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Tool wear prevention in ultra-precision polymer machining

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Abstract
Polymers become more relevant in the field of optical components as their optical properties, like refractive index n and wavelength dependent dispersion n = f(λ), can be adjusted easily by additives. Due to their low density ρ polymeric optics are lightweight compared to glasses. The demand for ultra-precision machined polymer lenses is increasing. Small series and individualised components can only be produced economically by using ultra-precision machining.
Within theses studies the influence of different measures to reduce diamond tool wear occurring during ultra-precision diamond face turning of polycarbonate (PC) and polysulfone (PSU) will be investigated. Continuous and interrupted face turning experiments are conducted to analyse the effects from separation of the diamond tool and workpiece. Results show increasing tool wear in interrupted cutting. Changes of the environmental conditions in the cutting process show an influence of increasing humidity H on diamond tool wear. This contribution gives a qualitative and quantitative overview on the influencing factors on diamond tool wear in ultra-precision turning of polymers and gives an outlook on strategies to avoid its occurrence.

Keywords: polymers, tool wear, ultra-precision turning

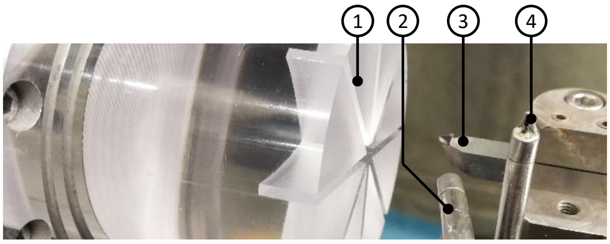
1. Introduction

Ultra-precision machining of polymeric materials with single point diamond turning (SPDT) is considered the applicable method to fabricate high-end optics. SPDT allows freeform surfaces and complex micro-structured surfaces to be machined with required form accuracy $G_F < 1$ µm and arithmetical mean deviation Ra < 5 nm. The development of ultra-precision machining has stimulated the design of complex optics [1]. Freeform optics are the next-generation of modern optics, due to their excellent optical performance and their uncomplicated system integration [2]. The wear of monocrystalline diamond tools is 5 to 10 times higher when cutting polymers than when cutting copper with the same parameters [3]. The diamond tool wear mechanisms are classified into adhesion and abrasion as well as thermal and tribo-chemical effects [4]. Electrical effects need also to be considered in diamond tool wear [5]. Usually, several wear mechanisms occur but one mechanism is dominant dependent on the polymer, machining parameters and the environmental conditions [6]. The dominant tool wear mechanism is can vary over the machining process [7].

2. Methodology

The experiments to investigate the tool wear during diamond turning of polymers are carried out on the ultra-precision machine tool Nanotech 350 FG by Moore Nanotechnology Systems, LLC, Swanzey, USA with uncoated single crystal diamond (SCD) tools manufactured by Contour Fine Tooling BV, Walkenswaard, The Netherlands with the corner radii $r_\varepsilon \approx 1.5$ mm. During the experiments the main effects on diamond tool wear material, humidity H, number of interrupts per revolution n_G and depth of cut a_p are investigated. The width of flank wear land VB_{max} is measured as a meaningful indicator for occurring tool wear on a Scanning Electron Microscope (SEM) JCM 5000 by JEOL Ltd., Tokyo, Japan. The investigated materials polycarbonate (PC) and polysulfone (PSU) are known for strong diamond tool wear [6].

In order to investigate the influence of the humidity H during machining, cutting is performed under environmental conditions with humidity H = 35 % and with increased humidity H = 70 % for both materials and all sample geometries. The increased humidity H = 70 % is achieved by a mist nozzle which is not aimed directly at the tool as displayed in Figure 1.



1 Workpiece with number of grooves per revolution $n_G = 8$
2 Air nozzle for chip removal
3 Single crystal diamond tool
4 Water nozzle for increased humidity H = 70 %

Figure 1. Setup with: 1 grooved workpiece, 2 air nozzle, 3 SCD tool, 4 water nozzle for control of humidity H

As interrupted cutting is presumed to worsen tool wear, samples with a flat surface and different number of grooves n_G are machined to represent interrupted cutting to evaluate the influence of a rising number of interrupts n_G. Specimens from both materials with the diameter D = 60 mm are prepared with the number of grooves per revolution $n_{G,1} = 8$ and $n_{G,2} = 24$ on the five-axis high-precision machine tool HSC MP7 manufactured by exeron GmbH, Oberndorf, Germany. The length of the interrupts l_i is taken into account when the experiments are performed with the cutting length l_c =70 km.

To investigate the influence of rough and fine cutting experiments with two sets of cutting parameters with depth of cut $a_{p,r} = 20$ µm and feed $f_r = 20$ µm/rev as wells as

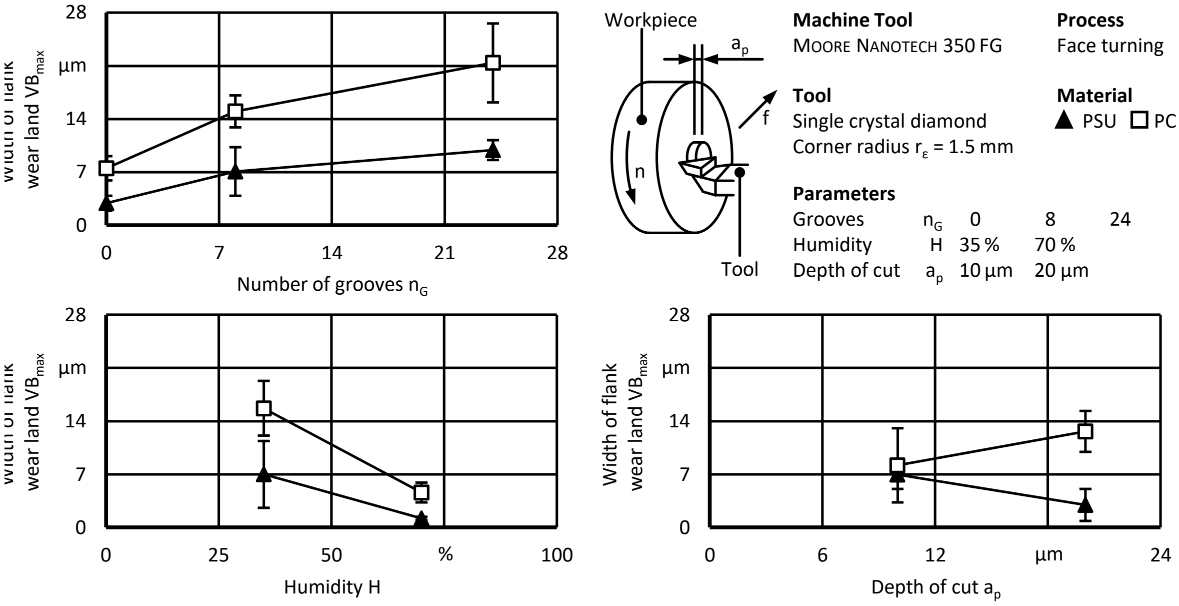


Figure 2. Diamond tool wear in cutting PSU and PC dependent on the number of grooves n_G, the humidity H and the depth of cut a_p

depth of cut $a_{p,f}$ = 10 µm and feed f_f = 10 µm/rev are performed. An overview over all parameters examined are summarised in Table 1. The spindle speed n = 2,000 1/min and the cutting length l_c = 70 km are constant during all experiments.

Table 1. Investigated Parameters

Parameter		Values		
Material		PC	PSU	
Grooves	n_G	0	8	24
Humidity	H	35 %	75 %	
Depth of cut	a_p	10 µm	20 µm	
Feed	f	10 µm/rev	20 µm/rev	

3. Results

Severe tool wear is observable during ultra-precision diamond turning of polymers. No detectable tool wear occurs during the cutting of aluminium with identical process parameters. Therefore, the mechanical material properties are supposed to be non-dominant.

The results of the investigations are summarised in Figure 2. The number of grooves nG increases the tool wear by 239 % for PSU and by 116 % for PC. Rising humidity in the cutting zone decreases the tool wear by 83 % for PSU and by 71 % for PC. The depth of cut $a_{p,f}$ = 10 µm results in a similar mean width of flank wear land VB_{max} ≈ 8 µm for PSU and PC. With increased depth of cut ap,r = 20 µm the width of flank wear land VB_{max} rises by 54 % for PC. Meanwhile in cutting PSU it decreases by 57 %.

By adopting the cutting parameters and controlling the environmental conditions according to a full factorial design of experiment (DOE) the occurring tool wear can be reduced by up to 91.7 % for PSU as shown in Figure 3.

4. Summary and Outlook

Severe diamond tool wear can be prevented, when the cutting parameters and the environmental conditions are controlled. A low humidity H and increasing number of interrupts in the cutting process increase the occurring tool wear. In order to minimise the number of interrupts during ultra-precision machining of polymeric optical components a specialised CNC-software is essential. The use of the software NanoCAM4 by MOORE NANOTECHNOLOGY SYSTEMS, LLC, Swanzey, USA is promising to optimise the lead-in/lead-out movements during the machining of complex optical components in order to reduce tool wear.The dominant wear mechanism is supposed to be a chemical reaction between the polymer chains and the carbon atoms in the diamond tool. The chemical behaviour and the inhibiting effects of humidity H will be examined in the wake of these investigations.

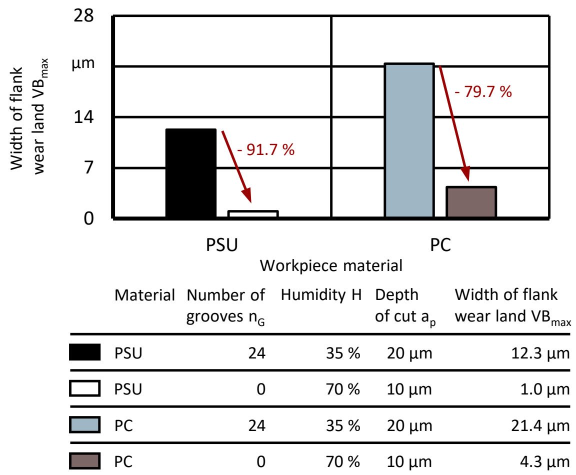


Figure 3. Highest and lowest tool wear in PSU and PC

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