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DESCRIPTION AND INVESTIGATION OF SIZE EFFECTS IN THE SCALING OF A HOT FORGING PROCESS AND A MILLING TOOL INTO THE MICROSCALE

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ABSTRACT

From the general trend towards higher miniaturization and functional integration results an increasing demand for metallic parts of smallest dimensions (down to 100 µm). Industrial realization of these parts and the further breakthrough of products containing microparts require suitable production technologies with respect to accuracy, productivity, efficiency and reliability. This aspect is still a significant limitation. The problems which occur at the production of microparts with scaled, conventional processes will be expound by means of a process (microforging) and a microtool (micro diamond milling cutter).

The application of metal forming technologies to the production of metallic microparts is limited by problems arising from size effects related to the small dimensions e.g. the influence of the microstructure becomes an important aspect to consider. An approach to these problems is the laser assistance of the microforming process. Laser light is used to increase the temperature of the material during forming, to increase the formability in the required area of the part and to reduce the flow stress and anisotropy of the material. To enable the transmitting of laser light into the workpiece, sapphire tools are used. Experimental investigations have shown that the use of sapphire tools in laser-assisted microforming processes is a suitable method for the production of microparts. Further investigations aim at modeling the material behavior and size effects in microforming processes and the integration of these models into FE simulations in order to extend its application to microproduction processes.

The increasing requirements on form and surface qualities for milling tools used in micromanufacturing increasingly become more difficult to fulfill with conventional manufacturing processes. Alternative methods, for example Chemical Vapor Deposition (CVD) based procedures, could offer advantages. They do not only make smallest dimensions possible, but also allow the desired manufacturing tolerances of the tools to be met. As an example of a diamond growth process the development and testing of diamond side milling cutters for application in microtechnology are described [1, 2, 3, 4].

INTRODUCTION

The progressing demand for integrated systems causes an increasing need for microcomponents. The most requesting branches of industry are automotive production, medical technology and optical industry to name a few. The standard methods of production engineering, like forming, forging, cutting or joining are well adapted to small dimensions in precision engineering. However the common size of tools and workpieces predominantly is still within the millimeter range. A further decrease in workpiece size needs for ultra-precise machines that are rather expensive and mostly not suited for mass production purposes. Therefore a qualification of alternative production methods or advancements in the known processes is highly desirable.

The microproduction engineering deals with sizes below one millimeter of workpiece dimension or with the realization of structures below this size in macroscopic workpieces respectively. Contrary to microsystems technology or even nano technology the microproduction engineering uses the "traditional" production methods by either scaling down the processes and/or combining several processes with new approaches (e.g. workpiece heating by laser, ultrasonic wave assisted cutting). The benefit is on one hand the existence of widespread knowledge concerning the processes and their known limits. On the other hand the materials that can be used in microsystems or nanotechnology are mostly non-ferrous metal or ceramics. The application of traditional production engineering materials, especially biocompatible stainless steels, is very limited but necessary though. Therefore the microproduction engineering provides adequate and necessary methods for the production of microparts.

SIZE EFFECTS IN MICROFORMING

In this paper microforming is understood as metal forming of parts or structures with at least two dimensions in the sub-millimeter range in accordance to [2]. In this range "size effects" occur, which lead to a different process behavior 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 nearly independent of the part dimensions to be produced and therefore cannot be scaled down in the same way as the geometry. Size effects in the frictional and the material behavior appear to be the main factors in microforming. Thus the influence of the microstructure becomes one of the most important aspects to consider.

With decreasing size the influence of single grains and their orientation has to be taken into account, especially when only few grains are present in one dimension [2, 5, 6]. Anisotropy and texture of the material are further parameters to be considered. An increasing variation in the material behavior has been observed, leading to reduced process stability and reliability.

LASER-ASSISTED MICROFORMING

The importance of the microstructure in microforming has been pointed out. An approach to compensate for or reduce the impact of size effects is to influence the microstructure during the forming process. This can be accomplished by heating the workpiece. At high temperatures an increased formability is achieved while the flow stress and thus process forces are reduced due to the activation of more slip systems. This reduces the anisotropic material behavior resulting in a more homogeneous forming with improved reproducibility [7, 8].

For the purpose of heating the material during the microforming process laser radiation seems the most suitable choice as it offers main advantages with respect to other methods:

- 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.
- Absorption of laser radiation allows short process times which cannot be accomplished with heat transfer from pre-heated tools.
- Reaching different materials properties by controlling the cooling rate via the control of laser power.

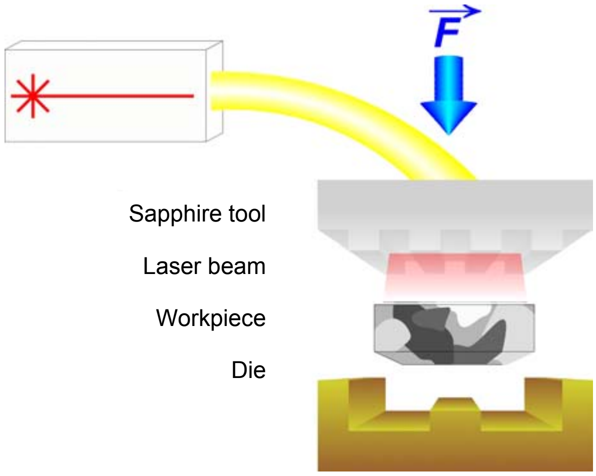


Figure 1: Principle of laser-assisted microforming

The proposed method (Figure 1) 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 > ultraviolet) 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 respectively hot forming of steel without destroying the tool.

EXPERIMENTAL SETUP FOR LASER-ASSISTED MICROFORMING

The application of metal forming technologies to the production of microparts requires suitable production systems with high accuracy and productivity. These requirements bring up serious difficulties to the technical implementation of the clamping of the tools and workpiece. The laser-assistance of the forming process requires the integration of the laser optics into the tool system. The laser optics should be located in a short distance to the sapphire tool in order to achieve a small laser spot and reduced losses of 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. A prototype of an experimental setup for laser-assisted microforming (Figure 2) has been developed at the Laboratory of Production Engineering of the University of the Federal Armed Forces Hamburg which comply with these requirements. In order to improve the accuracy of the tool positioning a new guiding system was implemented which is independent of the machines guiding into which this apparatus is integrated. The setup is built in a modular concept allowing to exchange workpiece and tool carriers for different applications. The laser optics are integrated into the tool carrier system. The distance between the tool and workpiece is adjustable. The laser system includes a diode laser package with a maximum output power of 20 W and a wavelength of 809 nm as well as an aiming beam for the purpose of laser beam alignment.

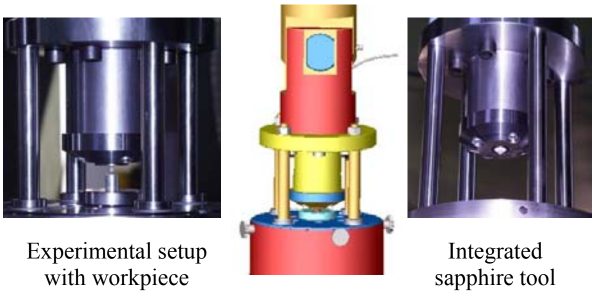


Figure 2: Prototype of a setup for laser-assisted microforming

Embossing experiments have been carried out for the verification of the applicability of microforming with sapphire tools. Previous experiments without laserpower P_L have shown that structures of 100 µm can be reproduced in aluminum. The punch with a prototype structure of rectangular shapes as well as the imprint in Al99.5 are shown in Figure 3.

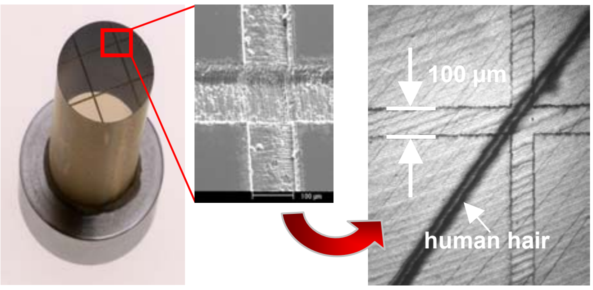


Figure 3: Prototype of a sapphire tool for embossing and imprint in aluminum in comparison with a human hair

EMBOSSING EXPERIMENTS WITH SAPPHIRE TOOLS

Equivalent experiments with harder materials like steel are a current object of research. Embossing experiments were carried out with workpieces of stainless steel [1.4301 (X5 CrNi 18/10)]. Figure 4 shows the punch with structures of cylindrical shape. The inner hole measures about 400 µm in diameter while the ring has a width of about 250 µm. The depth of the structures is 250 µm.

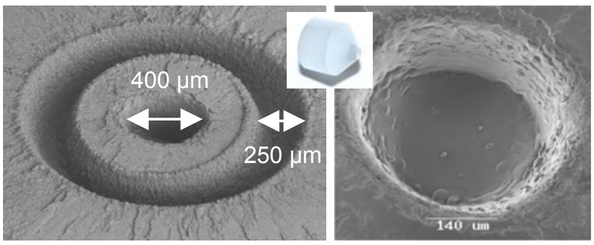


Figure 4: Sapphire tool for embossing experiments

The maximum force applied was limited to F = 5000 N because of the risk of rupture of the brittle sapphire tools. Experiments with and without laser-assistance of the forming process were carried out in order to assess the advantages of this technique. In order to maximize the absorbed laser power, the workpiece was coated with graphite which also acts as a lubricant. The influence of the graphite on the process result was also to be assessed.

Previous experiments showed that the absorption of the laser radiation can be increased by coating the workpieces with graphite (from about 40% to more than 65%). Further improvements have to be achieved as this is still unsatisfactory and further losses occur, e.g. in the laser optics and in the sapphire tool due to reflection and absorption.

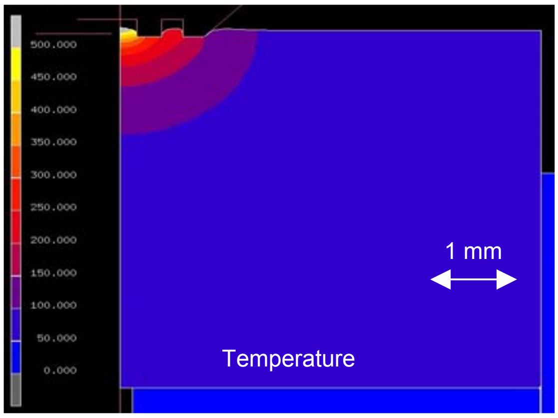
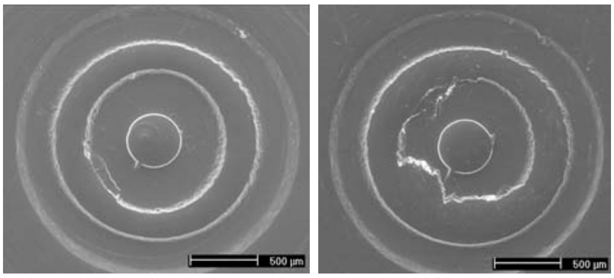


Figure 5: Results of FE simulations of the embossing experiments (F = 5000 N, P_L = 20 W)

The experimental results and finite element (FE) simulations (Figure 5) shows that the major problem is that the temperature in the forming zone is too low with a laserpower of 20 W (T = 150-300 °C) to achieve significant improvements by the laser-assistance of the forming process (stady-state is reached after few seconds) in comparison with cold forming. Following solutions are suggested for further experiments:

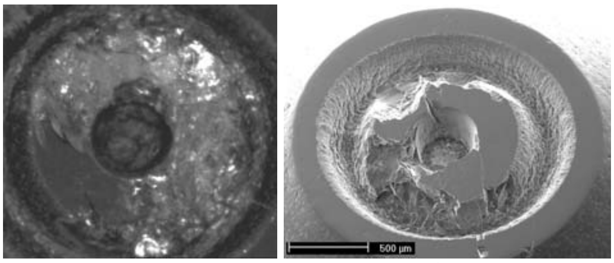
- Integration of materials with low heat conductivity (e.g. zirconia oxide) into the workpiece carrier system in order to reduce the heat transfer from the workpiece into adjacent parts to reach higher temperature in the workpiece,
- Integration of materials with high heat conductivity (e.g. aluminum) into the workpiece carrier system in order to arise the heat transfer from the workpiece into adjacent parts, to get higher temperature gradients in the workpiece,
- Application of anti-reflex coatings on the sapphire tool,
- Testing of different coatings of the workpiece in order to improve absorption,
- Application of lubricant coating with high transmission and low heat conductivity to keep heat flow between workpiece and sapphire small,
- Use of laser sources with higher output power.

Scanning electron microscope (SEM) images of imprints in stainless steel are shown in Figure 6. The depth of the imprints is about 100 µm, showing no significant differences between the experiments with (Figure 6 (a)) or without laser-assistance of the process (Figure 6 (b)) due to the insufficient heating of the workpiece. The process forces were not high enough to achieve a sufficient filling of the cavities of the tool. This emphasizes the importance of achieving high temperatures in order to reduce the process forces and improve the quality of the results. While this shows the limitations of microforming of stainless steel at lower temperatures, softer materials like aluminum can be processed (cp. Figure 3). In the imprints (Figure 6) the fracture of the sapphire tool and the progress of the breakage can also be observed. First indications of tool damage could already be detected after few experiments (Figure 6 (a)). Figure 7 shows the fractured sapphire tool. Nearly the whole surface of the ring structure in the centre is damaged and partially pulverized after 17 forming experiments, emphasizing the importance of reducing the process forces. The SEM image (Figure 7 (b)) shows further material loss of the damaged tool due to ultrasonic cleaning.



(a) (b)

Figure 6: Results of the embossing experiments: imprints in stainless steel 1.4301 (F = 5000 N, P_L = 20 W)



(a) (b)

Figure 7: Sapphire tool fractured during the embossing experiments (F = 5000 N, P_L = 20 W)

This discloses a main problem in the utilization of a brittle material like sapphire for metal forming tools. The nominal pressure on the contact area of the tool surface was 2500 N/mm^2, less than the compressive strength of sapphire (3000 N/mm^2). But the stresses acting on the edges of the tool may exceed this value (Figure 8) causing the fracture of the brittle material which is very sensitive to tensile stresses. These lead to crack initiation and tool breakage.

In this context microcracks, which are induced on the surface of the structure during the profiling process (ablation with excimer laser), have to be accounted for. Also small manufacturing errors of the tool and its clamping can lead to an asymmetric force distribution during the pressing process which induces tensile stresses [9]. The inaccuracies based on the experimental setup tolerances in respect of parallelism of the tool and workpiece surfaces are reasons for asymmetric force distribution in the tool. The inaccuracies based on the experimental set-up tolerances in respect of positioning the Sapphire to the workpiece and leading the sapphire during pressing into the workpiece can also cause asymmetric force distribution in the sapphire.

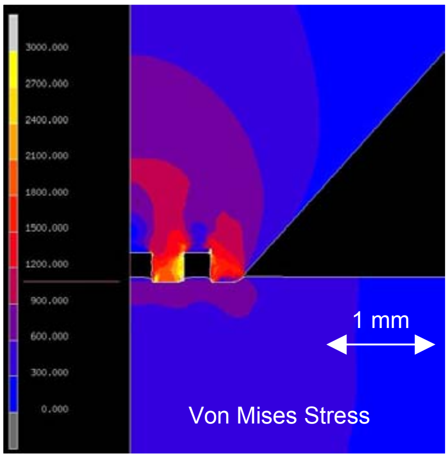


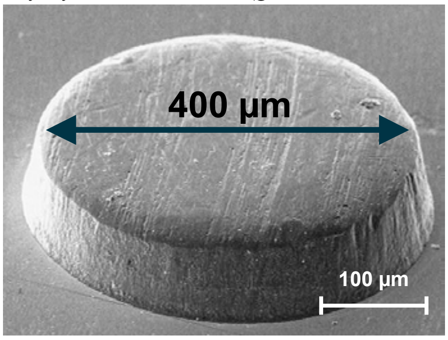
Figure 8: Results of FE simulations of the embossing experiments (F = 5000 N, P_L = 20 W)

INFLUENCE OF THE MATERIAL MICROSTRUCTURE IN MICROEMBOSSING OF STAINLESS STEEL

A substantial factor for the laser-assisted microforging process is the material microstructure. Therefore experiments were made which show the influence of the material microstructure on the result of the laser-assisted microforging process.

In these experiments specimens of both small and big grain size were used (with the same composition). Some of these specimens were forged with laser assistance (20 W laserpower) and the others without laser assistance. All other forming conditions were equal, e.g. the maximum force, the tool geometry and the punch velocity were the same. As you can see in Figure 9 and 10 the formfilling of the specimens with small grain size is much better than the formfilling of the specimens with big grain size. This phenomenon occur with (Figure 10) as well as without (Figure 9) laser assistance, whereas with equal grain sizes the laser-assisted formfilling shows better results than the formfilling without laser assistance. Furthermore, Figure 9 b) shows that the material flow in the die structure of the cold-forged specimen with big grain size is inhomogeneous. This phenomenon is due to the small number of grains involved in this forming process so that the influence of the local anisotropy gets greater with increasing grain size. This is an additional size 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)

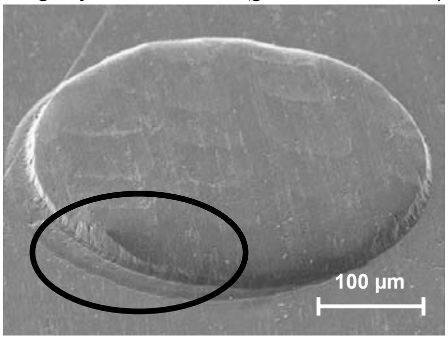
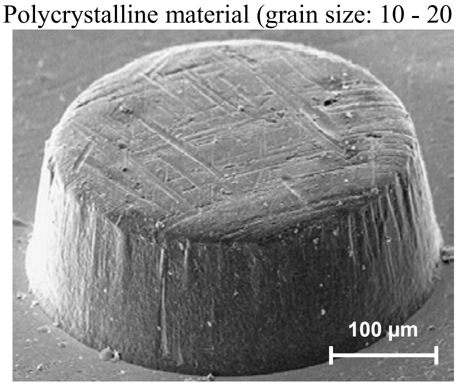


Figure 9: Cold embossing of stainless steel

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



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

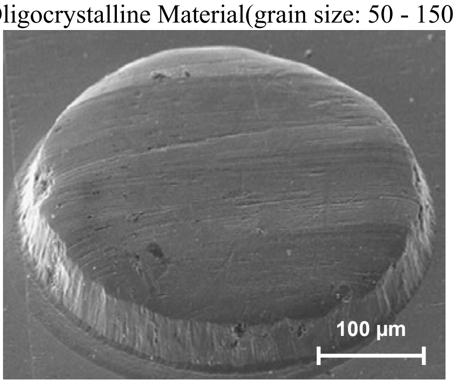


Figure 10: Semi-hot embossing (laser-assisted forming with P_L = 20 W) of stainless steel

MICRO DIAMOND SIDE MILLING CUTTERS

With scaling cutting processes similar size effects appear. Today most of the microcutting tools e.g. for drilling and milling are made of carbide and there cutting geometry is generated by abrasive processes. Due to the reproducibility and the limited capability of shaping the cutting tools by other (abrasive) cutting tools the miniaturization of tools for the geometrical defined cutting is limited.

In a cooperative research work a new method for the production of micro cutting tools out of polycrystalline diamond was developed. Basis is a generative plasma enhanced CVD process. For the tests side milling cutters were designed with exact cutting edges described by the angles known from macroscopic tools and were shaped during the generative process through a mask. Figure 11 describes the development steps of the micro diamond side milling cutters from the construction of the cutting disk geometry to the assembly of the cutting diamond disk on a shaft. The milling tools have 4 to 10 teeth, a maximum diameter of 2 mm and a thickness of 30 microns. Figure 12 shows an installed diamond side milling cutter with 6 teeth. The extreme high resolution of the production process makes even smaller geometries possible. [10, 11]

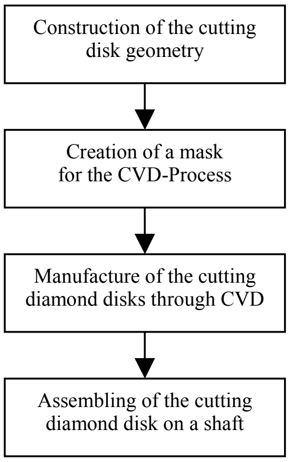


Figure 11: Development phases of the diamond micro side milling cutter

In order to test the application behavior cutting experiments with the prototypes of the diamond side milling cutters were carried out in a micromachining center KUGLER MICROGANTRY GU, which is designed for the requests of microproduction: air bearing linear axes, a measuring system with a resolution of 10 nm and a positioning accuracy of 0.3 µm as well as a high frequency spindle with a maximum speed of 160,000 revolutions per minute. For the experimental investigations the aluminum alloy AlMg3 and brass CuZn37 were used. The goal was the production of slots with an high aspect ratio, i.e. a high depth compared to the width of the slot. The first cutting parameters selected were:

- spindle speed $n = 160{,}000\ min^{-1}$
- feed rate $v_f = 10$ mm/min
- infeed $a_e = 0.025$ mm

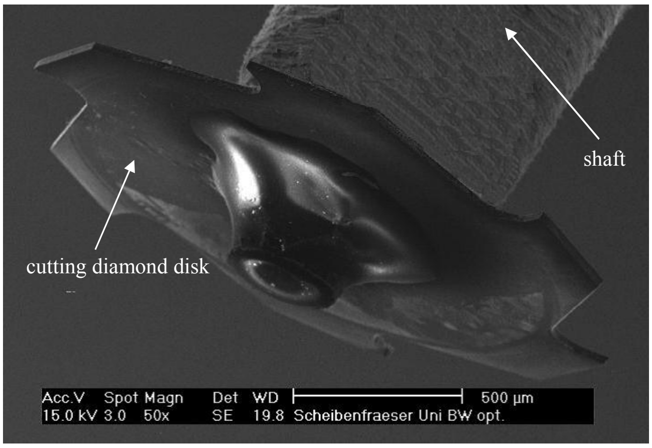


Figure 12: Installed diamond micro side milling cutter

Figure 13 shows the geometry of the produced slots in brass CuZn37. Flutes with a width of 40 microns were generated with a high aspect ratio. Typical applications for this kind of geometry can be identified in the field of micro fluidics (e.g. micro channels for heat exchanger) or in the field of micro optics (e.g. fixation and guidance of optical fibers for information or illumination technology).

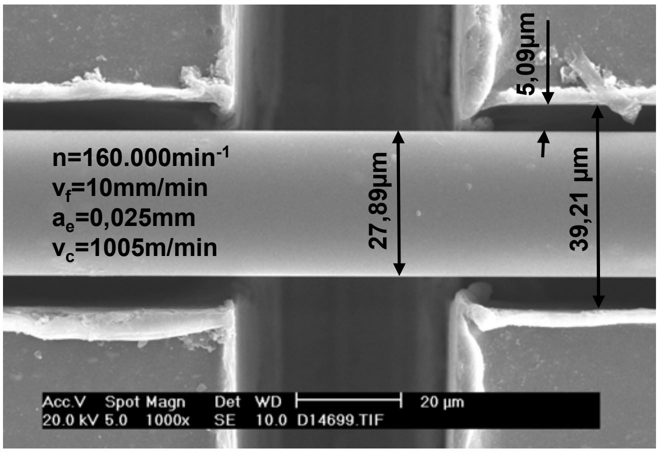


Figure 13: Groove in brass CuZn37 with inserted optical fiber produced with a diamond micro side milling cutter

In the following experiments the cutting parameters were successfully increased and optimized to:

- spindle speed $n = 160{,}000 \text{ min}^{-1}$
- feed rate $v_f = 500$ mm/min
- infeed $a_e = 0.05$ mm

Steel and ferrous metals are difficult to machine with diamond tools because of their chemical affinity for carbon. During the micromachining operations low cutting edge temperatures are assumed and thus the probability for the chemical interaction between carbon and iron is low. That is the reason why for the last experimental investigations the stainless steel 1.4301 were used. After a milling length of 1680 mm no outbreaks could be observed at the side milling cutters, showing that the tool life travel or the diamond micro side milling cutters end was not yet reached. On the workpiece a black film had only formed. This phenomenon must be examined in a further investigation of material scientist. On the diamond micro side milling cutters no abrasion or zoning could be seen. Figure 14 shows grooves in stainless steel (1.4301) and the moment of tool breakage produced with a diamond micro side milling cutter.

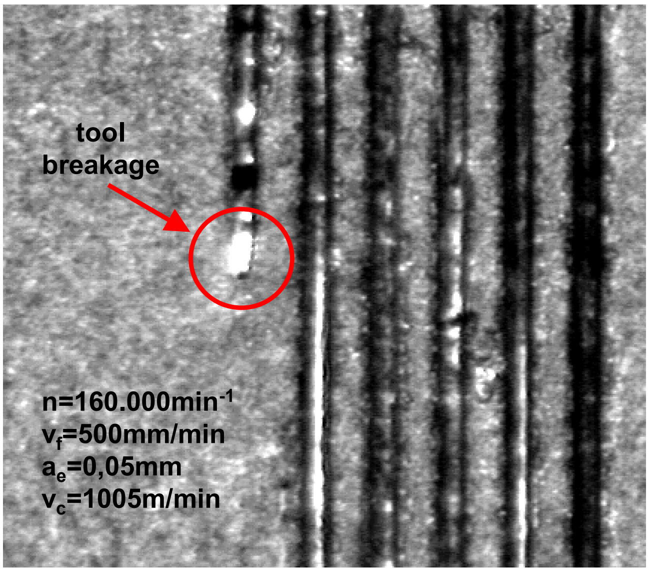


Figure 14: Grooves in stainless steel (1.4301) produced with a diamond micro side milling cutter

In all these experimental investigations carried out, mainly the general suitability of the multicristalline full diamond micro side milling cutters produced by the CVD-process should be reviewed.

REFERENCES

[1] Weule, H., Hesselbach, J., 2002, mikroPRO - Untersuchung zum internationalen Stand der Mikroproduktionstechnik, ed. by J. Hesselbach, Vulkan-Verlag, Essen.

[2] Geiger, M., Kleiner, M., Eckstein, R., Tiesler, N. Engel, U., 2001, Microforming (keynote paper), Annals of the CIRP, 50/2/2001: 445-462.

[3] Masuzawa, T., 2000, State of the Art of Micromachining, Annals of the CIRP, 49/2/2000:473-488.

[4] Schubert, A., Burkhardt, T., Schneider, J., 2001, Mechanische Mikrofertigungstechnik – Potenziale trennender und umformender Mikrofertigungsverfahren, Mikro-System-Technik Chemnitz'01: Mikromechanik & Mikroelektronik, Chemnitz, 151-158.

[5] Eckstein, R., Tiesler, N., Egerer, E., Engel U., 2001, Herstellung metallischer Kleinstteile – eine Herausforderung für die Umformtechnik, Idee - Vision - Innovation, ed. by Vollertsen, F., Kleiner, M., Meisenbach, Bamberg, 135-142.

[6] Raulea, L. V., Govaert, L. E., Baijens, F. P. T., 1999, Grain and specimen size effects in processing metal sheets, Proc. 6th Int. Conf. on Technology of Plasticity, Nuremberg, 939-944.

[7] Egerer, E., Neudecker, T., Engel, U., 2001, Grundlagenuntersuchungen zum Halbwarmmikro-umformen, Erweiterung der Formgebungsgrenzen bei Umformprozessen, Kolloquium im Rahmen des Schwerpunktprogramms 1074 der Deutschen Forschungsgemeinschaft (DFG), 82-88.
[8] Gillner, A., Bayer, A., Groche, P., Erhardt, R., 2001, Laserstrahlunterstütztes Mikroumformen metallischer Bauteile, Erweiterung der Formgebungsgrenzen bei Umformprozessen, Kolloquium im Rahmen des Schwerpunktprogramms 1074 der Deutschen Forschungsgemeinschaft (DFG), 89-95.
[9] Wulfsberg, J.P., Hilpert, S.-E., Ostendorf, A., Samm, K., 2003, Fundamentals of Laser-assisted Microforming, 1St Colloquium Processscaling, Bremen.
[10] Flöter, A., 2001, Synthetic diamond blade for microsurgery hits the market - Worldwide First in Cutting Technology. *http://www.gfd-diamond.com/presse/presse_1.pdf*
[11] Wulfsberg, J.P., Brudek, G., Lehmann, J., 2004, New micro diamond milling tools. In: Proceedings of the 4th international conference of the European Society for Precision Engineering and Nanotechnology, 131-13