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ScienceDirect

Physics Procedia 12 (2011) 60–66

Physics Procedia

LiM 2011

Microstructuring of Steel and Hard Metal using Femtosecond Laser Pulses

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Abstract

New results on three-dimensional micro-structuring of tungsten carbide hard metal and steel using femtosecond laser pulses will be presented. For the investigations, a largely automated high-precision fs-laser micromachining station was used. The fs-laser beam is focused onto the sample surface using different objectives. The investigations of the ablation behaviour of the various materials in dependence of the laser processing parameters will be presented. In the second part, complex 3D microstructures with a variety of geometries and resolutions down to a few micrometers will be presented. On of the Goal of these investigations was to create defined microstructures in tooling equipments such as cutting inserts.

Keywords: three-dimensional micro-structuring; femtosecond laser; steel and tungsten carbide hard metal

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1. Introduction

Currently there are a lot of different research activities based on femtosecond- (fs-) laser technology [1]. In an early publication we have presented some result on fs-laser-microstructuring of different metals such as brass and copper [2]. A purpose of this work is the investigation of the interaction of high-intensity fs-laser pulses with other high thermal conductive metals, such as steel THYRODUR® 2990 and tungsten carbide hard metal. It will be shown that ultrashort laser pulses are suitable for high-precision micromachining of these metals. Moreover, nearly no heat affected zone was observed in the neighboring of the laser processed microstructures and, in the case of the sintered hard metal, no decomposition and segregation due to the fs-laser interaction were detected.

These results were used to create specific microstructures in the surface of cutting tools using femtosecond laser pulses. In the last part of the presentation first results of the influence of different microstructures, especially of the three-dimensional microstructures, on the cutting process are shown. The motivation of the microstructuring of cutting tools is the increase of the efficiency and process stability as well as reduction of costs and environment pollution.

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doi:10.1016/j.phpro.2011.03.106

2. Experimental details

For the investigations, a largely automated high-precision fs-laser micromachining station from the 3D Micromac AG Chemnitz with an embedded Clark MXR fs-laser CPA 2010 was used [3]. The femtosecond laser system permits material machining using focusing technique, where the average wavelength of the fs-laser system is 775 nm, its maximum pulse energy 1 mJ, the pulse duration 150 fs and the constant pulse repetition rate 1 kHz. The fs-laser beam is focused onto the sample surface using different objectives. The sample is fixed at a holder mounted on an x- y- positioning stage (positioning accuracy 0.1 µm). Additionally, the objective can be moved in the z-direction (positioning accuracy 1 µm) allowing the precise adjustment of the focal plane on the sample surface or inside the material. The laser beam with a Gaussian radius of 3 mm was focused by means of either a transmission objective with 100 mm focal length or was expanded to a radius of 6 mm and then focused by means of a transmission objective with 32 mm focal length. The Gaussian Radii in the foci were 27 µm and 5.7 µm, respectively.

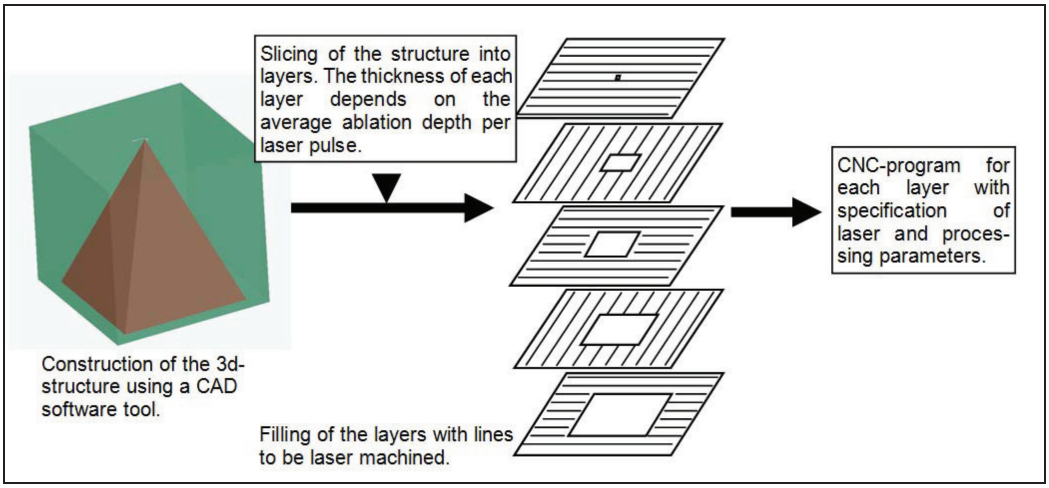

Figure 1: Schematics of the preparatory steps necessary for 3d-micromachining. The 3d-structures were produce by using layer by layer ablation. The focal plane will be adjusted after the ablation of one layer.

Layer by layer ablation is realized for producing 3d-microstructures, where the actual procedure is shown schematically in Figure 1 on a pyramid for example. After constructing the desired 3d-structure using CAD-software, a special converter software slices the structure into a stack of layers. Thereby, the layer thickness depends on the ablated depth per laser pulse, which is related to the material and the laser parameters and has to be determined in preparatory investigations. In the final step the actual computer program for controlling the sample motion and the laser as well as the optical system in each layer is created. To avoid preferential directions each subsequent layer was machined with the laser beam moving direction perpendicular to the preceding one. The entire microstructure is thus produced by using layer-by-layer ablation.

3. Results and Discussion

3.1. Fundamental Analysis

In order to explain the ablation process in metals by ultrashort laser pulses, the two temperature model will be used in the literature described in [4, 5]. This model shows that there are two different ablation regimes. In both regimes the ablation depth or the ablation volume per pulse depends logarithmically from the laser pulse fluence. In this chapter we will demonstrate the existence of two different ablation regimes in the investigated materials. Furthermore were determined the ablation parameters like threshold fluence and ablation depth per laser pulse as well as roughness R_a which can be used for practical applications. In these experiments, quadratic test fields (size of

400 µm x 400 µm) have been produced in the different metals using varying fluence and otherwise constant well-defined parameters (see caption of Figure 2), the depths of which were measured. The average ablation depths per laser pulse were then calculated from the total depth of these test structures. The results are shown in Figure 2 for tungsten carbide and steel Thyrodur® 2990.

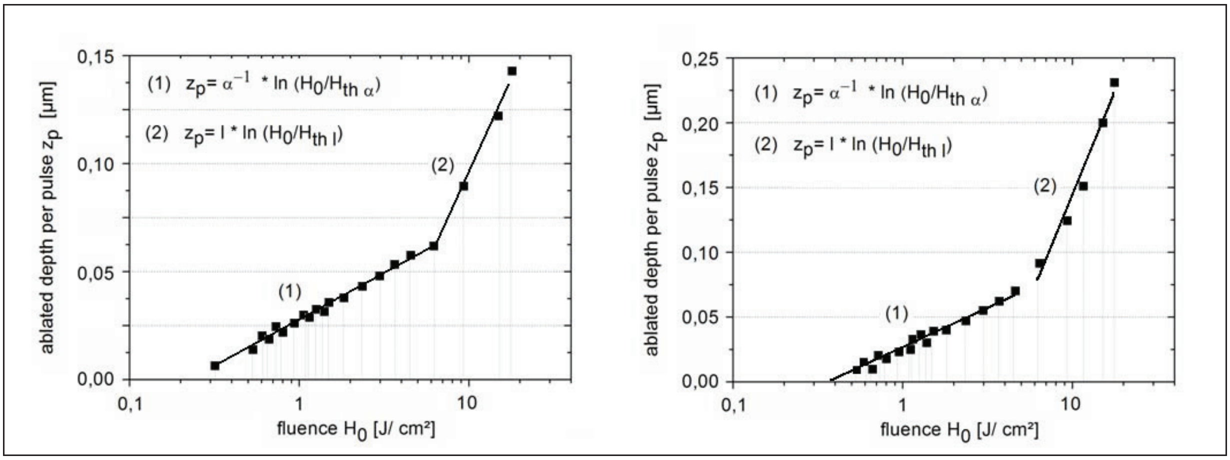

Figure 2: Ablated depth per pulse for steel THYRODUR® 2990 (left) and tungsten carbide (right) as a function of laser fluence (structuring parameters: 400 µm x 400 µm ablated area, 27 µm Gaussian radius of the focused laser beam on the sample surface, beam scanning with 7 µm pulse to pulse distance, ablation of 4 layers without focus setpoint tracing).

Two ablation regimes could be observed for all two metals, both characterised by a logarithmic dependence of the ablation depth per laser pulse on fluence and distinguished by different slopes. This behaviour corresponds to the two temperature model described in the literature [4, 5], which predicts two separate ablation regimes. In the low fluence ablation regime, the ablation depth per pulse z_p can be described by an equation, which follows from the Lambert's absorption law. The substitution of the intensity I_o by the fluence H_o, the absorption depth d by the ablation depth per pulse z_p and the intensity I(d) by the ablation threshold for the low fluence regime $H_{th\alpha}$ yields the expression

$$z_p = \alpha^{-1} \cdot ln(H_o/H_{th\alpha}) \,, \tag{1}$$

where α is the absorption coefficient. In the high fluence ablation regime the same dependence can be described by the expression

$$z_p = l_e \cdot ln(H_o/H_{thl}) \,, \tag{2}$$

where H_{thl} is the threshold for this regime and l_e is the new slope corresponding to the electron heat diffusion length according to the model. In Table 1, the ablation threshold, the absorption coefficient, the electron heat diffusion length and the fluence, at which the change of the regimes occurs, determined from the curves are presented. The results confirm well the two temperature model.

Table 1: Ablation threshold, absorption coefficient, change of ablation regime and electron heat diffusion length for tungsten carbide and steel THYRODUR® 2990.

Material	Ablation threshold (J/cm²)	Absorption coefficient (cm^{-1})	Approximate change of ablation regime (J/cm²)	Electron heat diffusion length (nm)
tungsten carbide	0.38	$4.43 \cdot 10^5$	5	114
steel Thyrodur®	0.23	$6.24 \cdot 10^5$	6	114

3.2. 3d-Microstructuring

Based on the fundamental analysis three dimensional test microstructures comprising various geometrical shapes have been produced in the two high thermal conductive metals using the objectives with 100 mm focal length for focusing the laser beam. The parameters have been chosen as following:

- an optimum pulse to pulse distance with respect to roughness
- the total structure size was 1 mm x 1mm
- the fluence such that the ablation depth per layer was 1 µm
- the number of machined layers was 100 in the case of 27 µm Gaussian radius
- the total maximum depth of the microstructures were 100 µm

After every layer the focal plane will be adjust on the sample surface. The process duration for these 3D – microstructure dependents form the process parameters and the material itself (duration: between 4 and 8 hours). Two examples of the three dimensional are shown in Figure 3.

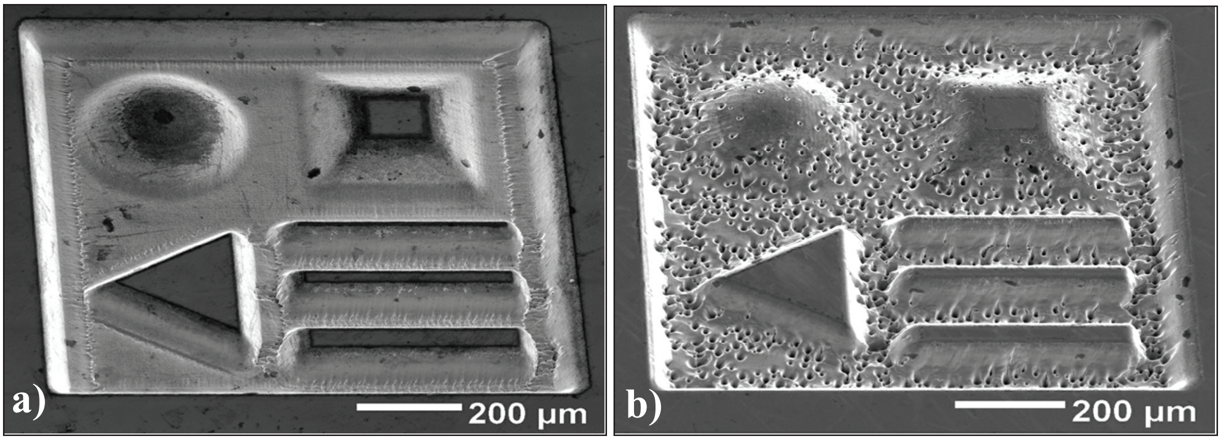

Figure 3: SEM micrographs of 3D microstructures with a depth of 100 µm in (a) tungsten carbide and (b) THYRODUR steel (microstructuring parameters: 27 µm Gaussian radius of the focused laser beam on the sample, ablation of 100 layers with focus setpoint tracing of 1 µm from layer to layer, fluences: (a) 1.37 J/cm² (b) 2.34 J/cm², pulse to pulse distances: (a) 8 µm (b) 9 µm, post-treatment in a ultrasonic alcohol bath and with cellulose acetate to remove some debris).

Generally, it can be seen that 3D-microstructures can be machined in the various metals and that the designed shapes can be realized. There is, however, a certain granular-like morphology developing at the side walls and the bottoms resulting in an increased roughness of some 100 nm. Confirming our pre-investigations the best microstructures were obtained for tungsten carbide. In the case of steel, micro-pores appear (see Figs. 3b) at the bottom as well as the side walls, which have not been observed in pre-investigations (where only 4 layers have been ablated) and begin to form only after a certain number of ablated layers. The reason for the formation of these pores is not yet clear. We assume that they might be related to the inhomogeneity of the material, but need further investigations to confirm this assumption.

EDX-Analysis has been used for the quantitative evaluation of changes in the materials composition in the machined areas. In particular, in the case of tungsten carbide no chemical decomposition could be detected. A small amount of oxygen has, however, been observed.

3.3. Microstructuring of cutting tools

The intention for the microstructuring of cutting tools is to improve the cutting process parameters. In our purpose we will produce firstly friction-reducing microstructures to minimize wear forces and process forces and secondly friction-enhancing microstructures to benefit chip breaking and the cutting speed. In view of the cooling- and lubricant-transport microstructures can act as a reservoir which reduces abrasive wear and thus the costs. First experiments should provide information on geometric shapes of the microstructures which can be used and about their effect on the cutting properties. We have generated line-structures and quadratic form elements. The line-structures have been produced in tungsten carbide hard metal cutting inserts. The structure size was 50 µm and their period was 100 µm. The line-structures are aligned from the cutting edge at an angle of 27.5 degrees (see Figure 4) or with 117.5 degrees, respectively. The lateral structure size could be adjusted over the laser pulse fluence, and the structure accuracy was influenced by the pulse-to-pulse-distance. The total structure depth depends on the number of laser beam crossings. The results are presented in Figure 4. In this case, the numbers of crossings were chosen so that a total depth of 15 µm was realized.

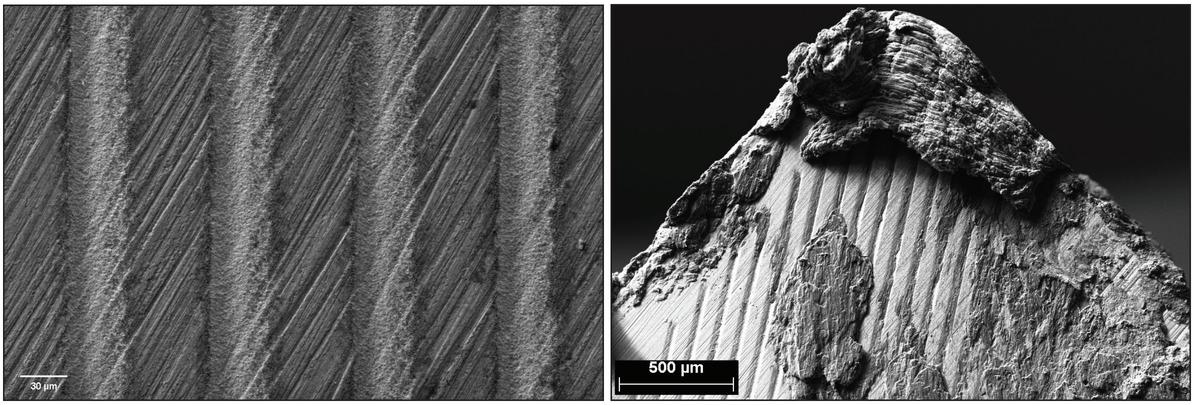

Figure 4: SEM micrographs of the line structure in a tungsten carbide hard metal cutting insert with a total structure depth of 15 µm before (left) and after (right) the cutting test process (structuring parameters: period of structure 100 µm, structure size 50 µm, Gaussian radius 27 µm, fluences 0.94 J/cm^2, pulse to pulse distances 6 µm, total ablation depth 15 µm without focus setpoint tracing, structure lines aligned form the edge at an angle of 27.5°, post-treatment in a ultrasonic alcohol bath to remove some debris; cutting test parameters: feed 0.2 mm, cutting speed 400 m/min, without lubricant).

In a further step the influence of quadratic form elements on cutting properties has been investigated. Based on the measured ablation depths as a function of laser fluence (see Chapter 3.1) test microstructures have been produced in tungsten carbide hard metal cutting insert. The geometrical size of the quadratic form elements was 100 µm x 100 µm and their distance was 150 µm and 200 µm, respectively. The form elements were arranged in lines with an offset from line to line (see Figure 5). The machining parameters of the ablated pits between the form elements have been chosen, so that the ablation depth per layer was 1 µm. The number of the machined layers was 21 and accordingly, the total maximum depth of the microstructure is 21 µm. After the ablation of every layer the focal plane was shifted into the material by 1 µm. More parameters can be seen in the caption of Figure 5.

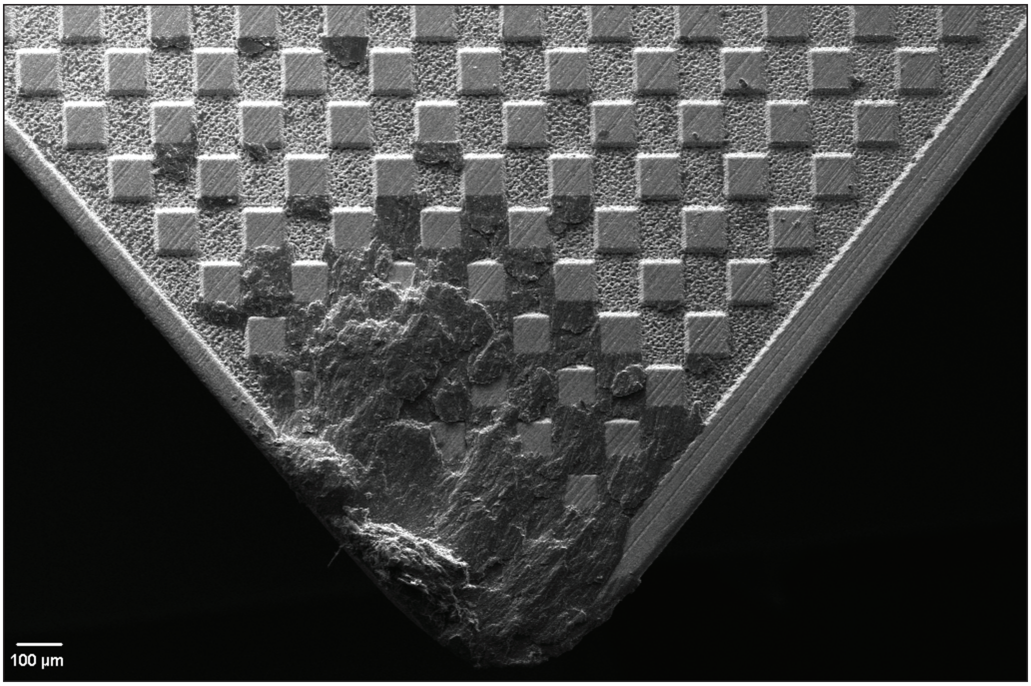

Figure 5: SEM micrographs of 3d-microstructure form elements in a tungsten carbide hard metal cutting insert with a structure depth of 21 µm after the cutting test process (microstructuring parameters: Gaussian radius 5.7 µm, ablation of 21 layers with focus setpoint tracing of 1 µm from layer to layer, fluence 118.72 J/cm², pulse to pulse distances 6 µm, post-treatment in a ultrasonic alcohol bath and with cellulose acetate to remove some debris; cutting test parameters: feed 0.2 mm, cutting speed 400 m/min, with lubricant).

The cutting tests and the analysis of the structured inserts were carried out in cooperation with the department of mechanical engineering at the University of Applied Sciences Mittweida. In these tests the cutting process of the inserts against an aluminum workpiece were analyzed. The experimental results show on the one hand, that the line-structures as well as the quadratic form elements reduce the dynamic process forces compared to unstructured tools and on the other hand, the static process forces can be increased. Through the reduction of the dynamic process forces it is possible to minimize peak loads and tools reveal a longer life time.

These benefits of the microstructures were reduced by the fact that the microstructured elements were local filled with the aluminum material after a certain process time (see Figure 4 right and Figure 5). The use of a lubricant could not avoid this fill-process so far; however the process forces have been decreased by the lubricant.

In future investigations, for the reduction of the fill-process and to increase of the wear resistance we will deposit a ta-C film on the microstructure elements. Furthermore, the influence of geometrical forms of microstructures as a lubricant reservoir will be investigated.

Acknowledgements

The authors are gratefully acknowledged financial support of the present work by Sächsische Ministerium für Wissenschaft und Kunst (Project Nr. 080937862/ PRANO: 1236340295926) and for the good research conditions on the University of Applied Sciences Mittweida.

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