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Performance of ultraprecision milling with thermally adjustable cutting edges

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Abstract
Advancing diamond milling from fly-cutting to the application of multiple cutting edges requires a tool setting mechanism for aligning all tools to a common cutting radius. Such a system, based on thermo-mechanical actuation, has been previously presented and it has been shown that the cutting radius can be selectively changed at spindle speeds of several hundred rpm.
Here, the recent state of development on the actuating mechanism, including the specifically designed ring light heat source, and evaluate its performance in cutting experiments. Therefore, the thermal expansion of the tool will be measured in-processes using a capacitive sensor targeted a reference section of the milling tool's shell surface which is located slightly below the cutting edge. During machining, isolated cuts for each cutting edge will sequentially be generated following a defined heating profile. After such a cycle, the depth of the cuts is measured ex-situ and compared to the expansion measured at the reference plane. By comparing selected spindle speeds and heating profiles, the performance of the actuating mechanism is assessed.

Ultraprecision milling, multiple cutting edges, thermal tool setting

1. Introduction

Diamond milling operations enable the flexible production of optical freeform surfaces for mirror optics [1,2], prisms [3] and as moulds for the replication of optical components [4]. In order to achieve the required tolerances, the milling process is typically conducted as fly-cutting, i.e. utilizing only a single cutting edge to ensure a precise radius of tool engagement. This, however has severe limitations when considering the material removal rate of the process, because the feed has to be reduced accordingly to guarantee an optical surface finish (Sa < 10 nm) [5]. In order to enable the use of multiple cutters on a milling tool, an actuating mechanism for aligning the cutting edges to a common radius has to be implemented. Such a system, based on the thermal expansion of selected portions of the tool holder was previously presented by the authors [6]. Most recently, it has been shown that the system is capable of achieving thermally induced tool shifts of up to 1 µm at spindle speeds of 240 min^{-1} [7].

This publication presents the recent state of development on the actuating mechanism, including the specifically designed ring light heat source, and evaluate its performance in cutting experiments.

2. System design and setup

2.1. Tool holder design for two adjustable cutting edges

The tool holder is designed as a circumferential milling tool with a nominal diameter of 158 mm that incorporates two tool-holding mechanisms at 180° spacing (Figure 1). The substrate materials is made of 1.2083 type steel which is dyed by black paint on the thermal actuating mechanisms in order to increase the thermal conductivity of that region. The actuators themselves are 20 mm wide, 30 mm long and 12 mm thick bars that are cut free from the rest of the tool holder except for two flexure hinges at the outer diameter ("front") and two connectors at the inner diameter of the actuator ("rear"). Inside of the actuating mechanisms, a rectangular tool shank is guided in an equivalently shaped channel and thereby limited to move in a single degree of freedom, i.e. in radial direction. The tool shank rests against a wedge mechanism that, when shifted in axial direction of the tool holder, enables a coarse mechanical alignment of the tool shank. After pre-setting the tool to the required precision (typically < 1 µm deviation of the fly-cut-radius), the tool shank is clamped in place and the remaining deviation is compensated by thermal expansion of the whole actuating mechanism.

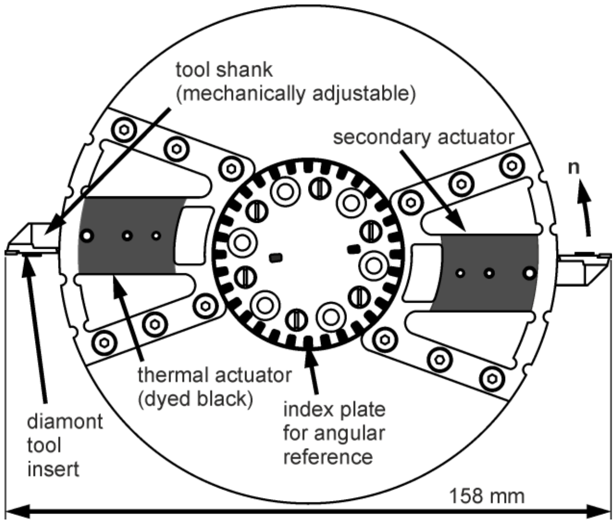

Figure 1. Tool holder design with two adjustable cutting edges

2.2. LED ring light as moving heat source

The heat input necessary for the expansion of the thermal actuator is introduced by a specifically designed ring light system with infrared light emitting diodes as a contactless heat source. This allows for the heat input to follow the rotation of the actuating mechanism during a milling process while the ring light itself remains stationary within the machine. To do this, the angular position of the actuator is optically captured using an index plate at the front face of the tool holder. The control electronics evaluate this signal and use it as a trigger to advance the heat output from one LED to the next during rotation.

Compared to previous iterations of the ring light system, which were designed as a full ring with 36 LED, the novel design (Figure 2) consists of four equally designed quarter ring segments with 8 LED each (i.e. 32 LED in total). This allows for an easier and economic production of the ring lights and facilitates the assembly and disassembly the ring light system as it now can mounted around the spindle shaft without prior disassembly of the tool holder.

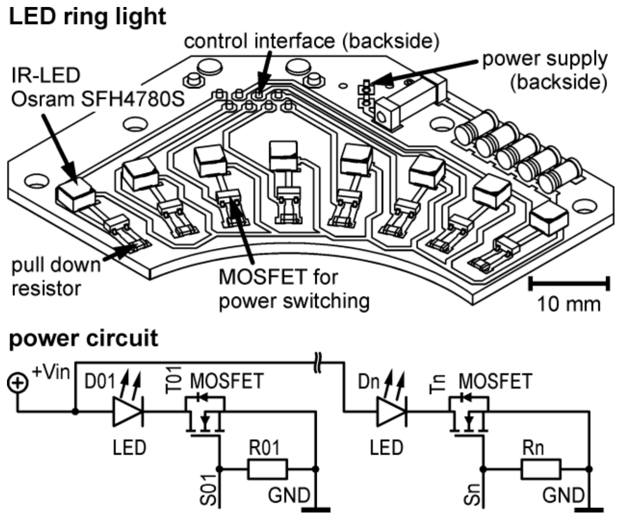

Figure 2: LED ring light system design and power circuit schematics

The applied LED offer a total radiant intensity of 680 mW at a centroid wavelength of 810 nm and an opening angle of ±10°. According to previous experiments, this should generate enough heat within the actuator to expand it by about 1 µm along its main axis.

3. Experimental setup for evaluating the actuator expansion

The complete system has been initially set up on a test stand outside of a machine tool. It consists of a Professional Instruments 4R air bearing spindle on which the tool holder with the thermal actuators is mounted (Figure 3). Two ring lights are assembled from four segments each and are positioned on the test stand to illuminate the front face and the back face of the actuator respectively, with a standoff distance of 10 mm. The reference plane of the tool holder was centred to the spindle axis with a precision of <2 µm and the overall system was balanced to G0.064 to avoid dynamic disturbances of the measurements.

For testing the performance of the actuator, the spindle was set to specified speeds while one of the actuators was illuminated by the infrared LED at full power. The resulting thermal expansion was continuously measured at a reference plane slightly below the tool shank by a capacitive probe (IBS CPL490 with C8-0.5 probe). For a full measurement cycle, the spindle was run at the selected speed without heating of the actuator for a couple of minutes to obtain a reference position of the tool. Then, the LED was switch on for about 20 minutes, i.e. until the maximum thermal expansion was expected. After switching off the LED, the actuator was allowed to cool down for another 20 minutes to return to its initial thermal state.

The resulting measurement data contains the development of the tool holder runout of the actuator during the aforementioned test cycle. For assessing the behaviour of the two actuators (one heated, one not heated) and the reference sections in between, the measurement data has to be segmented into individual revolutions and then divided by section.

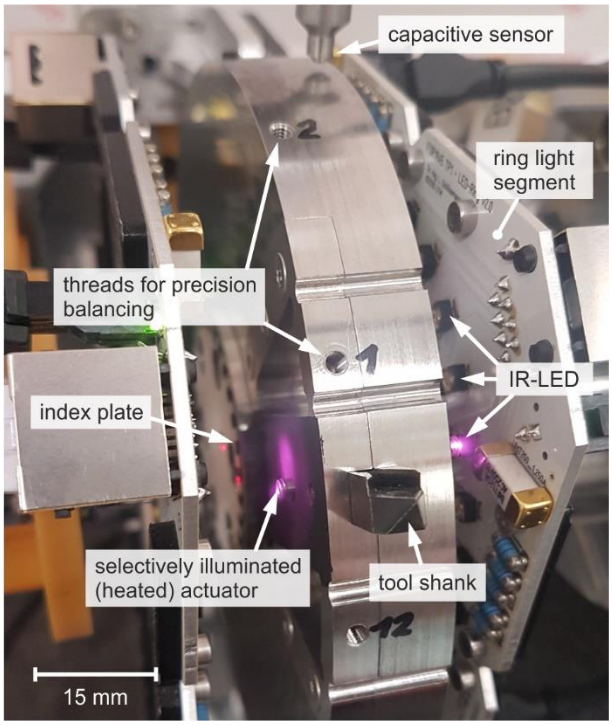

Figure 3: Actuator test setup with new segmented ring lights

This division is done in a MATLAB script that firstly searches for the trigger signals of the index plate to identify the start of a new revolution. After segmentation, the sections of the reference plane can be identified by the signal dropouts occurring at the flexure hinges, where the capacitive sensor is out of its measurement range (Figure 4).

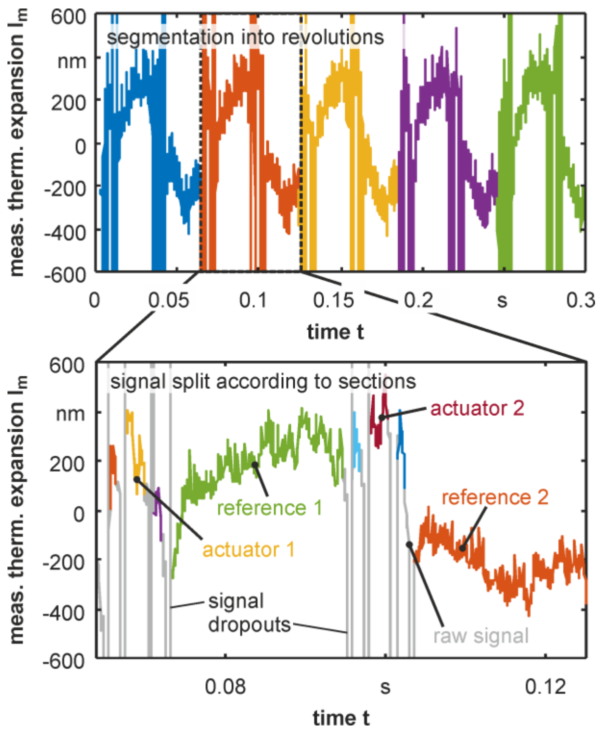

Figure 4: Segmentation of capacitive measurement into revolutions (top) and splitting of revolutions into sectional data (bottom)

The development of the thermal expansion is evaluated with reference to the mean runout of the first few revolutions, i.e.

those that were performed without any heat input from the infrared LED. Therefore, the mean of the first few revolutions is subtracted from current revolution for each data point (Figure 5) and the resulting differences are averaged and associated with the mean timestamp of the respective revolution.

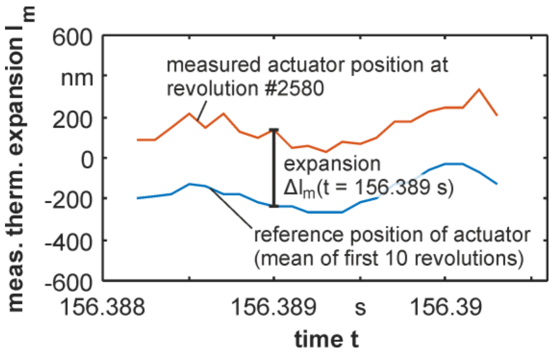

Figure 5: Determination of actuator expansion at a given revolution

The resulting thermal expansion of a test run at 300 min^{-1} spindle speed is shown in Figure 6. It can be seen that the selectively heated actuator (act. 1) is expanding up to ≈450 nm for using about half the available power of the LEDs (I = 1 A is applied to both rings in a parallel circuit, i.e. one LED only consumes 0.5 A of current).

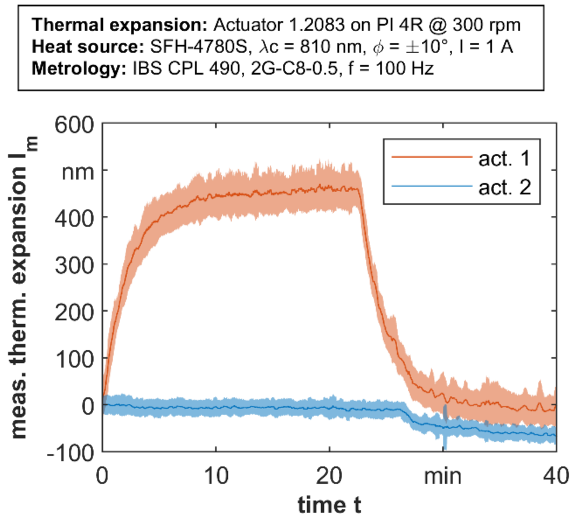

Figure 6: Development of thermal expansion for the adjustable milling tool at 300 min^{-1} spindle speed and a LED power of ≈1.5 W/sr. LED switched off after about 22 minutes.

The secondary actuator (act. 2), positioned at 180° of the tool holder is showing no significant expansion, as expected. This implies that the offset between both cutting edges can be adjusted by this means. Currently, the actuating mechanism in combination with the new ring lights is under evaluation at different spindle speeds and LED powers.

4. Cutting experiments

Achieving a thermally induced shift of one of the cutting edges under rotation is necessary for tool setting in a real milling process. However, it has to be verified, if the measurements of the expansion performed at the reference plane is also valid for the actual shift of the tool in the milling process. This can only be examined by actual cutting experiments in which the tool comes into contact with a workpiece.

In order to be able to identify the actual cutting depth of both tools individually, a high feed milling strategy is used. In this, the feed in axial direction of the tool is chosen according to the spindle speed *n*, in a way that both tools generate isolated cutting marks on the workpiece surface (Figure 7). Therefore, the feed *f* is set higher than the combined width of the cutting marks b_1+b_2, with calculates as follows:

$$b_i = 2\sqrt{a_{p,i}(2\cdot r_\varepsilon - a_{p,i})} \text{ with } a_{p.i} = a_p + \Delta r_{\text{fly},i}$$

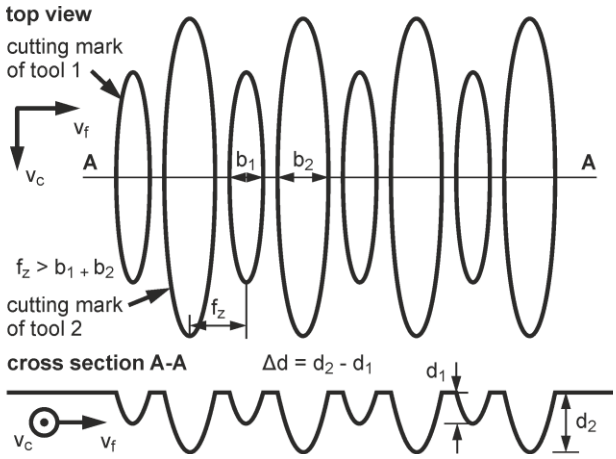

Figure 7: High feed milling strategy to achieve isolated cutting marks.

For the cutting experiments, the tool holder is applied on a Nanotech 500FG ultra precision machine tool. Therefore, it is mounted on the PI 4R air bearing spindle previously used on the test stand which is placed on the B-axis of the 500FG. The workpiece (OFHC copper) is clamped on the main axis (C) of the machine tool. The 4R spindle axis is aligned in parallel to the X-axis so that the cross feed motion v_f is performed in this direction.

Two diamond radius tools with nose radii of $r_{\beta 1}$ = 725 µm and $r_{\beta 2}$ = 762 µm are mounted on the tool holder. After mechanical pre-setting, the nominal fly-cut radius is r_{fly} = 79 mm with a Δr_{fly} = 402 nm deviation between the two cutting edges. At an infeed of a_p = 5 µm, this yields cutting mark widths of b_1 = 170 µm and b_2 = 206 µm. Thus, at a spindle speed of n = 500 min^{-1}, a cross feed of v_f = 200 mm/min (i.e. *f* = 400 µm) is applied.

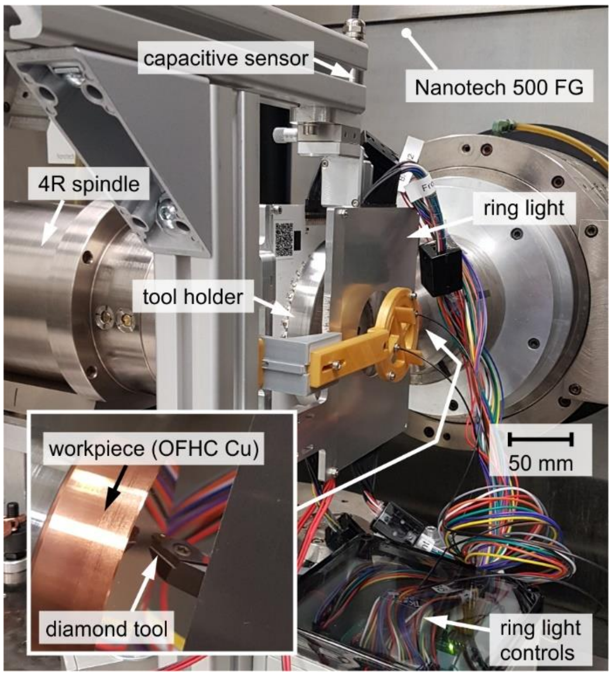

Figure 8: Setup for diamond milling with multiple cutting edges on a Nanotech 500FG machine tool

In this case, the original ring light shown in [7] with 36x SFH4783 LED was used at a maximum current of I_{LED} = 1 A. During the test cycle, the machine was programmed to cut a small section with length of l = 7 mm and several cutting marks for both tools every minute. After generating one section with the reference depth of the cutting marks, the LED heating was switched on for 30 minutes so that the sections 2 to 32 should show an increase of depth for one of the cutting marks. After switching off the heat source, another 28 sections were generated to contain the retraction of the previously expanded tool due to cooling. The resulting surface is measured using a white light interferometer and the depth is extracted for eight adjacent cutting marks (four for each tool, see Figure 9, top). This allows rudimentary statistics to be calculated later.

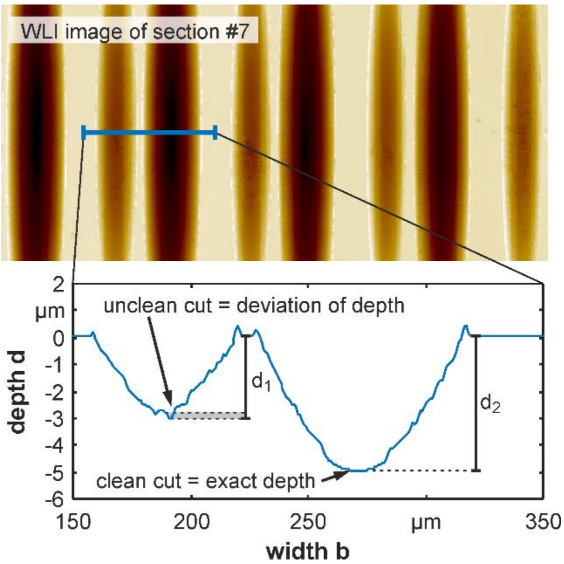

Figure 9: Evaluation of cutting mark depth

The following Figure 10 shows the development of the difference in cutting mark depth as an indicator for the thermal expansion ($l_m = \Delta d$). The red line shows the mean of four measurements while the light red area indicates the standard deviation. The measurement of the reference plane is shown in blue for comparison.

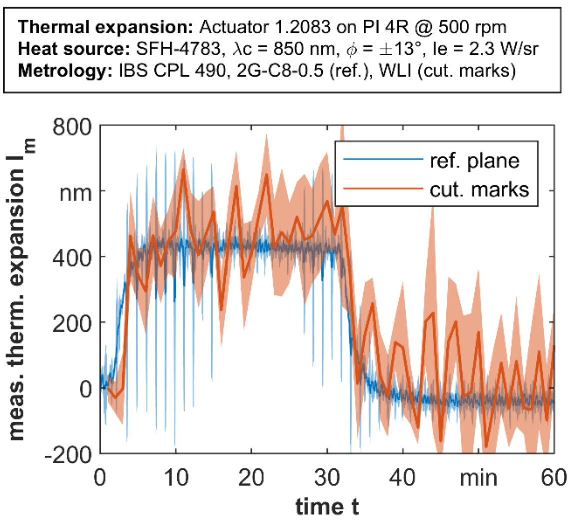

Figure 10: Shift of the reference plane (blue) in comparison to the development of the difference in depth of the cutting marks.

First, it is noticeable that the difference in cutting mark depth is a lot more unstable than that of the reference plane. Foremost, this can be attributed to instabilities in the cutting process as well as to difficulties in determining the correct (i.e. maximum) groove depth for each measurement due to artefacts occurring during cutting and measurements (cf. Figure 9).

Nevertheless, a change in cutting depth due to the thermal expansion is discernible in the cuts. Between section 10 and section 30 (equivalent to t = 10 to 30 min in Figure 10), i.e. in a range where the thermal expansion should have reached its maximum due to the capacitive measurements, the mean depth difference is $\Delta d = 481 \pm 98$ nm, compared to $\Delta l_m = 424 \pm 22$ nm for the capacitive measurement.

5. Conclusion and outlook

This paper shows the novel design of an LED ring light system to selectively heat up a thermal actuator on a diamond milling tool. Perspectively, this concept shall be used in ultra-precision milling with multiple cutting tools to align all cutting edges to a common fly-cut radius. The system consists of four segments with eight infrared LED each that are assembled to a full ring light. One of such ring lights is used to selectively heat the front face of the actuator while a second one heats the rear face. To synchronize the LED switching, dedicated control electronic have been designed and built. The first evaluation of this system show that a thermal expansion of around 420 nm is achieved at spindle speed of 300 min^{-1} on a test stand without actual tool-workpiece contact.

In subsequent experiments, the applicability of the thermal tool setting mechanism was demonstrated in an exemplary milling setup, utilizing a previous iteration of the LED ring light system. It could be shown that an expansion is visible in both the measurements of the reference plane during cutting as well as on the actual machined surface as proven by the evaluation of the cutting marks with a WLI. However, the results still show deviations for the machined cutting marks due to instabilities of the cutting process.

Therefore current investigations focus on improving the cutting process itself to generate clean cutting marks as well as to implement a robust and automated evaluation of the cutting mark depth.

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