euspen's 20th International Conference &
Exhibition, Geneva, CH, June 2020
www.euspen.eu

Ultrasonic assisted diamond turning of conventional and additive manufactured steel materials for optical components

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Abstract
During the machining of steel the excessive tool wear of diamond tools typically prevents their successful application. In recent years the application of ultrasonic assisted machining of steel dramatically reduced the tool wear by a superpositioned elliptical vibration motion of the diamond tool. Though the influence of different steel alloys and material properties was not yet taken into account. In this investigation different steel alloys generated with electroslag remelting (ESR) and selective laser melting (SLM) were machined with diamond tools at various cutting speeds. One hypothesis is, that the generation of a workpiece material by SLM offers positive effects to the ultrasonic assisted machining on otherwise identical steel compositions due to a different material structure. Another hypothesis states, that the machining of different steel alloys with different compositions and heat treatment conditions results in different surface properties and tool wear.

Surface roughness of the newly machined surfaces was measured and correlated with the cutting distance as an indicator for the tool wear. An optical surface (Sa < 10 nm) was archieved with nearly each steel type investigated whereas different cutting speeds (1.5 m/min, 3 m/min, 4.5 m/min) had little or no influence on the resulting surface roughness, although the surface revealed a different structure. This result was affiliated with a small change of effective cutting speed due to a high superpositioned ultrasonic induced speed and different kinematic movements of the tool. With new tools the machined surfaces exhibited a relatively low roughness, but after a specific cutting distance roughness raised rapidly. This critical cutting distance changed with the steel alloys.

Precision machining, Diamond cutting, Steel, Elliptical vibration, Tool wear, Surface quality

1. Introduction

Due to the technical advancements in the last years the demand of components with optical functions grew significantly. Examples are lenses for mobile phones as well as headlights and head-up-displays for the automotive industry. To produce large numbers of those components typically injection molding. A high durability of supplied molds is desirable, which can be archieved with steel as mold material. Unfortunately, a surface with certain optical properties can only be machined with diamond tools, although their use in the machining of steel results in catastrophic tool wear. [1, 2]

In the past years different ideas and methods to reduce the wear of diamond tools while machining steel were investigated [1, 2, 3]. Most promising is ultrasonic assisted machining, which in the meantime is successfully used in the industry. However, the exact mechanics and influences of the ultrasonic assisted machining are not yet known. The goal of this investigation is the correlation of surface integrity, tool wear and process parameters on steel materials manufactured with electroslag remelting (ESU) or selective laser remelting (SLM).

2. Elliptical vibration cutting

Elliptical vibration cutting is a further developed ultrasonic assisted machining process. Instead of vibrating on a linear path with the direction similar to to the cutting direction the tool vibrates on an elliptical shape. [2] The relative movement between the tool and the workpiece consists of two independent movements. The first one is the conventional cutting with the cutting speed v_c and the feed rate v_f, as shown on the left in Figure 1. The second movement is the vibration of the tool with the the amplitudes a and b of the ellipse and the ultrasonic vibration frequency f_{US}. The movements schematics are shown in Figure 1, right.

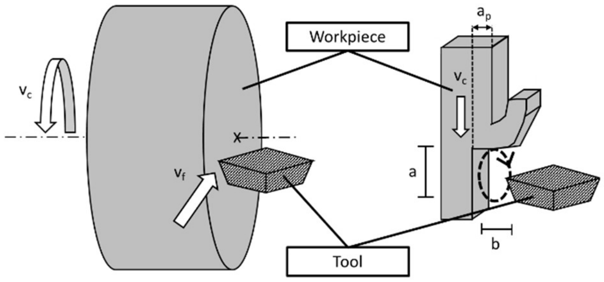

Figure 1. Schematic kinematics of conventional (left) and ultrasonic assisted (right) movements

The kinematical change of the process effectively reduces the percentage of the contact time between the tool and the workpiece, resulting in reduced friction, temperature and time for the carbon to diffuse into the steel.

3. Experimental setup

The experiments were performed on an ultra precision machine Moore Nanotech 500FG with single crystal diamond radius tools. The workpiece holder and the workpiece itself were mounted on the spindle with an aerostatic bearing, whereas the tool was mounted on top of the ultrasonic system on the rotary B-axis-table. The piezoelectric ultrasonic system enabled the tool to vibrate on a specific elliptical path with amplitudes of

$a = 3$ µm and $b = 0.3$ µm at a frequency of $f_{US} = 94$ kHz. The setup is despicted in Figure 2.

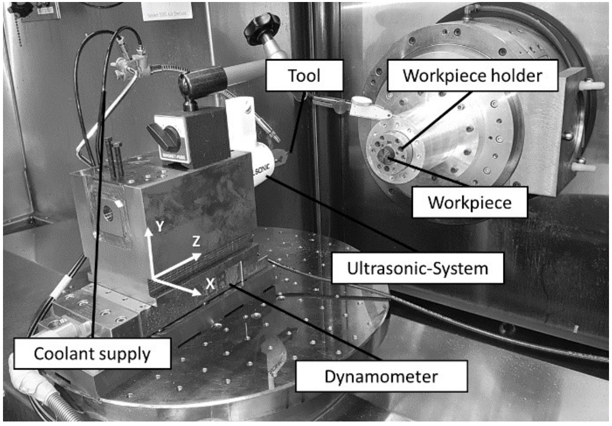

Figure 2. Experimental setup

The cylindric workpieces with a diameter of 20 mm were face turned with a single crystal diamond tool with a nose radius of $r_\varepsilon = 300$ nm. The conventional cutting speed was varied with $v_c = 1.5$ m/min, 3.0 m/min and 4.5 m/min, while cutting depth and feed were constant with $a_p = 5$ µm and $f = 5$ µm/rev for all experiments.

4. Analysis of the impact of cutting speed

Cutting speeds were varied during the experiments. The effect of the ultrasonic vibration is influenced by the ratio between the frequency f_{US} and the conventional cutting speed v_c. Therefore the local process kinematics and the tool wear are expected to alter in the experiments. A simulation of the kinematics shows, that the variation of the cutting speed within the examined parameters has little or no effect on the arithmetical mean height Sa, as well as the active contact time between the tool and the workpiece. However the maximum height Sz changes. This can be seen in Table 1.

Table 1 Simulated kinematic heights with variated cutting speed

Cutting speed	1.5 m/min	3.0 m/min	4.5 m/min
Active contact time	9.2 %	9.3 %	9.4 %
Sa	3.2 nm	2.8 nm	2.9 nm
Sz	11.0 nm	12.8 nm	15.9 nm

Table 2 Experimental results of the arithmetical mean height Sa while machining different steel alloys

Cutting speed	1.5 m/min	3.0 m/min	4.5 m/min
ESU-3	13.9 nm	8.5 nm	9.0 nm
ESU-7	3.7 nm	3.0 nm	2.4 nm
ESU-8	3.6 nm	2.9 nm	3.4 nm
ESU-9	3.3 nm	2.9 nm	3.1 nm

The experimental results as seen in Table 2 verify the simulations regarding the arithmetical mean height. Different steel materials were machined each with a new diamond tool. After changing the cutting speed v_c and comparing the resulting workpiece surfaces there is no significant difference visible in the values of Sa, other than a constant increase probably due to the normal tool wear.

5. Analysis of the impact of cutting length

The arithmetical mean height machined by each tool was correlated with the cutting length the tool had machined up to that point. Each tool was used with a different steel alloy as workpiece. The results are summarized in Figure 3.

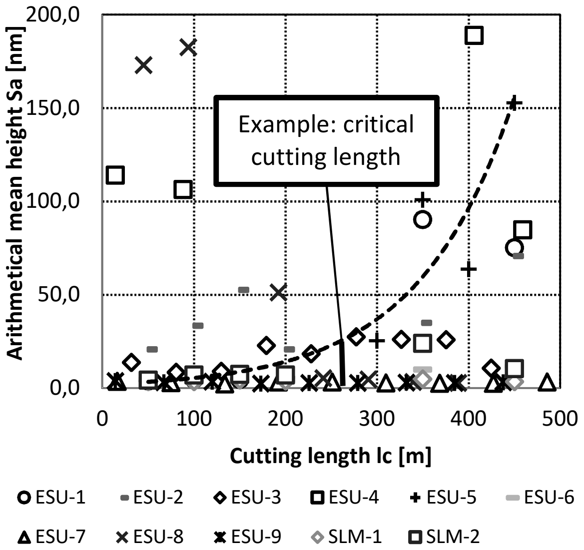

Figure 3. Measured arithmetical mean height correlated with the cutting length in machining different steel alloys

As expected, most investigated steel alloys could be machined to a relatively low surface roughness with a new tool, which increased only slightly with the cutting length. Additionally to the surface properties of the workpiece the cutting edge of the tool was measured periodically. The displayed trendline of ESU-5 shows the expected behaviour, where a critical surface roughness has to be specified to determine a critical cutting length. On the other investigated materials the cutting length was not high enough to reach a critical value. The alloy ESU-4 could not be machined to an optical surface, as the tool wear raised directly at a low cutting length. This was affiliated with the high carbon content in this specific steel, as it is ten times higher than in the other investigated alloys.

6. Conclusions

The conventional cutting speed and the manufacturing method of the steel have little or no influence on the average roughness in the machining of any investigated material. Althought the ultrasonic elliptical vibration reduces tool wear on certain steel alloys to a point, were diamond tools have a significantly higher lifetime, the average roughness increases with a progressive cutting length. In future works a hypothesis based on prior experiments should be investigated, which states that a critical cutting length exists, where the surface roughness rapidly increases due to different mechanics in the cutting zone. The value of the critical cutting length could be used to determine, whether a steel can be classified as diamond machinable with ultrasonic assistance.

Acknowledgements

The authors gratefully acknowledge the AiF Projekt GmbH for funding this work within the funding initiative “Zentrales Innovationsprogramm Mittelstand (ZIM)” as well as our industrial partner “Innolite” for enabling this project with their equipment.

References

[1] Simone D 2014 *Stahlzerspanung in der Ultrapräzisionstechnik* (Aachen: Abschlussbericht AiF 17359)

[2] Preuss W 2019 *A Guide to Diamond Machining* (Aachen: Shaker Verlag)

[3] Brinksmeier E and Gläbe R 2001 *CIRP Annals* vol 50 (Bremen: Elsevier) pp 385-388