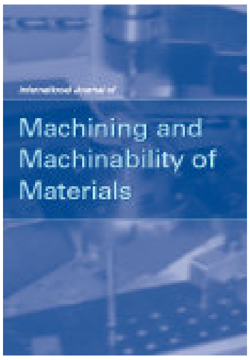

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Abstract: Ti-6Al-4V has extensive applications in high-tech industries like aviation, defence and biomedical. However, the cutting of Ti-6Al-4V is challenging due to its poor machinability. Recently, ultrasonic cavitation-assisted machining (UCAM) has emerged as a cutting process that utilises high-frequency and low-amplitude vibrations to induce the formation of cavitation bubbles, thereby improving cutting performance. Despite the benefits of UCAM, there is lack of research investigating its application in Ti-6Al-4V. This study aims to investigate the efficacy of UCAM in improving the cutting performance of Ti-6Al-4V and compare it with conventional methods. Specifically, the study compares UCAM with conventional machining (CM) under conventional cutting fluid. The study reveals that UCAM can reduce cutting forces by up to 49.5% and surface roughness by up to 51.9%. Additionally, UCAM yields more uniform, homogeneous surfaces with reduced surface damage compared to CM. These results demonstrate the potential of UCAM for enhancing cutting performance of Ti-6Al-4V.

Keywords: ultrasonic cavitation-assisted machining; UCAM; Ti-6Al-4V; cutting force; surface roughness; surface topography.

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1 Introduction

Ti-6Al-4V is a widely utilised titanium alloy renowned for its exceptional strength-to-weight ratio, corrosion resistance and biocompatibility (Yang and Liu, 1999). The demand for this material has progressively increased in high-tech sectors such as defence, medical and aviation industries (Namlu and Sadigh, 2022; Namlu et al., 2022). Machining, a frequently employed manufacturing operation for aerospace component production, encounters challenges when dealing with Ti-6Al-4V due to its significantly low thermal conductivity. Consequently, high cutting zone temperatures negatively impact tool lifespan, while the material's high strength retention at elevated temperatures poses difficulties in chip removal (Namlu et al., 2021). However, the extremely low thermal conductivity of Ti-6Al-4V causes high cutting zone temperatures, negatively affecting tool life, and maintaining its high strength at high temperatures makes it difficult to remove chips (Ezugwu and Wang, 1997). For such reasons, Ti-6Al-4V is often called difficult-to-cut material (Ezugwu, 2005; Namlu et al., 2021; Dawood et al., 2015; Airao and Nirala, 2022).

Ultrasonic vibration-assisted machining (UVAM) is a recent technique that enhances the machining process by incorporating high-frequency and low-amplitude vibrations (Airao et al., 2022a). The intermittent contact between the cutting tool and workpiece in UVAM improves cutting performance and operational efficiency compared to conventional machining (CM) (Nath and Rahman, 2008). UVAM is a proven method for facilitating the machining performance of difficult-to-cut materials such as Ti-6Al-4V (Namlu et al., 2021), Ni-Ti shape memory alloys (Namlu et al., 2023a) and Inconel materials (Airao et al., 2022b). Also, ultrasonic vibrations have been successfully implemented in various cutting processes. Namlu et al. (2021) investigated the application of UVAM with minimum quantity lubrication (MQL) on Ti-6Al-4V, resulting in an average reduction of cutting forces by 20% during rough cutting. Moreover, surface roughness values decreased by approximately 29% in finish cutting and 27% in rough cutting (Namlu et al., 2021). Tao et al. (2016) studied UVAM of

Ti-6Al-4V and found that the influence of UVAM was negligible at lower feed rates, but as feed rates increased, cutting forces initially increased and then declined. Another investigation on UVAM of Ti-6Al-4V by Ni et al. (2018) revealed a reduction of up to 37.24% and 46.3% in the cutting force components FX and FY, respectively. Niu et al. (2019) studied longitudinal-torsional ultrasonic assisted milling of Ti-6Al-4V and reported a decrease of 24.8% in FX and 29.9% in FY compared to CM. Namlu et al. (2023b) studied the effect of UVAM on chatter stability limit of Ti-6Al-4V milling and their result showed that UVAM increased the axial depth of cut limit by %40 compared to conventional milling. Airao et al. (2022a) showed that, surface roughness and power consumption are decreased when UVAM applied in turning of Ti-6Al-4V compared to CM.

As evident from the existing literature, UVAM has demonstrated remarkable achievements in various studies concerning Ti-6Al-4V material. Nevertheless, it is essential to acknowledge that UVAM comprises sub-categories that can further augment its effectiveness. Notably, ultrasonic cavitation-assisted machining (UCAM) emerges as a recent variation within the realm of UVAM, employing ultrasonic vibrations to induce cavitation and thereby elevating the overall cutting efficiency. Several studies have explored the application of UCAM on different materials. Goto et al. (2015) investigated UCAM on stainless steel and reported reductions in cutting forces and burr area ratio when compared to conventional methods. UCAM achieved a burr area ratio below 5% (Goto et al., 2015). Jun et al. (2014) conducted research on ultrasonic cavitation-assisted micro-EDM of deep holes and demonstrated that ultrasonic vibrations effectively improved micro-EDM performance in terms of hole quality, surface topography, material removal rate and maximum machining depth. Liang et al. (2019) examined ultrasonic cavitation micro-drilling of 304 stainless steel and observed decreased thrust forces, production of short chips, extended tool life, and improved micro-hole quality compared to conventional drilling processes. These studies provide evidence supporting the enhancement of cutting performance through UCAM in various materials, warranting further exploration of its potential benefits.

As observed in the existing literature, UCAM has found applications in various machining processes, such as micro-EDM and micro-drilling, and has been employed with materials like stainless steel, yielding successful outcomes in diverse process outputs. However, it is noteworthy that no UCAM study has been conducted on Ti-6Al-4V material, which holds significant importance in numerous critical sectors. Additionally, UCAM has yet to be explored in the context of slot milling operations. Furthermore, the investigation of whether applying ultrasonic vibrations in different directions yields varying effects on UCAM remains unexplored. This study aims to address the following research gaps:

1 Implementing UCAM on Ti-6Al-4V material in slot milling operations.

2 Analysing the impact of different vibration directions (axial, feed and axial-feed) on UCAM in terms of process outputs.

To accomplish these objectives, a comparative study is conducted between the UCAM process and CM techniques, along with the use of conventional cutting fluid (CCF). Different vibration directions are applied during the slot milling operation, and performance parameters such as cutting force, surface roughness, and surface topography are chosen for comparison and evaluation. By investigating these aspects, the research seeks to enhance the understanding of UCAM's potential benefits in slot milling operations and its responsiveness to diverse vibration directions.

2 UCAM mechanism

During machining operations, the cutting tool plays a crucial role in the process of chip removal from the workpiece's surface. However, the high temperature generated due to friction in the cutting zone, where the cutting tool and chip come into contact, often has a detrimental impact on cutting performance. Cutting fluids are employed to mitigate or eliminate this issue. Nevertheless, due to the complete contact between the cutting tool and workpiece during cutting, achieving adequate penetration into the cutting zone proves challenging. The application of ultrasonic vibrations to either the workpiece or the cutting tool introduces intermittent gaps between the tool and chip, thereby enhancing the penetration capability. Moreover, the application of high-frequency vibrations induces a cavitation effect in the cutting fluid. Ultrasonic cavitation alters the contact state and movement mechanism between the cutting tool and workpiece. Through its cavitation effect, the ultrasonic system generates microbubbles and pulverisation effects, thereby modifying the friction characteristics during cutting and facilitating chip removal.

In order to fully understand the enhanced efficiency of UCAM, it is crucial to gain insight into its cutting mechanism. UCAM utilises ultrasonic vibrations that can operate in all three axes of motion: X, Y and Z. This study specifically focuses on the application of axial vibrations (in the Z-direction), feed vibrations (in the X-direction), and combined or elliptical vibrations (in the XZ-direction) to the cutting tool. In contrast, CM generally involves unidirectional movement of the tool tip along the Z-axis during a given operation:

$$z(t) = 0 \tag{1}$$

The cutting tool tip movement of conventional milling can be seen in Figure 1. However, when the axial ultrasonic vibrations are applied, it turns out to be:

$$z(t) = a_l \sin\left(2\pi f_l t\right) \tag{2}$$

where a_l is the amplitude, f_l is the ultrasonic vibration frequency given to the cutting tool in longitudinal direction and t is the time. The cutting tool tip movement in the Z-direction of the vibrating UCAM can be seen in Figure 2. It represents the parameters of an 8 μm amplitude, 1,800 Hz frequency (since the demonstration of ultrasonic frequencies are hard to show only 1,800 Hz was given), 10 mm tool radius, 263.2 mm/min feed speed, and 1,880 rpm spindle speed.

Moreover, in the case where the ultrasonic vibrations applied to the cutting tool occur along the X-axis and Y-axis in Cartesian coordinates, and the tool's movement is governed by the initial phase (φ_l) in longitudinal direction, the equation describing the overall motion of the N^{th} tool tip in the UCAM system with only axial vibration can be expressed as follows:

$$x(t) = v_f .t + R\sin\left(\frac{2\pi nt}{60}\right) \tag{3}$$

$$y(t) = R\cos\left(\frac{2\pi nt}{60}\right) \tag{4}$$

$$z(t) = a_l \sin\left(2\pi f_l t + \varphi_l\right) \tag{5}$$

where v_f is the feed speed, R is the tool radius, and n is the speed of the tool.

Figure 1 Cutting tool tip movement of conventional milling (see online version for colours)

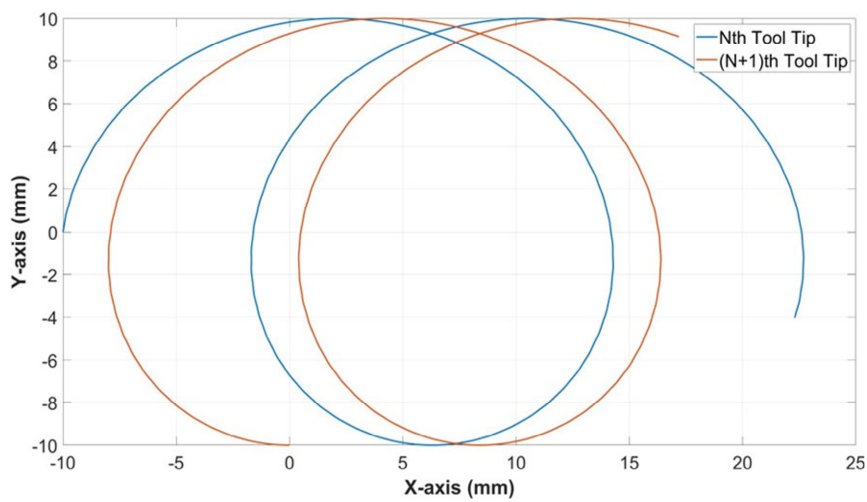
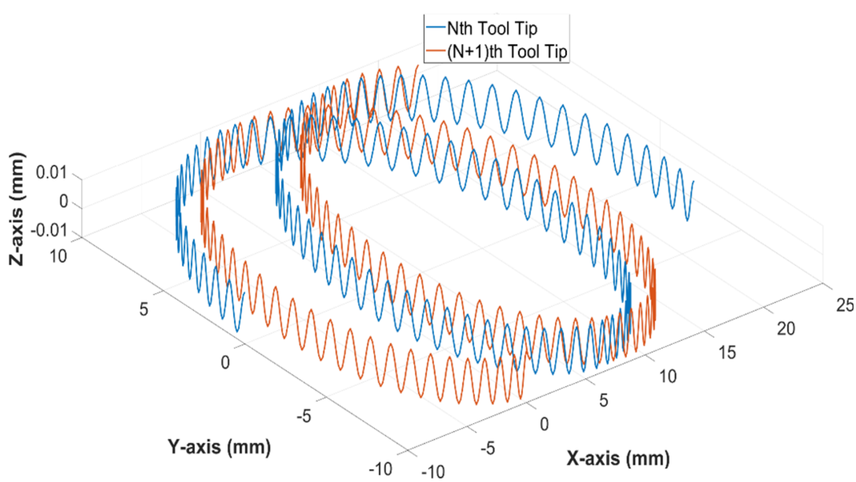


Figure 2 Cutting tool tip movement of axial (Z-direction) vibrated UVAM (see online version for colours)



Also, if the ultrasonic vibrations are given to the X-axis, the equation of motion of X-direction becomes:

$$x(t) = v_f.t + R\sin\left(\left(\frac{2\pi nt}{60}\right) + \frac{a_h \sin\left(2\pi f_h t + \varphi_h\right)}{R}\right) \tag{6}$$

where a_h is the amplitude, f_h is the ultrasonic vibration frequency and φ_h is the initial phase given to the cutting tool or the workpiece in horizontal (feed) direction.

Finally, when the combined XZ-directional ultrasonic vibrations are given to the system, the general cutting motion becomes:

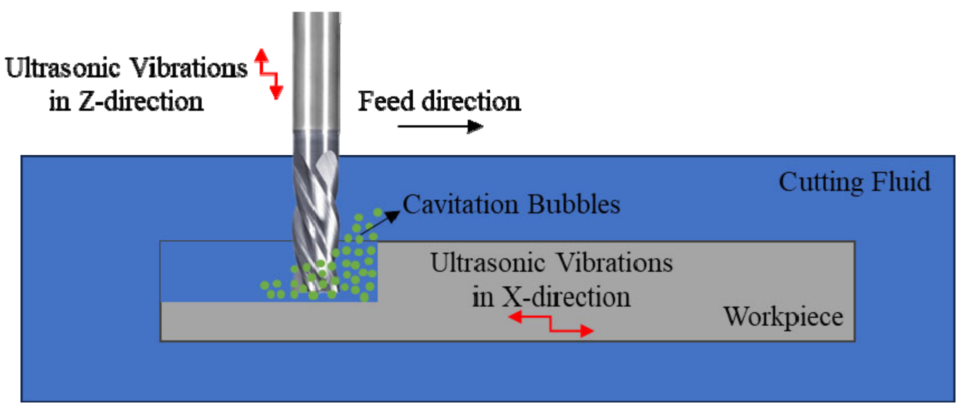
$$x(t) = v_f.t + R\sin\left(\left(\frac{2\pi nt}{60}\right) + \frac{a_h \sin\left(2\pi f_h t + \varphi_h\right)}{R}\right) \tag{7}$$

$$y(t) = R\cos\left(\frac{2\pi nt}{60}\right) \tag{8}$$

$$z(t) = a_l \sin\left(2\pi f_l t + \varphi_l\right) \tag{9}$$

Ultrasonic vibrations have the ability to alter the kinematics of the cutting operation, manifesting in both Z- and X-direction vibrations. Furthermore, the application of ultrasonic vibrations within a liquid medium gives rise to the formation of cavitation bubbles. Figure 3 illustrates the schematic representation of the cavitation phenomenon induced by ultrasonic vibrations.

Figure 3 Schematic of UCAM mechanism (see online version for colours)



The distinctive influence of vibrations in various axes on the cutting kinematics underscores the significance of investigating the practical implications of ultrasonic vibration. Consequently, it becomes crucial to explore the effects of vibrations in different directions within the context of UCAM, an innovative approach that integrates ultrasonic technology to facilitate cavitation-induced processing. Hence, in order to comprehensively understand the potential of this novel methodology, an examination of vibration effects in diverse directions within UCAM is imperative.

3 Material and method

The workpiece selected for this study is Ti-6Al-4V, with dimensions of 90 mm × 55 mm × 15 mm. Table 1 presents the material properties of Ti-6Al-4V. The experimental methodology employed in this study utilised by STARBIDE® brand carbide end mills with four flutes and a diameter of 10 mm, coated with TiSiN. To ensure comparability, a new cutting tool was used for each experiment. The experiments were conducted on an Akira Seiki SR3XP CNC milling centre as slot milling operation, with the application of ultrasonic vibrations in three different directions.

Table 1 Mechanical properties of Ti-6Al-4V

Tensile strength (MPa)	1,000
Yield strength (MPa)	820
Elastic modulus (GPa)	114
Poisson's ratio	0.33
Density (kg/m^3)	4,420
Tensile strength (MPa)	1,000

The first direction involved longitudinal vibration, which was achieved by an ultrasonic tool holder attached to the Z-axis cutting tool. This configuration aimed to produce cavitations as close as possible to the cutting zone. The second vibration, in the X-axis, was generated by an ultrasonic transducer that transmitted vibrations to the workpiece through a specially designed table. These two ultrasonic vibrations were simultaneously applied to create a multi-dimensional ultrasonic movement (XZ-vibration). The frequencies used for the ultrasonic transducer and ultrasonic tool holder were 21 kHz and 18 kHz, respectively, with an amplitude of 8 μm for both devices. To investigate the effects of commercially available cutting fluids, the workpiece was placed in a special-made liquid tank filled with half-synthetic CCF. The vibration and motor's recirculation induced cavitation phenomena in the liquid. A pump and filter system were employed to recycle the liquid and remove chips from the tank. Figure 4 illustrates the experimental setup.

Table 2 Properties of cutting fluid used in experiments

Base material	*Density (g/ml at 20°C)*	*pH*	*Mixing ratio with water (%)*	*Appearance*
Half-synthetic oil	0.997	9.4	8	Yellow-green

The experiments involved slot milling at three different cutting speeds under each vibration condition, with a constant feed rate and depth of cut. The specific parameters for the experiments are provided in Table 3.

After the cutting tests, the surface form of the middle of the slots was measured using the Alicona© InfiniteFocus, an optical 3D surface measurement device. The acquired data from Alicona© InfiniteFocus were analyzed using Gwyddion© software to determine the surface roughness (Ra) and 3D surface topography. Cutting forces were measured using a three-component piezoelectric quartz crystal dynamometer (Kistler© 9256B), equipped with a data acquisition system (Kistler© 5697A1) and a charge amplifier (Kistler© 5070). The acquired data were saved and processed using signal analyzer software (Dynoware©). A sampling frequency of 100 kHz was set for the measurements. The average value of the resultant cutting force during the stable cutting phase, excluding the slot entry and exit phases, was calculated. The general flow of the study is represented in Figure 5.

Figure 4 The experimental setup (see online version for colours)

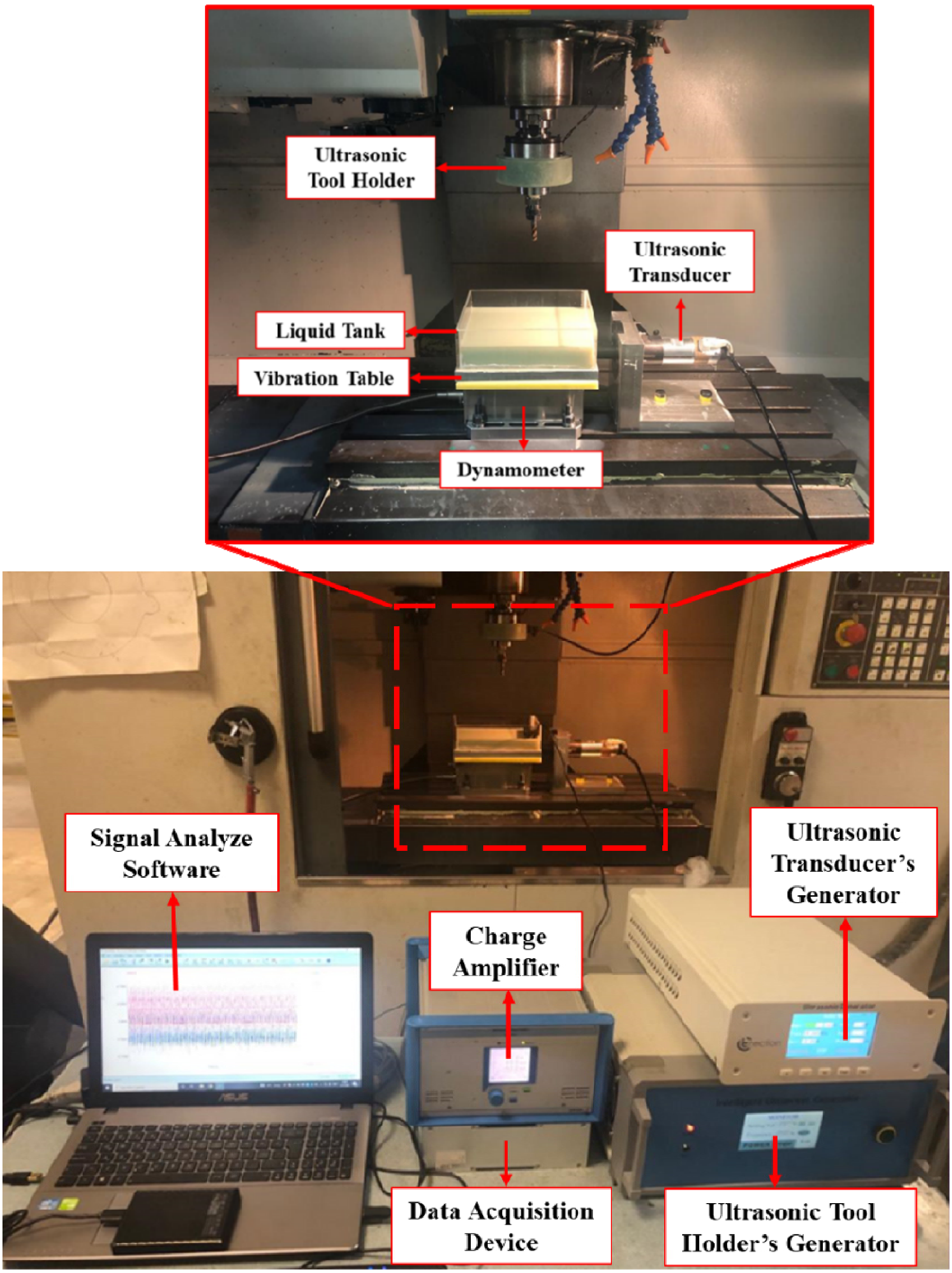


Figure 5 The general schematic flow of the study (see online version for colours)

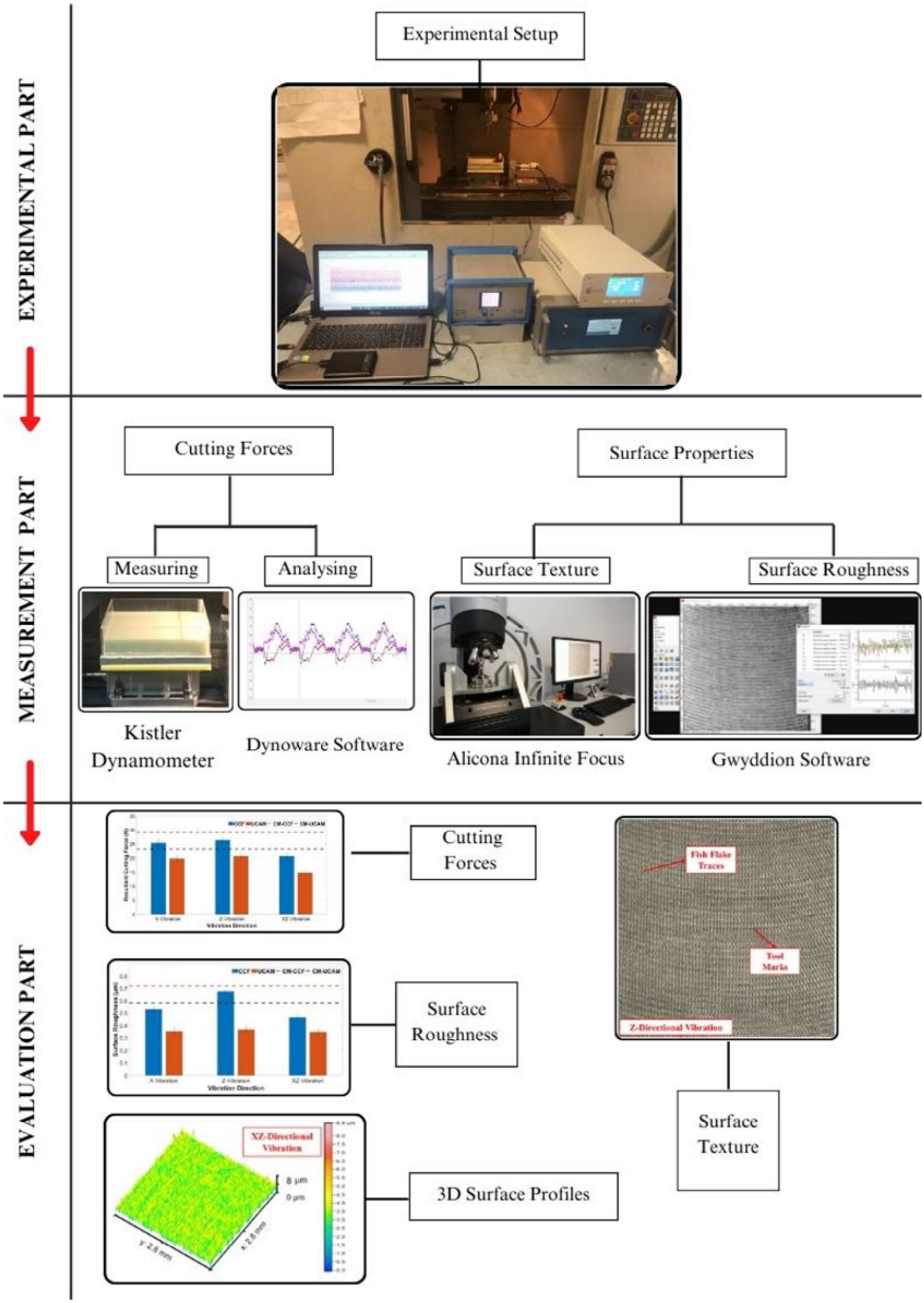


Table 3 The experimental conditions

Vibration direction	*Cutting speed (m/min)*	*Feed (mm/tooth)*	*Depth of cut (mm)*	*Coolant condition*
No vibration (conventional milling)	50	0.02	0.5	UCAM
No vibration (conventional milling)	50	0.02	0.5	CCF
X-direction	50	0.02	0.5	UCAM
X-direction	50	0.02	0.5	CCF
Z-direction	50	0.02	0.5	UCAM
Z-direction	50	0.02	0.5	CCF
XZ-direction	50	0.02	0.5	UCAM
XZ-direction	50	0.02	0.5	CCF

4 Results and discussion

4.1 Surface roughness

The measured surface roughness (Ra) values are presented in Figure 6 and the quantitative results are shown in Table 4. As evident from the obtained Ra values, the lowest value was observed in UCAM with XZ direction as 0.347 µm, while the highest Ra value was found in CM with CCF as 0.72 µm. Applying UCAM simultaneously in both the X and Z directions facilitates the formation of cavitation bubbles in close proximity to the cutting zone, resulting in improved cutting performance and a smoother surface finish. The higher Ra values observed with the conventional cutting combined with CCF can be attributed to the absence of a gap between the cutting tool and the surface during the traditional cutting process, as opposed to the vibration-assisted cutting process. Additionally, the material removal effect arising from cavitation is absent during CM with CCF, as the cutting process does not take place in a liquid tank. These factors contribute to the rougher surface finishes reported in the literature for CM with CCF (Liang et al., 2019).

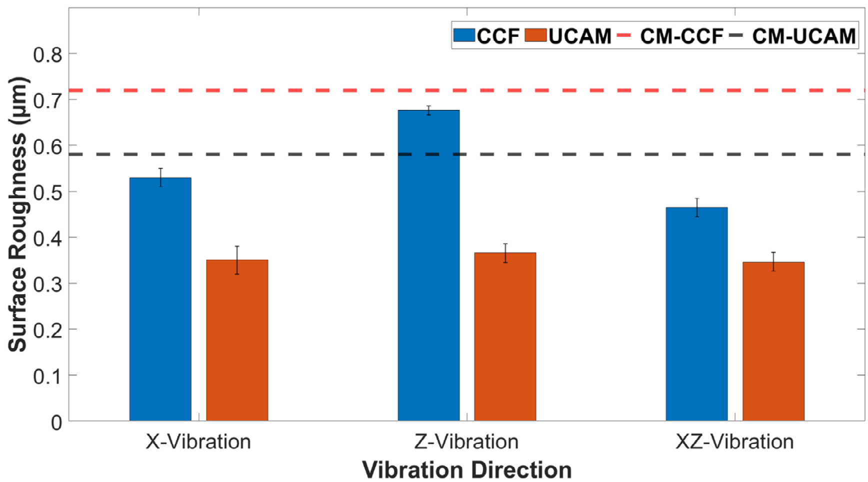
Table 4 Surface roughness results (µm)

Cutting type/coolant type	*Conventional cutting fluid*	*UCAM*
Conventional milling	0.72	0.58
X-direction vibration	0.53	0.351
Z-direction vibration	0.676	0.366
XZ-direction vibration	0.465	0.347

Upon investigating the effects of ultrasonic vibrations applied in different axes on surface roughness values, it was observed that the lowest roughness values were achieved with XZ-direction vibrations (0.347 µm in UCAM, 0.465 µm in CCF), followed by X-direction vibrations (0.351 µm in UCAM, 0.53 µm in CCF), while the highest values were obtained with Z-direction vibrations (0.366 µm in UCAM, 0.676 µm in CCF). This outcome can be explained as follows: X-direction vibrations occur in the feed direction during slot milling operations, thereby reducing friction by creating an intermittent cut.

On the other hand, Z-direction vibrations primarily act in the longitudinal direction, resulting in a relatively lower impact on the feed direction compared to X-direction vibrations. However, when considering the combined XZ vibrations, the vibrations applied in both directions contribute to a greater reduction in friction compared to X-direction vibrations alone, as they cause the cutting tool tip to move in an elliptical manner. Consequently, this reduction in friction minimises tool wear and facilitates the attainment of lower surface roughness values.

Figure 6 Surface roughness results (see online version for colours)



4.2 Optical microscope and surface topography results

Figure 7 presents optical microscope images, while Figure 8 displays surface topography. Upon examining these images and topographies, it is evident that the results align with the surface roughness values obtained. UCAM with XZ directional vibration yields the most uniform, homogeneous, and undamaged surfaces. In contrast, when CM is used with CCF, the surface exhibits prominent tool marks, non-homogeneity, burnt spots and chip spatter.

In XZ-UCAM, distinct fish-flake-like surface patterns are clearly visible. These surface patterns are attributed to the vibrations of the cutting tool and result in shallower tool marks compared to CM-CCF. Additionally, analysis of the 3D surface topography reveals that the peak-to-valley values are highest in the CM-CCF condition and lowest in the XZ-UCAM condition. Moreover, the CM-CCF condition exhibits dimples that disrupt surface homogeneity, while the waviness profile of the surface is negatively affected by the presence of tool marks.

These observations further support the conclusion that UCAM with XZ directional vibration leads to improved surface quality, as evidenced by the uniformity, homogeneity, and reduced tool marks. Conversely, CM with CCF demonstrates inferior surface characteristics, including non-homogeneity, burnt spots, and tool mark-induced waviness.

Based on the obtained data, an examination of the vibrations applied in different directions reveals that XZ-direction vibrations yield the most uniform and homogeneous surfaces. This is followed by X-direction vibrations, while Z-direction vibrations result in surface images with the most irregular surface profiles. This observation can be attributed to the influence of vibration directions, as indicated by the surface roughness results, on the feed direction.

Significantly greater improvements in cutting performance are observed with XZ and X-direction vibrations, which involve vibrations in the feed direction, compared to Z-direction vibration. Moreover, in XZ-direction vibration, the tool's movement in both the feed and axial directions enable intermittent cutting during the machining process, thereby facilitating efficient chip removal.

Figure 7 Optical microscope images (see online version for colours)

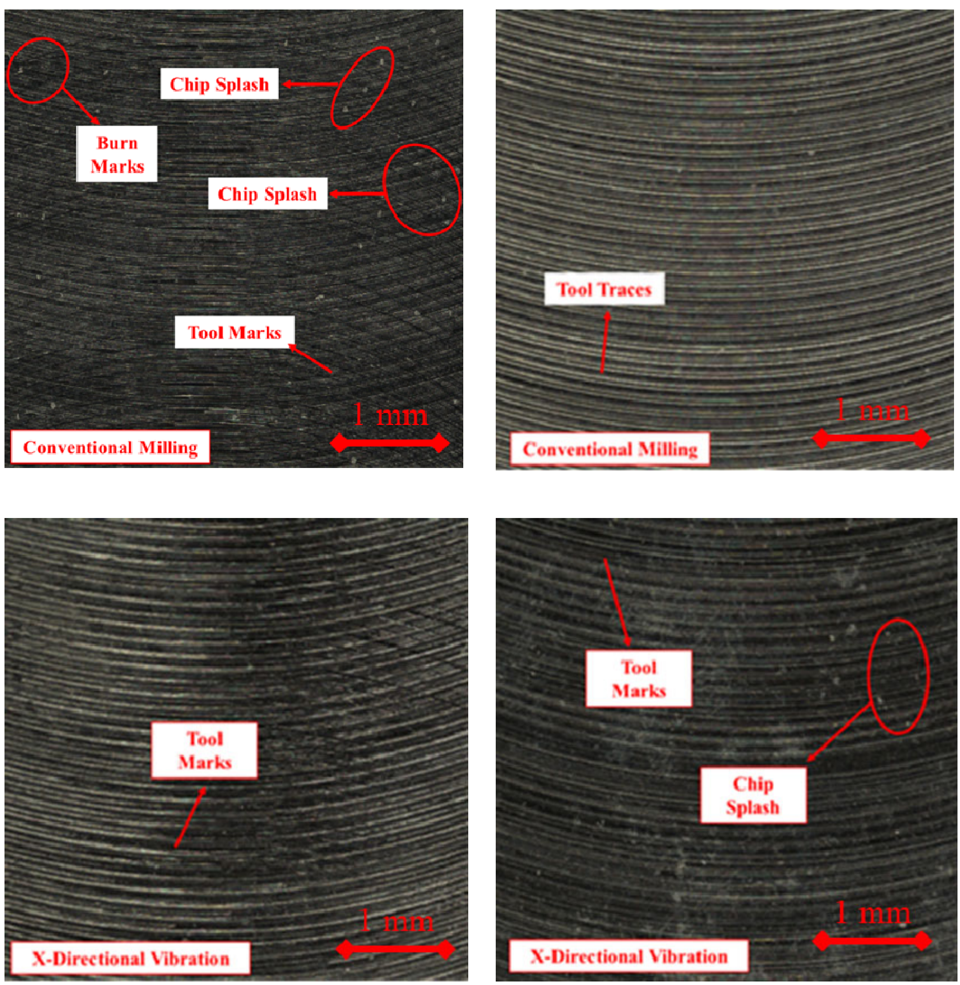
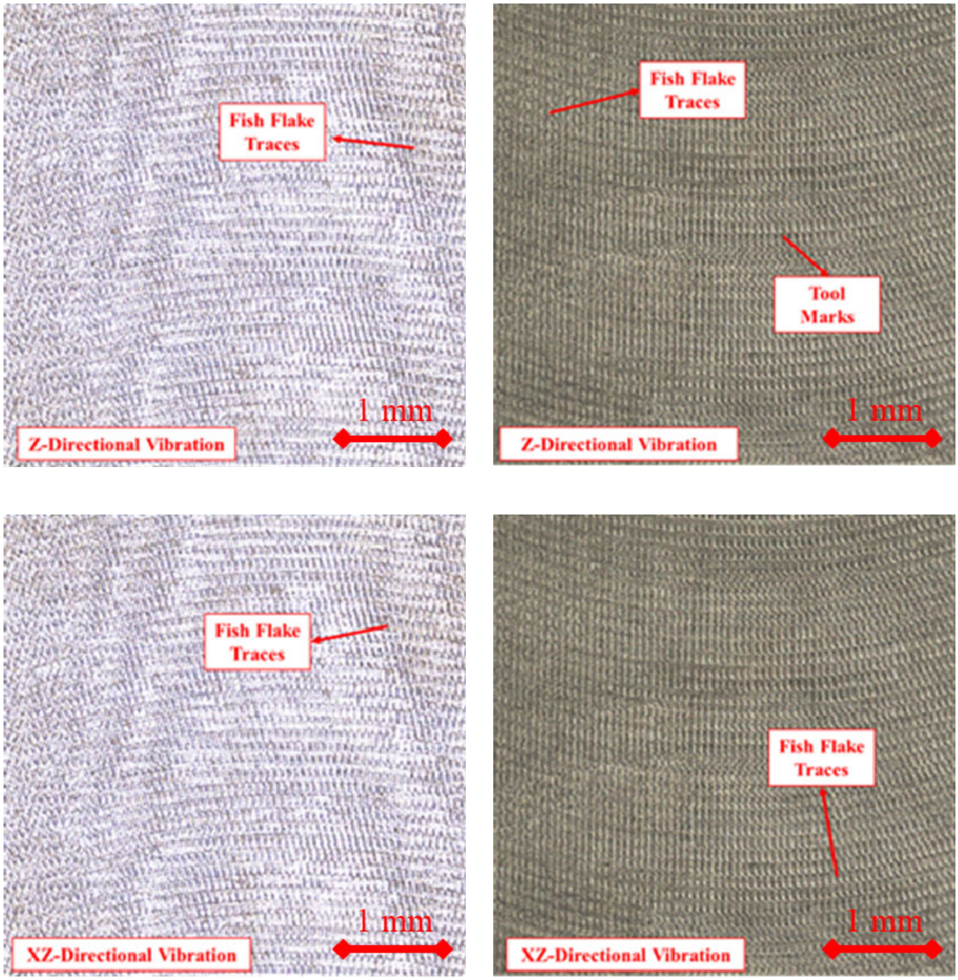


Figure 7 Optical microscope images (continued) (see online version for colours)



4.3 *Cutting force results*

The measurement of cutting force holds great significance as a key parameter in assessing the quality of machining processes. This force directly influences the stability of operations and the efficiency of cutting. The experimental analysis involves the calculation of resultant cutting forces by:

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{10}$$

and the corresponding outcomes are presented in Figure 9 while the quantitative results are shown in Table 5.

Figure 8 3D surface topography results (see online version for colours)

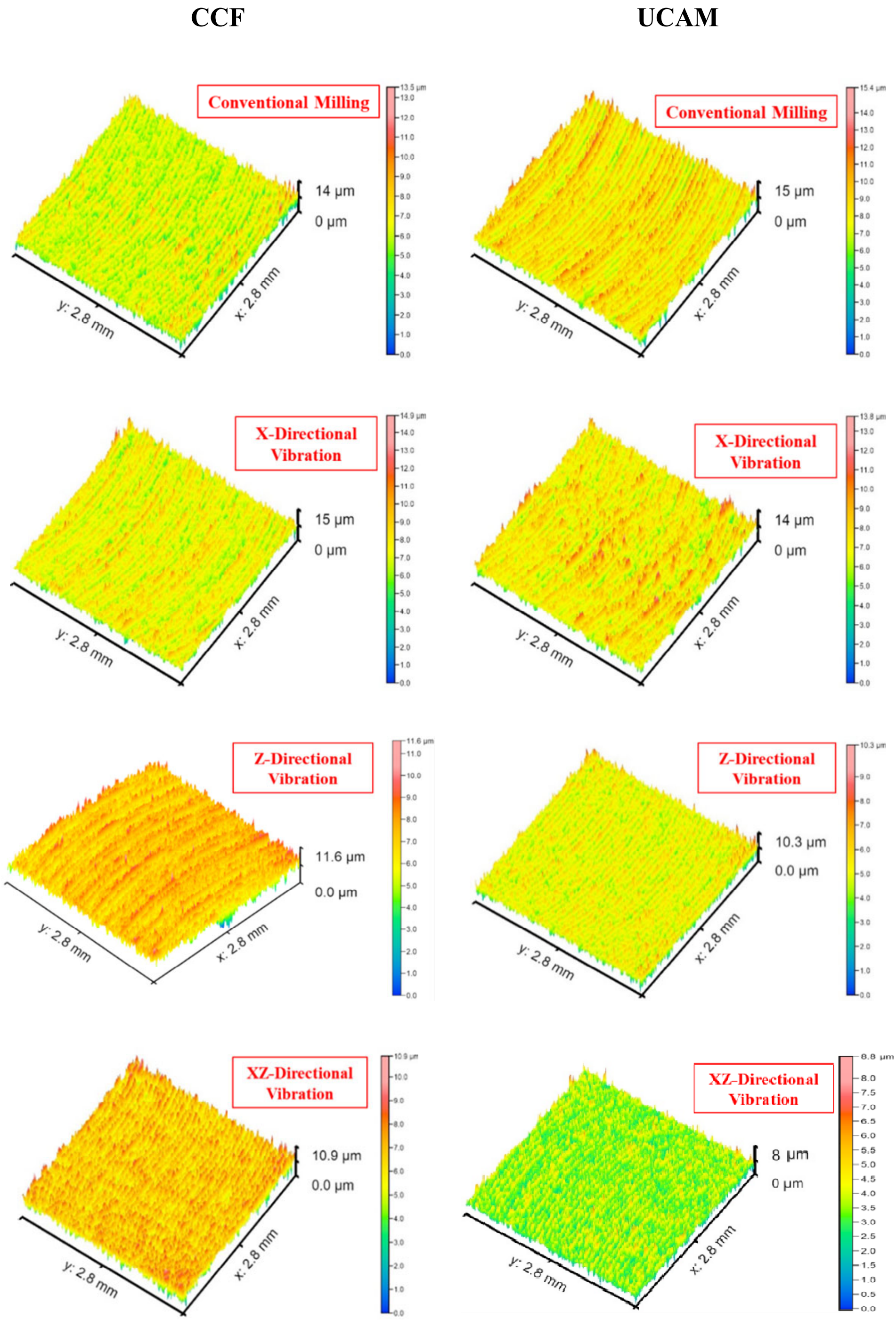


Figure 9 Cutting force results (see online version for colours)

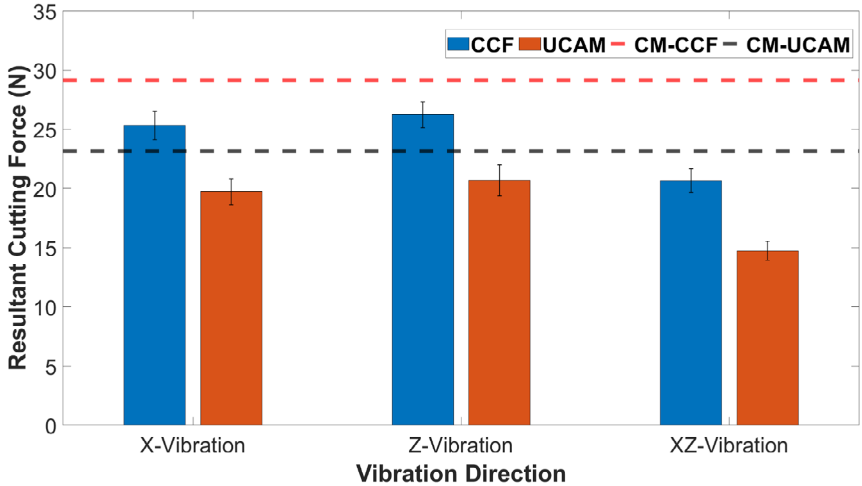


Table 5 Cutting force data

Cutting type/coolant type	*Conventional cutting fluid*	*UCAM*
Conventional milling	29.15 N	23.15 N
X-direction vibration	25.32 N	19.72 N
Z-direction vibration	26.22 N	20.67 N
XZ-direction vibration	20.66 N	14.73 N

When analysing the cutting forces, it was consistently observed that experiments conducted with UCAM yielded lower cutting forces compared to those with CCF. Notably, the XZ-vibrating UCAM exhibited the lowest cutting forces, while the highest forces were observed in CCF-applied CM. Specifically, the XZ-UCAM combination achieved a remarkable 49.5% reduction in cutting forces compared to the traditional CCF-CM method. Following this, X-UCAM and Z-UCAM demonstrated 22.1% and 21.2% lower cutting forces than their respective CCF counterparts. Furthermore, the occurrence of the cavitation phenomenon in UCAM-applied experiments enhanced machining efficiency compared to CCF-applied experiments. In conventional CCF applications, the cutting tool removes chips from the workpiece surface through a subtractive process, where friction significantly impacts the generation of cutting forces. However, in UCAM operations, chip removal occurs not only due to friction but also with the assistance of cavitation. Consequently, this combined effect results in decreased cutting forces, leading to a more efficient operation.

When comparing UCAM experiments, the cutting forces obtained from XZ-UCAM were found to be 25.3% lower than those from X-UCAM and 28.7% lower than those from Z-UCAM. Furthermore, X-UCAM demonstrated 4.6% lower cutting forces compared to Z-UCAM. The reduction in cutting forces varies depending on the direction of applied vibrations due to the consequent decrease in friction caused by ultrasonic vibrations. Vibrations applied in the Z-direction specifically reduce friction in the axial direction. However, the effect is more pronounced in the X-direction vibrations, which are aligned with the feed (cutting) direction. Notably, the elliptical or near-elliptical movement mechanism of the cutting tool, facilitated by XZ vibrations, minimises friction, and leads to the most significant reduction in cutting forces.

5 Conclusions

In this study, the effectiveness of UCAM, an emerging hybrid sub-operation of UVAM, is investigated and compared to the application of CCF and CM. The experiments were conducted on Ti-6Al-4V material in slot milling operation by applying different vibration directions. Specifically, the differential vibration directions employed were Z-direction (axial), X-direction (feed), and XZ-direction (elliptical or near-elliptical). The findings of the study can be summarised as follows:

1. The cavitation phenomenon occurring during UCAM enhances machining efficiency by facilitating chip removal, surpassing the capabilities of CCF. Moreover, regardless of the direction of application, ultrasonic vibrations yield more favourable results compared to CM.
2. UCAM demonstrates up to 49.5% lower cutting forces and up to 51.9% lower surface roughness values than CCF. Additionally, UCAM results in reduced tool and burn marks on surfaces, while achieving more homogeneous and uniform surface finishes.
3. Different vibration directions exert distinct effects on the quality of the operation. In terms of cutting forces, XZ-UCAM exhibits up to 25.3% lower values than X-UCAM and up to 28.7% lower values than Z-UCAM. Comparatively, the reduction rate in XZ-CCF is 18.4% when compared to X-CCF, and 21.2% when compared to Z-CCF.
4. Regarding surface roughness values, XZ-UCAM demonstrates a 1.1% reduction compared to X-UCAM and a 5.1% reduction compared to Z-UCAM. Similarly, in XZ-CCF, the reduction rates are 12.8% compared to X-CCF, and 31.2% compared to Z-CCF.

6 Future scope of work

UCAM, as an emerging hybrid machining method, garners attention as a promising technique, as evident from the findings of this study. Notably, the literature on UCAM has not yet provided comprehensive research in this field. Therefore, future investigations could explore the influence of ultrasonic vibration frequency and amplitude in UCAM, the impact of various machining parameters like cutting speed and feed, and delve into topics such as tool wear, chip formations and sub-surface examinations. Such studies would contribute to a deeper understanding and advancement of the UCAM process.

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