

Laser beam removal of micro-structures with Nd:YAG-Lasers

D. Hellrung, A. Gillner, R. Poprawe
Fraunhofer-Institut Lasertechnik, Aachen, Germany

ABSTRACT

Laser beam removal with Nd:YAG-lasers is a manufacturing method to produce micro-structures with the precision of a few micrometers. Because many materials can be structured with laser radiation, especially hard metals and ceramics, it is a very flexible technology for the production of tools for micro-embossing and micro-stamping. The combination of the laser and stamping technology offers the possibility to produce high quantities of micro-parts at moderate costs. A system for laser beam removal, existing of a handling with a CAD/CAM coupling and a diode pumped solid state laser was developed and in several investigations the quality of these micro-tools was tested.

Keywords: laser, micro-technology, micro-structure, tools, hard metal

1. INTRODUCTION

The need for flexible and fast manufacturing methods to produce micro-structures and parts at low costs is very high [1]. Especially the demand for micro-tools with small dimensions or micro-structures with the following requirements grows:

- dimensions of the structure $< 100 \mu\text{m}$
- high aspect ratio of more than 20
- surface roughness $< 1 \mu\text{m}$

Since the tools are used e.g. for stamping, embossing, injection moulding and other techniques, they must be made of hard materials because of the wear. For this reason cutting and milling as well as etching are not applicable. The electric discharge machining is a possible alternative, but the costs for micro-structured electrodes are high. The laser beam removal of micro-structures, especially the direct writing method with a Nd:YAG-laser [2], can solve this problem. This method has nearly no material restrictions, so that hard metals and ceramics can be structured. Furthermore the development of high quality diode pumped solid state lasers with higher harmonic generation, high beam quality and short laser pulse length in combination with high precision positioning tables improves the quality of laser beam ablated micro-structures.

2. LASER AND POSITIONING SYSTEM

The laser beam removal system is set up from of several standard components. In Fig. 1 the main part of the system is shown.

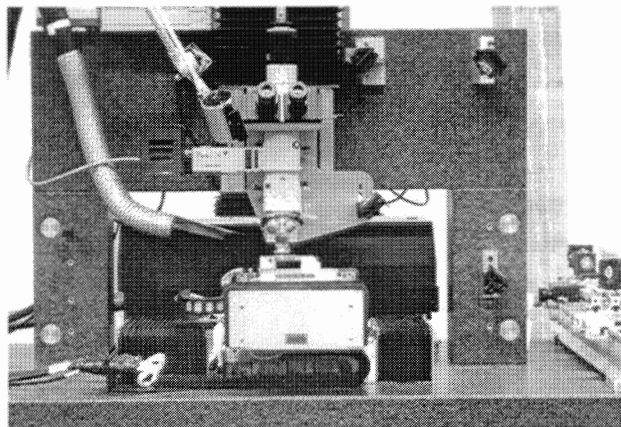
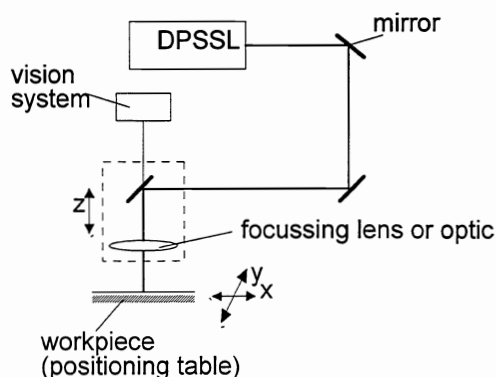


Figure 1: Direct writing laser beam removal system

For further author information -

D.H. (correspondence): email: hellrung@ilt.fhg.de; Telephone: 0049+241/8906-273; Fax: 0049+241/8906-121

Not visible is the control unit of the positioning tables and the supply unit of the laser. The laser is a diode pumped solid state laser (DPSSL) with a gaussian mode, a high energy stability and a beam divergence of less than 1.5 mrad. Additional to the first harmonic wavelength of 1064 nm the laser has an external generation of the second and third harmonic. The focus diameter is around 50 μm (see Tab. 1) for an optics with a focal length of 50 mm and a beam diameter of approximately 2.0 mm. For the third harmonic and with an adapted optic a focus diameter of 5 μm is possible. The pulse length of 10 ns is fixed in the pulse frequency spectrum of 1 to 1000 Hz. With this short pulse length, the ratio of vaporised to melted material is very high, so that the material can be removed without residue.

λ	1064 nm	532 nm	355 nm
P_{Av} (1 kHz)	9 W	4.2 W	3 W
f_d ($f=50$ mm)	50 μm	35 μm	-
P_p	900 kW	420 kW	300 kW
F	458 J/cm ²	436 J/cm ²	-

Table 1: Parameters of the DPSSL ([-] not measured, P_p = Pulse peak power, F = Fluence)

The positioning system is set up from high dynamic and precise linear drives with a resolution of 0.1 μm , a positioning accuracy of 1 μm and a maximum velocity of 500 mm/s. The laser beam is guided to the optics by several mirrors (Fig. 1). The optics is connected with the z-axis and focuses the laser beam on the workpiece, which is fixed on the x- and y-axis. With the z-axis the position of the focus of the laser beam relative to the workpiece can be adjusted. Furthermore there is the possibility to observe the process with a CCD-camera and a microscope.

3. CAD/CAM COUPLING

For a fast and flexible production of micro-tools an efficient CAD/CAM-coupling is necessary. With some modifications and adaptations to the specific demands of the laser technology, it is possible to use a CAD/CAM-software for milling. The process of laser beam removal by using a CAD/CAM-software is divided in three steps (Fig. 2):

1. Design
2. Slicing
3. Postprocessing

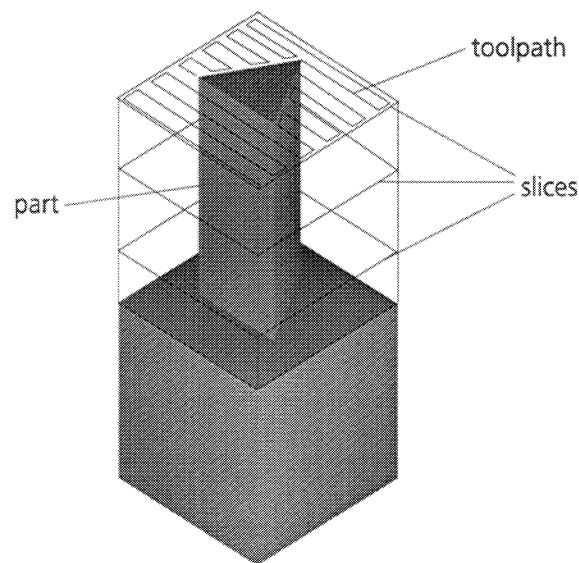


Figure 2: Schematic drawing of a sliced geometry

The design of the micro-structure can be made with any CAD-software, a volume as well as a surface modeler. The second step is the slicing of the micro-structure. To achieve a 3-dimensional geometry, the micro-structure is divided into several slices with a definite thickness. This thickness corresponds to the average depth of removal per laser pulse, which mainly depends on the energy and the overlap of the laser pulses, the properties of the material and the wavelength of the laser radiation [3]. These parameters were determined in additional investigations. The thickness can be varied e.g. between 1 and 10 µm for a hard metal. After slicing the geometry, the corresponding NC-data for the moving system is generated by a postprocessor and completed with the laser specific data.

4. ABLATION STRATEGIES

The strategy of removal has a great influence on the results, regarding the surface quality and the geometry. In Fig. 3a a cross section of an ablated groove is shown, where all slices started at the same side. Every slice was scanned in the same way from the right to the left. This ablation strategy results in two different walls. The vaporised material condenses on the surface in front of the laser beam. With every scan additionally to the basic material condensed material has to be removed. Because of the fixed removal depth per laser pulse, the same depth is not reached at the left side of Fig. 3a. In Fig. 3b a groove with an alternative ablation strategy is shown. Here the starting point and the directing of scanning was changed every slice. In this case the walls are very similar. The ablation was performed in silicon nitride, but there are similar results in other materials. Due to the propagation of the focused laser beam it is difficult to produce vertical walls. By tilting the workpiece relative to the incident laser beam, the ablation can be controlled to generate vertical walls. For a basic geometry it is easy to tilt the workpiece. For more complex geometries a special tilting device for the laser beam is necessary, which provides higher dynamics and accuracy.

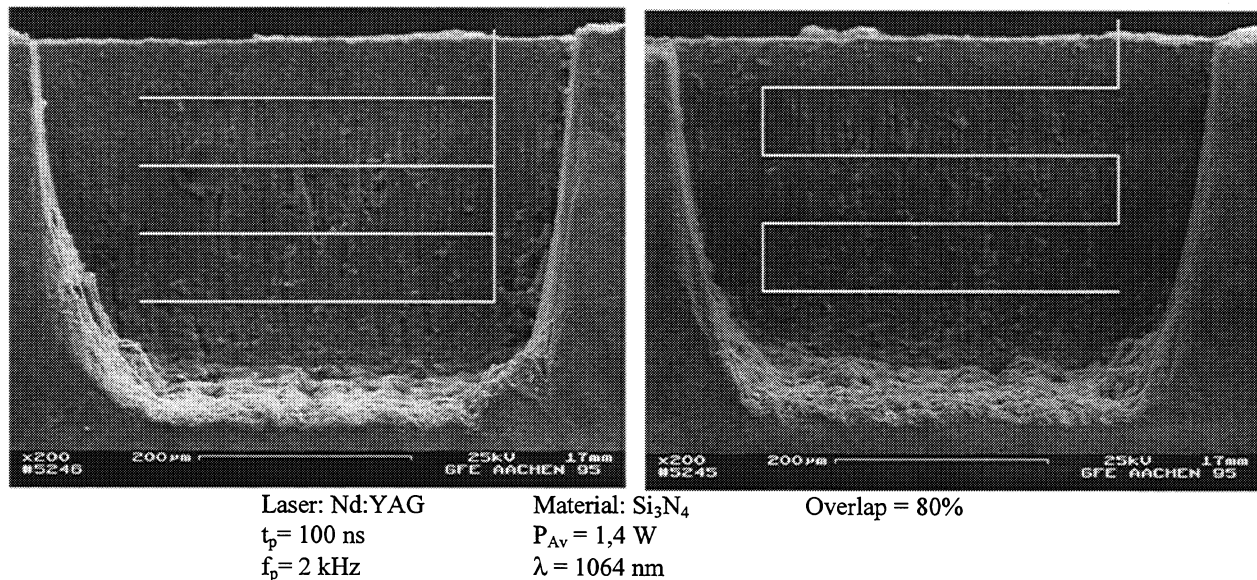


Figure 3: Influence of the removal strategy

An important parameter for the laser beam removal with a Q-switch Nd:YAG-laser is the overlap of the laser pulses. This parameter determines the average depth of removal per laser pulse, which can be higher than the depth of a single laser pulse, and the quality of the worked surface. In Fig. 4a the overlapping of the single laser pulses in x- and y direction for a scanning movement of the positioning system is shown. The relation between the overlap and the single laser pulses is shown in Fig. 4b. The definition for the overlap O is:

$$O = \left(1 - \frac{m}{d_w}\right) \cdot 100\%$$

with: O = overlap [%]
m = movement of the axis between two laser pulses
d_w = effective working diameter of the laser beam

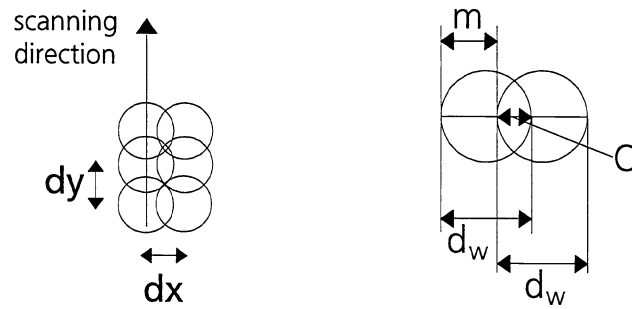


Figure 4: Definition of the laser pulse overlap

At an overlap of 0 % the average depth of removal per laser pulse is equal with the removal depth of a single laser pulse. With an increasing overlap the average removal depth per laser pulse, respectively the thickness of a single slice, grows. The effective working diameter d_w need not to be equal to the focus diameter. The definition of the focus diameter does not depend on the maximum of the power density of the laser beam, but on the distribution. Because the material has a specific threshold, it is possible to vary the effective working diameter by changing the maximum of the power density of the laser beam (Fig. 5).

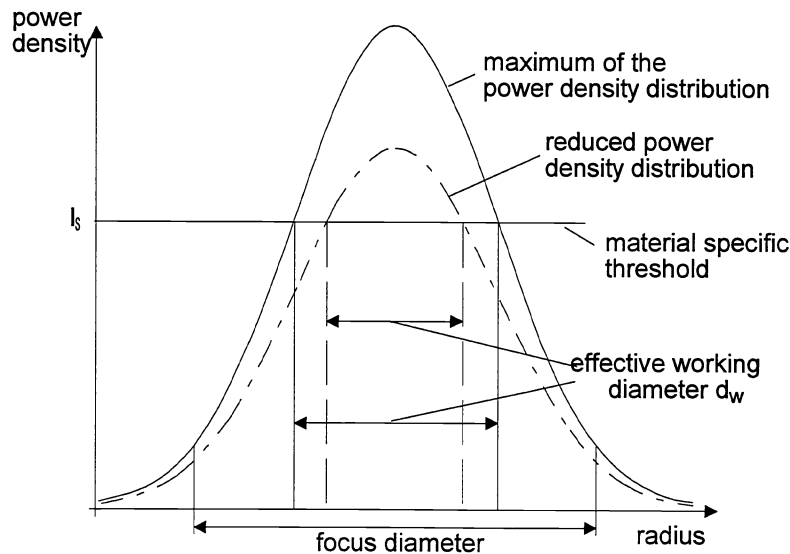


Figure 5: Difference between focus diameter and effective working diameter

A criterion for the quality of a micro-structure is the roughness and the structure of the machined surface. For this reason a hard metal was examined, which is used for stamping and embossing tools. The average diameter of the tungsten carbide grains is $0.7 \mu\text{m}$. The hard metal contains 10 % cobalt and the hardness is 1550 HV30. Although the same overlap of the laser beam pulses was used in x- and y-direction there is a different roughness. In Fig. 6 the roughness R_a and R_z in x- and y-direction depending on the overlap is shown. At an overlap of 40 % the minimum roughness $R_a = 0.25 \mu\text{m}$ was reached, which is in the range of the grind material.

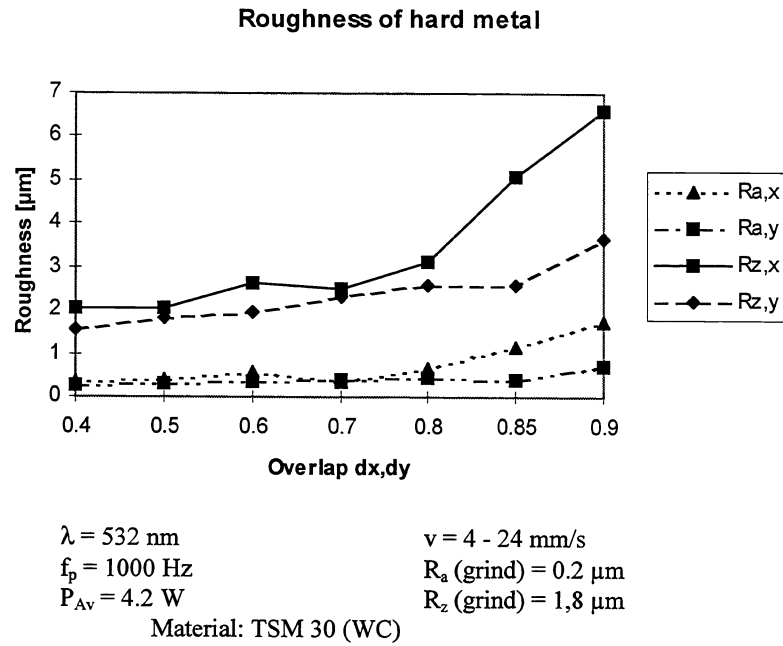


Figure 6: Roughness of hard metal after laser beam removal

But not only the roughness is a criterion for the quality of a laser beam removed micro-structure. It is also the mechanical and chemical structure of the worked surface. At an overlap of 40 %, no thermal damage is visible (Fig. 7a).

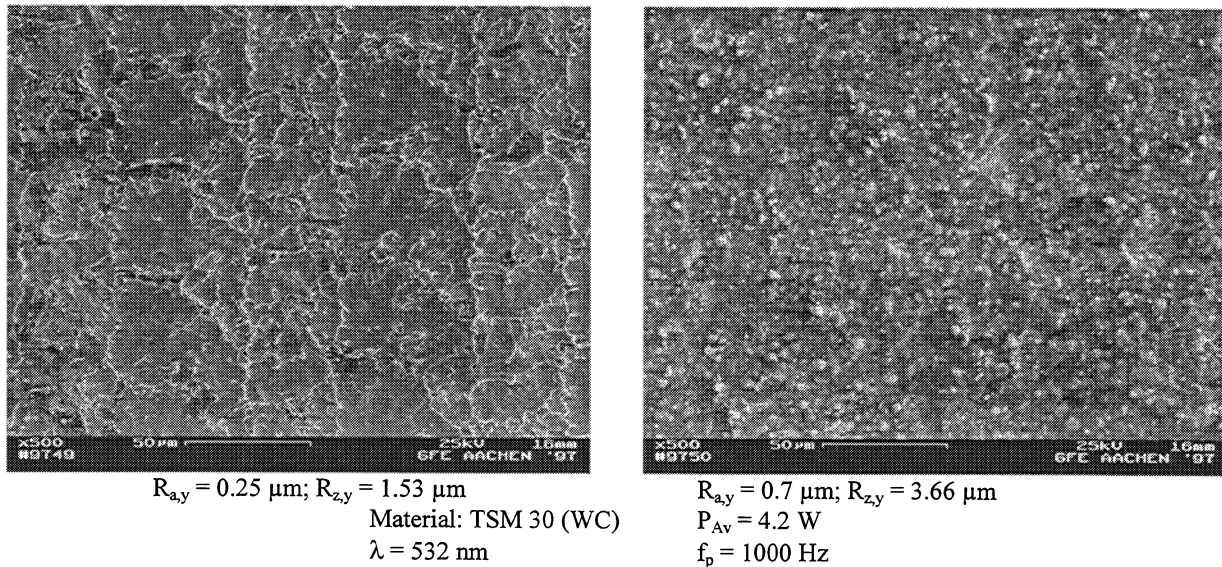


Figure 7: Surface morphology of a laser beam structured hard metal (Overlap a) 40%, b) 80%)

At an overlap of 80 % (Fig. 7b) the surface looks more homogeneous, but the roughness is higher and there are micro-cracks visible. These micro-cracks can cause a failure of the tools. A variation of the chemical structure on the laser beam treated surface could not be detected in an ESCA-investigation.

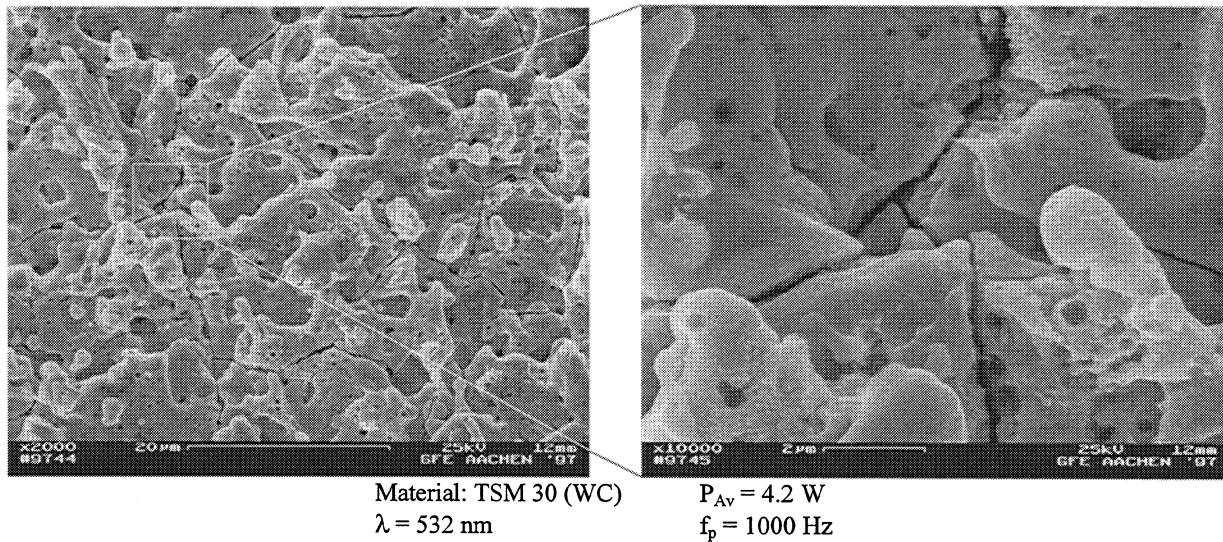


Figure 8: Surface morphology of a laser beam structured hard metal (Magnifications of Fig. 7b)

5. TOOLS

The first micro tools for stamping and embossing are shown in Fig. 9. The tools are made of hard metal with a laser wavelength of 532 nm. As it can be seen from the figure, basic as well as complex geometries are possible. The triangle and the horse can be used for stamping and embossing of metal parts, for ultrasonic machining or for injection moulding of plastics. The edges are defined and the surfaces on the ground and on the sides are smooth. The height of the triangle is around 1.5 mm. This is the smallest possible height which is needed to stamp a sheet of 100 μm . The dark lines along the contour result from a higher removal rate. This is caused by the acceleration and deceleration of the positioning tables. The problem can be solved by adapting the laser pulse frequency to the velocity of the movement. This will be done in future refinement works to produce free-form surfaces with high quality for direct applications and for stamping technology.

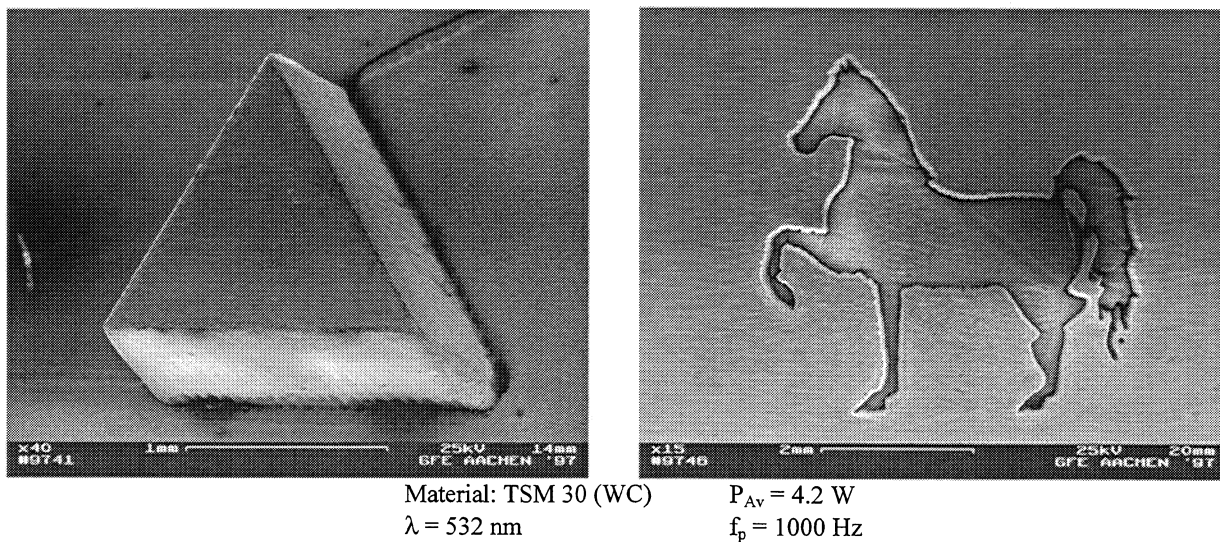
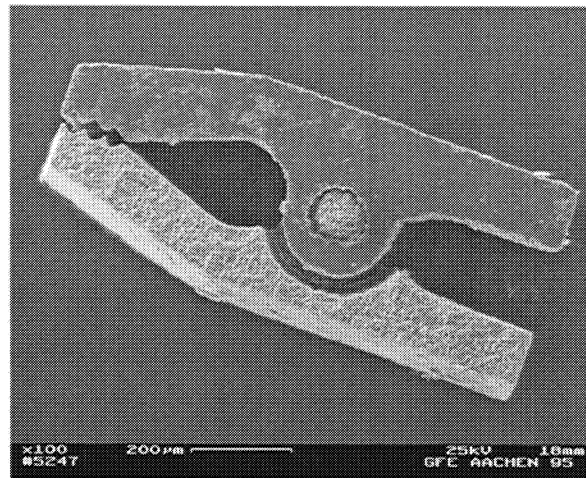


Figure 9: Tools for stamping and embossing made of hard metal



Material: Si_3N_4 $P_{\text{Av}} = 1.4 \text{ W}$
 $\lambda = 1064 \text{ nm}$ $f_p = 2000 \text{ Hz}$

Figure 10: Laser beam structured micro-clamp

An example for a direct application of the laser beam removal technology to produce micro-parts is the clamp shown in Fig. 10. It is made of Si_3N_4 and has a thickness of approximately $200 \mu\text{m}$.

ACKNOWLEDGEMENTS

These investigations were financially supported by the BMBF of the Federal Republic of Germany (Förderkennzeichen: 02PV76054). The authors are responsible for the contents of this publication.

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