euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Fundamental study on embedded displacement sensor arrays for ultrasonic-assisted ultraprecision machining

E. Uhlmann[1,2], M. Polte[1,2], B. Bulla[3], O. Dambon[3], C. Dicke[3], T. Hocke[1], K. Thißen[1], M. Heper[1]

[1] Institute for Machine Tools and Factory Management IWF, Technische Universität Berlin, Berlin, Germany
[2] Fraunhofer Institute for Production Systems and Design Technology IPK, Berlin, Germany
[3] son-x GmbH, Aachen, Germany

m.heper@tu-berlin.de

Abstract
Ultraprecision machining is a key technology for manufacturing complex steel moulds with dimensional accuracies in sub-micrometer range for mass production of optical components using micro-injection moulding. According to the state of the art, during the machining of carbide-forming metals, such as steel alloys, used single crystal diamond tools suffer from excessive tool wear. In order to overcome this technological und economical limitation, ultrasonic-assisted ultraprecision machining is applied successfully in a broad range of industrial and scientifically applications. Based on the reduction of the contact time between the tool and the workpiece excessive chemical and related tribological tool wear can be avoided. Nevertheless, the cutting speed is strictly limited to deceed critical contact times. Therefore, the monitoring of the tool vibration characteristic and thus the process control is a major challenge and of current industrial and scientifically interest. To overcome these challenges a method for in-situ measurement of the ultrasonic vibration is currently being developed and first results are shown. Using the sophisticated ultrasonic system, developed by son-x GmbH, Aachen, Germany, up to a frequency $f_{US} \geq 100$ kHz the application of a dedicated eddy current sensor enabled the determination of the real path lines and the exact position of the cutting edge during the whole process with a displacement amplitude $A_D \leq 1$ µm. The results were subsequently verified by laser vibrometer measurements. As a result of the investigation, an elliptical path movement of the cutting edge in the longitude direction $A_{D,y} = \pm 1.0$ µm and in z-direction $A_{D,z} = \pm 0.34$ µm could be determined using a frequency $f_{US} \geq 100$ kHz. Based on this new measurement method, the vibration characteristic can be specifically varied and adapted to the application. In addition, a comprehensive scientific knowledge of the process can be gained and used to improve tool wear models.

Keywords: condition monitoring, diamond tool, ultrasonic frequency, ultra precision machining, displacement sensor

1. Introduction

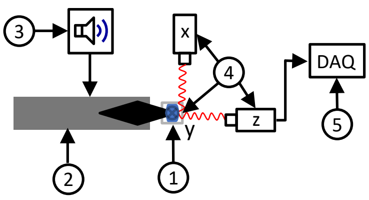
Ultrasonic-assisted ultraprecision machining enables the production of complex steel moulds for the mass production of optical components by micro-injection moulding. These steel moulds are typically machined with tools made of single crystal diamond, which are generally offered commercially as facet or radius tools with a rounded cutting edge radius of $r_\beta \leq 50$ nm and radius waviness of $W_R \geq 50$ nm [1, 2]. Within the ultrasonic-assisted turning process, the constant turning kinematics are superimposed on the highly dynamic component of ultrasonic vibration, which decisively influences the contact conditions for chip formation [3]. Due to the ultrasonic vibration the tool is in high-frequency cyclic contact with the rotating workpiece. This results in a crucial reduction of the chemical induced tool wear strongly related to tool contact times t_c. Dedicated increases in vibration amplitude A_{us} and ultrasonic frequency f_{us} result in higher kinetic energies e_{kin} and enable an ultraprecision machining of brittle-hard materials [4]. State of the art ultrasonic systems do not enable a characterisation and control of cutting edge's vibration with related limitations of undefined ultrasonic frequency f_{us} during the machining. Any correlation between the displacement amplitude A_D, the wear mechanisms, the surface roughness and process forces f_p are unknown.

To gain further knowledge and to enable a process-reliable and efficient ultrasonic-assisted ultraprecision machining shown equipment related limitations need to be overcome. Sophisticated sensor systems based on dedicated eddy current sensors are a promising approach for detection of ultrasonic frequencies of $f_{us} \geq 100$ kHz. Within this work the sensory basics for process monitoring and achieved results are shown.

2. Experimental Setup

2.1. Testing methods and devices

For detection of cutting edge's vibration during the machining a specific setup composed of a sonotrode as well as a sensor system was developed. The sonotrode enables the mechanical attachment of the oscillating quartz and the diamond tool, whereby ultrasonic frequencies of $f_{us} \geq 100$ kHz could be realised. Due to additional resonances affected by the sonotrode the occurring ultrasonic vibration can be further increased at the Tool-Center-Point (TCP), which enhances the efficiency and performance of the ultrasonic system. The schematic overview of the sensorised measurement setup is shown in figure 1.



1 diamond tool
2 transmission element
3 ultrasonic source
4 laser vibrometer
5 data acquisition device

Figure 1. Schematic overview of the sensorised measurement setup

To overcome state of the art challenges concerning the characterisation and control of cutting edge's vibration dedicated sensor prototyps were developed by the company EddyLab, Otterfing, Germany. Based on the size and specifications, these sensors can be integrated into the developed sensor system of the company son-x GmbH, Aachen, Germany, and enable the detection of vibrations with frequencies of $f_{us} \geq 100$ kHz. Within this investigation, three eddy current sensors were used to measure the vibration characteristics in x-, y- and z-direction. Each sensor was calibrated and includes an associated probe driver. Using the active oscillating circuit of the sensor results in an alternating magnetic field, which enables the detection and recording of the distance-proportional eddy current losses with a sufficient frequency f. This type of sensor leads to a reduced amplitude A of the oscillating circuit in order to avoid unnecessary interferences. The mechanism is decoupled of the oscillating circuit and is integrated into the signal processing. The signal is acquired, transformed and visuelly evaluated by an oscilloscope. Since sensory detection is an application of indirect process monitoring and the sensors do not detect the TCP during processing, a transformation of the signal is required. The ideal mounting location for the sensors as well as the parameters to transform the signals from the measuring location to the TCP was determined through extensive preliminary testing. For this purpose, the mathematically evaluation of indirect measurements with the eddy current sensors were compared to time-synchronous and direct measurements of a laser vibrometer type OFV-503 of the company Polytec, Waldbronn, Germany, at the TCP. Based on the gained transformation parameters, the trajectory of the cutting edge during the machining could be determined indirectly.

3. Experimental investigations

According to the developed specific ultrasonic setup, the investigations were carried out in a dedicated lab to avoid additional interferences, which could influence the experimental results. During sonotrode's vibration the cutting edge oscillated free without any contact to a workpiece. The three different eddy current sensors recorded the displacement amplitude A_D with an acquisition time t_a = 1 ms. The results are visualised in figure 2 as a 2D-histogram of the TCP.

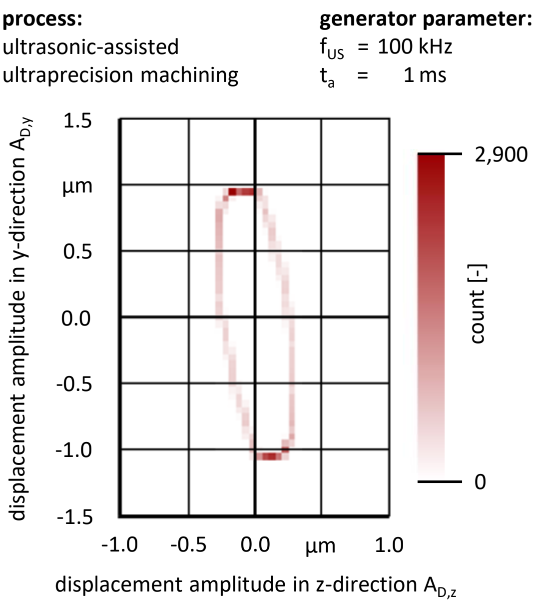


Figure 2. Displacement amplitude A_D in TCP-coordinates

The vibration of the piezo element shows an elliptical trajectory of the TCP with a maximum displacement amplitude in y-direction with a value of $A_{D,y3} = \pm 1.0$ µm. Furthermore, the corresponding time-synchronous displacement amplitudes could also be measured with $A_{D,x} = \pm 0.11$ µm and $A_{D,z} = \pm 0.34$ µm. As expected, the main oscillation could be proven in the y-direction with a maximum amplitude A and a trajectory as an inclined straight line for the TCP. For a more precise assessment of the trajectory line with regard to the main vibration direction, an elliptical motion was selected concerning the same data set. The visualisation of the time dependent trajectory is shown in figure 3.

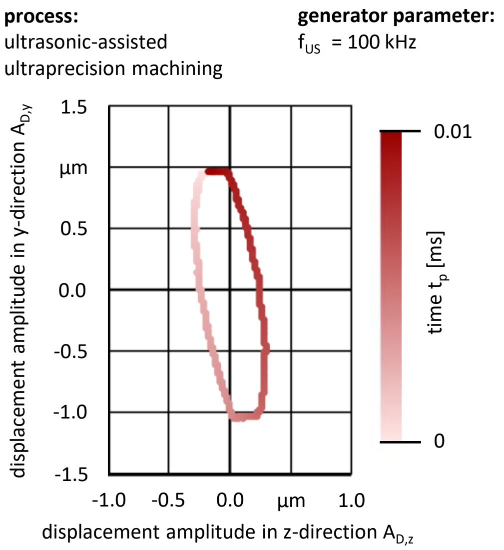


Figure 3. Time depended TCP-coordinates of the displacement amplitude $A_{D,y}$ and $A_{D,z}$

4. Conclusion and further investigations

The aim of the investigation was the identification of suitable sensory fundamentals for a reliable process monitoring in ultrasonic-assisted ultraprecision machining. The findings show that the developed sensor prototypes by the company EddyLab, Otterfing, Germany, are suitable for the detection of ultrasonic vibration characteristics, while using the sophisticated ultrasonic sonotrode developed by son-x GmbH, Aachen, Germany. As a result of the investigation, an elliptical trajectory of the cutting edge in main oscillation direction with a maximum amplitude of $A_{D,y} = \pm 1.0$ µm and in z-direction with an amplitude of $A_{D,z} = \pm 0.34$ µm could be proven using a frequency $f_{us} \geq 100$ kHz.

Further investigations will address the development of a dedicated control system to modified and control the vibration amplitudes A according to the application. Based on the shown investigations the scientific knowledge as well as the process efficiency could be significantly improved.

This work is supported by the funding program Zentrales Innovationsprogramm Mittelstand (ZIM) by the Federal Ministry for Economic Affairs and Energy (BMWI), Berlin, Germany.

References

[1] Uhlmann, E.: 5th Meeting of the Collaborative Working Group on Micro Production Engineering. CIRP Winter Meeting, Paris, 2014.

[2] Polte, J.: Kubisch-kristallines Bornitrid ohne Bindephase als Schneidstoff in der Ultrapräzisions-Zerspanung. Berichte aus dem Produktionstechnischen Zentrum Berlin., Hrsg.: Uhlmann, E. Stuttgart: Fraunhofer IRB, 2017

[3] Klocke, F.; Dambon, O.; Bulla B.: Ultraschallgestützte Diamant-zerspanung. Wt Werkstatttechnik online, Onlinearticle, 2008.

[4] Klocke, F.; König, W.: Fertigungsverfahren: Abtragen, Generieren und Lasermaterialverarbeitung, 9. Auflage. Berlin, Heidelberg: Springer, 2018.