STUDY OF SIZE EFFECTS BY LASER-ASSISTED MICRO FORMING
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Abstract

The use of metal forming technologies on metallic micro parts is limited by problems arising from size effects related to small dimensions. This study is on the development of a new, laser-assisted, micro forming technique for stainless steel in which UV-laser-structured sapphire tools are used as forming moulds. To enable the micro forming process, a localized area of the workpiece is heated through the transparent tools using a laser beam ($\lambda = 809$ nm). The key aspects of the presented research are the influence of scaling effects due to miniaturization on both, the tool structure and the work piece. The advantages and disadvantages of several strategies are discussed.

Introduction

The main application area for laser-assisted forming is the electronic sector, but MEMS and other fields, such as micro fluidic systems for the chemical or medical technology, are playing an increasingly important role [1]. The industrial realization of these products and their market breakthrough require suitable production technologies with respect to accuracy, productivity, efficiency, reliability and ecological viability. Metal forming technologies offer the advantages of high production rates, minimal or zero material loss, excellent mechanical properties and small product tolerances, making them suitable for mass production. However, the use of metal forming in the production of micrometer sized components is still limited, as a series of problems arise in using this technology down in the micro scale [2]. In this paper, micro forming refers to the forming of structures in metal with dimensions in the micrometer range. On this scale, the forming process has a different frictional and material behavior as compared to that of conventional dimensions. For example, miniaturization leads to a reduction of the forming heat which supports the forming process. One method to overcome this problem is to provide thermal energy to the microstructure during the process. The method shown in Figure 1 requires transparent die materials which allow the laser radiation to be transmitted and have an effect on the forming area [3,4].

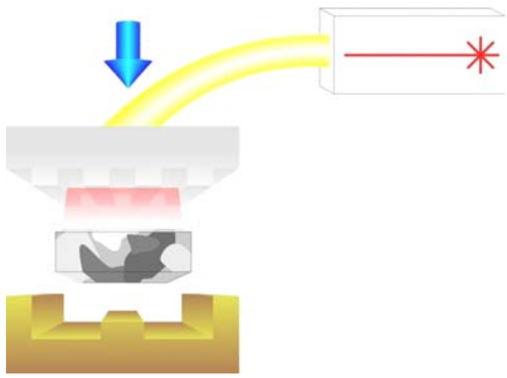

Figure 1: Tool manufacturing for micro forming.

Sapphire is both transparent for laser irradiation at $\lambda = 809$ nm and it has excellent mechanical properties like high hardness and compressive strength, making it suitable for metal forming [4]. In addition, its melting temperature of 2300 K allows warm or hot forming of steel (with a melting point of about 1300 K), without damaging the tool. Furthermore, sapphire shows a transmission < 60% for the range of 160 nm - 245 nm, meaning that UV laser radiation will be absorbed, and can be used to structure the sapphire die. Moreover sapphire has a high transmission for higher wavelengths (85 % for 809 nm), so the die will be transparent for the heating radiation used at this wavelength. During miniaturization of this micro forming process, scaling effects occur within the tool manufacturing and the laser-assisted embossing process. These scaling effects influence the forming result, making it necessary to find compensation strategies to reach the highest possible accuracy for micro forming.

Structuring of the Sapphire Die

Size Effects

The goal of this project is to identify and investigate size effects, for example decreasing dimensional accuracy and increasing damage, and process limitations with regard to drilling depth and process speed while miniaturizing the microstructure in the sapphire die [5]. Decreasing form accuracy, for example, influences the structure in the workpiece after micro forming with the structured die.

In this paper, the results of investigations regarding the limitations of drilling with decreasing diameters is presented. In order to determine the maximum depth that can be reached using this technique, an investigation was carried out which consisted of irradiating a sapphire sample with different numbers of laser pulses. Figure 2a presents the depths achieved with a 248 nm excimer laser at a maximum fluence of 4.6 J/cm². The curves in each graph represent structures with different diameters, obtained through a projection of circular masks. All the curves show a similar behavior, with a linear increase that approaches a maximum depth saturation point. The smaller the mask, the lower the depth limit. Fluence less than 1.5 J/cm² (Figure 2b) leads to a lower kinetic energy of the ablated particles, and consequently, only shallow structures can be fabricated.

When drilling small holes, the ablation quality in terms of sharpness clearly decreases. This effect represents another limitation of this micro structuring technique: a resolution limit, the diffraction limit. Figure 3 depicts the experiment carried out to study this limitation. Ideally, the energy density would not depend on the geometry of the mask; however, the diffraction losses at the mask are significant if the mask is very small. This explains the steep drop measured for mask sizes below 0.3 mm, setting the resolution limit, when using a projection ratio of 20:1 – of 15 µm. At this point, the diffraction effects begin to be significant.

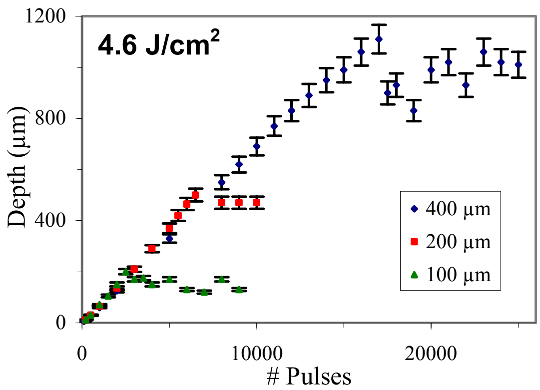

Figure 2a: Maximum depth for: 4.6 ± 1 J/cm², with different spot sizes.

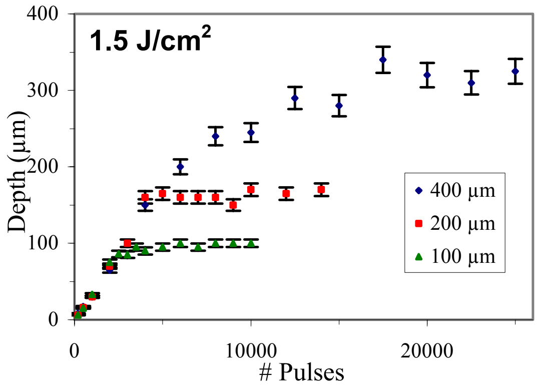

Figure 2b: Maximum depth for: 1.5 ± 1 J/cm², with different spot sizes.

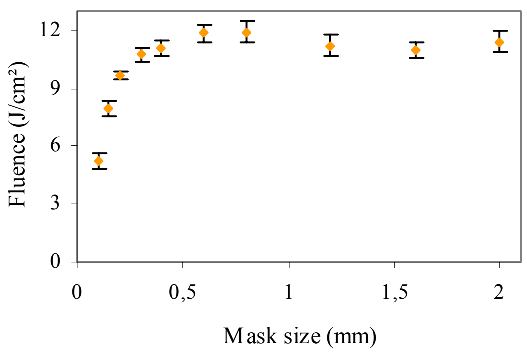

Figure 3: Measured fluence as a function of the size of a square mask. λ = 193 nm.

Furthermore, the diffraction at the border of the masks also leads to a relative decrease of image sharpness. The curvature caused by diffraction at the corners has a radius of approximately 4 µm, which has a more significant influence as the ablated surface becomes smaller. Therefore, the ablated shape can no longer be recognized as a square with sharp edges (see microscope pictures on Figure 4) compared to the square on the left side, ablated using a mask with an edge length of 4 mm.

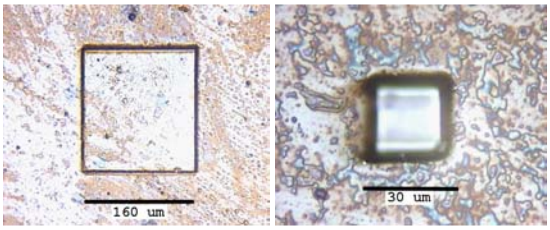

Figure 4: Reduction of sharpness with size. Left side: ablation with 4 mm mask, right side: ablation with 0.5 mm mask.

Modeling

Two processes explain the energy transport inside the material when using UV laser pulses for ablation: the energy transport by photon diffusion, and heat conduction. A model which describes the ablation mechanism will help us to understand the appearance of size effects.

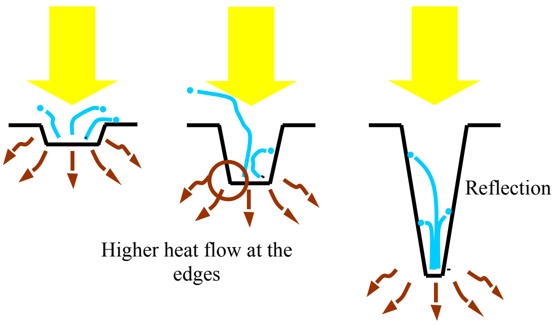

Figure 5: Modeling of deep drilling.

There are three main effects that, according to this model, limit depth under equal conditions of energy and spot size. The first limiting effect is the focus depth of the image. Magnitude and homogeneity of the energy density decrease as the drilling goes deeper and away from the image plane. At some point, the fluence may decrease below the ablation threshold of the material, setting a maximum limit for the depth.

Two further effects depicted in Figure 5 limit the depth. One is the collision of the ablated material with the walls of the hole. The ablated particles cannot escape from the hole, and fall back to the bottom. In order to prove this effect, holes were ablated with their centers exactly at the edge of the sapphire die, so that the material could easily be ejected. Compared to the drillings made completely within the surface of the die, an increase of the maximum depth is achieved, as can be seen in figure 6.

The last effect that causes limitation is the higher heat flow at the bottom corners of the hole. The surface surrounding the corners is larger than that surrounding the walls. This allows the heat to propagate faster. The corners will cool down, and return to a solid state. The result is that the walls are not completely vertical, but with an angle dependant on the energy and the material used.

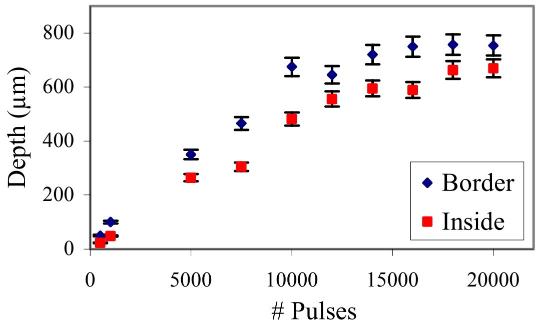

Figure 6: Maximum depth for a density of energy: 4 ± 1 J/cm², drilled inside and at the border of the sapphire die.

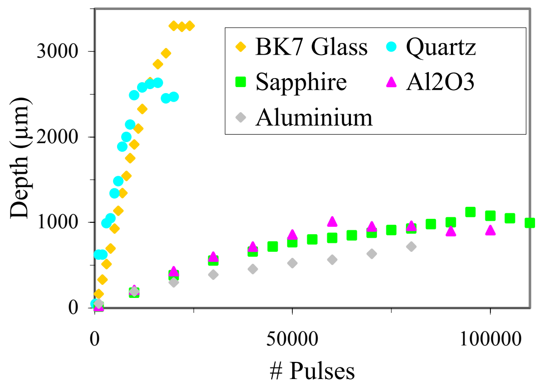

Figure 7: Maximum depth for different materials with a density of energy between 4.6 and 5.1 J/ cm².

Figure 7 shows an experiment similar to those carried out for the results in Figures 2a and 2b. In this case, different materials were used. All other parameters were kept constant in order to compare the properties of the materials. An excimer laser with a wavelength of 193 nm and a pulse frequency of 100 Hz was used. The energy is kept inside the range of 4.6 to 5.1 J/cm², and the diameter of the resulting ablation is around 380 µm. The materials chosen were metal. (aluminum); two different structures of aluminum oxide: its crystalline form (sapphire) and the ceramic form known as alumina; two types of glass: BK7, a Borosilicate glass commonly used in optics, and fused silica (SiO_2).

The curves show that a higher depth limit is reached for BK7 and fused silica, parallel a steeper slope is observed. The curves for sapphire and alumina, which have the same chemical composition (Al_2O_3), show a similar behavior. Finally, aluminum reaches the lowest depth with the same number of pulses.

For the interpretation of these results, Table 1 is presented. According to this model, one of the depth limiting effects is heat conduction, which is highly dependent on the material. This is shown in the table (thermal conductivity). The selected materials can therefore be divided into three categories: glass, which has a very low thermal conductivity; Al_2O_3 compounds, and metals, with the highest conductivity. According to this model, a higher heat conduction should induce a faster cooling on the bottom corners of the hole, thus leading to holes with a large wall angle and therefore a low aspect ratio.

Table 1: Physical properties of the selected materials.

Material	Ablation threshold [J/cm^2]	Thermal conductivity [W/m·K]
BK7 Glass	1.0	1.114 (20°C)
Quartz glass	1.7	1.38 (20°C)
Alumina (Al_2O_3)	0.7	16-30
Sapphire (Al_2O_3 crystal)	1.0	46.06 (0°C)
Aluminum	0.5	237 (25°C)

Contrary to our expectations, there is no identifiable direct dependence of the maximum depth on the ablation threshold of the materials in Table 1. Apparently, the decrease of density and homogeneity of energy as the drillings become deeper and the different thermal properties of the materials seem to have a more significant influence on the limitation of depth. Further experiments must be carried out in order to investigate the influence of the ablation threshold.

Micro Forming

The importance of knowledge about the thermal behaviour in micro forming is pointed out. Lower forming temperatures in smaller workpieces can be expected as the surface-volume-ratio increases enhancing the heat transfer to the environment (Figure 8). The dissipation energy E_{disp} (heat energy released during the forming process) decreases with decreasing scale factor λ. This thermal size effect is shown in Figure 9. The temperature and its distribution within the workpieces at the end of the deformation process change with varying workpiece size, although the initial temperature and the deformation degree of 50 % remain constant.

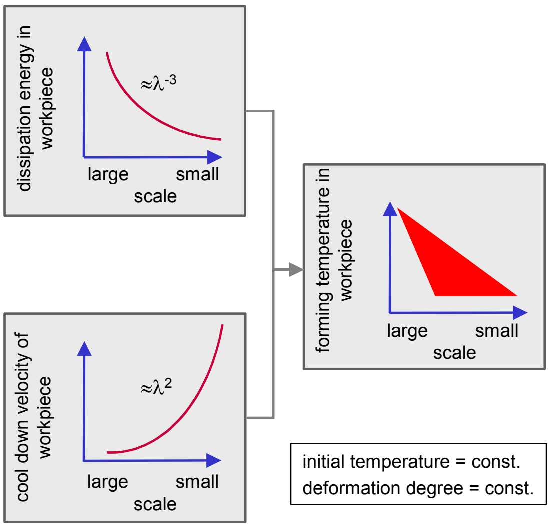

Figure 8: Workpiece size influence on forming temperature and its distribution.

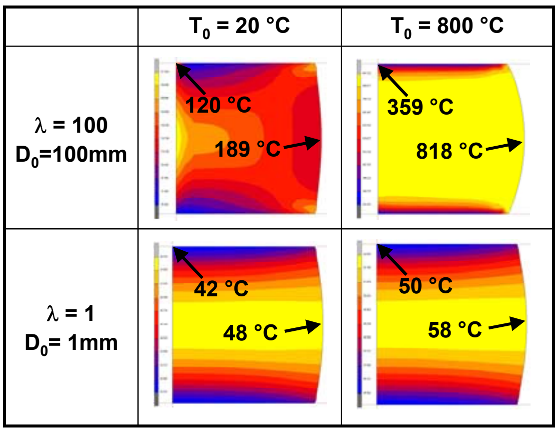

Figure 9: Workpiece size influence on forming temperature.

An approach to compensate or reduce the impact of size effects is to influence the temperature during the forming process. This can be accomplished by heating the workpiece. At high temperatures an increased formability is achieved while reducing flow stress and thus process forces as more slip systems are activated. This reduces the anisotropic material behaviour resulting in a more homogeneous forming with improved reproducibility [6,7].

Laser radiation seems the most suitable choice for the purpose of heating the material during the micro forming process as it offers several advantages in comparison to other methods:

- The laser energy input and thus the resulting temperature in the workpiece, can easily be controlled via the current of a diode laser.
- Local heating of selected areas of the workpiece is possible, allowing to limit the heating to the forming zone.
- Needed temperature gradients can be achieved by control of laser power.
- The absorption of laser radiation allows short process times which cannot be accomplished with heat transfer from pre-heated tools.
- Material properties can be manipulated by controlling the down cooling time via laser power.

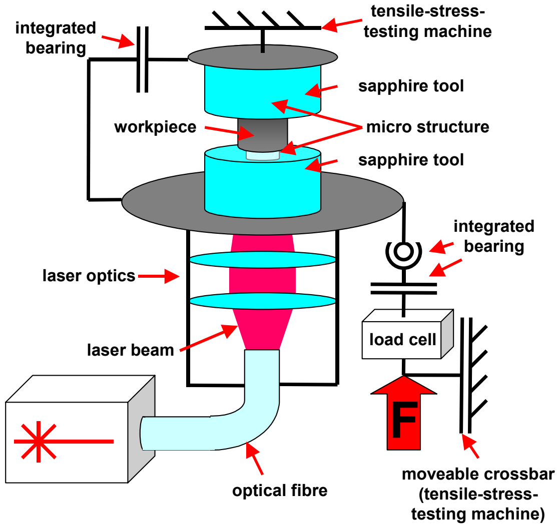

Figure 10: Principle of laser-assisted micro forming.

The proposed method (Figure 10) requires transparent tools in order to allow the transmittance of the laser light to the forming region. Sapphire combines the required transparency to laser radiation (at wavelengths $\lambda > UV$) with excellent mechanical properties like high hardness, compressive strength and Young's Modulus, making it suitable for metal forming. In addition its melting temperature of 2050 °C allows warm and hot forming of steel without destroying the tool.

Experimental Set-Up for Laser-Assisted Micro Forming

The application of metal forming technologies to the production of micro parts requires suitable production systems with high accuracy and productivity. A series of challenges in technical implementation of the clamping tools and workpiece arise from these requirements. The laser-assistance of the forming process requires the integration of the laser optics into the tool system. A minimum distance between laser optics and sapphire tool is favourable in order to achieve a small laser spot and reduce losses in laser power. This leads to conflicting demands as high stiffness and mechanical strength are needed in order to transmit the process forces of several 1000 N while meeting the desired accuracy of positioning.

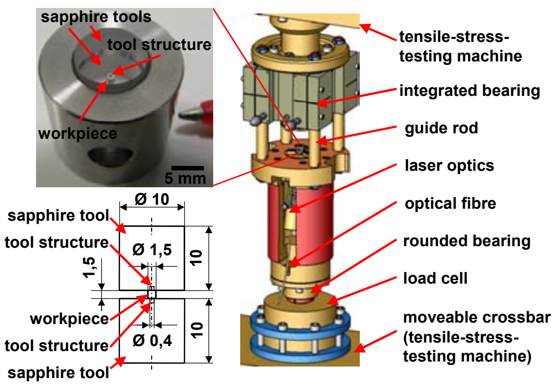

Figure 11: Exemplary tool-workpiece assembly and Experimental set-up.

A prototype of an experimental set-up for laser-assisted micro forming (Figure 11) has been developed at the Laboratory of Production Engineering of the Helmut Schmidt University / University of the Federal Armed Forces Hamburg accounting for these requirements. A new guiding system was implemented working independently from the carrying machine's guiding in order to improve the accuracy of the tool – workpiece positioning. The set-up is build in a modular conception enabling the exchange of the workpiece and the tool carriers for different applications. The laser optics are integrated into the tool carrier system. The distance between tool and laser optic is adjustable. The laser system includes a diode laser package with a maximum output power of 80 W and a wavelength of 809 nm as well as an aiming beam for the purpose of alignment of the laser beam.

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Meet the Authors

Katja Samm studied physics at the RWTH Aachen in Germany. Since 2002 she is working as a research scientist in the Microtechnology Group of the Laser Zentrum Hannover (LZH). Her main work is UV laser manufacturing of different materials, in particular sapphire.

Dipl.-Ing. Mahdi Terzi graduated in mechanical engineering with focus on mechanical engineering design / product development at the Technical University Hamburg-Harburg. Since December 2004 he is working as a research assistant in the field of micro forming at the Laboratory of Production Engineering of the Helmut-Schmidt-University/ University of the Federal Armed Forces Hamburg.

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