Short Communication

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Diamond machining of steel molds for optical components

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Abstract: The requirement of ultra precision diamond machining of lens molds in steel is identified. A solution for this type of machining is presented and results of such a machining in steel compared to standard milling and polishing process are shown.

Keywords: 5-axis ultra precision machining system; diamond machining; micro-milling; molds.

1 Introduction

Optical components made from plastic material are used today in many different areas of application. These range from optical elements for LED-pocket lights to lenses for car illumination that are manufactured by multi layer injection molding. These optics have in common that a mold is required. The lifetime of these molds is essential for a low price of the product, for example, for the consumer market.

Different techniques are used for the manufacturing of such molds. Pre-hardened steel molds are pre-machined by milling or eroding and then polished to optical quality. This polishing process improves the surface roughness but deteriorates the form of the surface. Especially when the surface of the mold is superimposed with a microstructure the polishing process may lead to considerable deviations of the form of the mold.

The direct structuring of molds or mold inserts by the means of diamond optical machining is, under normal circumstances, limited to the machining of materials like brass, German silver, high strength aluminum alloys or steel molds with an electroless nickel coating. In this process the optical surface is generated directly by diamond machining like diamond turning or flycutting. Unfortunately the use of those materials limits the lifetime of the mold or mold inserts. (Lifetime of an aluminum mold is some 10 000 to a few 100 000 parts while a mold made from hardened steel can exceed 1 000 000 injections). Furthermore heterogeneous molds suffer from different thermal expansion coefficients and different heat conductivities of the used materials leading to a difficult to control injection molding process. The different thermal conductivity's lead to different cooling rates across the part and cause residual stress in the component. In optical applications residual stress creates stress birefringence or variations in the refractive index and should be avoided.

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2 Ultrasound assisted diamond machining

Therefore it would be highly beneficial to machine steel molds directly by diamond machining. Unfortunately the contact zone of the tool and the workpiece reaches 500°C–700°C [1, 2] leading to a chemical reaction between the iron in the steel and the carbon of the diamond, resulting in the destruction of the tool. Different approaches have been tested to overcome this restriction. The best approach at the moments seems to be the use of ultrasound-assisted diamond machining.

For this reason, the tool is set into vibration in such a way that the tooltip moves on an elliptical path with a vibration frequency of several 10 kHz. With this setup the contact time between the tool and the workpiece can be made so short that the temperature buildup at the tooltip is uncritical and no chemical tool wear occurs.

Until now this process has mainly be used in diamond turning of steel on ultra precision lathes. The Kugler GmbH in Salem (Germany) has implemented this machining process now on its hydrostatic 5-axis micromachining center MICROMASTER® (Kugler GmbH, Salem, Germany). Now it is possible to realize parts that cannot be produced by a turning process. Especially in the making of injection molds it is possible to pre-machine the mold on this machine using a standard or a micro-milling process and then to apply the optical surface on the same machine. The setup of the Kugler MICROMASTER® is so flexible that it is possible to use milling spindles, laser focusing systems and the ultrasonic diamond tool consecutively. An increase in precision with respect to position tolerances that are very important in mold making can be easily achieved this way. The combination of different types of machining in one clamping eliminates clamping- and measurement errors. For example, a position accuracy of 1–2 μm of alignment features (e.g. fit bores or stop edges) with respect to the optical axis of the mold (and therefore the optical axis of the part) can be achieved. This in combination with the machine integrated tool and part measuring systems allows an efficient manufacturing of molds with and without microstructures in optical quality.

3 Surface roughness

The ultrasonic-assisted diamond machining creates two types of regular structure on the optical surface of which one may create stray light. Especially when illuminated with coherent monochromatic light. The first structure results from the ultrasonic vibration of the tool. The tool moves back and forth while the workpiece rotates below the tool tip. Thus along the tool path a modulation can be seen. This modulation depends on the vibration frequency and the federate. The second structure is due to the cutting with a defined cutting edge and the regular tool paths during machining. This structure is modulated perpendicular to the feed direction and is caused by the single tool paths lying side by side. The height of this structure depends on the tool radius and the distance of the tool paths but is normally in the range of <40 nm. So if this structure creates

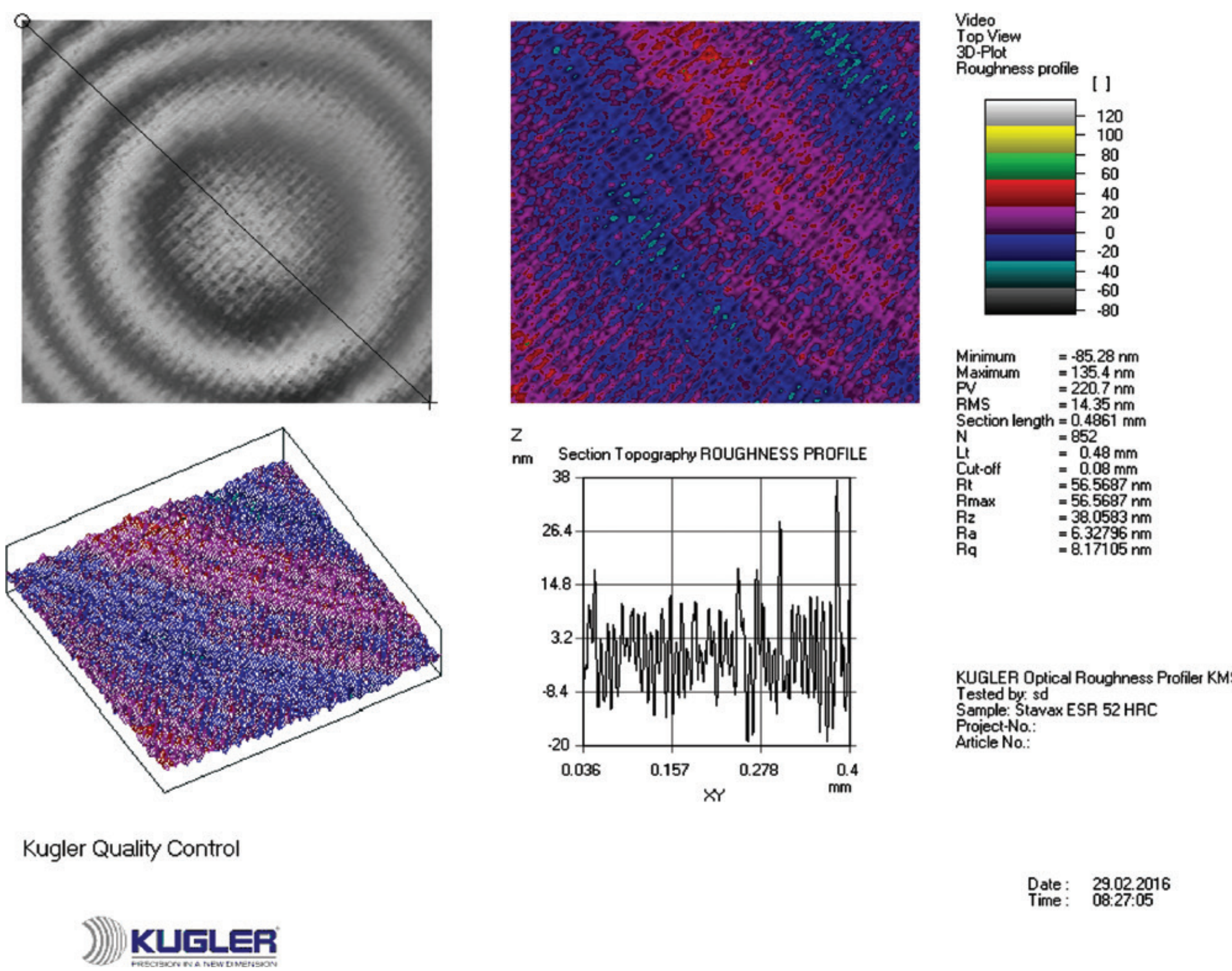

Figure 1: Roughness measurement with a Kugler KMS (Kugler GmbH, Salem, Germany) phase shifting microscopic interferometer (Linnik Type with a vertical resolution of 0.3 nm). Field of view is 340 μm by 340 μm. Therefore the diagonal allows a measurement length of 480 μm (according to norm).

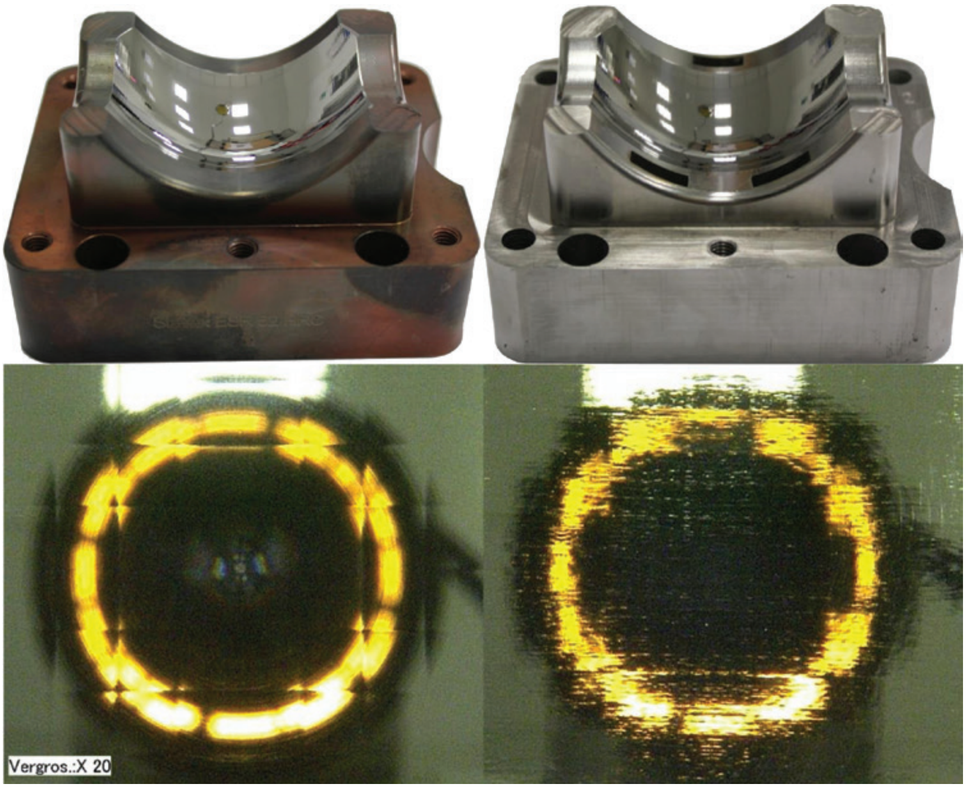

Figure 2: Comparison of a diamond machined (on a Kugler MICROMASTER®) (left) and a polished (right) steel mold. Roughness of both parts is comparable.

unwanted stray light it can be blurred using a brief polishing step without damaging the form of the optical surface.

The roughness measurement shown in Figure 1 was made in a mold for a lens with a microstructure of several microns height and shows the typical surface structure of an ultrasonic assisted diamond machined steel. Roughness is Ra 6.3 nm.

The image in Figure 2 is a microscopic image with a magnification of 20× and shows the difference between an ultrasonic diamond machined and a polished mold. The polished mold shows the same microstructure as the diamond machined but due to the (over-) polishing it cannot be seen clearly anymore.

Kugler tested two different tools for ultrasonic assisted diamond machining. Both tools had advantages and disadvantages. The selection process led to the decision that the tool with the lower ultrasonic vibration frequency (40 kHz Ultrasonic Tool, A.L.M.T. Corp., Tokyo, Japan) was selected over the tool with the higher vibration frequency (80 kHz Ultrasonic Tool, SON-X Systems, Aachen, Germany) because the housing of the 40 kHz tool allows to machine molds with a much higher aspect ratio (depth to width ratio) than the 80 kHz tool. Even when the feed rate is limited by the lower frequency and therefore the machining time becomes longer.

Finally it can be stated, that the manufacturing of complex optical surfaces in difficult to machine materials like hardened steel on a machine, like the Kugler MICROMASTER®, opens new possibilities in optics manufacturing. The elaborated layout of this system provides the user with a significant additional benefit in combination with an increase in productivity and the production possibilities in the manufacturing of highly complex parts.

References

[1] W. Grzesik, M. Bartoszuk, P. Nieslony, J. Mater. Process. Tech. 164–165, 1204–1211 (2005).

[2] D. A. Stephenson, T.-C. Jen, A. S. Lavine, J. Manuf. Sci. Eng. 119, 494–501 (1997).

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