LASER-ASSISTED MICRO-FORMING WITH LASER STRUCUTRED SAPPHIRE DIES

Paper M601

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Abstract

We report on the development of a novel laser-assisted micro-forming technique for aluminium and stainless steel. This procedure uses UV-structured sapphire dies as molds for the components. A second laser beam (λ = 809 nm) is transparent to the sapphire dies and heats a localized region of the metal to enable the micro-forming process. The advantages and disadvantages of several micro-forming strategies will be discussed. This includes the influence of laser radiation on the accuracy of the forms. Influence of grain size and scaling effects associated with miniaturisation in micro-forming.

Introduction

The main application area for laser assisted forming is the electronic sector, but MEMS and other fields as microfluidic systems for the chemical or medical technology are playing an increasingly important role [1]. Industrial realization of these products and their breakthrough require suitable production technologies with respect to accuracy, productivity, effiency, reliability and ecological considerations. Metal forming technologies offer the advantages of high production rates, minimal or zero material loss, excellent mechanical properties of the product and small tolerances making it suitable for mass production. But the application of metal forming to the production of micrometer sized components is still limited as a series of problems arise in scaling this technology down to the micrometer. In this paper microforming is understood as metal forming of structures with their dimensions down to micrometer range. For these sizes, effects occur leading to a different frictional and material behaviour compared to conventional dimensions. This results from the fact that some factors like the microstructure of the material or the surface topology and roughness are independent of the dimension of the part to be produced and thus are not scaled down in the same way as the geometry. With decreasing size, the influence of single grains and their orientation must be taken into account. An increasing variation in the material behavior has been observed, leading to reduced process stability and reliability. Various research activities have dealt with these and other phenomena of production processes in the sub-milimeter range. However there is still a lack of knowledge, limiting the process design and the process stability, leading to a primilarily empirical process design for industrial applications. One method to overcome these problems concerning the material behavior is to influence the microstructure during the process. This can be accomplished by heating the workpiece. At high temperatures, an increased malleability is achieved and necessary process forces are reduced as more slip systems are activated. This reduces the anisotropic behavior resulting in a more homogeneous forming with an improved reproducibility. Warm forming combines these advantages with those of cold forming, such as good mechanical properties and surface quality. At even higher temperature i.e. above the recrystallization temperature, dynamic recrystallization is induced during the deformation process. This allows the newly formed microstructure to flow into the given structure of the die. For the purpose of heating the material, laser radiation seems the most suitable choice as it offers two main advantages with respect to other methods:

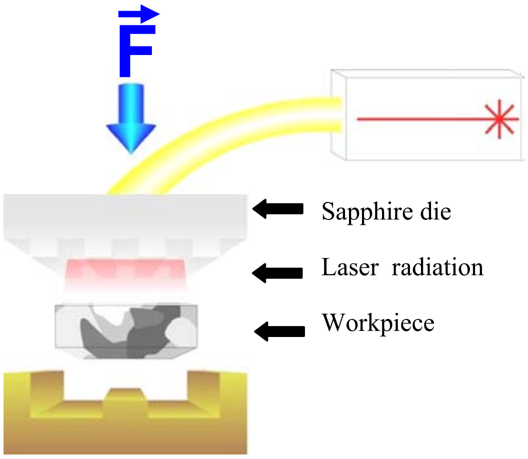


Figure1: principle of the laser assisted microforming process with laser structured sapphire dies

Local heating of selected areas of the workpiece and controlled energy input, i.e., through regulation by the temperature in the workpiece via the current of a diode laser. The proposed method shown in Figure 1, requires transparent tools in order to allow the transmittance of the laser light to the forming region [2,3]. Sapphire combines the required transparency for laser irradiation at $\lambda = 809$ nm with excellent mechanical properties like high hardness and compressive strength, making it suitable for metal forming. In addition its melting temperature of 2300 K allows warm or hot forming of steel (with a melting point of about 1300 K) without destroying the tool.

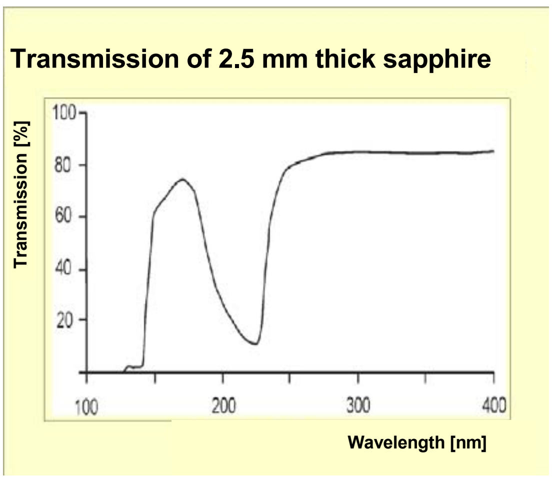


Figure 2: Transmission curve of sapphire

The transmission curve in Figure 2, shows a transmission < 60% in the region of 160 nm -245 nm. Light in this UV range will be absorbed, thus a structuring of the sapphire die with UV laser radiation as tool is well suited. Moreover sapphire has a high transmission for larger wavelengths (> UV), so the die will be transparent for the used heating radiation with its wavelength of 809 nm [3]. Miniaturisation of this microforming process, scaling effects occur during tool manufacturing and the laser assisted embossing process. The scaling effects influence the forming result, so that it is necessary to find compensation strategies to reach the highest accuracy possible for microforming.

Tool manufacturing for micro-forming

The first goal was to structure simple geometries like two concentric cylinders shown in Figure 3 a), with a depth of 100 µm and diameters of 400 µm and 200 µm. Different laser sources and manufacturing strategies have been tested. The Scanning Electron Microscope (SEM) image in Figure 3 b) shows the result of structuring with a frequency quadrupled Nd:YVO_4 solid state laser with a wavelength of 266 nm and a repetition rate of 200 kHz.

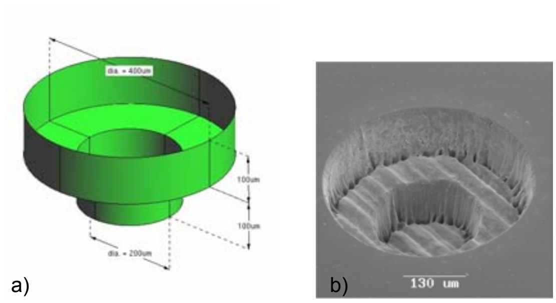


Figure 3: a) drawing of the required structure b) result of structuring with a solid state laser λ =266 nm, hatching of the two concentric cylinders.

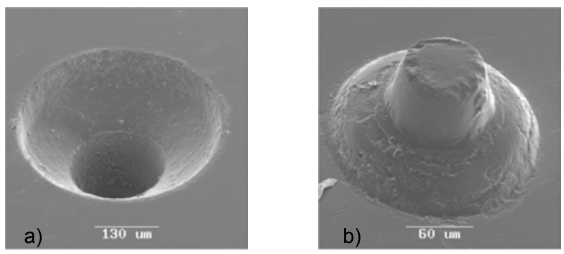
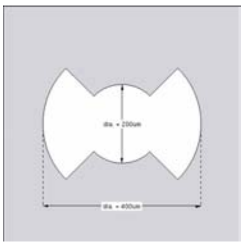


Figure 4: a) twin-cylinder, structured with excimer laser λ = 193 nm, imaging procedure, b) replica of the structure in 4 a) .

The laser beam is focussed to a diameter of 10 µm using a high precision galvano scanner. The galvano scanner consists of an f-theta lens and two galvano mirrors. The structure in Figure 3 b) is produced with a scanner speed of 1 m/s. The walls of the structure are vertical and straight with nearly 90° angle to the bottom. But the scanning strategy leads to a very rough surface, because the areas of the two cylinders are formed by hatching. The single lines of the hatch pattern influence the surface quality. An excimer laser leads to a very different result as shown in Figure 4a. The image beam form with a mask image ratio of 20:1 allows an ablation of the cylinders without moving the laser beam and the sample. To reach the desired structure, first the smaller cylinder with a diameter of 200 µm was ablated using a mask with a diameter of 4 mm. In the second step, the larger cylinder with 400 µm was ablated using an 8 mm mask. This sequence of steps has an advantage that no debris are deposited on the larger cylinder. The SEM picture in Figure 4 a shows that the surface is very smooth. This high surface quality is the biggest advantage of this imaging technique. However, the disadvantage is that the drilled cylinders are not vertical. The material at the border is less ablated since the energy density is lower at the border of the structure. The replica of this structure, which demonstrates this rounding effect clearly is shown in Figure 4 b. This deviation of the real structure from the desired structure using excimer radiation for structuring increases as the structure size decreases.

This decreasing form accuracy influences the structure in the work-piece after microforming with the structured die. To obtain the best forming result, a compensation of this effect is necessary. One strategy to decrease the deviation of the obtained structure from the desired is the use of a rotation mask shown in Figure 5.



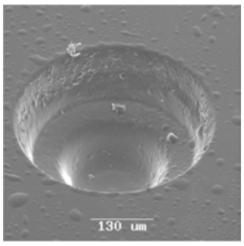


Figure 5: Rotation mask Figure 6: result

While using a mask with such a design, the sample is rotated during ablation. The result is shown in Fig. 6. The rotating mask leads to an improvement in the obtained structure in respect to the desired structure. The undesired shape of the walls is compensated and the bottoms are flat. The second advantage of such a rotation mask is the lower energy of the generated plasma cloud, and a consequential lower thermal stress, so that this strategy represents a possibility to minimise microcracks [5], described in the following section.

The size of microcracks, induced by thermal stress during ablation and the size of the melting zone at the border of the structure, are independent on the size of the structure, so that a miniaturisation of the geometry leads to a relative growth of the cracks and melting with respect to the structure size. Figure 7 shows the domination of cracks with a typical length of up to 10 µm for the smaller structure with a diameter of 200 µm to comparison with the larger structure with a diameter of 400 µm (left side). The relative for smaller size of cracks is larger. There are different possibilities to compensate this effect, for example using a buffer gas which leads to minimisation of microcracks, because the cooling effect of this gas minimises the thermal stress in the material. Furthermore, the buffer has a lower density than air, thus the ablated material can be thrown further away, leading to less debris in the structure surroundings. A further minimisation of cracks and debris can be achieved with a F_2 excimer laser with a wavelength of 157 nm, where a different beam-material-interaction takes place [4]. Furthermore, working under vacuum leads to less redeposition of the ablated material.

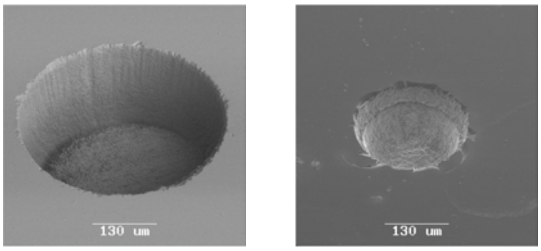


Figure 7: Increasing of micro-cracks in respect to a decreasing structure size

Tool characterisation

An important point in this laser assisted microforming method is the longevity of the sapphire die. One reason for the choice of sapphire as tool material is its high rigidity. To guarantee the stability and a long life of the tool, possible damaging effects were investigated. Figure 8 shows a hole drilled with an excimer laser (λ = 248 nm) in a 350 µm thick sapphire sample with a diameter of 200 µm and a depth of 300 µm. Regarding the transmission behavior of sapphire in Figure 2 one can see that more than 20 % of the radiation will not be absorbed in a 2.5 mm thick sample. The part of the radiation that is not absorbed gets reflected at the backside and re-reflected on the bottom of the drilling.

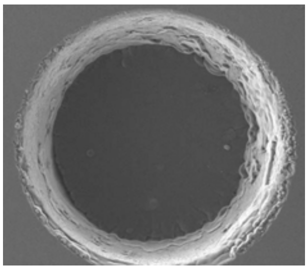


Figure 8: 300µm deep drilling in a 350 µm thick sample

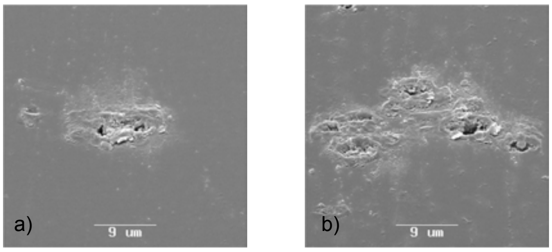


Figure 9: Damaging of the sapphire sample backside induced by interference of the non-absorbed radiation at a residual thickness of 80 µm (9a) and 50 µm (9b).

Figure 9 shows the resulting damaging of the backside of the sapphire sample which occurs at a residual thickness of up to 80 µm (9a). The damaged area is twice as big at 50 µm (9b). The damage can be reduced by reducing the high refractive index difference of sapphire/air of 1.77. The use of emersion oil or alternative liquids leads to a shift of the minimal thickness for unharmed backsides from 80 µm to 60 µm [6].

Another risk minimising the dies life duration is the pressure of the plasma cloud, that develops during laser ablation. Figure 10 shows the structuring of a pyramidal structure with a solid state laser (λ = 1064 nm) of pulse duration of 5 picoseconds, a relative high pulse energy of 500 µJ and a focus diameter of 25 µm.

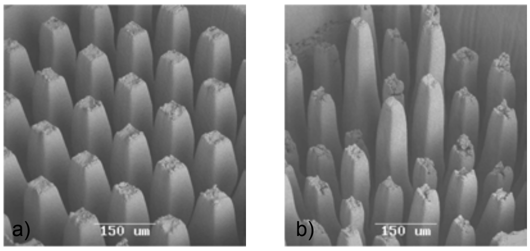


Figure 10a) Pyramidical structures in sapphire, with an aspect ratio of 5 (100 µm to 500 µm) Figure 10b) and 10 (50 µm to 500 µm)

If the aspect ratio of the structure gets too high, the pressure of the cloud leads to a braking of the pyramids. In these experiments, pyramids with an aspect ratio of 5 (100 µm diameter to 500 µm depth) were stable (Figure 10a), while the pyramids with the ratio of 10 (50 µm to 500 µm) broke (Figure 10b). Figure 11 shows a structure made with the 193 nm excimer laser at a fluence of F = 18,5 J/cm^2. In contrast to the laser having high fluence, one can see that it is possible to reach a high aspect ratio of 25.

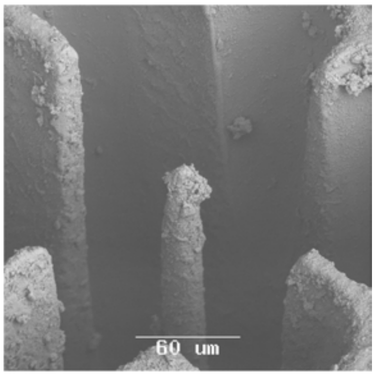


Figure 11: Structure generated with Excimer radiation (193 nm), diameter of the tip on the top: 20 µm

The imaging beam shape leads to a much lower density of energy, thus the pressure of the plasma cloud is much lower. In further investigations, the durability of dies with these complex structures and also of those with simple geometries described above will be investigated statistically.

Sapphire Tool Heating

Experiments have been carried out to examine the influence of laser beam heating (wave length: λ = 809 nm) on the sapphire tool temperature. For these experiments, sapphire tools with and without microcracks were used. Figure 12 shows the assembly with the workpiece (stainless steel 1.4301). The experiment was repeated without workpiece to determine its influence on the tool temperature. The laser power of the used diode laser with a laser beam diameter $\varnothing_L$ = 2,3 mm was set to P_L = 8,5 W.

Figure 13 illustrates that defective sapphire tools (sapphire tools with microcracks) warm up more than intact ones, regardless if there is a contact between tool and workpiece or not. This can be explained by the fact that the microcrack regions absorb more laser energy than intact regions, converting it into heat. Furthermore the laser beam is partially reflected at the microcracks lengthening the beams path within the sapphire and therefor leading to an increase of the tools temperature due to energy absorption.

It is shown that the sapphire tool heat up more when the tool is in contact with a workpiece. The reason for this is the reflection of the beam at the contact surface on the one hand and the heat transfer from workpiece to tool on the other hand. As in the case of the defective tool the reflection causes a lengthened path through the sapphire and therefor a higher energy absorption. As the laser assisted micro forming technologie is based on the heat insertion into the workpiece to reduce scaling related effects and process forces, a sideeffect is the heat transfer from the workpiece to the tool in contact.

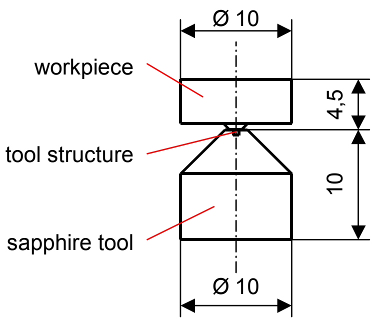


Figure 12: assembly and dimensions of the sapphire tool and the workpiece

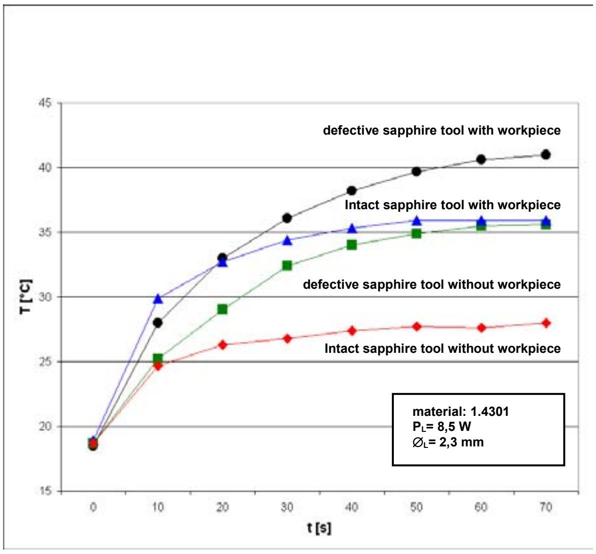
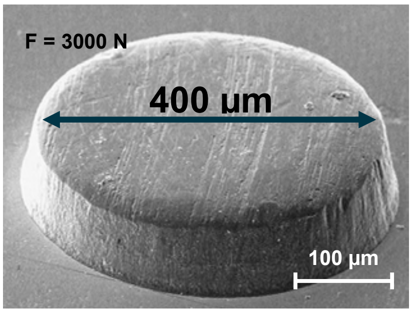


Figure 13: sapphire tool heating depending on the condition of the sapphire tool with and without workpiece contact

Microforming Results – Microstructure / Laserpower

A substantial factor for the laser assisted microforming process is the materials microstructure. Therefore experiments have been carried out which show this influence on the result.
Specimens of the same material (1.4301 stainless steel) with variing grain size were formed in these experiments with and without laser assistance (P_L = 6,7 W laser power). All other forming conditions remaind constant, e.g. the maximum pressing force, the tool geometry and the forming velocity. As shown in Figure 14 and 15 the formfilling of the specimens with small grain size is much better than the formfilling of the specimens with bigger grain size. This phenomenon occurs without (Figure 14) as well as with (Figure 15) laser assistance, whereas the laser assisted formfilling shows better results than the formfilling without laser assistance of specimens with the same grain size. Furthermore, Figure 14 b) shows the inhomogeneous material flow with big grain size. This phenomenon arises from the small number of grains involved in the forming process so that the influence of the local anisotropy gets stronger with increasing grain size. This is an additional scaling related effect which has to be quantified by future investigations.

a) Polycrystalline material (grain size: 10 - 20 µm)



b) Oligocrystalline material (grain size: 50 - 150 µm)

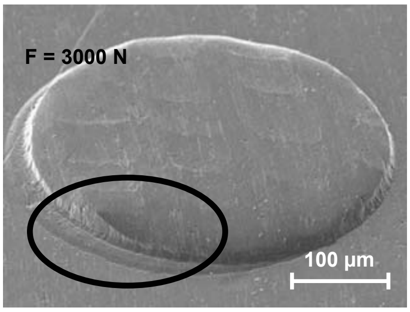
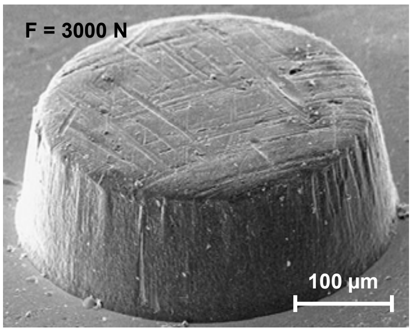


Figure 14: cold embossing of stainless steel

a) Polycrystalline material (grain size: 10 - 20 µm)



b) Oligocrystalline material (grain size: 50 - 150 µm)

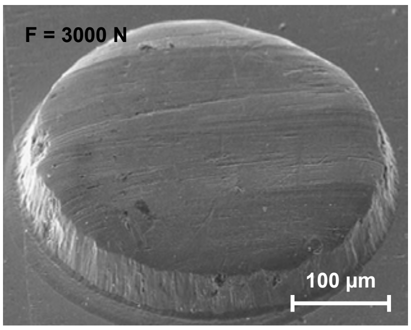
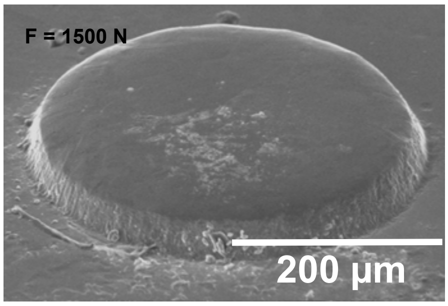


Figure 15: Semi-hot embossing (laser assisted forming with P_L = 6,7 W) of stainless steel

Microforming Results – Microstructure / Tool Structure Size

Further 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 variing 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 remaind constant, e.g. the maximum force and the forming velocity. As it is shown in Figure 16 and 17 the formfilling of the specimens with small grain size is better than the formfilling of the specimens with bigger grain size. This phenomenon occurs with big as well as with small tool structure. The ratio between formfilling and structure size increases with smaller structures. This can be explained by the fact that the experiments has been carried out with unscaled workpieces and unscaled process parameters. Thus the ratio between forming way and structure size increases with decreasing structure size.

a) used tool structure diameter: 400 µm



b) used tool structure diameter: 167 µm

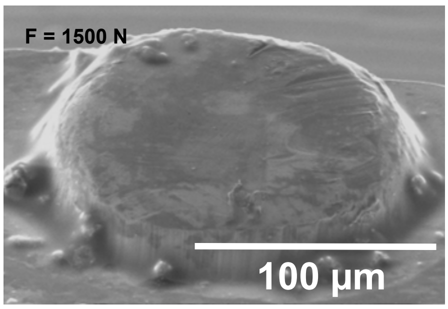
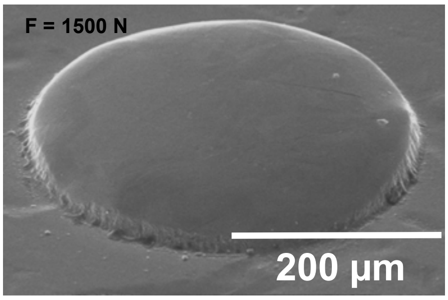


Figure 16: Formfilling of scaled tool structures with polycrystalline material (grain size: 10 – 20 µm)

Figure 16 b), 17 a) and b) show an inhomogeneous formfilling in comparison to Figure 16 a). 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.

a) used tool structure diameter: 400 µm



b) used tool structure diameter: 167 µm

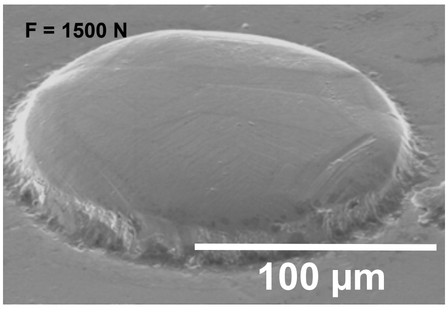


Figure 17: Formfilling of scaled tool structures with oligocrystalline material (grain size: 50 - 150 µm)

Outlook

Several tasks are envisioned in the near future. A quantitative description of the scaling effects during tool manufacturing will be formulated, to achieve a better understanding of the microforming process. A second material, quartz, will be used and compared to the sapphire dies. Quartz is expected to improve the results over sapphire, since a lower amount of melting and debris during laser ablation have been observed. A main point of work is the investigation and increasing of the longevity of the sapphire dies. The increased performance of these dies is necessary for industrial applications, which are foreseen to increase in importance in the next two years. One possible industrial example of these dies can be seen in Fig. 18, which shows a microfluidic system in Sapphire with channel diameters of 50um in width. This form can be transferred to aluminum and stainless steel.

Further goals are to investigate in the influence of different grain sizes, structure sizes, and laser power on the forming of sapphire dies.

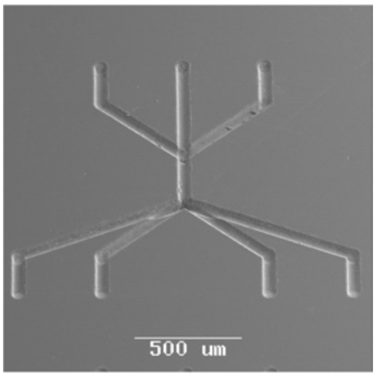


Figure 18: Microfluidic system in sapphire

A second application is to investigate functional surfaces by laser assisted embossing. A series of sapphire surfaces with various roughness (controlled by spacing of hatching) have been created. An investigation whether the roughness can be transferred to the surface of the embossed workpiece and its functionality will be made. Further goals are to investigate in the influence of different grain sizes, structure sizes, and laser power on the forming of sapphire dies.

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