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Ultra-precision-milling of silicon by means of single crystal diamond tools

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Abstract

Silicon is an important material often employed on most of micro-electro mechanical systems (MEMS), integrated circuits, micro-chips, and micro-fluidic devices. Therefore, strategies and process parameters to machine those planar 2.5-D geometries of silicon are essential. Moreover, silicon belongs to the group of hard-brittle materials, which means that it is very likely to originate cracks during the milling operations as a result of the intermittent interaction of the cutting edge and the silicon surface. Besides, the machining of silicon results on severe tool wear. The ductile-brittle transition and tool wear reduction of the silicon-milling are aspects still not completely investigated. Consequently, this paper aims at finding the proper parameter range for ductile ultra-precision milling (UP-milling) of 2.5-D silicon geometries employing single crystal diamond cutting tools. Furthermore,the evaluation the tool wear after the process is a crucial part of the investigations. In order to fulfil such knowledge gap, single groove experiments are proposed. The milling process to generate those grooves is monitored by means of force measurements. Also, surface aspects of the machined grooves are measured through white light interferometry (WLI). For evaluating tool wear, dry UP-milling investigations are conducted and images of the cutting edges are taken by means of a scanning electron microscope (SEM). The experiments show that the machining of silicon is feasible and the ductile material removal is possible. Moreover, the process forces F_{pr} generated by the UP-milling process of single crystal silicon are able to be employed for monitoring and avoid the transition from ductile to brittle material removal.

Keywords: Ultra-precision-milling, single crystal diamond tool, hard-brittle materials

1. Introduction

Silicon is an essential feedstock material for manufacturing most of the micro-electro mechanical systestems (MEMS), integrated circuits, micro-chips, and for micro-fluidic applications [1]. As a conquence, an efficient method to shape 2-D, 2.5-D and even 3-D geometries is crucial to meet industrial demands. To achieve an effective machining process, at least three aspects must be taken into account. Firstly, it is necessary to understand the fundamental aspects of silicon during the machining process to predict or control the manufacturing of a specific component. That means, the influence of the tool geometry on the ductile-brittle material removal transition. Secondly, the influence of the machining parameters on the surface formation, such as depth of cut a_e and cutting speed v_c, along with the influence of the tool geometry must be identified. Thirdly, it is essential to understand the influence of the width of cut a_e along with the depth of cut a_e and the cutting speed v_c in order to machine surfaces with a ductile material removal behaviour as well as achieving optical surface quality.

With the development of single point diamond turning (SPDT) or ultra-precision-turning (UP-turning) it was possible to machine efficiently micro-features of silicon with a surface roughness in a single digit nanometer range. By employing such machining technology, the elastic-plastic deformation of silicon can be achieved by identifying the brittle-ductile material removal transition phenomenon. This phenomenon occurs due to a high-pressure phase transformation as function of the tool geometry and the machining parameter conditions. Depending on the hydrostatic pressure during the process, a metallic phase can be found and consequently a ductile material removal of silicon is feasible [2, 3, 4]. This study was confirmed by several nanoindentation trials, where the different silicon phases were observed [3]. Also, molecular dynamic simulations show the different transformation phases of silicon during an nanoindentation procedure.

Uhlmann et al. [5] complemented the previous studies by depicting the main cutting issues during ultra-precision-turning experiments and discussed the influence of the depth of cut a_e and the rake angle γ on the ductile-brittle removal transition of silicon. Moreover, a finite element model were proposed to understand the influence of the cutting parameters and tool geometry on the cutting forces F_{pr} and temperature T. However, few studies were conducted aiming at understanding how to transfer the know-how from the UP-turning technology to the UP-milling process of silicon [6].

To generate a fundamental knowledge and to achieve an effective method for machining the 2-D and 2.5-D geometries in silicon, this paper aims at giving continuity to the research proposed by Uhlmann et al. [5]. Which means that the provided knowledge from UP-shaping and UP-turning experiments will be transfered to the UP-milling process of silicon. The key aspects discussed are the influence of the cutting speed v_c, depth of cut a_p, and feed per tooth f_t on surface formation by means of slot UP-milling process. Moreover, once the influence of these cutting paramters were apraised, surfaces were machined in order to test the capabilities to achieve optical surface quality.

2. Methodology

In order to transfer the knowledge from UP-turning to UP-milling of silicon workpieces, experiments consisting of assessing the influence of the cutting speed v_c, depth of cut a_p, and feed per tooth f_t on the surface formation were conducted. During these experiments, the process forces F_{pr} were monitored. The experiments conducted are depicted in Table 1. Finally, using the best combination of cutting parameters, surfaces were machined by UP-face-milling. To identify the main wear mechanisms, several scanning electron microscopy images (SEM) were taken of the milling tool after machining.

Table 1. UP-slot-milling parameters applied during the experiments.

Depth of cut a_p/µm	Cutting speed v_c/m/min	Feed per tooth f_t/nm
0.001	20	100
0.004	70	500
0.008	-	-

2.1 Experimental set-up

The experiments were conducted on a modified UP-machine tool LT-Ultra MMC 1100 from the company, LT Ultra Precision Technology GmbH, Herdwangen-Schönach, Germany. This UP-machine tool is designed to manufacture parts with optical surface quality. Therefore, the UP-machine tool is equipped with a granite structure, vibration damping systems, and a temperature control system. The UP-machine tool has also an aerostatic milling spindle from the company Levicron GmbH, Kaiserslautern, Germany. Moreover, the UP-machine tool has attached a chromatic sensor in order to measure the flatness deviation F_l of a workpiece. Figure 1 presents the UP-machine tool model employed during the experiments. The process parameters selected were based on the previous experiments conducted by Uhlmann et al [5].

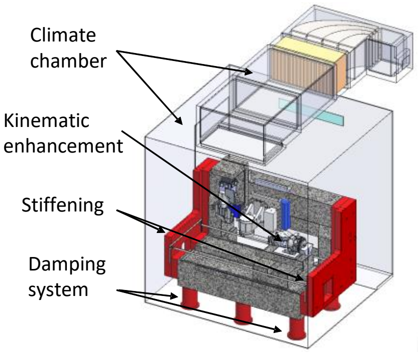

Figure 1. LT-Ultra MMC 1100 model used for the experiments.

2.2 Tool and measurement equipment

The experiments were conducted employing a single crystal diamond (SCD) corner mill, single flute and a cemented carbide shank from the company Chardon Tool & Supply Co. Inc., Chardon, USA. The geometries and dimensions are described in table 2.

Table 2. Single crystal milling tool specifications.

Corner radius r_β /µm	Rake angle γ /°	Cutting radius r /mm	Shank diameter D X length L /mm
60	-20	0.5	6 x 50

For the measurements a Neoscope JCM-5000 SEM, from the company JEOL Ltd., Tokyo, Japan, and a White Light Interferometer (WLI) ZygoLOT New View 5010, from the company Zygo Corporation, Pennsylvania, USA, were employed. Also a piezoelectric dynamometer Kistler 9256B1 from the company Kistler Instrumente AG, Winterthur, Switzerland, was used along with a programmed Labview interface.

3. Ultra-precision-milling procedure

3.1 UP-slot-milling

The results of the UP-slot-milling experiments were divided into three analysis. Firstly, the influence of the cutting speed v_c on the surface formation and process forces F_{pr} were assessed. Followed by the influence of the depth of cut a_p and the feed per tooth f_t on the surface characteristics and process forces F_{pr}.

3.1.1 Influence of the cutting speed v_c

The influence of the cutting speed v_c on the arithmetical mean deviation Ra, maximum height of the profile Rz and root mean square Rq are presented in Figure 2. Meanwhile figure 3 shows the WLI images of the machined surfaces.

The experiments show an increase of the surface roughness by increasing the cutting speed v_c. Moreover, no evidence of cracks were found by using both both cutting speeds v_c. Due to the cutting parameters employed, no variation on the cutting forces F_{pr} were observed.

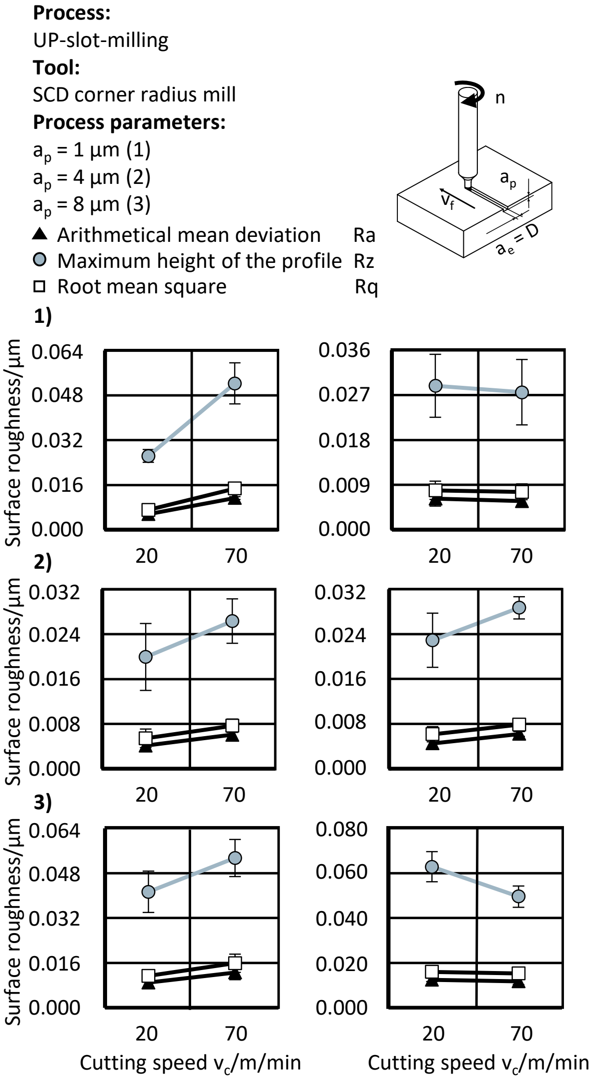

Figure 2. Results from UP-slot-milling experiments.

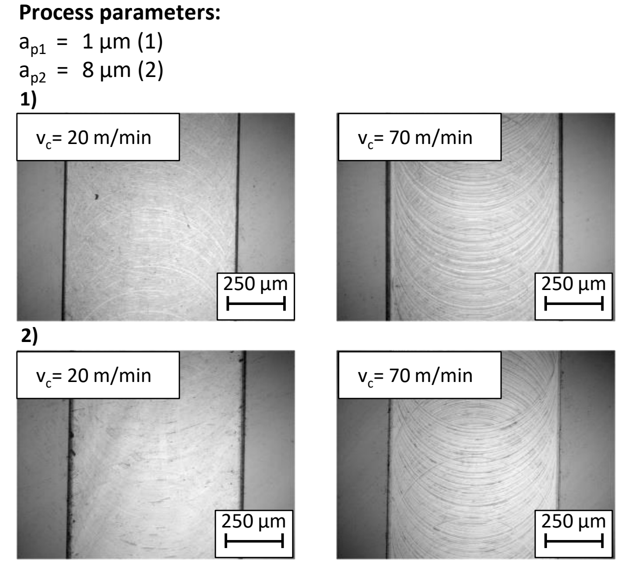

Figure 3. WLI images of the machined surfaces.

3.1.2 Influence of the depth of cut a_p

The experiments were conducted with a varying depth of cut in a range of $a_p = 1$ µm, $a_p = 4$ µm and $a_p = 8$ µm. Moreover, the feed per tooth f_t and cutting speed v_c were kept constant at $f_t = 0.5$ µm and $v_c = 70$ m/min. The results indicated an increase of the roughness values for the arithmetical mean deviation Ra, maximum height of the profile Rz and root mean square Rq. Figure 4 presents the results provided from the UP-slot-milling experiment with varying depth of cut a_p. Even with the increase of the depth of cut a_p, the process forces F_{pr} were too low to be measured.

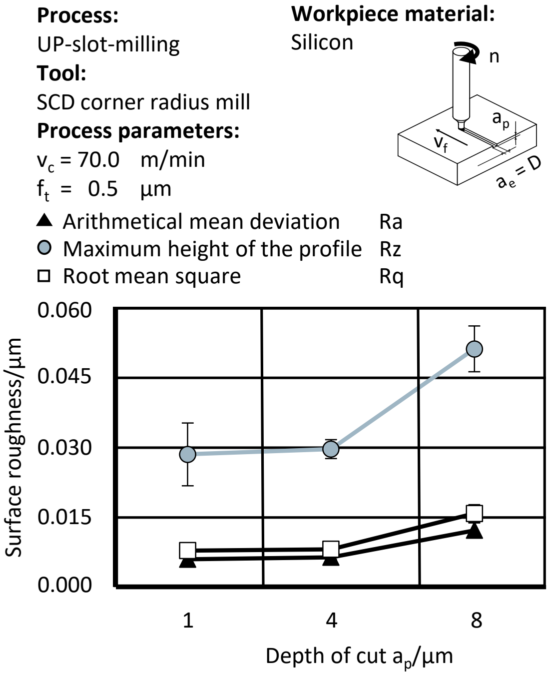

Figure 4. Influence of the depth of cut a_p on the surface roughness Ra, Rz, and Rq.

3.1.3 Influence of feed per tooth f_t

Figure 5 shows the UP-slot-milling experiments results with a varying feed per tooth $f_t = 0.1$ µm and $f_t = 0.5$ µm. Also, two different cutting speeds $v_c = 20$ m/min and $v_c = 70$ m/min and three depths of cut $a_p = 1$ µm, $a_p = 4$ µm and $a_p = 8$ µm were used.

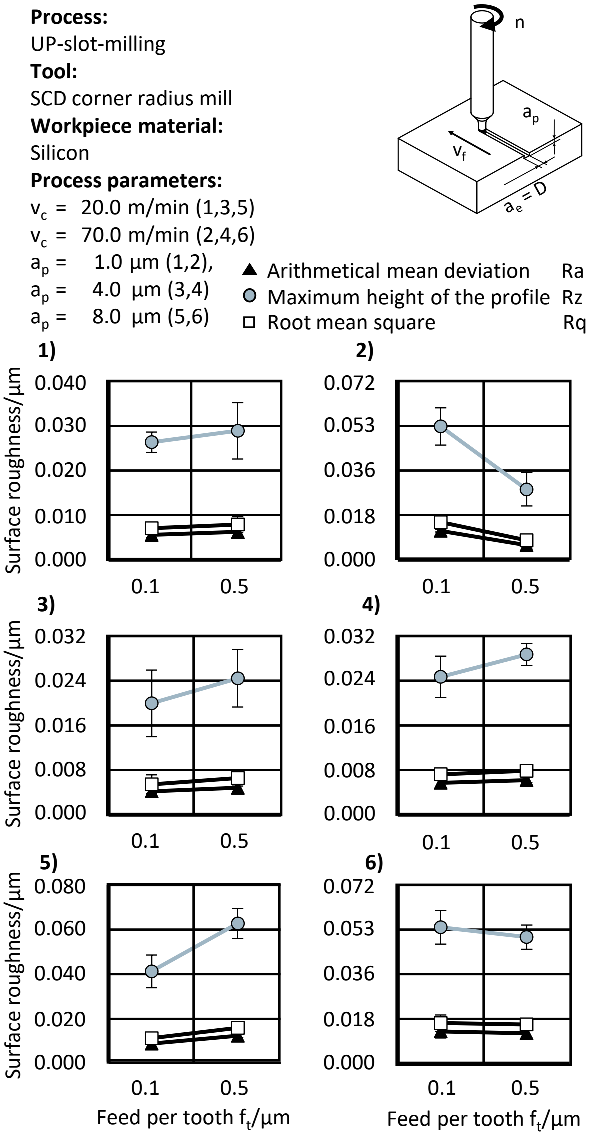

Figure 5. Influence of the feed per tooth f_t on the surface formation during UP-slot milling experiments.

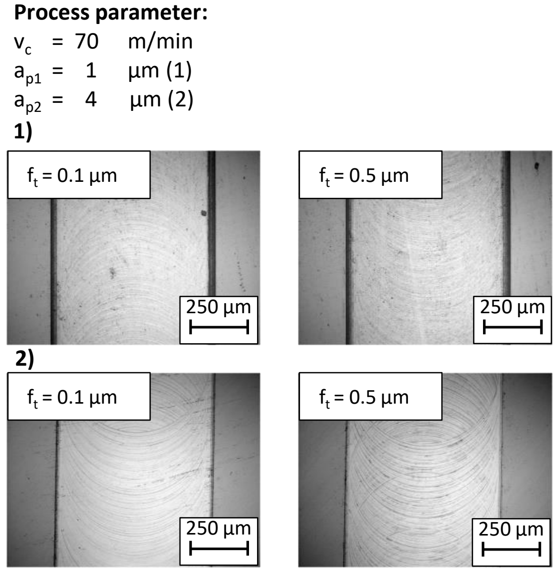

Figure 6. WLI images of the machined surfaces.

3.2 UP-face milling experiment

The UP-face-milling experiments varying the width of cut $a_e = 5$ µm, $a_e = 10$ µm and $a_e = 15$ µm, employing a cutting speed $v_c = 70$ m/min, and a depth of cut $a_p = 4$ µm show a reduction of the surface roughness for the arithmetical mean deviation Ra, maximum height of the profile Rz and root mean square Rq while increasing the width of cut a_e value. Those values are show in Figure 7. Figure 8 shows the machined surfaces with the UP-milling process marks generated due to the tool rotation.

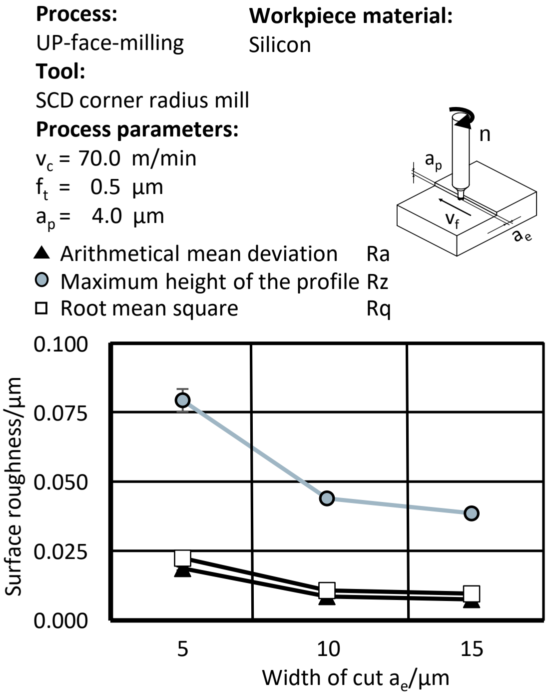

Figure 7. Roughness Rz, Rq and Ra values of UP-face-milling experiments.

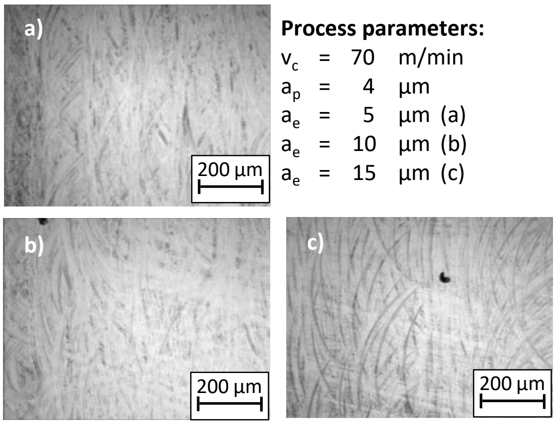

Figure 8. WLI images of the machined surfaces.

4. Discussion

Based on the results, by employing UP-milling process it is possible to generate surfaces with optical surface quality. Also, it is possible to observe that there are no cracks in the workpiece surface. Even though there are tool rotation marks. This evidence suggests that the cutting conditions generated a complete or mostly ductile material removal of the silicon workpiece. However, by using the described set-up, it was not possible to measure the process forces F_{pr}. Nevertheless, based on the WLI images, it is also possible to observe that the applied hydrostatic pressure σ generated from the cutting conditions were in the range of $10\,\text{GPa} < \sigma < 13\,\text{GPa}$. This hydrostatic pressure σ range is the main responsible for the transformation of the silicon into a more ductile silicon (Si-II).

Subsequently, by analysing the arithmetical mean deviation Ra, maximum height of the profile Rz and root mean square Rq of the machined surfaces, some influence of the cutting speed v_c, depth of cut a_p, and the feed per tooth f_t were observed. However, it is necessary to increase even more those cutting parameters in order to observe a more significant influence of those process parameters on the surface formation and the process forces F_{pr}.

It is important to emphasize that the experiments were conducted without using cutting fluids. Thus, some abrasive wear marks on the milling tool cutting edge were observed.

5. Summary and Outlook

Despite the difficulties involved in machining brittle materials like silicon, the capabilities of UP-milling for achieving optical surface roughness in silicon were proved. It has been shown that it is possible to transfer the fundamental knowledge acquired of UP-turning to UP-milling.

For future investigations, it is recommended to increase the cutting parameters until a brittle condition is found. Moreover, to further understand the characteristics of silicon phase transformation, molecular dynamic simulations that emulates the cutting conditions of UP-milling are essential. Finally, it would be suggested to investigate the usage of different lubricant fluids during the UP-milling process to minimize the tool wear. Moreover, it is suggested to further expand the acquired knowledge from 2.5-D to 3-D geometries and more complex shapes.

6. Acknowledgement

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