euspen's 18th International Conference & Exhibition, Venice, IT, 2018
www.euspen.eu

Ductile machining of brittle materials for manufacturing micro-optic components

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Abstract

Due to the geometry and specification of micro-optic components, these may not be ground or polished, therefore they demand other manufacturing processes such as ultra-precision (UP) machining with defined cutting edge tools. Despite previous studies, the machining of brittle materials remains a challenge for manufacturing those components in UP processes. For example, ductile machining of silicon is extensively studied, however, ductile machining of materials such as Zerodur®, GaP, U.L.E.® and glass is still a challenge to overcome. Therefore, this paper aims at reporting the ductile or part-ductile machining of silicon and Zerodur® pieces in UP processes. Experiments were carried out using UP-shaping and plane turning processes in an UP-machine tool. Moreover, monocrystalline diamond tools were employed. During UP-turning experiments, the process forces were measured. The machining results were obtained by White Light Interferometer (WLI) of the representative machined surfaces. In order to complement the experiments, simulations were performed in finite element software to comprehend the influences of the rake angle on ductile machining of those materials. After the UP-shaping experiments, the depth of cut was determined for each of the mentioned materials together with the main influence of each process parameter. Furthermore, a reduction of parameter ranges for UP-turning experiments was accomplished. Using Design of Experiments for UP-turning tests, the main influences of process parameters were observed and detailed, together with tool geometry optimization and recommendation for further experiments. The local optimum of process parameters was found as well as the accomplishment of ductile removal during the machining tests. These results and simulation models are going to be further used for a more detailed process description, as analogous tests and optimization of UP processes such as micro-milling.

Keywords: ultra-precision turning, ultra-precision shaping, brittle materials, micro-optics

1. Introduction

Processes like grinding and polishing techniques are not always possible to be employed to manufacture micro-optics. Mostly, this is due to the optical component dimensions and geometry, therefore an approach must be established to fulfil this gap in the optical industry. However, most of the materials machined for this industrial sector are composed of brittle materials which, due to their material characteristics, are difficult to machine through alternative methods such as ultra-precision (UP) turning, shaping and milling. Research related to the machinability of those materials are, until certain extent, already ongoing. Most of these studies concluded positively regarding the possibility of machining brittle materials such as silicon [1,2], gallium phosphide [3] and Zerodur® [4] in a ductile regime or at least with indications of ductile behaviour. This paper aims at describing the UP-shaping and UP-turning process of silicon and Zerodur® by measuring the process forces, and building a simulation model to describe the machining of silicon using a Finite Element (FE) model.

2. Experimental setup

2.1. Machine and measurement

The machining of silicon and Zerodur® was conducted in a modified UP-machine tool centre LT-Ultra MMC 1100. For acquiring optical surfaces, the machine is equipped with a granite structure, vibration damping systems and temperature control system. The tool selected was a monocrystalline diamond tool (MCD). This tool is suitable to machine a variety of hard materials, but limited by chemical wear.

The measurement systems employed were a White Light Interferometer (WLI) ZygoLOT NewView 5010, while the process forces were measured during UP-turning employing a piezoelectric dynamometer platform Kistler 9256B1.

2.2. FE-Simulation

To understand the cutting mechanisms as well as to estimate forces during process, 2D thermo-mechanic cutting simulations of silicon were carried out in a FE software (DEFORM 2D). To describe the ductile cutting mechanisms of silicon under high pressure, the generalized JC model was employed (Equation 1).

$$\sigma = \left(A + B\,{\varepsilon_{pl}}^{n}\right)\left(1 + C\,ln\left[\frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_{0}}\right]\right)\left(1 - \left[\frac{T - T_{room}}{T_{melt} - T_{room}}\right]^{m}\right) \qquad (1)$$

Where σ is the flow stress, A the yield stress, B a pre-exponential factor, C the strain rate factor, n the work-hardening exponent, m the thermal-softening, T_{melt} the melting point of the material and T_{room} the room temperature. The diamond tool and the silicon workpiece were modelled as rigid and plastic respectively. Friction between both objects was included through the shear.

The effective plastic strain ε_{pl}, plastic strain rate $\dot{\varepsilon}_{pl}$, reference strain rate $\dot{\varepsilon}_0$ and the temperature of the material T are parameters that vary along each step of the simulation, therefore they are not given as input to the JC model.

3. Procedures and Results

3.1 UP-shaping

The experiments were conducted in two steps, firstly a ramp UP-shaping experiment, where the workpiece was tilted approximately 2 µm, consequently the depth of cut a_p varies along the tool path from 0 to 2 µm. The tool marks along the workpieces surface were measured with the WLI and a profile perpendicular to the tool path was analysed. This profile is traced exactly on the ductile-brittle transition area and its depth is then measured. During this experiment, the rake angle α was also varied from α = - 10° to α = - 50° by tool manipulation to find the most suitable angle to machine efficiently such materials. Subsequently, UP-turning experiments were carried out using two fixed rake angles α and a cutting speed v_c for each material. Also, the process was repeated minimum four times for each rake angle α to build a statistical relevant result.

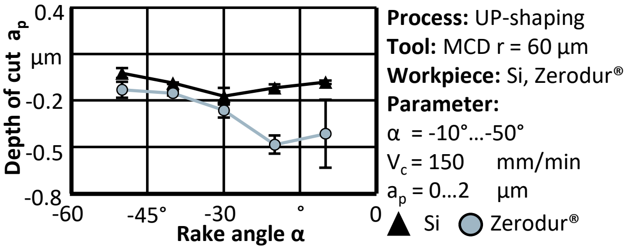

Figure 1. Influence of variation of the rake angle α on the maximum depth of cut $a_{p,\,max.}$

3.2. Johnson-Cook model

The JC parameters (Table 1) for silicon were appraised by Venkatachalam [1] using a Nelder-Mead search algorithm based on an initial guess. These appraised parameters describe the silicon under plastic phase transformation (Si-II).

Table 1. Johnson-Cook Parameter for silicon [1].

A [MPa]	B [MPa]	C [-]	n [-]	m [-]	T_{room} [°C]	T_{melt} [°C]
896.394	529.273	0.4242	0.3758	1.0	20	1412

3.3. UP-turning

dFor UP-turning experiments, the selected rake angles were α = -20° and α = -30° for silicon and Zerodur®. During these tests, the cutting and passive forces were monitored. Figure 2 shows the significant forces measured while silicon machining and simulation results. In Figure 3, the Zerodur® process forces are displayed. The WLI measurement of the machined surfaces of silicon and Zerodur® are shown in Figure 4. Due to the low cutting speed, no significant difference was observed using vc = 20 m/min or vc = 70 m/min. by analysing the rake angle α, it was noticed a significant difference between the rake angle α = -20° and α = - 30°.

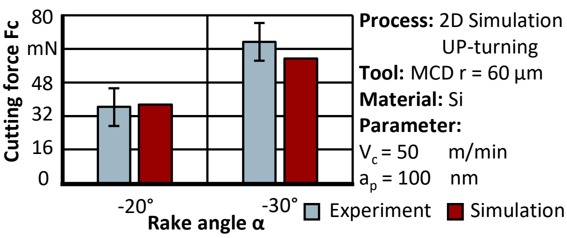

Figure 2. Influence of the rake angle on the cutting force Fc for Si while UP-turning of silicon and 2D simulation results.

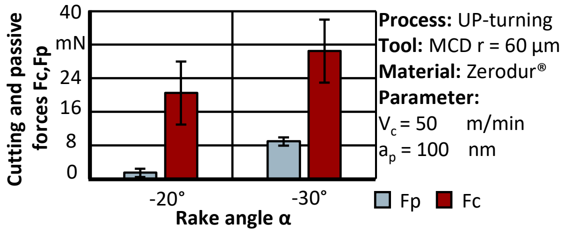

Figure 3. Influence of the rake angle on the cutting force Fc and Fp for Zerodur® UP-turning.

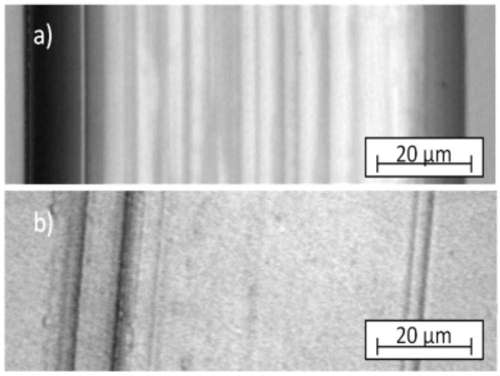

Figure 4. a) UP-turned silicon surface Rq = 9 nm. b) Machined Zerodur surface Rq = 11.2 nm.

4. Discussion

Both materials have shown indications of ductile behaviour during machining, according to the images acquired from WLI. As expected, the maximum depth of cut $a_{p,max}$ is heavily influenced by the rake angle α, particularly at rake angle α = - 20° and α = -30°. Therefore, concluding that those rake angles are the most suitable for machining silicon and Zerodur® in UP-shaping and UP-turning. During UP-turning experiments a significant influence of the rake angle on process forces during ductile processing of silicon were noticed. According to Goel [2], the main reason of the ductile behaviour of silicon, is the 13 GPa pressure of the cutting edge on the silicon surfaces. For Zerodur®, it was noticed the same tendency of forces as for silicon, but further experiments to analyse the subsurface damages are required to understand the ductile removing mechanisms.

5. Summary and Outlook

It was possible to recognize for silicon and Zerodur® the influence of the rake angle on the maximal depth of cut $a_{p,\,max}$ for achieving ductile machining. Moreover, the simulations proved to be a reliable method to predict forces during process. However, a detailed material characterization approach is necessary to understand the removal mechanisms while machining Zerodur® and silicon. Then, adjust the JC parameters.

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