Investigation of Laser Heating in Microforming Applying Sapphire Tools

J.P. Wulfsberg[1], M. Terzi[1]
[1]Laboratory of Production Engineering, Helmut-Schmidt-University / University of the Federal Armed Forces, Hamburg, Germany
Submitted by D. Schmoeckel (1), Darmstadt, Germany

Abstract
The application of metal forming technologies to the production of metallic micro parts is limited by problems arising from size effects related to small dimensions. An approach to solve these problems is the laser-assistance of the micro forming process to benefit from e.g. the growing influence of thermodynamic aspects. Experimental investigations were carried out to determine the workpiece temperature by varying laser power at constant heating time. This is a substantial factor for the laser-assisted micro forming process design. Results from a numerical analysis using FEM techniques were compared with the ones from the test series. Furthermore micro forming investigations were made showing a dependence of the material micro structure from tool structure size and laser power.

Keywords:
Laser, Forming, Miniaturization

1 INTRODUCTION

From the general trend towards greater miniaturization and functional integration results an increasing demand for metallic parts or structures of smallest dimensions (down to 100 µm) like miniature springs and screws, connector pins, shafts or gears. Industrial realization of these parts and the further breakthrough of products containing microparts require suitable production technologies regarding accuracy, productivity, efficiency and reliability. This aspect is still a significant limitation [1,2].

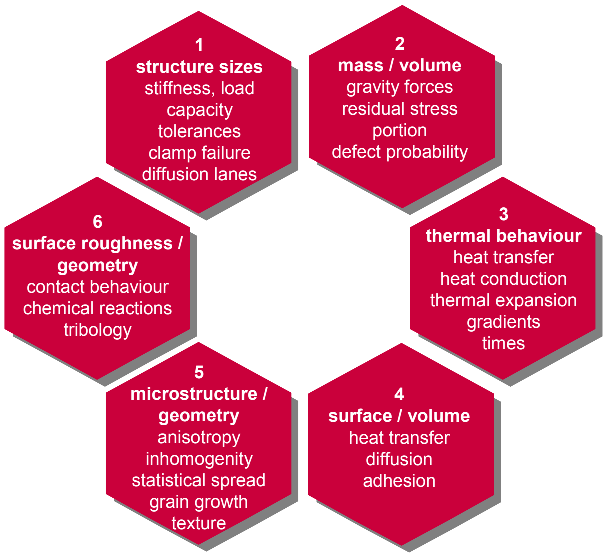


Figure 1: Fields influenced by size effects.

The production processes of microsytem technology like LIGA and etching are either not suitable for processing metals like steel or the productivity is low. Despite the advances in the downscaling of several classical production technologies like cutting or laser machining these are still far from being established in the production for microparts [3,4].

Metal forming offers 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 and near net shape technology. But the application of metal forming technologies to the production of microparts is still limited as a series of problems arise in down scaling this technology to the micro size. Figure 1 illustrates these problematic fields for the transfer process.

The purpose of this work is to approximate lab results taken after a series of experiments with computer simulations, in order to be able to predict the outcome of future experiments by simulations. The object of prediction of main concern is the time needed, until the laser heated workpiece reaches the desired temperature. The computer simulation tool “MSC Superform 2005” was used.

2 LASER-ASSISTED MICRO FORMING

The importance of knowledge about the thermal behaviour in micro forming has been 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 2). 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 3. 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.
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 [5,6].

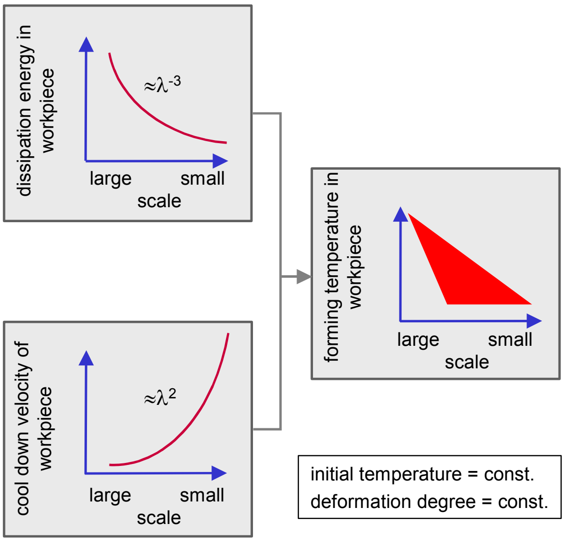


Figure 2: Workpiece size influence on forming temperature and its distribution.

Laser radiation seems the most suitable choice for the purpose of heating the material during the microforming 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.

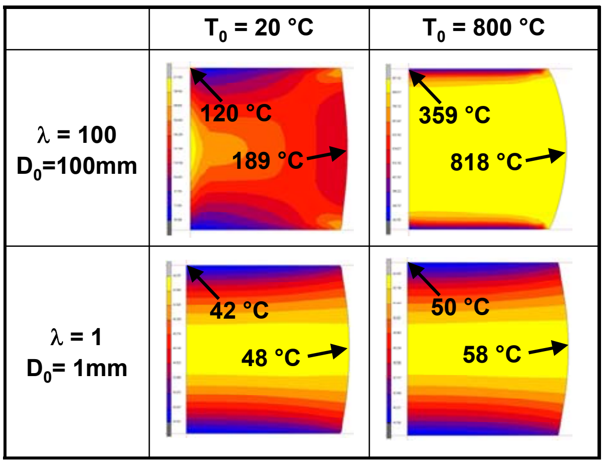


Figure 3: Workpiece size influence on forming temperature.

The proposed method (Figure 4) 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 λ > 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.

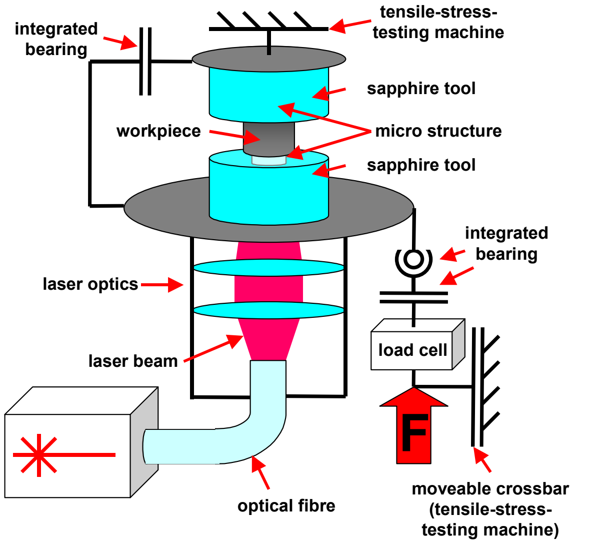


Figure 4: Principle of laser-assisted micro forming.

3 EXPERIMENTAL SET-UP FOR LASER-ASSISTED MICRO FORMING

The application of metal forming technologies to the production of microparts 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.

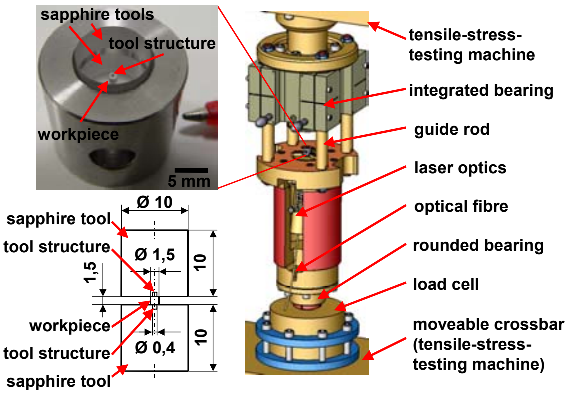


Figure 5: Exemplary tool-workpiece assembly and Experimental set-up.

A prototype of an experimental set-up for laser-assisted microforming (Figure 5) 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.

4 HEATING EXPERIMENTS

Experimental investigations to determine the workpiece temperature during the heating processes with laser energy were carried out. Therefore a cylindrical workpiece made of steel (1.4301) and set between a punch and a die is heated by a laser beam on one side, while no actual compression takes place. The punch and die are made of sapphire (Figure 6). The initial temperature of workpiece and tools is 20 °C. This must be taken into account, when evaluating the experimental curves. As the pyrometer measures only temperatures exceeding 300 °C, lower values cannot be depicted (Figure 7). The instruments setting time is responsible for the high fluctuation of the measured temperatures up to t = 1 s. The pyrometer was set to measure the workpiece temperature on the cylinder peripheral surface 0.5 mm from the energy absorbing front surface (cf. chapter 5). The duration of the measurement was t = 10 s. This was performed with workpieces height and diameter of 1,5 mm and laser power of 15, 25 and 35 W.

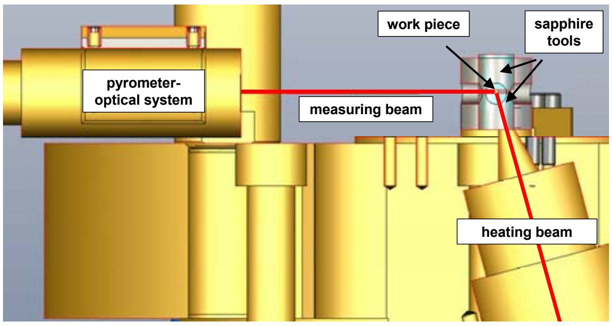


Figure 6: Experimental set-up for workpiece temperature measurement.

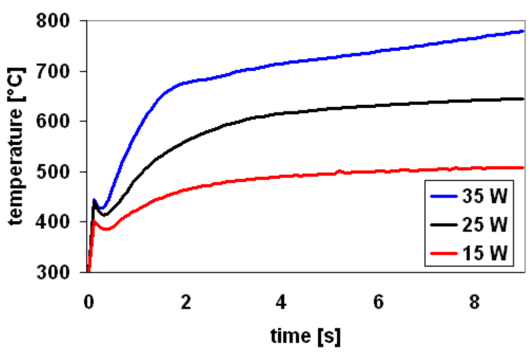


Figure 7: Workpiece temperature during heating.

5 HEATING SIMULATION

All curves from the experimental measurements (Figure 7) for each laser power ends up in an almost constant temperature. After a specific time of 3.4 seconds. Approaching these curves by varying the unknown parameters was the primary aim of the simulations. For the simulations three different models were build to find out the model with the best results by keeping the simulation time low. In Figure 8 all used models are shown: a) simplified tool dimensions, b) correct tool dimensions and c) correct tool dimensions with environment (full simulation). In Figure 8 a) the tools were not modeled in their correct size. Instead simplified tools were build, consisting of the surfaces in contact and the adjacent material. The height of the tools is 0.3 mm and the diameter is 3 mm. The die is the geometry under the workpiece and the punch is the one over. In Figure 8 b) the tools have the correct dimensions of 10 mm height and width. In Figure 8 c) the tool carrier were added to improve the modeling precision of the machines peripherals. The curves that resulted from the simulations by using the three different models are shown in Figure 9. It can be seen, that the temperature curve achieved with the model the simplified tool deviates from both other curves from the more detailed models. Models b) and c) do not have significant difference (< 2%) in the achieved temperature, but the simulations using the model including the environment needs extensively more resources (e.g. computing time), because of the higher number of elements. Hence it is not necessary to proceed with the full simulation. All following results are an outcome of simulations using model type b).

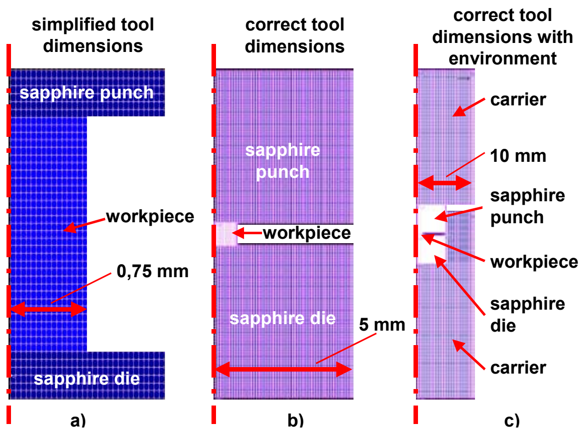


Figure 8: Models for numerical investigations.

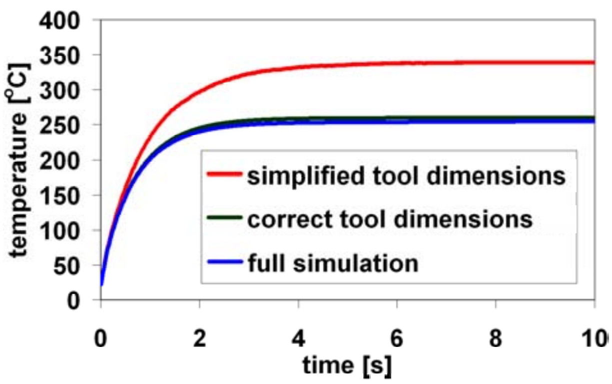


Figure 9: Numerical results by using different models.

Figure 10 shows the results of the comparison between experimental measured and simulated heat up by different laser power.

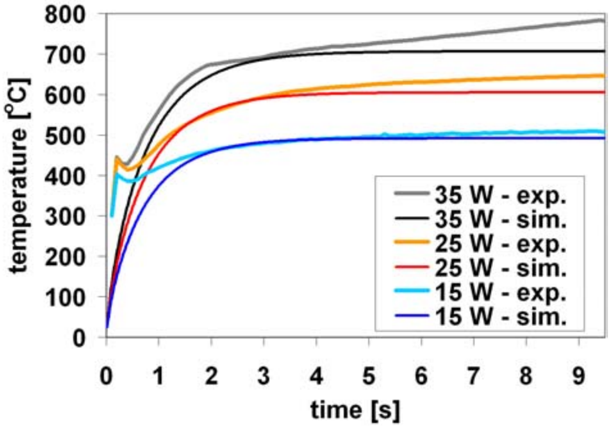


Figure 10: Experimental and simulated results.

The following effect, which affects the results, must be taken into account. In laboratory experiments, convection takes place in the molecules of air bordering the workpiece's surface and is delayed. During this time interval, no significant heat exchange takes place between the workpiece and air. In the simulations however, this time is not taken into account, so there is a constant heat exchange between workpiece and air. On account of that, the film coefficient to environment was adjusted. The temperature sequence at two other points, 0.25 mm and 0.75 mm from the surface of the workpiece heated by the laser, was simulated and compared with the temperature at the ideal measuring point (0.5 mm) to investigate the measurement error by potential nonconformities in positioning the laser beam of the pyrometer. Figure 11 shows the temperature sequences for the explained conditions.

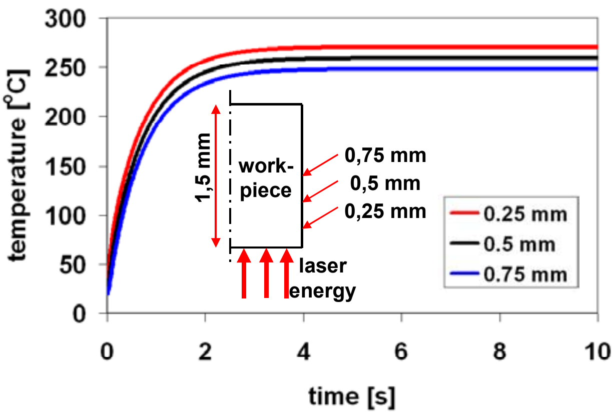


Figure 11: Simulated temperature during laser heating at different distances to the heated surface.

6 MICRO FORMING EXPERIMENTS

In the following two chapters micro forming experiments are described showing a dependence of the material micro structure from tool structure size and laser power.

6.1 Microstructure / Laser Power

A substantial factor for the laser assisted micro forming process is the materials microstructure. Therefore experiments have been carried out which show this influence on the result. Figure 12 shows the assembly with the workpiece and the sapphire tool with integrated structure.

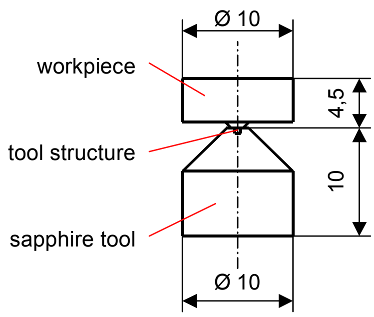
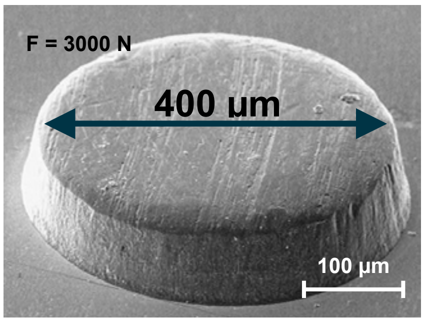


Figure 12: assembly and dimensions of the sapphire tool and the workpiece.

Specimens of the same material (1.4301 stainless steel) with varying grain size were formed in these experiments with and without laser assistance (P_L = 6,7 W laser power). All other forming conditions remain constant, e.g. the maximum pressing force, the tool geometry and the forming velocity. As shown in Figure 13 and 14 the form filling of the specimens with small grain size is much better than the form filling of the specimens with larger grain size. This phenomenon occurs without (Figure 13) as well as with (Figure 14) laser assistance, whereas the laser assisted form filling shows better results than the form filling of specimens with the same grain size without laser assistance. Furthermore, Figure 13 b) shows the inhomogeneous material flow with large grain size. This phenomenon arises from the small number of grains involved in the forming process (oligocrystalline material) so that the influence of the local anisotropy gets stronger with increasing grain size relative to the structure 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)

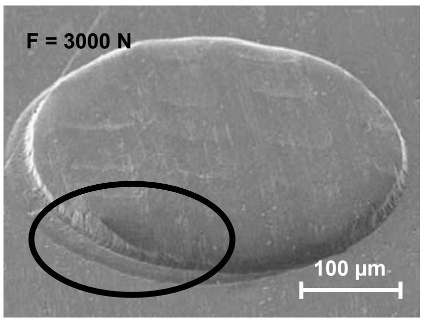
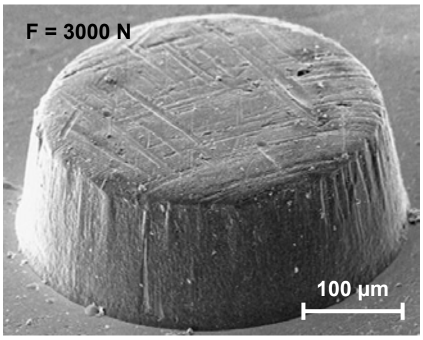


Figure 13: cold embossing of stainless steel.

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



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

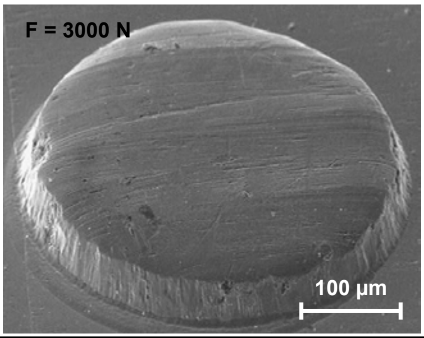
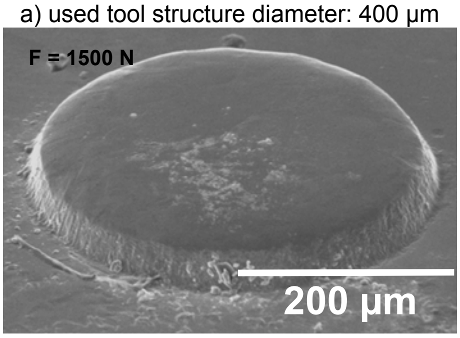


Figure 14: Semi-hot embossing (laser assisted forming with P_L = 6,7 W) of stainless steel.

6.2 Microstructure / Tool Structure Size

Further experiments have been carried out which show the influence of the material microstructure on the result of the micro forming process with down scaled tools and specimens of the same material (1.4301 stainless steel) but varying grain size.

a) used tool structure diameter: 400 µm



b) used tool structure diameter: 167 µm

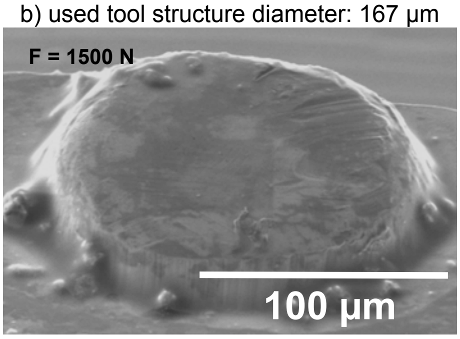
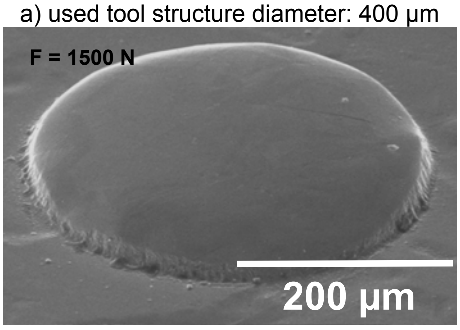


Figure 15: Form filling of scaled tool structures with polycrystalline material (grain size: 10 – 20 µm).

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, e.g. the maximum force and the forming velocity. As it is shown in Figure 15 and 16 the form filling 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 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.

Figure 15 b), 16 a) and b) show an inhomogeneous form filling in comparison to Figure 15 a). This phenomenon can be explained with the small number of grains involved in this forming process. The influence of the local anisotropy increases 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

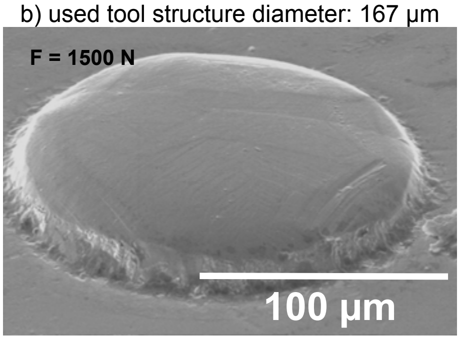


Figure 16: Form filling of scaled tool structures with oligocrystalline material (grain size: 50 - 150 µm).

7 SUMMARY

Laser-assisted micro forming with sapphire tools is proposed for the production of metallic micro parts. Sapphire tools meet the requirements for transparency and excellent mechanical properties. An experimental set-up has been developed for laser-assisted micro forming and the applicability of the proposed method verified in forming experiments. The optimisation of this technique is a current object of research. Laser heating is used to minimize size effects, e.g. the compensation of heat transfer to environment in micro forming processes and the inhomogeneous form filling of processes with high ratio between materials structure size and tool structure size. Further investigations aim at modelling the material behaviour and size effects in micro forming processes. It is intended to integrate these models into finite-element-simulations in order to extend the application of this technique to the simulation of micro production processes.

8 ACKNOWLEDGMENTS

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