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PROCESSES

Experimental investigation of ultrasonic vibration-assisted cryogenic minimum quantity lubrication for milling of Ti-6Al-4V and grinding of Zerodur

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Abstract

Increasing demands on component properties are leading to the development of high-performance materials for which conventional production methods are reaching their limits from an economic and ecological point of view. In recent years, two technologies have been developed that show great potential compared to conventional machining processes, particularly in machining high-performance materials such as the titanium alloy Ti-6Al-4V. Ultrasonic-assisted machining leads to reduced cutting forces and increased tool life. Cryogenic minimum quantity lubrication prevents the occurrence of high machining temperatures and allows higher material removal rates without a negative impact on tool life. This paper shows the influence of ultrasonic-assisted milling and grinding processes in combination with cryogenic minimum quantity lubrication on the machinability of the high-strength materials Ti-6Al-4V and Zerodur. The investigation addressed cutting forces, tool wear, and surface roughness. The superposition of the technologies resulted in longer tool life and lower tool wear for both milling and grinding. However, the surface roughness was consistently higher due to the ultrasonic superposition. Nevertheless, machining with ultrasonic vibration-assisted cryogenic minimum quantity lubrication has great potential for difficult-to-machine materials, especially due to the reduction in tool wear.

Keywords Vibration-assisted machining · Ultrasonic vibration · Cryogenic cooling · Minimum quantity lubrication · Ti-6Al-4V · Zerodur

1 Introduction

Increasing demands on components in terms of strength and quality are leading to a growth in use of high-strength construction materials. These include the glass–ceramic Zerodur and the titanium alloy Ti-6Al-4V, which are used in the aerospace industry. During manufacturing, machining is most commonly applied for the removal of excess material. Consequently, the efficiency of machining technologies plays a significant role in the economical processing of high-performance materials. Conventional machining of these materials results in high cutting forces, increased tool wear, and a low material removal rate [1]. These disadvantages can be counteracted by ultrasonic vibration-assisted machining (UVAM) [2–4] and cryogenic minimum quantity lubrication (CMQL) [5–8]. In vibration-assisted machining, a high-frequency oscillation – often in the ultrasonic (US) range – with an amplitude of a few micrometers is superimposed on the machining process. The advantages of vibration-assisted machining are reduced cutting forces, an increased tool life, and an improved component quality [1, 9–12]. CMQL has become the focus of many investigations in recent years, which have demonstrated that adding oil to carbon dioxide (CO_2) cooling has an additional lubricating effect. The consequences are a longer tool life and a higher material removal rate [5–8].

This paper presents a superposition of both UVAM and CMQL (UCMQL) in milling and grinding, based on recent publications investigating UVAM and CMQL separately.

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The research hypothesis was that an even greater increase in tool life and material removal rate can be expected due to the assumption that the lubricant can better reach the cutting edge through the periodically interrupted cutting process. The findings were compared to milling and grinding operations with a conventional flood cooling with emulsion (FC).

2 State of the art

Both UVAM and CMQL have been the focus of investigations with respect to their application for different kinds of machining processes. This chapter gives a brief overview of the relevant literature concentrating on milling and grinding.

Vibration superposition has already been applied to machining processes like turning, milling, drilling, and grinding. It can be generated by vibrating the tool or the workpiece. Most investigations thus far have focused on turning because it is easier to apply a vibration superposition on a stationary tool than on a rotating one (e.g., milling). Rinck et al. [1], however, studied the influence of longitudinal vibration-assisted milling on machining of Ti-6Al-4V. Peripheral milling and slot milling were investigated. For peripheral milling, the cutting forces decreased by 44.3%. The surface roughness of the side wall improved, and the bottom surface roughness in the slot-milled experiments decreased with a vibration amplitude of 4 µm but increased with a higher amplitude. The surface roughness of the side wall in the peripheral milling experiments also improved. The tool wear of the minor cutting edges was increased, whereas the tool wear of the primary cutting edges was reduced. Ni et al. [10] used UVAM for milling of Ti-6Al-4V. They concluded that the cutting force components could be reduced by up to 46% and surface roughness by up to 48% compared to conventional milling. Razafar et al. [13] investigated UVAM for AISI 1020 steel by vibrating the workpiece. A reduction in cutting forces and surface roughness in comparison with conventional machining was achieved in these investigations as well.

Reif et al. [14] investigated the influence of US-assisted grinding of the glass–ceramic Zerodur. They showed that for peripheral grinding the machining force and the workpiece roughness can be reduced by a superposition of a 10.8 µm US amplitude. Sun et al. [15] studied the effects of the orientation of the US superposition during grinding of the glass material Ultra Low Expansion Glass. When the direction of the vibration was in the feed direction, the machining forces applied were 47% lower and the surface roughness was 23% lower compared to conventional grinding. With a vibration direction perpendicular to the machined surface, the machining forces were reduced by 69%, but in this case the surface roughness increased by about 23%.

Various publications have dealt with CMQL machining of difficult-to-machine-materials. CMQL combines cryogenic cooling of the contact zone, usually by liquid CO_2 or liquid nitrogen, with a small amount of oil added to ensure lubrication. Gross et al. [5], for example, investigated the performance of different minimum quantity lubrication (MQL) oils for CMQL milling of Ti-6Al-4V and compared them to flood and cryogenic cooling. The tool wear as well as the mechanical tool load (i.e., the bending moment) were lower for CMQL milling regardless of the oil choice. Bagherzadeh et al. [6] compared different lubricating/cooling methods during slot milling of Ti-6Al-4V. They concluded that CMQL enhances the machinability of Ti-6Al-4V and lowers flank wear, cutting forces, and surface roughness compared to separate MQL or cryogenic machining, especially for higher cutting speeds. Wu et al. [7] investigated the application of CMQL in milling thin-walled Ti-6Al-4V components. They found that for CMQL machining cutting forces, surface roughness, and tool wear decreased compared to MQL and flood cooling, particularly at higher spindle speeds.

For grinding, investigations into CMQL are rather scarce and have focused on machining of metals rather than ceramics. Sanchez et al. [8] achieved a lower surface roughness and a reduction in tool wear when grinding tool steel with CO_2-based CMQL. Arafat et al. [16] demonstrated higher surface roughness on the workpiece compared to conventional machining, but lower forces during the machining process when grinding roller bearing steel with a combination of supercritical CO_2 and MQL.

The literature contains few initial studies for milling and no initial studies for grinding in which UVAM was combined with MQL or cryogenic cooling. Namlu et al. [17] studied a combination of UVAM and MQL for machining of the aluminum alloy EN AW-6061-T6. They found that the simultaneous application of both technologies led to the lowest surface roughness and tool marks on the workpiece in their test series. Ni et al. [18] investigated the tool wear mechanism and the corresponding machined surface characterization in the milling of Ti-6Al-4V. They studied UVAM in combination with MQL to improve the lubrication and cooling performance. Compared to conventional machining and UVAM, the combination of both technologies resulted in the lowest surface roughness. Madakar et al. [19] used a US-assisted MQL for grinding Ti-6Al-4V. The addition of the US assistance led to lower grinding forces but higher surface roughness compared to a conventional MQL. No studies are known to the authors in which UVAM and CMQL were combined for milling or grinding processes.

3 Objective, materials and methods

The objective of the investigations leading to this paper was an assessment of the combination of UVAM and CMQL for machining processes. The superposition of both techniques has the potential to further increase tool life and decrease machining forces. It had to be investigated whether a cryogenic cooling fluid has better contact with the cutting zone in such a process due to the contact interruption between the workpiece and the cutting edge. This was examined in a milling and a grinding process. The measurement values during machining were the cutting forces, the tool wear, and the surface roughness of the workpiece. These were used to evaluate the process efficiency. For comparison, a separate application of UVAM and CMQL and a conventional process were studied.

In the following section, the experimental setup is described. First, the equipment used for both the milling and grinding experiments is outlined. Afterwards, parameters and methods specific to the milling or the grinding process are described separately.

3.1 General experimental setup

The experiments were performed on a five-axis machining center, a DMG MORI ULTRASONIC 40 eVo linear (Bielefeld, Germany), which was able to perform UVAM in the longitudinal direction along the z-axis of the tool. For the CMQL experiments, the mixing unit described in Gross [20] was employed. The unit allowed a separate supply of liquid CO_2 and a minimum quantity lubrication oil into the machine and the transportation of the corresponding mixture to the cutting zone after mixing.

The tool wear analysis was carried out on a Keyence VHX-6000 (Osaka, Japan) digital microscope. The roughness values *Ra*, *Rt*, and *Rz* were used to evaluate the workpiece surface. They were measured in feed direction using a Mahr MarSurf LD 260 Y machine (Goettingen, Germany) for the milling experiments and using an optical Leica DCM 3D surface roughness system (Wetzlar, Germany) for the grinding tests. A quartz crystal 3-component dynamometer Kistler 9257 B (Winterthur, Switzerland) was applied to continuously record the cutting force components in three spatial directions during the machining process with a sampling rate of 1600 Hz for the milling tests and 1000 Hz for the grinding experiments. The force components were analyzed with the software DynoWare from Kistler (Winterthur, Switzerland). The cutting force was calculated as a vector addition of the three cutting force components.

During a previous investigation (see [21, 22]) using CMQL without the addition of US-vibrations, a suitable oil was chosen out of several experimental blends by Jokisch (Berlin, Germany), which differed both in base oil (mineral- or alcohol-based) and additives (with or without). Operating parameters of the aforementioned mixing unit, nozzle positioning, and nozzle orientation were also selected according to previous testing results and kept constant for all experiments.

The focus of this article are the experiments which utilized the chosen oil in a US-assisted CMQL while keeping the setup used in the previous experiments. The experimental setup for the milling process is displayed in Fig. 1. It is identical for the grinding process. Each milling and grinding experiment was conducted three times with a new milling tool or a dressed grinding tool.

3.2 Milling

For milling, the titanium alloy Ti-6Al-4V (annealed) was employed as workpiece material. Experiments were conducted using two different tools for which suitable machining parameters were chosen in previous tests. Both the tool and the machining parameter specifications are listed in Table 1.

The nozzle was positioned in front of the tool in the feed direction and kept at a constant angle (see Fig. 2). The experiments were conducted by using a milling process in

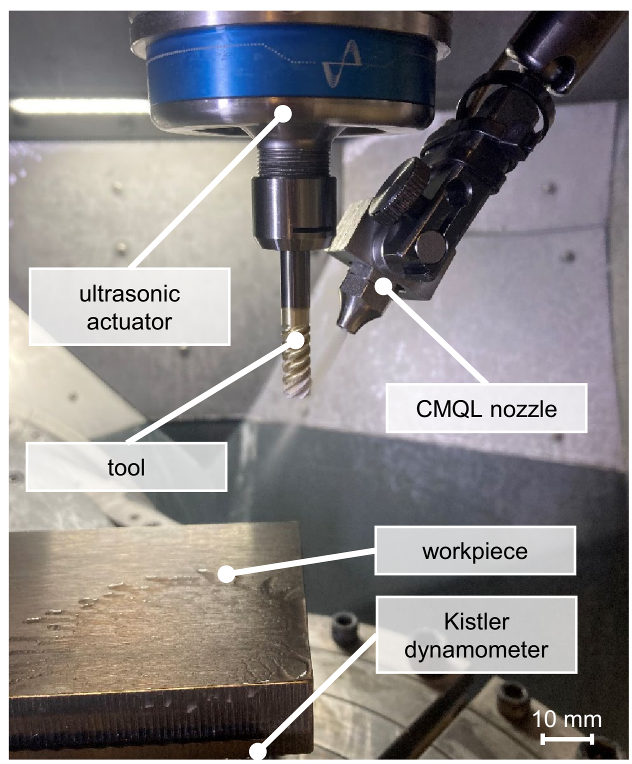

Fig. 1 Experimental setup

Table 1 Tool and machining parameters (milling)

Tool and machining parameters	Unit	Value	
		Tool 1	Tool 2
Product development state		Serial	Prototype
Tool diameter d	mm	10	8
Number of teeth z	–	4	5
Material and coating	–	Solid carbide, TiAlN coating	Solid carbide, TiAl-based coating
Feed per tooth f_z	mm	0.05	0.04
Cutting depth a_p	mm	5	
Cutting width a_e	mm	0.5	
Cutting speed v_c	m/min	240	125
Feed rate v_f	mm/min	1528	995
CO_2 mass flow m_{CO2}	kg/h	3.0–3.5	
Oil volume flow V_{oil}	ml/min	0.8	
CMQL oil	–	Mineral-based oil without additives	Alcohol-based oil with additives
Reference tests	–	Flood cooling with emulsion (Oemeta NOVAMET 760 at 3.3%)	
US amplitude A (resonance frequency: approx. 21 kHz)	µm	3	2–3

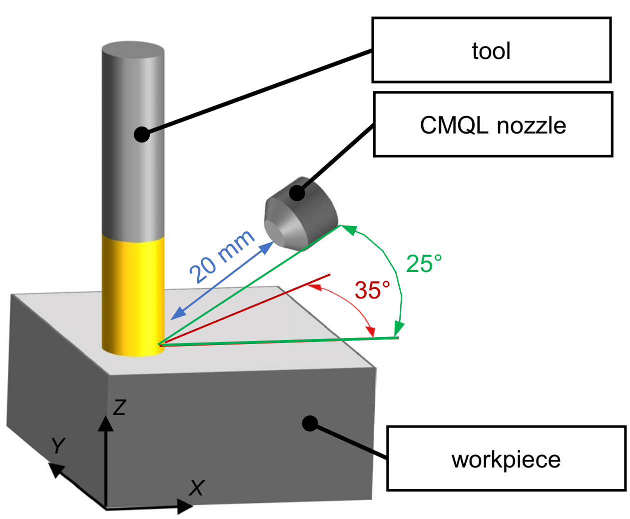

Fig. 2 CMQL nozzle positioning (milling)

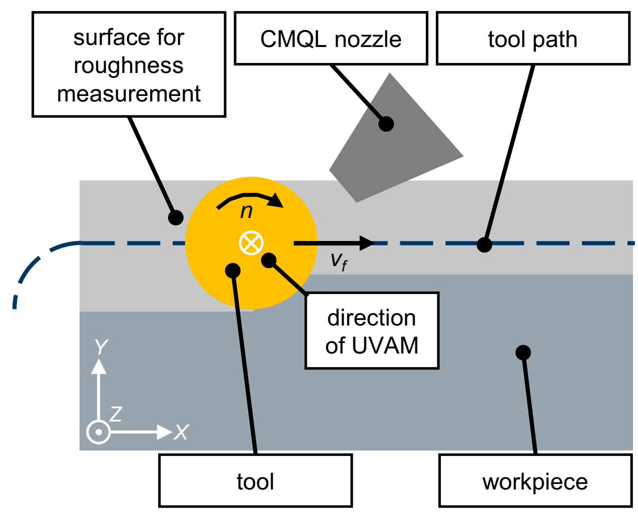

Fig. 3 Milling process schematic

climb milling. Entry into the workpiece was performed by rolling into the cut, which leads to a reduction in vibration and tool wear when milling difficult-to-machine materials [23]. Afterwards, the workpiece material was removed under constant contact conditions. A schematic of the milling process is shown in Fig. 3.

Tool wear was analyzed in terms of the width of the wear marks on the main cutting edge. Tool wear as well as workpiece surface roughness analyses were conducted after reaching predefined machining paths (see Table 2). The arithmetic mean and standard deviation were calculated out of the analysis of the three tools.

The cutting force was measured continuously throughout the machining process. The data then was filtered with a low pass Butterworth filter with an edge frequency of 50 Hz and a filter order of 2. For displaying the progression, the mean cutting force was calculated out of the data from one line of milling at the measurement points used for tool wear and surface roughness (see Table 2).

Regardless of the tool type, the maximum flank wear land width VB_{max} was selected as the tool life criterion. If VB_{max} exceeded a value of 200 µm on at least two cutting edges of the tool, a test series was completed. The test series was also terminated if a cutting edge fractured or a milling distance of 500 m was achieved without significant wear phenomena.

Table 2 Measurement intervals (milling)

Process quality criterion	Measurement interval (machining path)
Tool wear	1 m, 5 m, 10 m, 25 m, … (each 25 m until 200 m, then each 50 m until 500 m)
Surface roughness R_z, R_a, R_t	1 m, 5 m, 10 m, 25 m, … (each 25 m until 200 m, then each 50 m until 500 m)
Cutting force	Continuously

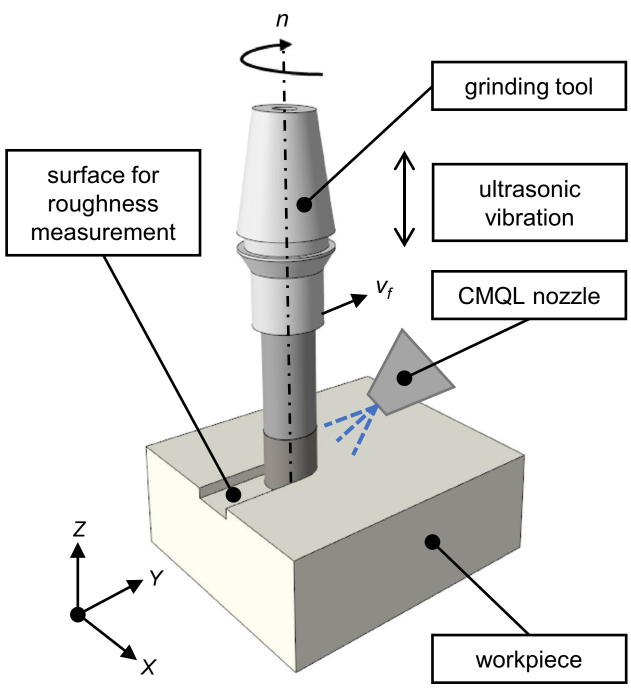

Fig. 4 Grinding process schematic

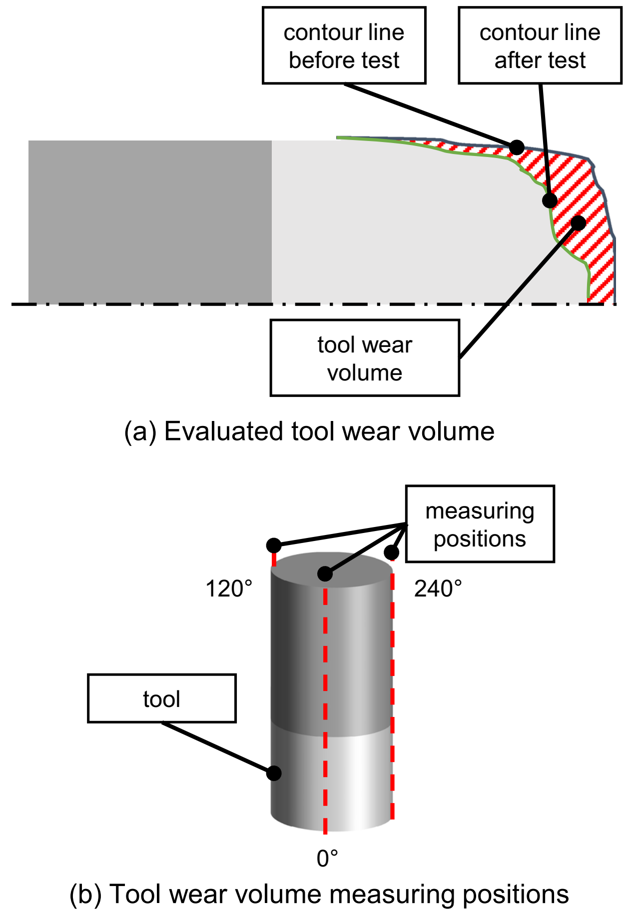

Fig. 5 Grinding tool wear analysis

3.3 Grinding

The tests were performed as slot grinding with a diamond mounted point as grinding tool. Regarding the workpiece material, the glass–ceramic material Zerodur was used. The cutting width corresponded to the outer diameter of the grinding tool of 9.1 mm. The cutting depth was 0.2 mm. The surface roughness of the workpiece was measured at the bottom surface of the ground slot. A schematic of the grinding program can be seen in Fig. 4.

Tool wear was determined using a Keyence VHX-6000 digital microscope. For this purpose, the contour of the lateral surface was recorded at three positions distributed equidistantly around the circumference before each test and after 528 slots with a length of 0.12 m each, which equals 63.36 m machining path. The difference between those contours equals the wear volume at that measuring position (see Fig. 5). This analysis ensures both length reduction and step formation on the tool are taken into account. The mean value of the three measuring positions resulted in the wear volume of the grinding tool.

To ensure comparable tool conditions, the grinding tool was dressed before each test and got a run-in of 1.32 m machining distance. For the evaluation of the cutting forces, first the mean value was calculated out of the data from one line of grinding. In order to compare the process forces for the different grinding strategies, the mean cutting force value over the course of the investigated machining path of 63.36 m was then calculated.

The machining parameters for tool dressing, run-in and the different test types are shown in Table 3. For the roughness tests, surface roughness was measured in the stable

Table 3 Machining parameters for dressing, run-in, roughness test and wear test (grinding)

Parameter	Unit	1) Dressing	2) Run-in	3a) Roughness testing	3b) Wear testing
Cutting width a_e	mm	9.1	9.1	9.1	9.1
Cutting depth a_p	mm	1	0.2	0.2	0.2
Feed / Revolution f_{rev}	mm	0.2	0.05	0.05	0.10
Cutting speed v_c	m/min	132.5	265	265	265
US Amplitude A (resonance frequency: approx. 22.5 kHz)	µm	0	0	0; 3	0; 3

process window (after 10 m). For the wear tests, a higher feed-per-revolution-ratio and a longer machining path were chosen to accelerate the wear behavior.

According to the previous studies, a CO_2 mass flow of 10 kg/h, an MQL volume flow of 0.8 ml/min and a nozzle position of 0° in feed direction led to a stable process, especially for longer grinding durations. With lower CO_2 and MQL flow rates, the grinding tool was thermally overloaded.

The wear study of the previous CMQL tests without US and with different CMQL fluid types had a substantial influence on the process results (see [22]). The alcohol-based media lead to less tool wear than the mineral-based media. Therefore, all further tests were conducted with alcohol-based CMQL fluid.

4 Results and discussion

In the following sections, the results are first presented and thereafter discussed regarding possible cause-and-effect relations due to the different machining processes.

4.1 Milling

4.1.1 Tool life and tool wear

The average tool life of the test series with conventional flood cooling and CMQL with the associated standard deviations are shown in Fig. 6. The change in cooling lubrication strategy already had a positive influence on the achievable tool life with the given test setup for both tools. For tool 1, compared to FC, a tool life extension from an average of 58.8–137.8 m was achieved with CMQL. With UCMQL, a further extension to 185.0 m was realized. For this tool, VB_{max} exceeded 200 µm on at least two cutting edges at the end of each experiment. In relation to FC, tool life extensions of 134% with CMQL and 215% with UCMQL machining were therefore possible. Furthermore, the deviation between the tool lives achieved in the three test runs was reduced using US assistance. The standard deviation for the UCMQL was 25% lower than for FC and 62% lower than for the regular CMQL. For tool 2, compared to FC, a tool life

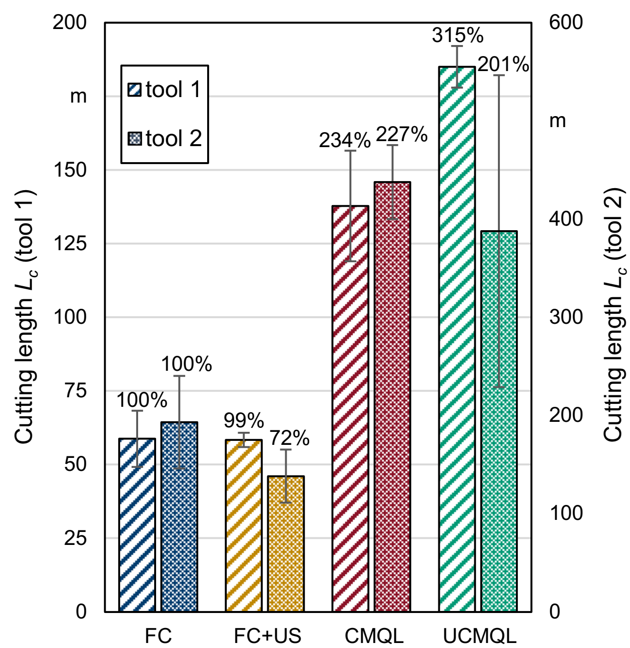

Fig. 6 Tool life with different machining technologies

extension from an average of 193.2–437.6 m was achieved with CMQL. As can be seen from the large standard deviation, no statement can be made as to whether the process combination contributed to a further increase in tool life due to the additional US assistance. However, with the UCMQL, a machining distance of 500 m was achieved in two test runs, which was the highest achieved milling path in the whole study. At this point, the VB_{max} only reached values of 58.8 µm and 85.4 µm, respectively.

For tool 1, the initial tool wear as well as the wear progression were lower in tests with UCMQL compared to FC. Considerable differences in the maximum wear value or in the deviation of the measured wear across the four cutting edges of a tool, which were observed for FC, were not detectable with the UCMQL. Figure 7 displays examples of various tool wear phenomena that were observed with the two machining strategies. With FC, flank wear, adhesion of workpiece material, and chipping occurred. These wear phenomena were mainly present at the end of the engaged

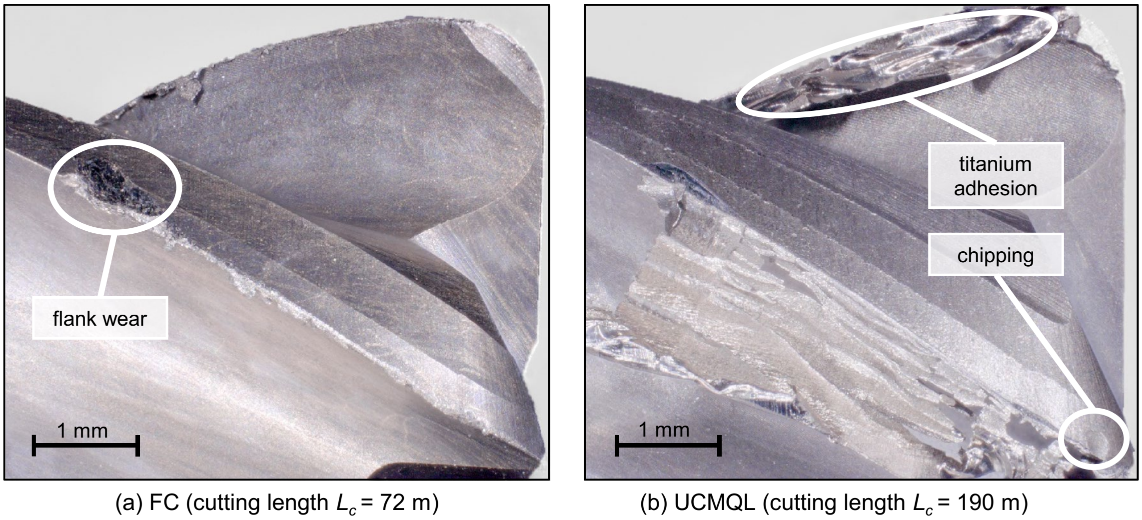

Fig. 7 Tool wear phenomena using FC and UCMQL (tool 1)

cutting edge, but they also occurred partially at the cutting corner. In general, UCMQL initially only led to flank wear, especially at the end of the engagement area. At the end of the tool life, titanium adhesions and built-up edges were more prevalent. In addition, small chipping sometimes occurred on the cutting edge.

Similar observations were obtained for tool 2. Over the course of the machining process, flank wear and titanium adhesions formed, which were more pronounced for UCMQL than for FC. In contrast, chipping occurred in FC but not with a UCMQL.

4.1.2 Cutting forces

The cutting force progression for tool 1 is shown in Fig. 8 for both series of tests with FC and UCMQL. After 5 m milling path, when the tool wear was still low and therefore comparable in all tests, the cutting force was between 63 and 73 N for FC. In comparison, forces between 58 and 63 N were documented for UCMQL. In relation to FC, a reduction of the cutting force of up to 18% was possible.

When comparing the cutting forces for tool 2, no differences could be identified between the experiments of the different machining variations. The mean cutting forces were almost identical at the beginning (FC: 79.7 N; UCMQL: 80 N), and increased with incipient tool wear.

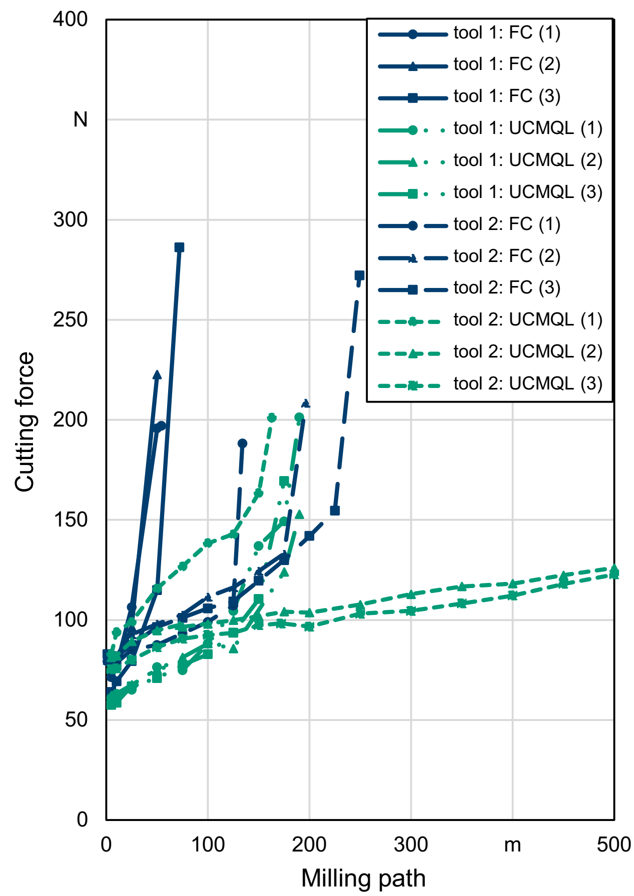

Fig. 8 Cutting forces using FC and UCMQL

4.1.3 Surface roughness

Since the roughness values did not change over the milling path, the values were averaged over the complete tool life. Due to the US assistance, higher surface roughness values were obtained in all experiments (FC + US, UCMQL) compared to the respective tests without US assistance (FC, CMQL). Compared to FC, the averaged Rz value for tool 1 for the UCMQL increased by 59% from 2.13 to 3.39 µm

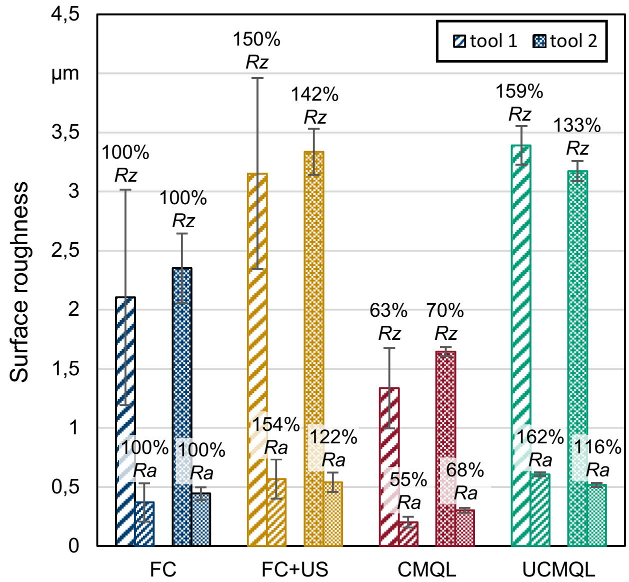

Fig. 9 Surface roughness for different machining technologies and different cooling and lubrication strategies

and the averaged *Ra* value by 62% from 0.37 to 0.60 µm. For tool 2, the average *Rz* value increased by 33% from 2.4 to 3.2 µm and the *Ra* value by 16% from 0.44 to 0.51 µm (see Fig. 9). However, the measured values for the UCMQL were significantly less scattered across the test series than for FC for both tools.

4.1.4 Discussion

The experiments carried out confirm observations published in literature about the positive impact of CMQL on the machinability of Ti-6Al-4V [5–7] and the differences in wear behavior depending on tool and oil combination [24]. While a pure CO_2-cooling can be insufficient because of the lack of lubrication, CMQL improves the results, especially with oils whose properties ensure good transportability into the cutting zone [5]. In the case of UCMQL, the high-frequency vibration aids the oils transport into the cutting zone and helps to improve the results further.

Overall, with tool 1, UCMQL increased tool life by 215% compared to FC. In addition, the cutting forces with comparable tool wear were around 10% lower with the technology combination. The measured surface roughness was slightly higher with US assistance than without it. In the case of tool 2, an average tool life extension of 127% was achieved with CMQL compared to FC. Due to the large scatter of the tool life of the UCMQL tests and because two tests were stopped at 500 m machining path, no statement can be made about the tool life extension. However, the highest tool life was achieved with the technology combination using this tool. In addition, a reduction in wear phenomena was noted with UCMQL machining.

In general, a higher surface roughness was always measured with US assistance than without, regardless of the machining strategy; this is in accordance with the findings of Rinck et al. [1]. With the US assistance along the tool axis, a high-frequency contact interruption of the secondary cutting edges and therefore a high-frequency hammering of the tool onto the workpiece surface occurred in the investigated side milling process. This effect causes a higher surface roughness and increased tool wear, especially at the end of the engagement area and at the cutting corner, as shown with the previous series of tests.

For the investigated experiments with constant contact conditions between the milling tool and the workpiece, US assistance enables a more targeted supply of the cooling lubricant to the actual cutting zone due to the high-frequency vibration. However, because of the high cutting speeds and the low US amplitudes, no complete cutting edge detachment of the main cutting edges took place. The low amplitudes are the reason for the less pronounced cutting force reduction compared to the literature. In the case of a longitudinal excitation of the tool, the critical cutting speed, below which a cutting interruption takes place, can be calculated according to

$$v_{crit} = 2\pi \cdot f_{US} \cdot A_l \cdot \tan(\beta) \quad (1)$$

with f_{US} being the frequency of the tool, A_l the amplitude of the vibration and β the helix angle of the tool [1]. With a frequency f_{US} of approximately 22 kHz, an amplitude of 3 µm, and a helix angle of approximately 40°, the critical cutting speed is calculated to be 20.88 m/min. This value is far below the cutting speeds of 125 m/min and 240 m/min tested in the process. Consequently, a complete cut interruption was not possible in any of the tests. However, the secondary cutting edges periodically detached from the workpiece surface, which allowed the CMQL to be introduced into this area with a potential transfer of the medium to the main cutting edges via the flutes. These improved lubrication conditions are the reason for the reduced tool wear and therefore longer tool life with UCMQL.

4.2 Grinding

4.2.1 Tool life and tool wear

Figure 10 displays the tool wear volume after 63.36 m machining path for different cooling strategies with a US superposition at an amplitude of 3 µm. With FC, US-assisted machining results in a wear increase of 29%. With CMQL the wear was reduced by 24% through the US assistance and reached an even lower level than with FC. The standard deviations with CMQL are higher compared to FC, which may be due to more process instabilities of the CMQL system. Nevertheless, over all test runs, the two lowest wear values have been achieved with UCMQL.

Figure 11 displays examples of the observed signs of tool wear which include attritious wear, grain fractures and bond wear. These phenomena were present to varying degrees regardless of machining strategy.

4.2.2 Grinding forces

The mean grinding forces for the different machining technologies in the 63.63 m machining path are shown in Fig. 12. Grinding with FC led to an average grinding force of 87 N, whereas US superposition reduced this to 65 N. With CMQL, US machining reduced the mean grinding forces from 200 to 138 N. Nevertheless, machining with cryogenic cooling led to higher force levels. Without US assistance, the values increased by 129%, while with US assistance the values increased by 58% compared to FC. The lowest force levels were achieved with FC and US superposition.

4.2.3 Surface roughness

The averaged surface roughness values *Rz* and *Ra* of the workpiece after 10 m machining path are displayed in Fig. 13. Machining with FC led to a higher roughness than grinding with CMQL. Compared to FC, the averaged *Rz* value decreased by 36% with CMQL. The average *Ra* value showed a similar behavior and is 37% lower with CMQL than with FC. With US superposition this effect is lower, and *Rz* and *Ra* decreased by 27% compared to FC.

Generally, with US superposition the surface roughness increases. With FC the average *Ra* value increased with US machining by 6%, and the *Rz* value by 3%. Machining with UCMQL leads to 15% higher surface roughness (*Rz* and *Ra*) compared to CMQL. The lowest roughness values of all cooling strategies can be reached with CMQL.

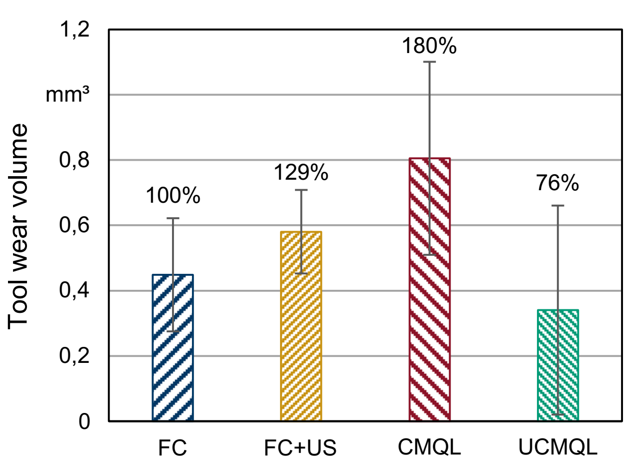

Fig. 10 Tool wear volume after 63.36 m machining path with FC and CMQL with and without US superposition

4.2.4 Discussion

The wear tests with US superposition showed different results depending on the cooling strategy. With US-assisted FC, the tool wear increased compared to FC, whereas with UCMQL it decreased compared to CMQL. Machining with UCMQL reached the lowest wear values of all test series. The tool wear with CMQL was much more sensitive than with FC when applying US superposition. For both cooling techniques, grinding forces could be reduced with US superposition, which is in accordance with Reif et al. [14]. With FC, the US assistance reduced the cutting force by 26%, whereas with CMQL it decreased by 31%.

Generally, grinding with CMQL leads to over two times higher grinding forces but lower surface roughness values than with FC. The reason for this could be that with CMQL attritious and bond wear was higher compared to FC because of the different lubricating conditions. If the cutting edges become rounder, the surface roughness decreases. The reduced sharpness of the rounded grains also causes higher grinding forces. The grinding dust produced is removed more slowly by CMQL than by FC. This also affects the engagement conditions.

US superposition led to higher roughness values in FC and CMQL machining. The increase in surface roughness is caused by a kind of hammering effect, which was discussed for milling in Sect. 4.1.4. In this case, the grinding tool is struck on the surface of the workpiece in ultrasonic mode; this is reflected in the surface structure and increases the roughness values.

The current results are not sufficient to describe the phenomena. Further research is needed, especially regarding the behavior of workpiece and tool materials under the thermal conditions when using CMQL.

5 Conclusion and outlook

This paper presents a superposition of CMQL and US assistance as a new technique for milling Ti-6Al-4V and grinding Zerodur. The series of tests conducted indicated great potential for UCMQL machining of these difficult-to-machine materials. The superposition of the technologies had a positive influence on the different target variables in both machining processes.

While US superposition led to a faster tool failure in the investigated milling process with FC, tool life could be increased by up to 215% compared to conventional FC with UCMQL. In an industrial environment, the focus is often

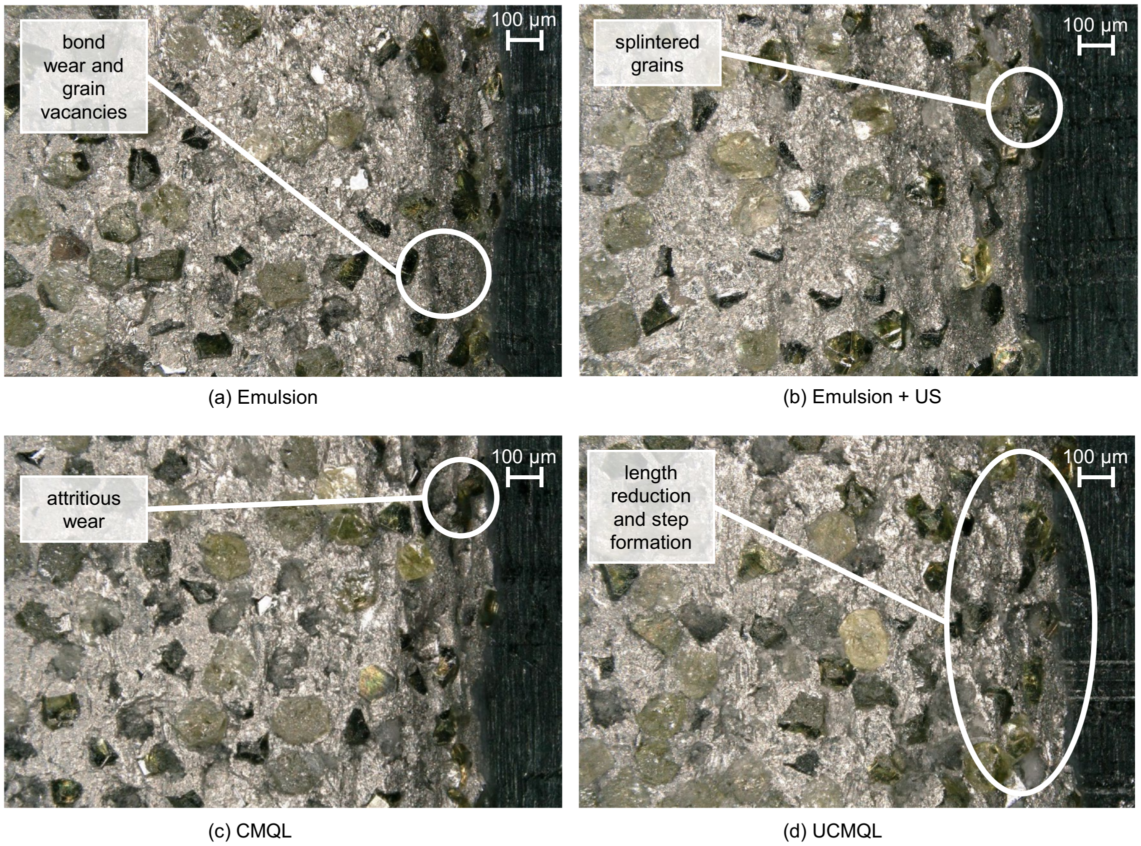

Fig. 11 Tool wear phenomena after 63.36 m machining path with FC and CMQL with and without US superposition

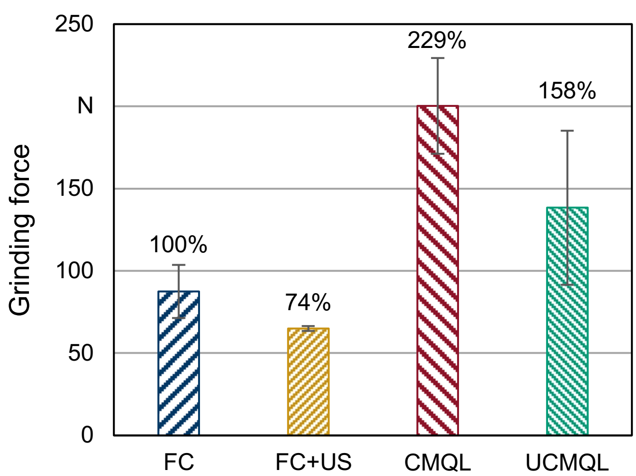

Fig. 12 Grinding force after 63.36 m machining path with FC and CMQL with and without US superposition

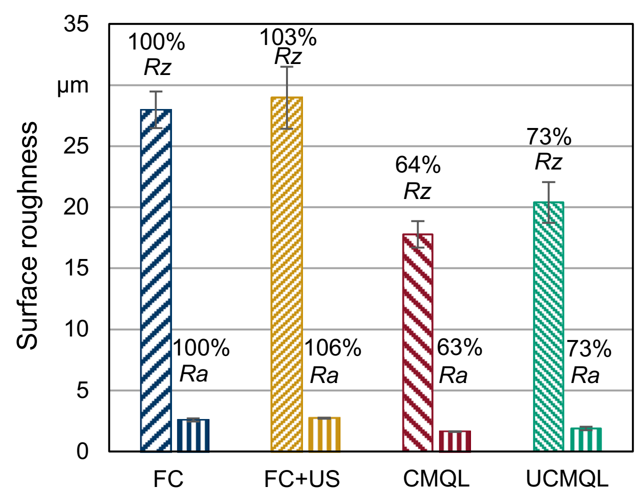

Fig. 13 Surface roughness after 10 m machining path using FC and CMQL with and without US superposition

less on tool life and more on the productivity of the manufacturing processes. Tool life extension with the selected parameter combination opens up the option of increasing the cutting parameters instead; this increase might reduce the previously mentioned tool life extension, but it improves the material removal rate of the process.

Regarding the grinding of Zerodur, investigations into using alternative cooling strategies have been rare. While currently the grinding process of Zerodur with CMQL has not yet achieved comparable or better results in terms of force and wear than with FC, the conducted experiments were able to demonstrate the potential of CMQL for grinding brittle-hard materials. With UCMQL, the tool wear could be reduced to a level comparable to FC or even lower. The positive effects of the combination of CMQL and US assistance are starting points for further developments of the proposed machining method.

The investigations presented in this paper considered only simple line geometries. In future studies, the machined geometries can be expanded to more complex and closer to industrial workpieces. Based on the investigations conducted, the following conclusions can be drawn:

- UCMQL increases the tool life of milling and grinding tools compared to FC, US-assisted FC, and regular CMQL.
- Vibration-assisted milling and grinding lead to a higher surface roughness.

UCMQL is a new approach for combining advanced machining techniques. The first investigations indicated great potential for machining high-performance materials, but further studies are necessary for industrial uses.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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