with powers from 0.5kW-2kW were applied at repetition rates in the range of 5-20kHz. The cross sections of the microparts are processed with the pulsed radiation in a way that the pulses are distributed evenly across the selected areal segments. The resulting solid area is not a closed coating of metal, but is more a network of craters or wedges that root about 10µm below the mean surface level with crests above between 1 and 3µm. This effect accounts for the higher quality of the generated vertical surfaces compared to the horizontal surfaces. Specific regimes are applied for bottom and top horizontal surfaces respectively.
Metallic micro free forms can be either fused to the metal substrate or attached to the substrate surface by narrow sinter necks, frail enough to be sheared off without destruction of the generated free form but stable enough to fix the part throughout the raking and sintering process. Also, for stable positioning, the adjacent powder zone is processed with low power embedding the freeforms in a crust that can be removed completely by subsequent ultrasonification.

Results:
test structures and applicable tools

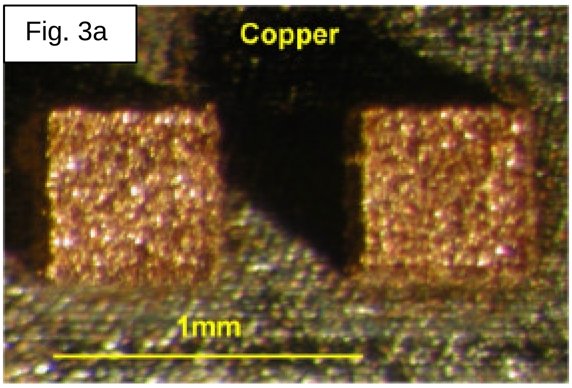


Fig. 3a

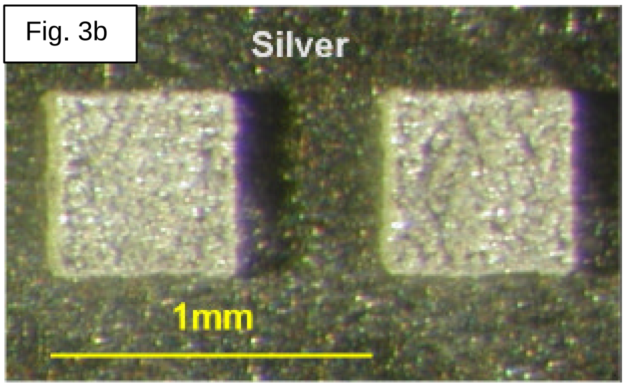


Fig. 3b

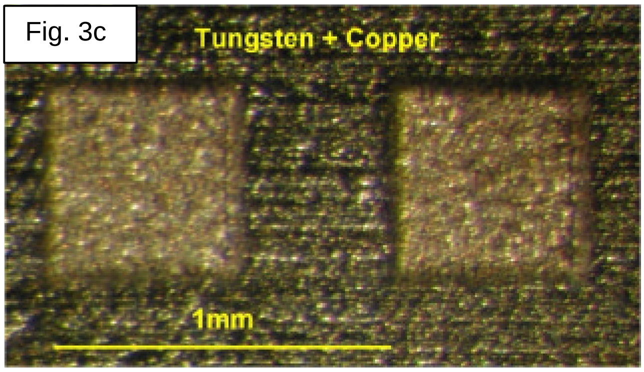


Fig. 3c

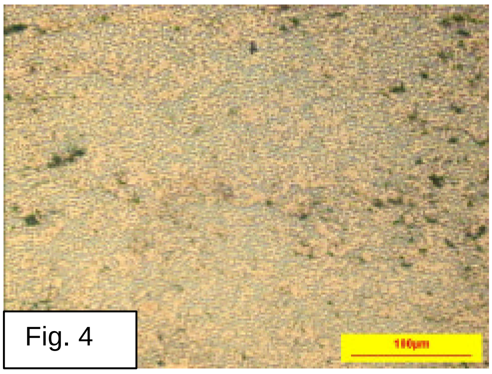


Fig. 4

Figs. 3: Cuboids sintered from metal powder: copper (a), silver (b) and copper/tungsten(c).
Fig. 4: Cross sectional view of a sintered mixture of 25wt% tungsten and 75wt% Copper that takes the role of the liquid phase during sintering. The density of the sintered body exceeds 90%.

Figures 3 show cuboids from copper and silver powders as well as from a tungsten/copper powder mixture. Highest densities of 90% and above have been achieved from copper/tungsten powder mixtures with a mass ratio copper:tungsten of 75:25 [*Fig.3*]

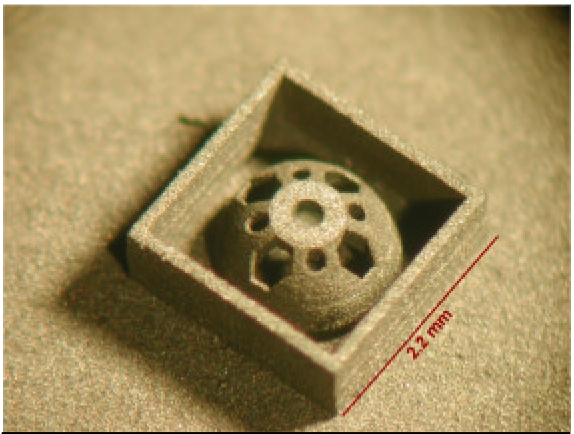


Fig. 5a: Open work hemispherical shell; wall thickness 200µm; material: tungsten

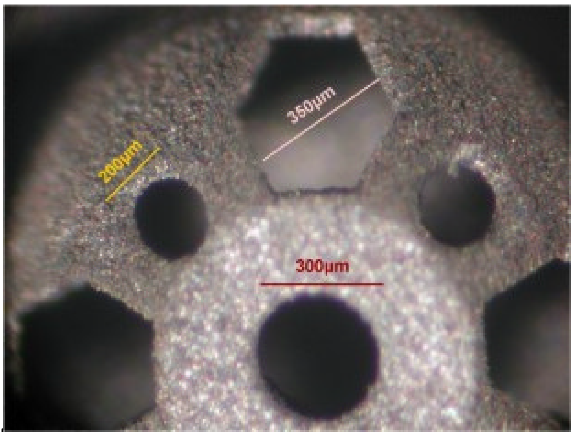


Fig. 5a: Detail view of open work shell

As already mentioned, one of the characteristics of selective laser sintering is the potential to generate undercuts and hollows. Figs. 5 show an open work hemispherical shell with a wall thickness of 200µm.
Using the appropriate parameters the intact generated bodies can be removed by ultrasonic loosening. Figures 6 show an arrangement of cuboids separably attached to the stainless steel base plate (6a,b). Figure 6b shows a cuboid that was split off the substrate by a slight chop with a spatule.

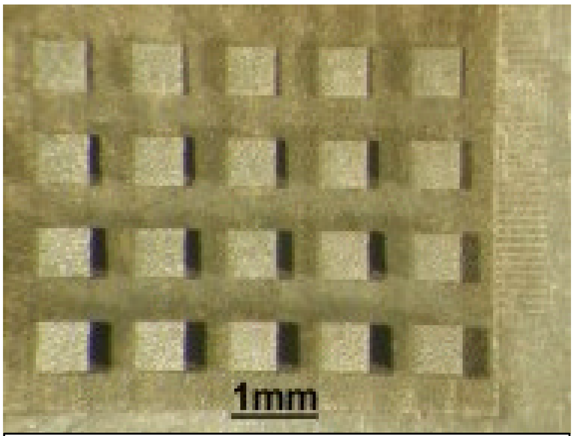


Fig. 6a: Tungsten cuboids before loosening procedure

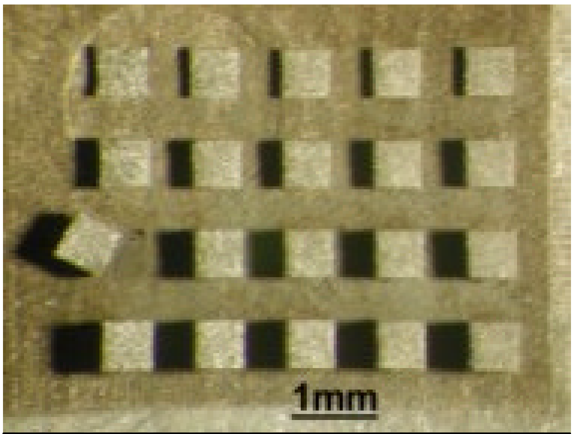


Fig. 6a: Loosened tungsten cuboids; one specimen dissevered (see text)

Figures 7 show SEM views of a tungsten structure with a depth of 400µm. It contains notches with a width of <40µm, amounting to an aspect ratio and a resolution that cannot be achieved by micro-milling techniques.
As mentioned above, the roughness of the horizontal surfaces is higher than the roughness of the vertical surfaces. The two halves of the structure are not intended to be complementary.
After the method had proved reliable to generate micro freeforms with a sufficient fidelity, a tool component was built to fulfil a function in an industrial routine. The part (also made of tungsten) is 10mm at its longest dimension. It is partly solid; a slit

Table 2: Surface Roughness (R_a)

Surface Type	R_a
horizontal	5µm
vertical	3.5µm
separation cross section	7µm

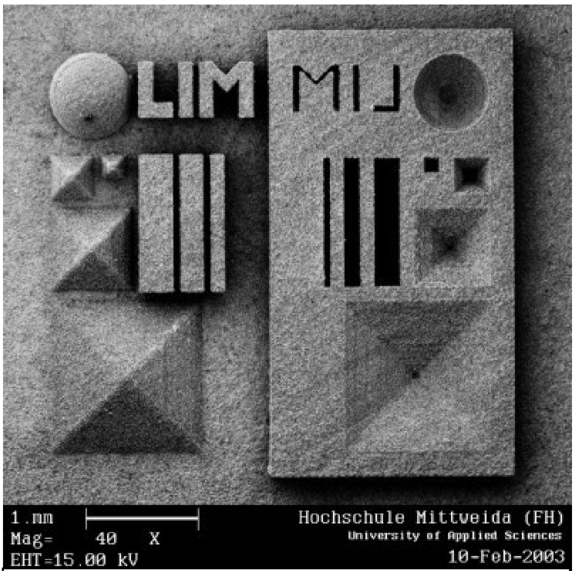


Fig. 7a: Tungsten structure with a depth (height) of 400µm

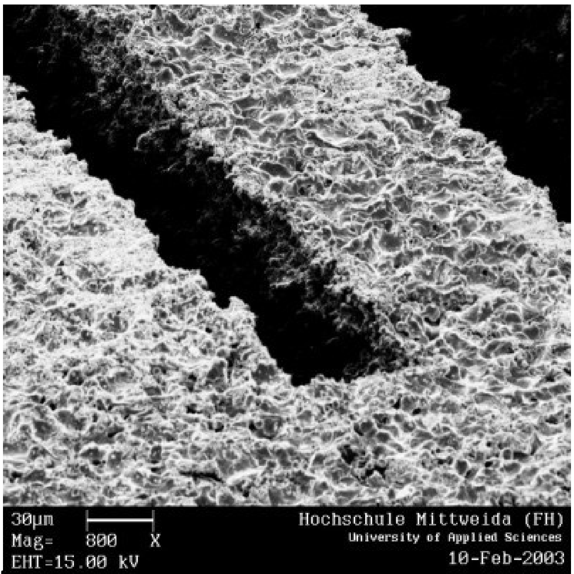


Fig. 7b: Detail of Fig. 6a: notch with an aspect ratio >10

with an open width of 480µm and a length of 3.75mm is connected to a circular window (diameter: 1mm) by a tunnel through the solid body. The roughness values shown in Table 2 were reported by our client, by whose courtesy we are able to present views of the sinter part in Figures 8a,b.

For the fundament of the freeform, parameters were chosen to allow easy detachment and, as we were informed, holding the part between thumb and forefinger, it could be separated from the substrate easily by a gentle twist.

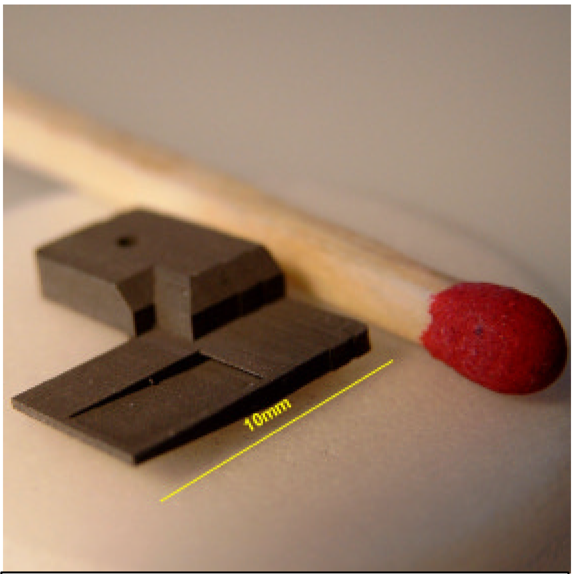


Fig. 9a: Tool; comparison to dimensions of a match

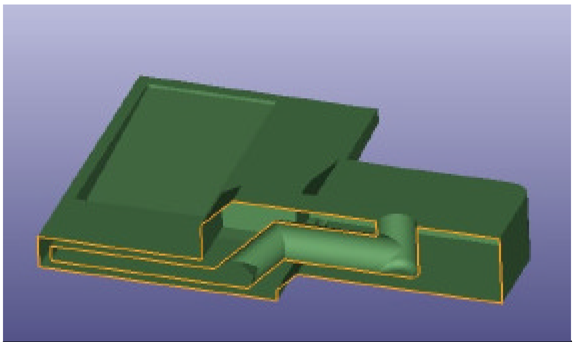


Fig. 9b: Tool; cross sectional view of the construction plot

Conclusion and Perspectives:

A novel set up and processing regime, have extended the applicability of freeform generation by selective laser sintering into a range of structural resolution and reproduction fidelity heretofore unachieved /4,5,6/. The results presented here are obtained from powders of tungsten copper, silver and tungsten/copper mixtures. They prove the technique an effective and versatile method for rapid micro tooling.
With a slightly different approach, the technique is also applied for the selective sintering of ceramics and composite materials; this will be subject of forthcoming publications.
The ideas and applications of the innovations are registered in Germany as patents and utility models.

Appreciations:

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