Structuring sapphire dies with short laserpulses and the resulting micro-forming structures

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Abstract

Due to the insufficient heat during the miniaturisation of a structure, additional energy in the form of laser radiation is used on the work piece during or before the forming process. The requirements of the die structures are high surface quality, shape accuracy, reproducibility, high stability and durability [1]. For the structuring of the sapphire tool several laser sources are available.

In this paper the achievable structures using rotation masks will be discussed. Furthermore the influence of the grain size of the workpiece and the die structure size on the micro-formed structures will be presented.

1. Laser assisted micro-forming

In this paper micro-forming is the metal forming of structures with their dimensions down to the micrometer range. On this scale, effects during the forming process occur leading to a different frictional and material behaviour compared to conventional dimensions. One method to overcome the problems concerning the material behaviour and the miniaturisation dependent lack of forming heat is to provide thermal energy to the microstructure during the process. The proposed method requires transparent materials in order to allow the propagation of the laser light to the forming region [2]. Sapphire combines the required transparency for laser irradiation at λ = 809 nm with excellent mechanical properties [3].

2. Complex strucutres with rotation masks

The structuring of the sapphire die with simple shapes, such as cylinders with a constant depth, can be easily achieved by applying mask imaging and shooting a certain number of laser pulses. More complex structures with a variable depth require a movement of the mask (or, analogously, of the sample) during the ablation process [4]. This section focuses on the microstructures that are rotational symmetric, such as cones and hemispheres. Figures 1a and 1b show the simulated rotation process: a simple shape is rotated around an axis to produce a grey-level image, in which a darker level corresponds to a deeper ablation. The depicted masks are defined respectively by the equations in polar coordinates:

$$r = \frac{2\theta}{\pi} \quad with\ \theta \in \left[0, \frac{\pi}{2}\right] \qquad\qquad r^2 + \left(\frac{2\theta}{\pi}\right)^2 = 1 \quad with\ \theta \in \left[0, \frac{\pi}{2}\right]$$

where r is the radial coordinate and θ is the angular coordinate. Our calculations of the resulting ablation profiles show that a linear equation in polar coordinates generates a structure with linear walls (Figure 1a below), while a circle equation in polar coordinates generates walls that follow a circular shape, thus creating a hemisphere (Figure 1b below). For the simulations a perfect top head beam profile was assumed.

Mask Geometry Simulated Ablation depth Mask Geometry Simulated Ablation depth

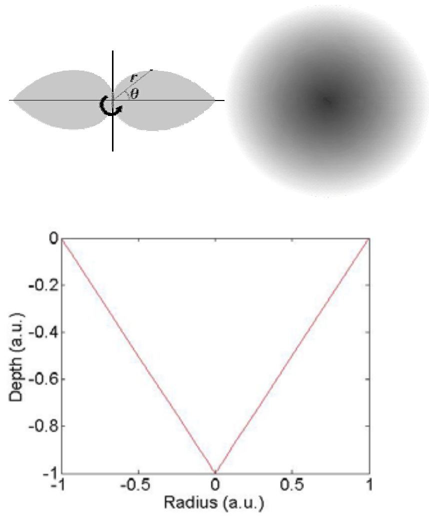


Figure 1a: simulation of rotated ablation

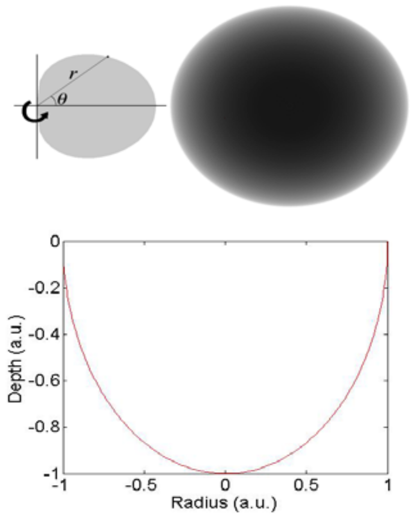


Figure 1b: simulation of rotated ablation

The resulting structures in sapphire made with an excimer laser with 193 nm, using the described rotation masks and the cross section images shown in figure 2 in sapphire affirm the simulations.

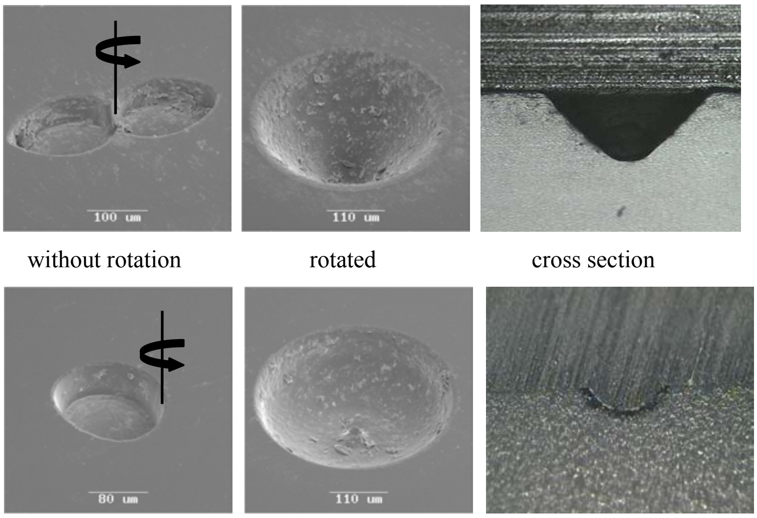
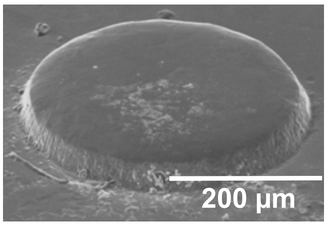


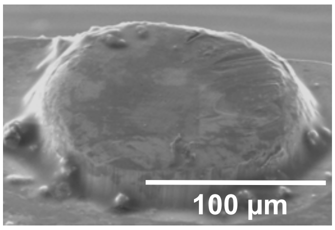
Figure 2: Microstructures in sapphire with rotation masks

4. Microforming Results – Microstructure / Tool Structure Size

Microforming experiments have been carried out which show the influence of the material microstructure on the result of the microforming process with down scaled tools and specimens of the same material (1.4301 stainless steel) but varying grain size. Some of these specimens were formed with big (400 µm diameter) and the others with small tool structure size (167 µm diameter). All other forming conditions remained constant, i.e. the maximum force and the forming velocity. As it is shown in Figure 3 and 4 the formfilling of the specimens with small grain size is better than the form-filling of the specimens with bigger grain size. This phenomenon occurs with big as well as with small tool structure. The ratio between form-filling and structure size increases with smaller structures. This can be explained by the fact that the experiments have been carried out with unscaled workpieces and unscaled process parameters. Thus the ratio between forming method and structure size increases with decreasing structure size. Figure 3b) and 4a) and b) show an inhomogeneous formfilling in comparison to Figure 3a). This phenomenon can be explained with the small number of grains involved in this forming process. The influence of the local anisotropy gets bigger with increasing grain size and decreasing structure size. This is also a scaling related effect which has to be quantified in future investigations.

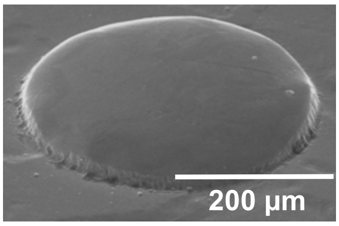


3a) used tool structure Ø: 400 µm

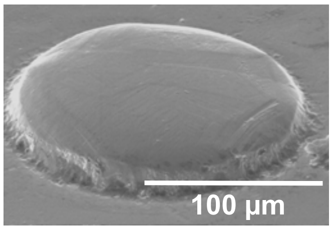


3b) used tool structure Ø: 167 µm

Figure 3: Formfilling of scaled tool structures with polycrystalline material (grain size: 10 – 20 µm)



4a) used tool structure Ø: 400 µm



4 b) used tool structure Ø: 167 µm

Figure 4: Formfilling of scaled tool structures with oligocrystalline material (grain size: 50 - 150 µm)

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Acknowledgement: The authors gratefully acknowledge the financial support of the German Research Foundation (DFG) within the framework of the Prority Programme SPP 1138 'Modelling of scaling effects on manufacturing processes'.