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Ultrasonic vibration cutting of freeform steel insert

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Abstract

The ever increasing number of high precision polymer optical component required in general lighting, automotive lighting, displays, healthcare devices and metrology devices is pushing forward tighter tolerances for optical manufacturing. There is a large number of mass produced polymer optical components that need to be manufactured within nanometric level surface roughness and preferable with submicron form accuracy. Moulded polymer optics are mainly produced by using dies and molds that are made from hardened tool steels. Cutting of tool steel materials to low surface roughness and high accuracy has always been challenging. The traditional way to make steel inserts uses high accuracy manufacturing techniques such as grinding, high speed milling and spark erosion in conjunction with a polishing step. Recent development in the ultrasonic vibration assisted cutting of tool steels with a diamond tool has significantly improved the possibilities to generate low surface roughness and high accuracy steel inserts for optical quality moulding. This study will go through manufacturing and metrology of an ultrasonic assisted diamond turned optical quality freeform W720 tool steel insert. Nanometric level surface roughness accuracy was reached on the insert and profilometer scan traces were fitted against a STEP file of the part within few microns accuracy. The process is quite suitable for making low aspect ratio and gently sloped freeform steel inserts.

1. Introduction

Optical quality moulding of polymers require low surface roughness and high accuracy of the inserts that give the part its shape in the moulding process. The traditional way to make steel inserts is to use high accuracy manufacturing techniques such as HSM and EDM and then polish the surfaces to low surface roughness. Quite often the polishing is done by hand polishing in which case low roughness values can be reached but the intended shape of the polished surfaces is lost. The path from optical design to a manufactured optical quality steel insert in moulding applications is not yet well established. For injection moulding hardened tool steels inserts are the obvious choice as a mould material for their durability, chemical resistivity and high tolerance for mold temperature changes [1]. However most of the machining processes for optical quality insert manufacturing are grinding and deterministic polishing based processes having many working steps [2].

As an alternative to traditional precision manufacturing steel insert may be manufactured to optical quality by applying ultrasonic assisted cutting technology in diamond machining [3]. This technology allows new and more complex optical quality freeform shapes to be manufactured on hardened tool steel inserts. In general freeform optical surfaces need to be manufactured at near micrometer form accuracy and at nanometric surface roughness [4]. This example goes through manufacturing and characterization of an optical freeform steel insert. The goal is to assess the process capability of manufacturing an optical quality surface from a STEP (Standard for Product Model Data Exchange) geometry. Ultrasonic assisted diamond cutting will be evaluated. White light interferometry and multi axis contact profile tracing will be used to measure the quality of the machining. Freeform metrology has proven itself rather difficult to tackle, both contact probing and optical approaches are being developed [5].

2. Manufacturing of a freeform tool steel insert

The steel lens insert manufactured and measured in this study is one cavity side from a dual sided oval shaped polymer freeform lens design. The polymer lens design contains freeform lenses on both sides of the lens. The optical quality mold itself contains a positive boss freeform shape and a negative cavity freeform shape. The freeform shapes are gently curved shapes having a sag of roughly 3 mm and slope of +-17 degrees. The oval shaped lens overall dimensions are 18 x 27 mm. Creo CAD representation of the lens insert is given in figure 1.

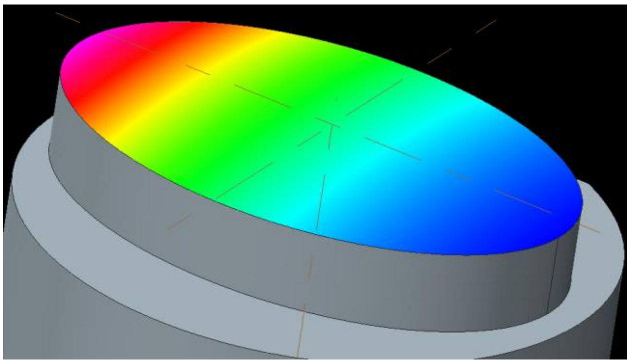

Figure 1. Lens insert design in CREO CAD/CAM software

The working steps for the manufacturing process follow the path according to figure 2. The path involves going through STEP based optical design file, mould and cavity design in Creo software, Rhino3D point array creation followed by Diffsys tool path creation, diamond machining and metrology.

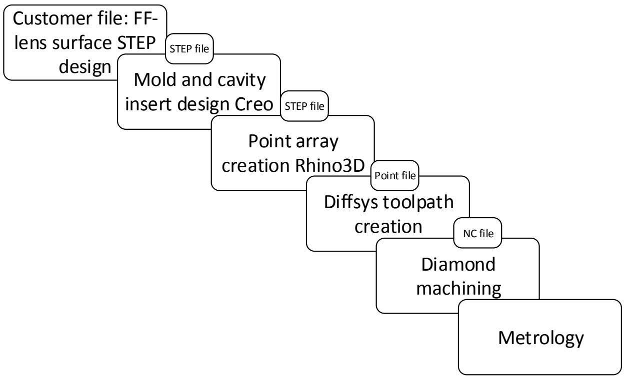

Figure 2. Processing steps

Taga Electrics EL-50 Ultrasonic assisted elliptical vibrational device and a Moore 350 FG diamond turning machine were used to produce the machined optical surface on a 54 HRC hardened W720 maraging tool steel slab. Critical processing information for the machining is given on the table 1.

Table 1 Machining data

Tool	Lathing diamond tool R 0,75 mm
Cut strategy	XZC spiral inverse time at 0,001 ms
Point interval	0,04 degrees, total 27 million points
Tool vibration type	40 kHz, elliptical motion 4 x 3 µm
Width of cut	6 µm
Depth of cut	6 µm
Machining time	roughly 8 hours per one cycle

Theoretical surface roughness for the machined part was calculated from the equation [6]:

$$R_a \sim \frac{f^2}{32R}$$

Where R_a is the surface roughness, f with of cut and R the tool radius. The cutting data given in table 1 would give a surface roughness R_a of 1,5 nm on a flat surface. The equation does not take into account the ultrasonic system elliptical motion of the tool. The part was pre-machined to 10 µm working allowance resulting that the diamond cutting process was repeated three times to get rid-off pre-machining marks.

3. Metrology

After the machining the part was measured with a Mitutoyo CS-H5000 CNC profilometer. This profilometer can be used for scanning surface area by running parallel contact probing traces over part. Fifty evenly spaced XYZ probing point lines were scanned over the optical surface with 5 µm diamond probe and 1 µm point interval. Scanned traces were then imported to Creo software where a six degrees fitting of the points was done over the STEP file of the lens. Figure 3 shows the part being measured by profiling and the unfiltered XYZ data fit over STEP file in Creo. The unfiltered point data was fitted with ± 4,3 µm accuracy and Gaussian filtered curve data with ± 3,4 µm accuracy.

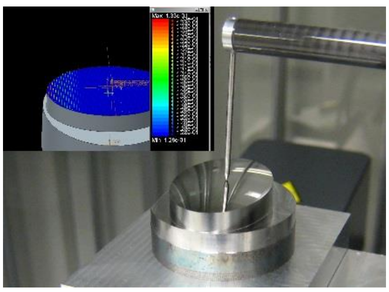

Figure 3. Profilometer metrology and fitting

The centre of the turned lens was also measured with WYKO NT9300 white light interferometer. A square matrix of 5 x 5 measurement with 0,2 mm spacing was done at the center of the lens part. An example of one measured area is shown in figure 4.

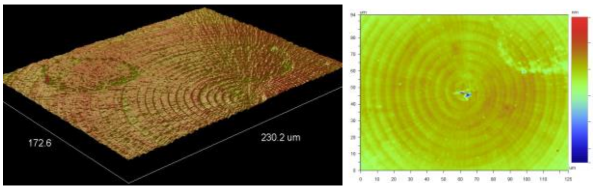

Figure 4. Interferometric results at the centre of the lens

According to interferometric measurement of the 5 x 5 matrix the optical surface topography got following mean value and standard deviation values: R_q 6,51 nm (STD 1,95 nm) and R_a 4,76 nm (STD 1,05 nm). A larger 25 pictures interferometer composition of 4 x 3 mm was also made from the centre of part. The diamond tool used in the process was also measured with a 1000X Leica microscope. The tool wear was well under 1 µm.

4. Conclusions

As a conclusion ultrasonic assisted cutting of freeform lens on hardened tool steel with a diamond tool is a working process. Very slight tool wear was observed during US cutting of tool steel. Freeform shapes are rather difficult to measure with conventional measuring machines. The multi-axis profilometer used in this study can be used for measuring freeform shapes. Interferometric surface roughness measurements results were not as good as theoretically calculated but they did exceed the expectations. Further improvements of the process flow will be:

- Getting rid of diffraction markings left by the diamond turning (fluid jet polishing or laser polishing)
- Find correlation between white light multi image scan results and multi axis profilometer traces
- Use other high end contact probing systems to find correlation for multi axis profilometer approach
- Evaluating all the working steps to find out which phase contributes mostly to the form error measured

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