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FTS-Diamond turning of structured surfaces and impact of the structure angle on the process forces

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Abstract
Diamond turning has been proven to be a highly flexible machining process, which is able to effectively fabricate high performance optics. For several years, the machining of diffractive optical elements by Fast Tool Servo assisted diamond turning has been developed further towards the manufacture of holograms (DTH) capable to shape laser beams into designated intensity patterns.
In order to further expand the degrees of freedom of this machining process and thus the spectrum of machinable geometries, the structure angle on the workpiece surface can be varied during the cutting process by a rotation of the cutting tool around the y-axis of the machine's coordinate system. This leads to diffractive freeform surfaces which can be used in optical applications for the modulation of the phase gradient of an incoming wavefront enabling a wavelength-independent light-modulation.
The additional twisting tool movement is associated with a variation of the cutting tool engagement as the cross-section of the undeformed chip and the local depth of cut are varying. Therefore load conditions on the diamond tool are changing. For this reason, cutting tests have been conducted on an ultra-precision machine tool, in order to determine the influence of the structure angle on the process forces during cutting of two different cutting materials. The tests have been conducted on ultra-fine grained aluminum as well as German silver. These results are a preparation for setting up process simulations for the prediction of tool failure.

Keywords: diamond turning, microstructure, diamond tools, tool movement

1. Introduction

There is a commercial demand for functional optical surfaces, which can be produced by ultra-precision machining. In order to generate diffractive optical elements (DOE), a face turning process has been combined with a nano Fast Tool Servo (nFTS) which is modulating the depth of cut in a range of 1000 nm and at a frequency of 5 kHz [1]. The current developement includes the improvement of the machining process in terms of optical quality and geometric accuracy [2].

The market for imaging and illumination systems is constantly converging and growing, enlarging the field of applications from digital cameras, over diffraction optical instrumets up to reflecting or collimating devices in the automotive industry. To fulfil the optical requirements of the industry, structured freeform optics are required inevitably [3]. Different strategies have been developed, which are mostly constrained to finishing of freeform surfaces with a subsequent structuring ([3], [4], [5]). In terms of time efficiency and machining costs, a direct machining of structured freefrom surfaces in one operation is favourable.

Diamond turning on an ultra-precision lathe is highly flexible and still offers many possibility in increasing the number of degrees of freedom [6]. Therefore, the machining process has been expanded by additional tool movements. The nFTS together with the diamond tool are mounted on the B-axis of the machine tool. In this way, the structure angle can be modulated constantly during the machining process [1]. Doing so, a freeform surface is imitated by the structure angle (cf. Figure 1). Together with the variation of the depth of cut, executed by the nFTS, a diffractive structured freeform surface can be machined.

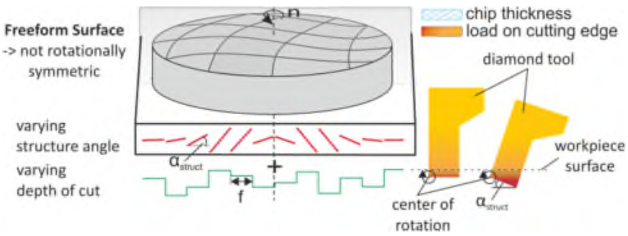

Figure 1: Imitation of a freeform surface and combination with a diffractive structure.

Nevertheless, this additional degree of freedom yields new challenges, among others caused by the varying forces on the cutting tool.

2. Machining Process

The basic machining operation for the generation of diffractive structured freeform optics is based on a face turning process, conducted on a Nanotech 350 FG ultra-precision machine tool. The lathe is running with a spindle speed of 100 rpm, while cutting with an initial depth of cut of a_p = 2 µm. The applied feed is depending on the nominal width of the diamond tool [2], which has a rectangular geometry. The diffractive structure is generated by the nFTS which modulates the depth of cut $a_{p,nFTS}$ in a range of 1000 nm at a frequency of 5 kHz; up to 2000 structure elements are generated per revolution. Additionally, the B-axis of the machine tool is conducting an alternating tilt movement, allowing an angular motion of up to 1.2° per 90° workpiece rotation.

3. Experimental Setup and Results

In order to examine the influence of different machining parameters on process forces, cutting experiments have been conducted with a piezoelectric multicomponent dynamometer (MiniDyn 9256C2 Kistler). The dynamometer was installed beneath the diamond tool on the B-axis. In Table 1 the variation of the machining parameters is shown.

Table 1: Variation of parameters.

Parameters	**Range**
Structure angle $\boldsymbol{\alpha_{strcut}}$ [°]	0, 4.8, 8
Tool width $\mathbf{w_t}$ = feed **f** [µm]	10, 20, 30
Depth of cut $\mathbf{a_P}$ [µm]	1.5, 2.0, 2.5
Cutting speed $\mathbf{v_C}$ [mm/s].	104.7, 52.4, 21.0

In the experiments, there was no evidence for a dependency between the cutting forces and cutting speed. Due to the face turning process, the cutting speed is decreasing during the process down to zero at the center of the workpiece (see also Table 1). This confirms the common fact, that the cutting force it is an uncritical parameter in ultra precision diamond turning.
Due to the small depth of cut, the measurement results lay in the range of the signal noise and showed no obvious relation between the cutting force and the depth of cut.
Figure 2 shows the influence of the structure angle α_{struct}, for a tool width w_t of 30 µm. The tool width is equal to the feed f for all experiments. It can be seen, that the cutting forces are increasing with increasing structure angle. This seems reasonable, since the changing structure angle is going along with an increase of the actual depth of cut and thus a change of chip thickness. This effect is also shown in Figure 1: due to the change of the structure angle, the tool will plunge deeper into the material with one corner of the cutting edge, which is affecting the load on the cutting tool. In Figure 1, it can be seen, that the chip thickness is enlarging with the twist of the diamond tool. For a twist of 8° and a tool width of 30 µm, e.g. the chip thickness alomst doubled, which is leading to a greater effect on the process forces.

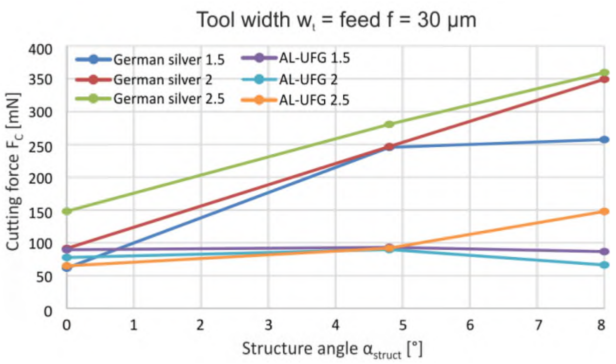

Figure 2: Influence of the structure angle on the cutting force.

In Figure 3 the cutting forces for an increasing tool width are shown. Again, the tool width w_t corresponds to the feed f for all experiments and is fixed to 30 µm. The experiments have been conducted with a constant structure angle. An increase of the the cutting force F_C was expected with an increasing feed f, which complies with our results. The experiments which have been repeated with smaller depth of cut as well as with a variation of the structure angle, are showing a similar behaviour.
In Figure 3, also is the influence of the workpiece material on the cutting force can be seen: ultra fine grained aluminium (AL-UFG) always shows lower process forces than German silver. This is reasonable, since Al-UFG has a lower hardness and smaller grain sizes than German silver, which is leading to a cutting process with lower mechanical loads.

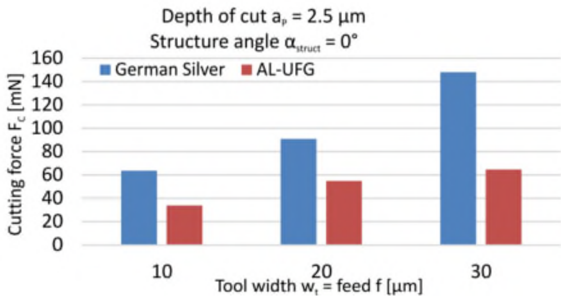

Figure 3: Influence of the tool width on the cutting force.

4. Summary

Cutting experiments have been conducted in an ultra-precision diamond turning process based on various parameter and structure geometry variations in order to examine the influence of these parameters on the cutting forces. Thereby, no evidence was found, for neither an influence of the cutting speed, nor of the depth of cut on the resulting cutting forces. This is standing in a contrast to conventional cutting experiments, thus an explanation for this phenomenon could lie in the low cutting forces and the range of signal noise. However, a positive influence was determined regarding the structure angle as well as the feed or tool width, respectively, which will help to understanding the cutting process in a simulative description. A clear influence of the workpiece material on the cutting force was found. It was observed, that cutting forces were lower for ultra fine grained aluminium compared to German silver.

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