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Research Article

Investigation of the Combined Effects of Ultrasonic Vibration-Assisted Machining and Minimum Quantity Lubrication on Al7075-T6

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The aluminum alloy Al7075-T6 finds extensive application in the aviation and automotive industries, where machining plays a pivotal role. Emerging techniques such as Ultrasonic Vibration-Assisted Machining (UVAM) and Minimum Quantity Lubrication (MQL) hold promise for enhancing machining efficiency. In this study, the combined use of UVAM and MQL for slot milling of Al7075-T6 was investigated. The results demonstrate that UVAM reduced cutting forces by an average of 10.87% in MQL and 8.31% in Conventional Cutting Fluid (CCF) conditions when compared to Conventional Machining (CM). In addition, UVAM yielded significantly improved surface finishes, characterized by an average reduction in surface roughness of 41.86% in MQL and 32.11% in CCF conditions relative to CM. Furthermore, surfaces subjected to UVAM exhibited fewer instances of burn marks and tool-induced markings, reduced chip splashing, and more uniform surface integrity compared to those manufactured with CM. Lastly, chips generated through UVAM exhibited distinct characteristics, notably shorter length, curvier shape, and a distinctive half-turn morphology when compared with the irregular chips produced through CM. In conclusion, our findings underscore the potential of UVAM in synergy with MQL to augment the machining of Al7075-T6 alloy, thereby yielding superior-quality machined components with enhanced operational efficiency.

1. Introduction

Aluminum alloys are extensively applied in the aerospace, automotive, machinery, and medical industries, and Al7075, characterized by its superior strength compared to most aluminum alloys, as well as its high corrosion resistance, is commonly employed in the aerospace and automotive sectors [1]. Nonetheless, its comparatively poor machinability, when contrasted with other commercially available aluminum alloys, presents challenges during various manufacturing processes [2]. Inadequate machining conditions can lead to reduced cutting efficiency, increased cutting forces [3], rapid tool wear [4], high tool consumption, and inadequate surface finish [5], necessitating secondary operations. Moreover, the excessive use of cutting fluids is demanded in order to achieve a successful cutting which is detrimental for the environment [2, 6]. All of these circumstances contribute to suboptimal process efficiency. Conventional machining (CM) techniques prove inadequate in addressing these issues, necessitating the development of enhanced cutting techniques.

Ultrasonic vibration-assisted machining (UVAM) is an advanced hybrid machining technique that employs high ultrasonic frequency and low amplitude vibrations to the cutting tool and/or workpiece [7–10] to enhance the efficiency of the machining process. UVAM has been successfully applied to many aluminum alloy machining operations. Shen et al. [11] studied the ultrasonic-assisted micromilling of aluminum alloys, and the study showed that cutting forces decreased and surface defects reduced and more uniform surfaces were obtained when ultrasonic vibrations were applied. Another research was conducted by Shen et al. [12] on the UVAM of aluminum alloy 2A12 in slot milling operation, and the results showed that UVAM reduced the vertical side wall surface roughness; however, the slot bottom surfaces were adversely affected by UVAM, and this is mainly due to the vibrational direction. Wang et al. [13] conducted a study on the cutting force comparison between CM and UVAM in 2195 aluminum alloy, and the study showed that UVAM reduced the cutting force component F_y up to 62% when the optimum machining conditions were selected; also, due to the reduction of the cutting forces, the surface topography found enhanced compared to CM.

As mentioned earlier, in order to enhance the cutting process efficiency, excessive amounts of coolants are also used. In that manner, it becomes a problem for environment and labor health [14]. Concerning this problem, more environmentally friendly and sustainable coolant methods are proposed. One of these methods is named minimum quantity lubrication (MQL). MQL sprays aerosol which contains a little amount of lubricant to the cutting zone. The aerosol form penetrates the cutting zone more efficiently than conventional cutting fluids; therefore, more effective cutting occurs, and since the amount of oil is minimized, it is more economical and environmental [15–17]. Also, MQL improves the surface quality and reduced the power consumption and cutting temperature in several materials [18–21]. There are several studies on the effects of MQL on the machining of aluminum alloys. Tosun and Huseyinoglu [22] investigated the surface roughness changes in the milling of Al7075-T6 material, and their results showed that at higher cutting speeds, MQL gave lower surface roughness results than conventional cooling due to the accessibility of MQL form to the cutting zone. Bankar and Shelke [23] studied the effects of different lubrication methods (dry, wet, and MQL) on the machining of Al7075, and the study concluded that MQL decreased the roughness values by 26% compared to dry and by 14% in wet and also the temperature reduced with the help of MQL by 10% and 5% in comparison with dry and wet, respectively. Namlu et al. [24] revealed that in slot milling of Al6061-T6 material, MQL reduced the resultant cutting force by 48% compared to dry condition and 44% compared to wet condition. Moreover, surface roughness values were found to be 81% less compared to dry and 14% reduced compared to wet condition.

As can be seen from the literature, both UVAM and MQL have a direct impact on the cutting performance efficiency, separately. From this point of view, it can be expected that the combined use of UVAM and MQL will be more effective. There are some studies that investigated the combined application of UVAM and MQL. Namlu et al. [25] investigated the surface integrity of the UVAM and MQL combination of Al6061-T6; according to their results, together use of UVAM and MQL reduced the surface roughness, gave more homogeneous and uniform surface topography, and achieved less tool and burn marks on the surface compared to CM and conventional cutting fluid conditions. Namlu et al. [26] also studied the combine application of UVAM and MQL on Ti-6Al-4V material, and the results showed that in rough cutting operation, the lowest cutting forces and surface roughness values were found in UVAM and MQL combination and also the most homogenous and uniform surfaces were observed in this combination. Li and Wang [27] investigated the effects of ultrasonic vibrations and MQL techniques in micromilling operation on SKD61 tool steel, and their study showed that the tool life is extended, surface roughness is decreased, and burrs are reduced when vibration are applied; in fact, MQL has even further increase the efficiency of vibration-assisted micromilling, contributing to reducing tool wear. Another research was done by Yan et al. [28]; the study showed that in the turning operation of Ti-6Al-4V, ultrasonic vibration reduced the cutting forces 21.9% in 17.6 m/min and 17.1% in 35.2 m/min compared to traditional machining. Airao and Nirala [29] also studied the ultrasonic-assisted turning (UAT) of Ti-6Al-4V with vegetable-based canola oil, and the study showed that UAT with vegetable oil decreases the cutting forces up to 25% and the flank wear by 12% compared to other conditions.

The literature shows that the combined application of UVAM and MQL can be beneficial in machining applications. However, most of the studies are focused on advanced engineering alloys and super alloys and there is a lack of study about aluminum alloys; in fact, there is no study found about Al7075-T6 material. In this study, UVAM and MQL applications on Al7075-T6 material were investigated and compared with CM and conventional cutting fluid (CCF) applications in terms of cutting forces, surface roughness, surface texture, 3D surface topography, and chip formation.

2. Ultrasonic Cutting Mechanism and MQL Interaction

To elucidate the improved efficiency of UVAM, it is imperative to comprehend its cutting mechanism. The ultrasonic vibrations of UVAM are capable of functioning in all three axes of operation, namely, X, Y, and Z. Specifically, this study is focused on the axial (Z-directional) ultrasonic vibrations imparted to the cutting tool. In conventional machining, the tool tip's movement along the Z-axis at any given time is typically defined by a unidirectional motion.

$$z(t) = 0. \quad (1)$$

However, when the axial ultrasonic vibrations are applied, it turns out to be

$$z(t) = a_l \sin(2\pi f_l t), \quad (2)$$

where a_l is the amplitude and f_l is the ultrasonic vibration frequency given to the cutting tool in the longitudinal direction. Besides the added Z-axis motion with UVAM, the general equation for the cutting tool's movement continuing in the X-axis and Y-axis directions for every N th tool tip can be expressed as follows:

$$x(t) = V_f t + R\sin\left(\frac{2\pi nt}{60}\right),$$
$$y(t) = R\cos\left(\frac{2\pi nt}{60}\right), \quad (3)$$
$$z(t) = a_l \sin\left(2\pi f_l t\right),$$

where R is the cutting tool radius, V_f is the feed speed, t is the time, and n indicates the rotational speed. The equations show that the axial vibrations given to the cutting tool in UVAM create a sinusoidal movement in Z-direction. This reciprocating movement with the frequency of f_l and the amplitude of a_l results in an intermittent contact between the tool and the workpiece. This separation characteristic of UVAM decreases the tool-workpiece contact ratio (TWCR). TWCR is directly related with the cutting tool-workpiece contact time. When the cutting tool-workpiece contact time decreases, TWCR decreases as well and due to the intermittent cutting mechanism of UVAM, the noncutting time increases which leads to decreased TWCR. The decreased TWCR can be led to less cutting forces, longer tool life, and enhanced surface quality [30]. In order to visualize the tool tip movement, the CM and UVAM cutting tool tip trajectories are given in Figure 1.

The aim of this study is to investigate the combined effect of UVAM and MQL and, therefore, it is crucial to comprehend the interaction between these two methods. UVAM can facilitate the MQL's efficiency by increasing its penetration capacity. The axial vibrations of the cutting tool, as determined by the amplitude value, create a gap between the tool and the bottom surface of the workpiece. As this study employs two nozzles, this gap facilitates the penetration of the MQL aerosol into the region between the cutting tool and the workpiece. The increased penetration of the aerosol leads to greater lubrication and cooling capacity, thereby improving efficiency. In order to understand visually, Figure 2 can be seen.

3. Materials and Methods

The workpiece material chosen for this study was Al7075-T6, and its mechanical properties can be seen in Table 1. Akira Seiki SR3XP three-axis CNC milling center was used for the slot milling experiments. The workpiece size was 130 mm × 250 mm × 25 mm as a rectangular plate. Two different coolant conditions, conventional cutting fluid (CCF) and MQL, were selected to see the interactions with UVAM. The experiments were full factorial designed and carried out with three different levels of cutting speed and feed for each different cutting condition (UVAM and CM) and coolant condition (CCF and MQL) with the intention of seeing the effects of machining parameters since it is known that machining parameters directly affect the performance outputs [31]. A total number of 36 experiments were conducted. Each experiment was repeated three times in order to ensure reproducibility. The chosen depth of cut was kept constant, and it was 0.5 mm in all the experiments. Four-flute HSS end mills, which are suitable for aluminum machining, were used for slot milling operations. The detailed experimental conditions can be seen in Table 2. The selected MQL was Cuttex® Al-32 with 75 ml/h of flow rate with 6 bar pressure. Selected cutting fluid for CCF applications was a water emulsion of Eurolub® Force K-102 with a flow rate of 500 l/h, and oil concentration of 5.5%. Ultrasonic vibrations were given by an ultrasonic tool holder with the help of an ultrasonic generator. The ultrasonic frequency sound of the ultrasonic tool holder before cutting was measured by PCB® brand 130A24 model microphone, and frequency response function (FRF) of the raw sound data is obtained to find the exact frequency which is found 18200 Hz; the measured FFT of the ultrasonic tool holder can be seen in Figure 3. In order to evaluate the cutting forces, Kistler 9265B three-component dynamometer was used. Optical microscope images were taken using Nikon® LV150N, 3D surface topography images were taken by Alicona® InfiniteFocus, and surface roughness values were measured by Mahr® MarSurf PS1. The experimental setup can be seen in Figure 4. In order to understand the basic steps of the study, a flowchart is given in Figure 5.

4. Results and Discussion

4.1. Cutting Forces Results. Cutting forces are essential outputs for understanding the process efficiency. Figure 6 shows the resultant cutting force results with different cutting conditions. According to the results, UVAM yielded lower cutting forces than the CM condition regardless of the coolant type. On average, the percentage differences between UVAM and CM were found to be 8.31% (between 6.96% and 9.5%) in CCF condition and 10.87% (between 9.67% and 11.97%) in MQL condition. The intermittent cutting mechanism of UVAM can account for these results, where longitudinal ultrasonic vibrations are applied to the cutting tool during the cutting process. Several potential explanations exist for these phenomena. First, the separation between the cutting tool and the workpiece likely resulted in a reduction of the frictional force component. When the tool became detached from the workpiece, the cutting forces theoretically became zero due to the absence of cutting action. In addition, the ultrasonic vibrations facilitated faster chip separation from the workpiece, reducing the energy required for chip removal and ultimately leading to lower cutting forces. When the coolant conditions were compared, MQL always yielded lower cutting forces than CCF condition. This is mainly the outcome of the aerosol form of MQL since MQL sprayed as aerosol form helps to penetrate to the cutting zone more efficiently and MQL can enter the contact area between the cutting tool and the workpiece more efficiently than CCF. This helps to increase the lubrication and cooling effect; therefore, the chip removal process becomes easier and less cutting forces can be obtained. The lowest cutting forces were obtained from the UVAM-MQL combination, while the highest cutting forces were obtained from the CM-CCF condition. As mentioned before, UVAM creates a gap between the cutting tool and the workpiece because of the intermittent cutting mechanism,

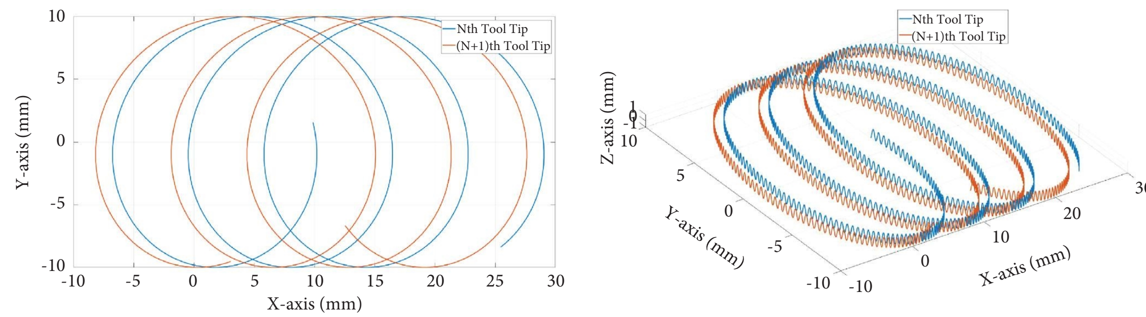


Figure 1: The cutting tool trajectories.

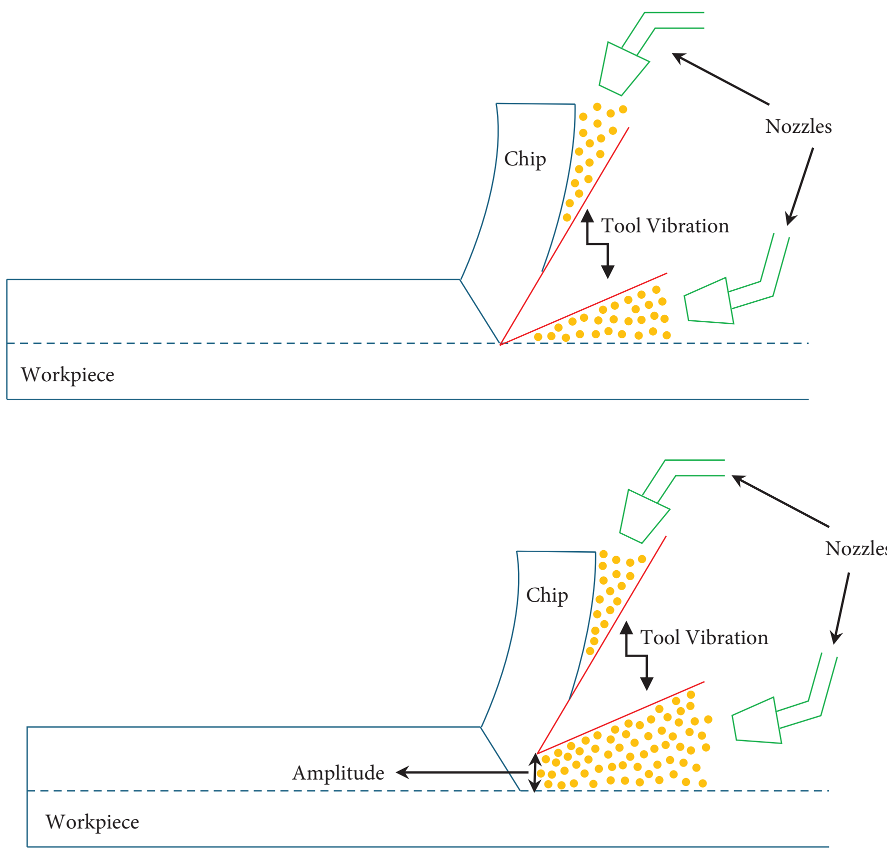


Figure 2: UVAM application with MQL.

Table 1: Mechanical properties of Al7075-T6.

Ultimate tensile strength (MPa)	Tensile yield strength (MPa)	Density (g/cc)	Poisson's ratio	Modulus of elasticity (GPa)
571	504	2.81	0.33	71.7

Table 2: Design of experiments.

Parameters	Cutting speed (m/min)	Feed (mm/min)	Frequency (Hz)	Amplitude (μm)	Coolant condition
Levels	100 150 200	500 600 700	18200 0 (CM)	8 0 (CM)	CCF MQL

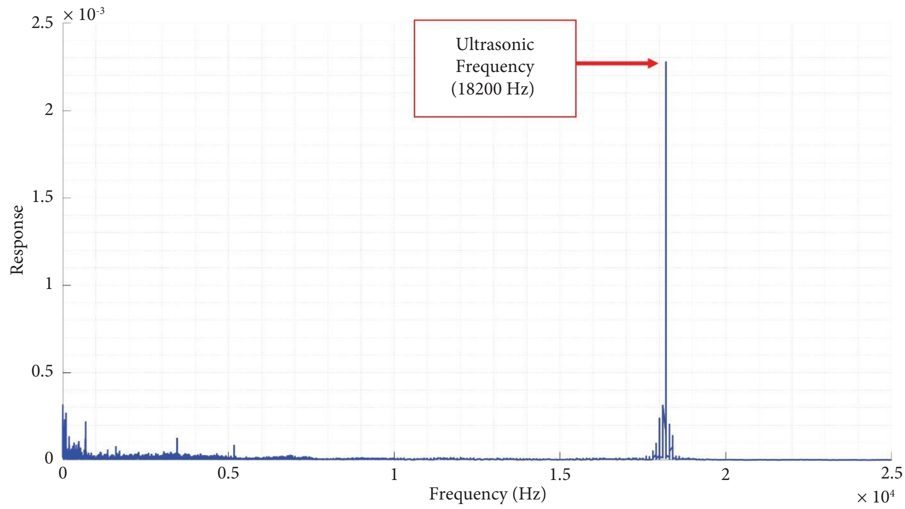


Figure 3: FFT of the ultrasonic tool holder's vibrations.

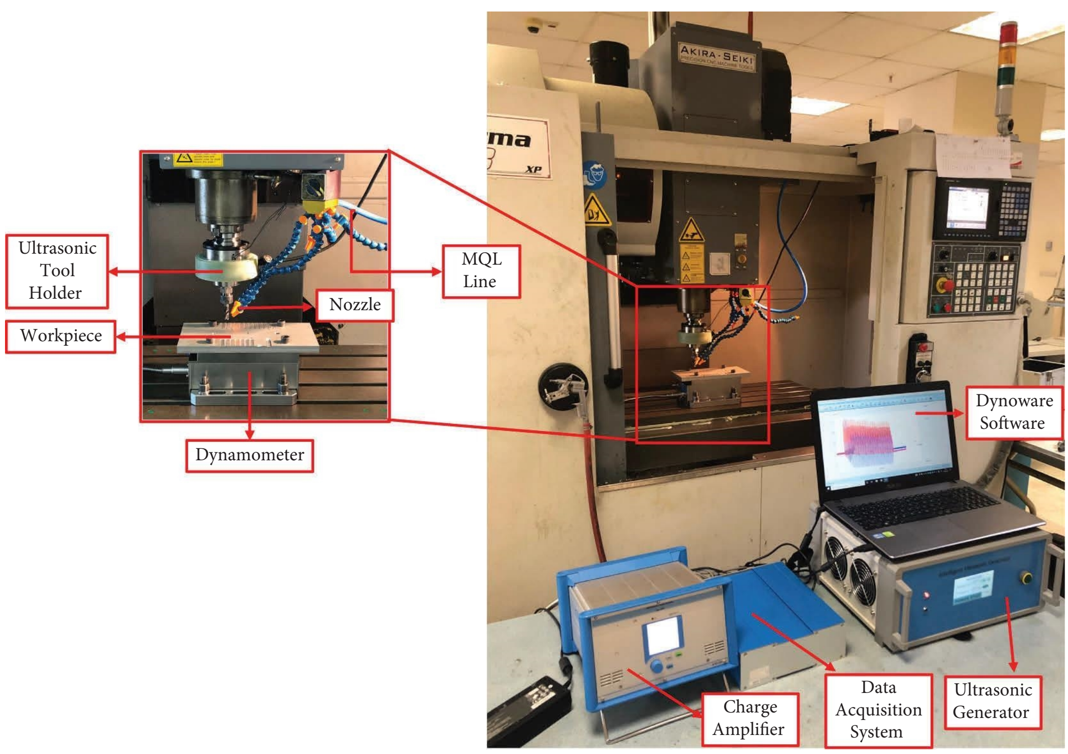


Figure 4: Experimental setup.

and MQL can fill the created gap more effectively due to its aerosol form. Therefore, this separation mechanism accelerates the MQL's efficiency [25].

Machining conditions, feed, and speed are also directly affecting the cutting forces. The results showed that cutting forces were increased by increasing in feed regardless of other parameters. This is due to the higher chip load on the tool when the feed increased; since the higher chip load requires more power, it leads to increase in the cutting forces [32]. Another finding is that when the cutting speed increased, the cutting forces decreased. The reason of it is that at higher cutting speeds, the temperature in the tool-chip contact area increases and this may lead to a drop in shear strength as temperature gets higher; therefore, the chip removal process requires less cutting forces [33].

4.2. Surface Roughness Results. The surface roughness is another output in order to evaluate the cutting performance. The surface roughness results can be seen in Figure 7. According to the results, UVAM yielded reduced surface roughness values than CM, both in CCF and MQL conditions. Notably, the percent reduction of UVAM was estimated to be 41.86% (within the range of 38.21%–46.61%) in

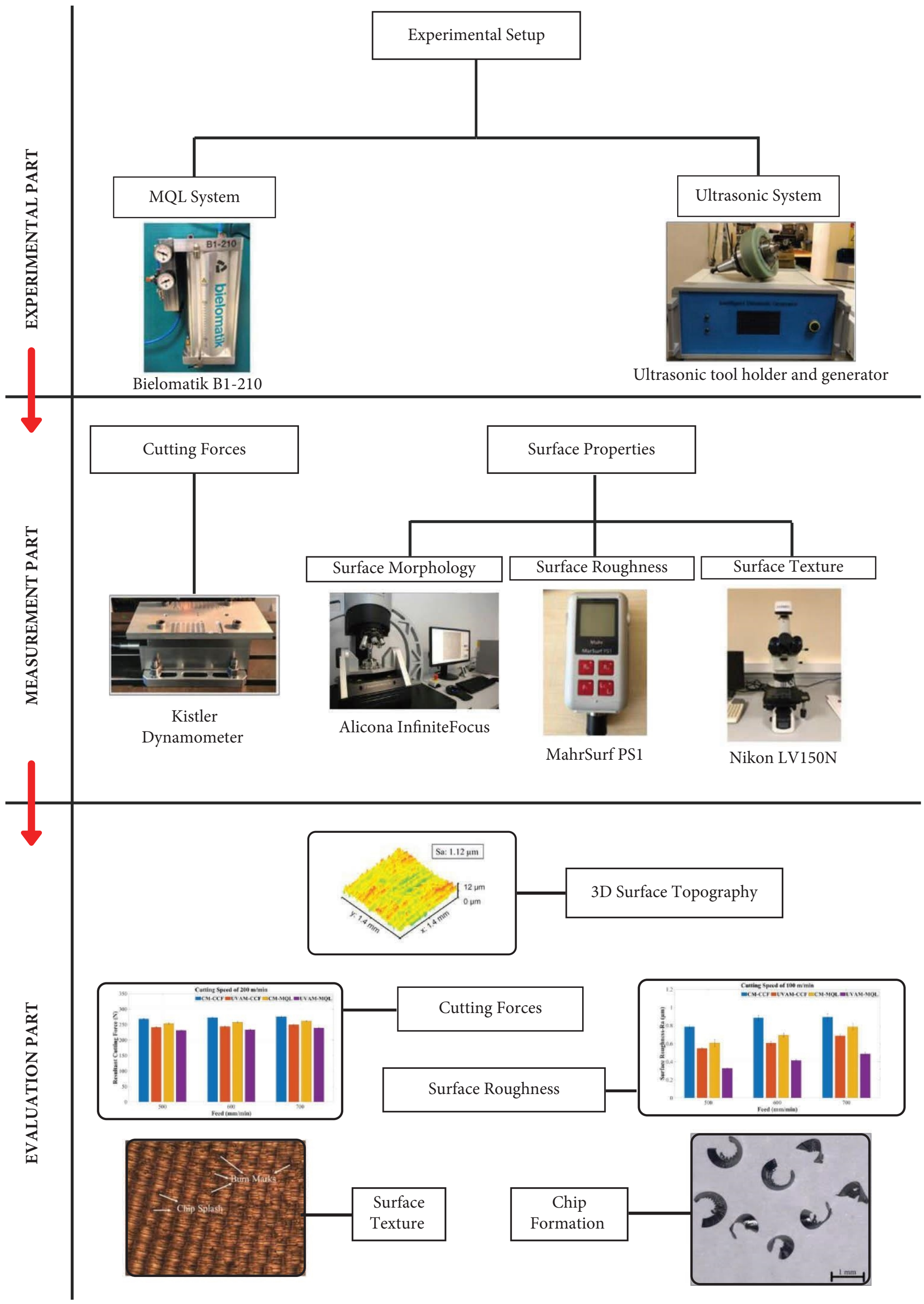


Figure 5: Flowchart of the study.

MQL and 32.11% (within the range of 23.12%–38.16%) in CCF cutting conditions in comparison to CM. The reason behind it is that the intermittent cutting mechanism of the UVAM which is obtained by the longitudinal vibrations is given to the cutting tool. Compared to CM, the pulse-like intermittent cutting phenomenon helps to prevent the formation of built-up edge (BUE) and reduces tool wear. Consequently, it assists in maintaining the sharpness of the cutting tool, leading to a reduction in surface roughness.

Upon comparing the coolant conditions, it was observed that the use of MQL resulted in lower surface roughness values when compared to the CCF coolant method. The percent reduction rates were found to be 31.04% (within the range of 26.41%–40.36%) in UVAM and 19.57% (within a range of 11.89%–24.42%) in CM. This notable reduction in surface roughness can be attributed to the superior penetration capacity of MQL, which is sprayed as an aerosol form to the tool-chip interface. The enhanced cooling and lubrication capabilities of MQL effectively reduce friction,

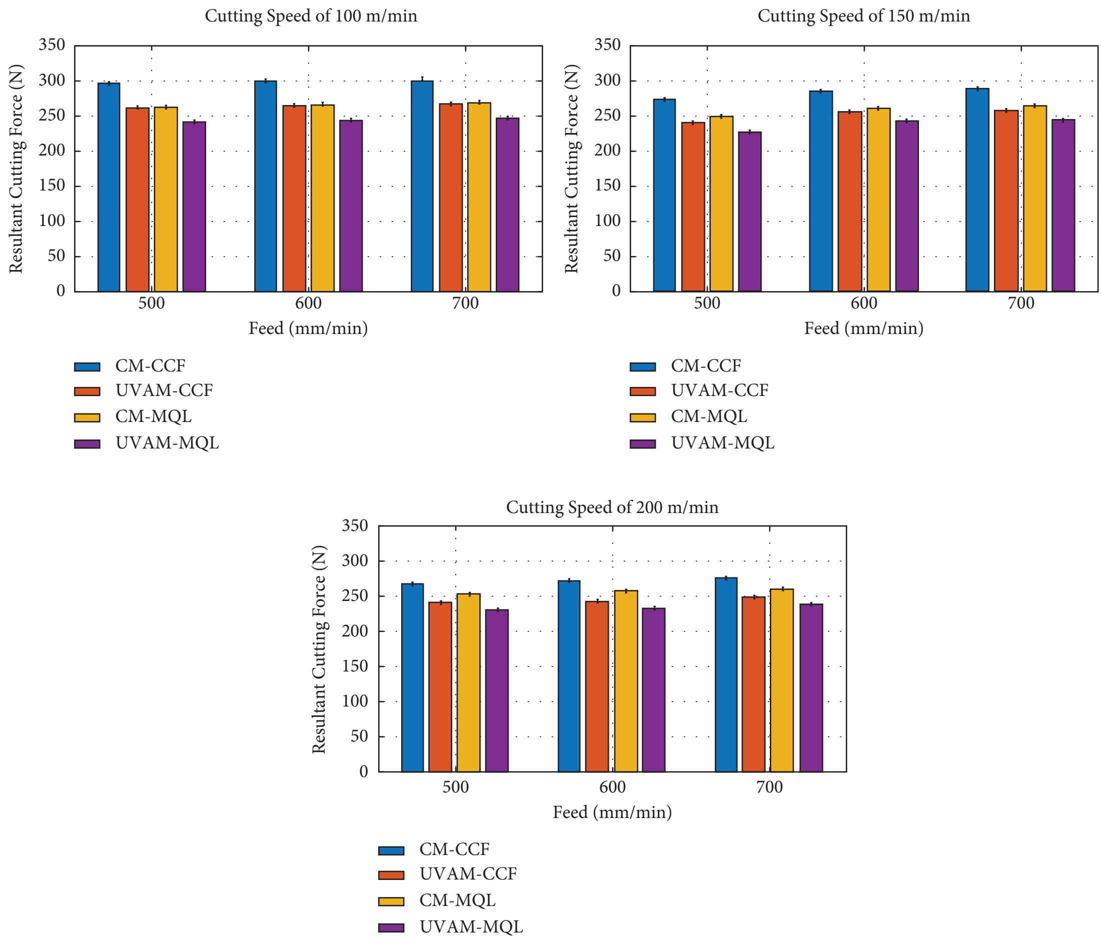


Figure 6: Cutting force results.

which subsequently decreases tool wear and results in a reduction of surface roughness.

As evidenced by the percent reduction rates, the application of MQL in conjunction with UVAM facilitated a superior reduction in surface roughness when compared to CM. The reduction rate in UVAM was found to be greater than in CM, and the lowest surface roughness values were obtained through the combination of UVAM and MQL. This can be attributed to the gap created between the cutting tool and the workpiece during intermittent cutting, which is subsequently filled by the MQL aerosol. This mechanism enhances the penetration capacity of MQL during cutting, resulting in further improvements. These findings align with the results obtained from the cutting force measurements.

Another finding is about the machining parameters feed and cutting speed. When the cutting speed increased, the surface roughness values decreased. Since aluminum alloys have relatively high ductility in general, this may lead to BUE formation. At higher cutting speeds, before the chips begin to be adhesive to the cutting tool and form as BUE, chip breakage can happen; therefore, BUE formation can be prevented. However, increased feed resulted as increased surface roughness values. Increased in the chip load due to higher feed leads to instability problems, and the higher friction occurs between the chip and the cutting tool because of higher chip thickness, which leads to temperature rise and thus increasing tool wear so that the surface roughness increases.

4.3. Evaluation of Surface Topography and Textures. The 3D surface topography and the surface texture images of CM and UVAM can be seen in Figures 8 and 9, respectively. The 3D surface topography images were captured from the central regions of the slot bottoms. Also, both topography and texture images were taken from 200 m/min cutting speed and 700 mm/min feed.

The surface textures produced by CM exhibit highly visible tool marks, chip splashes, and burn marks, with poor homogeneity, uniformity, and high peak-to-valley values in the topography, as evidenced from the images. This is largely attributed to the high cutting speeds utilized, which can cause the removed chips to splash and even adhere to the surface of the workpiece, leading to nonhomogeneity across the surface. The occurrence of burn marks over the surface is a common issue resulting from overheating during cutting, which can be attributed to the high cutting speeds generating concentrated heat in the cutting zone. These burn marks also serve as an indicator of high tool wear rates. In order to avoid

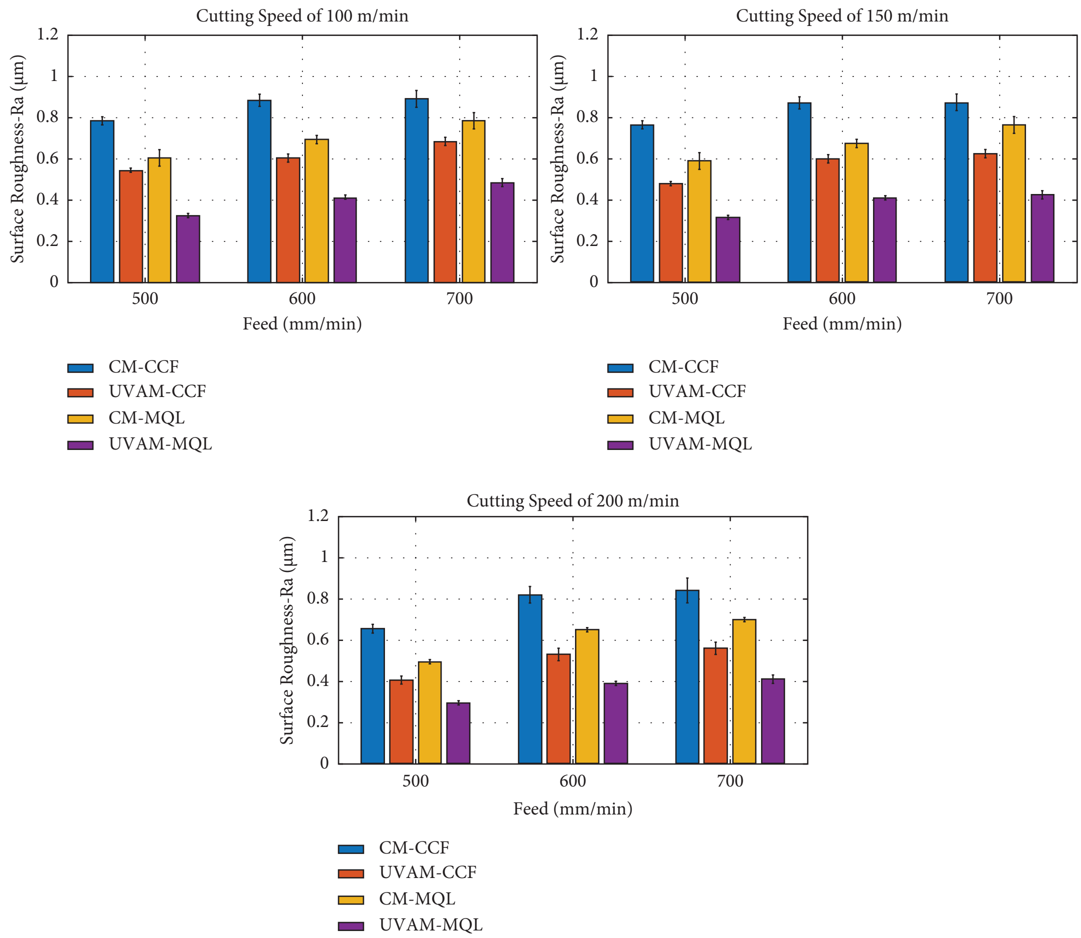


Figure 7: Surface roughness results.

these issues, appropriate adjustment of cutting parameters or provision of cooling to the cutting zone is necessary. However, when the surfaces generated by UVAM are investigated, it can be seen that the surface is more homogeneous, uniform with lower peak-to-valley values in topography images, and the defects such as burn marks and chip splashes are not seen in texture images. This can be attributed to the intermittent cutting mechanism of the UVAM process; since the cutting tool is separated from the surface during cutting, there will be no cutting action occurring theoretically. This leads to less heat generation in the cutting zone due to a reduced amount of friction and burn marks can be preventable by this way. Moreover, intermittent cutting can be helpful to chip breakage due to the vibrational axial hammer effect and because of that reason, the chip splash can be avoidable. Moreover, as mentioned before, the created gap between the cutting tool and the workpiece as a result of the axial vibration accelerates the coolant advantageous effects. The UVAM-generated surface seems like fish flakes; this is related to the axial ultrasonic effect. The fish-flake traces eliminate the deep tool marks over the surface, and this helps to create better surface roughness than CM-produced surface. This result also helps to explain surface roughness results in Figure 7.

4.4. Chip Formations. Chip formations are one of the most important outputs to examine in order to evaluate a milling operation. Obtained chips from the experiments can be seen in Figure 10 which were obtained under MQL conditions with cutting speeds of 200 m/min and a feed rate of 700 mm/min.

As can be seen, the chips obtained in the experiments using the UVAM method are shorter and thinner (up to % 18) than the chips obtained from CM. It was also observed that the chips produced from the UVAM applied experiments were more like half-turn shaped which is a desirable characteristic of a chip; meanwhile, the formation of the chips from CM experiments was found helical. These findings can be explained by the separation characteristic of UVAM. The literature suggests that ultrasonic vibration may reduce the effective number of teeth by causing separation between the tool and the workpiece in a slot milling operation, thereby changing the chip thickness [34]. Also, due to the ultrasonic vibrations given to the cutting tool in the axial direction, the contact area and cutting time of the tool with the chip are shorter than CM. In this case, the cutting tool makes a difference in chip regeneration compared to the CM, which is in constant contact with the chip. Ultrasonic vibrations help in chip breaking due to the vibrational impact, resulting in shorter chips. In addition, the cutting

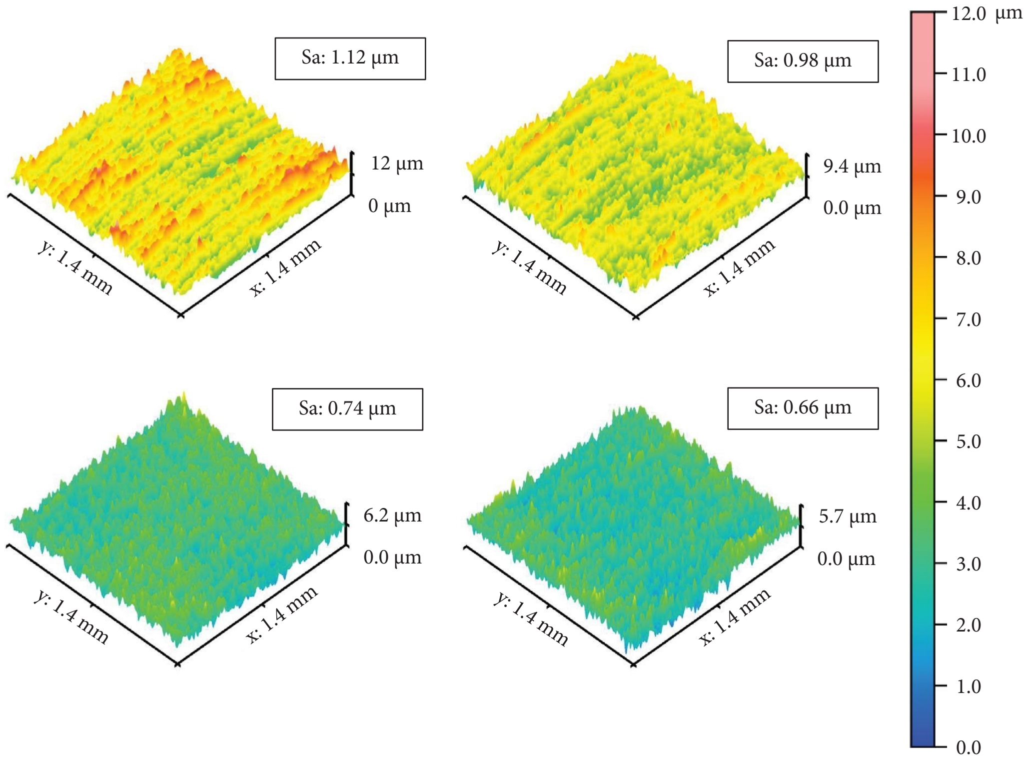


Figure 8: 3D surface topography images.

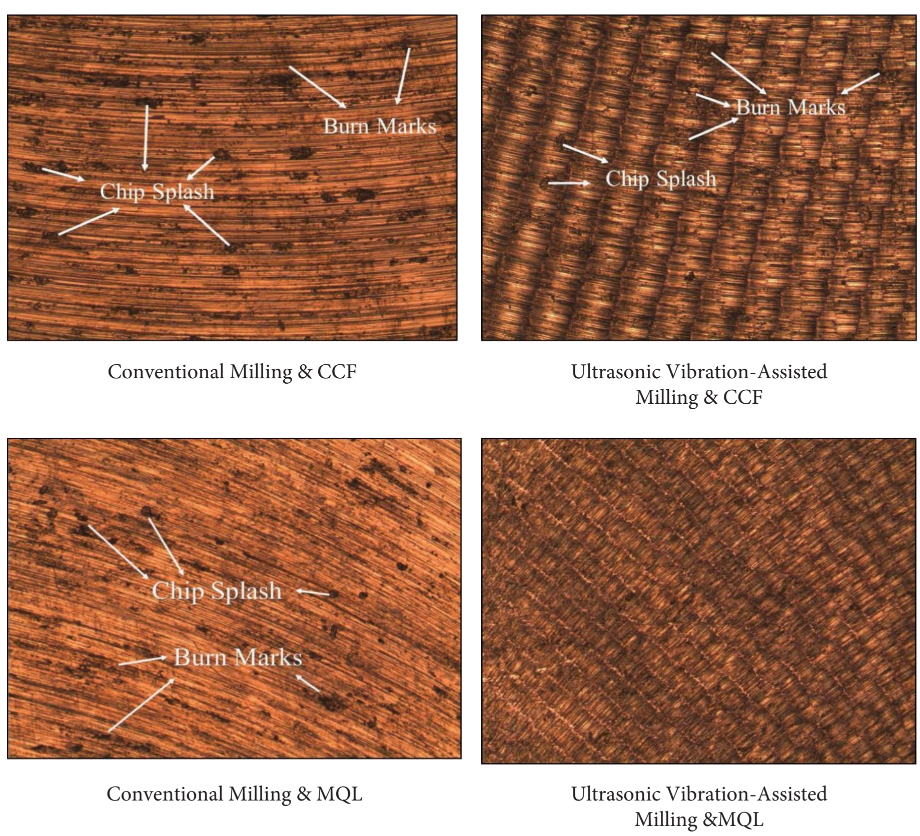
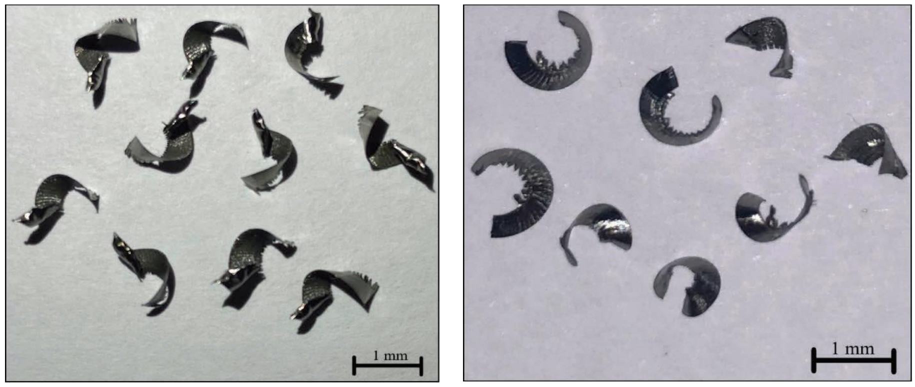


Figure 9: Surface textures.



Conventional Milling   Ultrasonic Vibration-Assisted Milling

Figure 10: Chip formations.

tool that is regularly separated from the bottom surface of the workpiece caused by ultrasonic vibrations in the axial direction and rejoins creates a kind of rubbing effect, causing half-turn chips to come out. Considering that Al7075-T6 is a ductile material, a high level of plastic deformation is required to remove chips from the workpiece surface, and also, longer chips may increase the tool wear rate because of the higher contact time between the cutting tool and the chip. Due to the previously mentioned intermittent cutting mechanism features, UVAM can significantly eliminate these problems and leads to a more desirable type of chip formation.

5. Conclusions

This study introduces the novel application of UVAM and MQL methods in combination for slot milling operation in Al7075-T6. Experimental examination of UVAM-CM and CCF-MQL methods is conducted for comparison of the results, with the outputs analyzed in terms of cutting forces, surface roughness, 3D surface topography, surface texture, and chip formations. The findings of this study can be summarized as follows:

(i) The findings of this study demonstrate that the application of UVAM results in a reduction of cutting forces, with reductions of 10.87% in MQL condition and 8.31% in CCF condition observed on average when compared to CM.

(ii) UVAM application also yielded a significant reduction in surface roughness, with average reductions of 41.86% and 32.11% observed in MQL and CCF cutting conditions, respectively.

(iii) The optimal combination of UVAM and MQL was found to yield the lowest cutting forces and surface roughness.

(iv) Surfaces generated by UVAM were observed to be more homogeneous and uniform, with reduced chip splash, burn marks, and tool traces when compared to CM.

(v) An increase in cutting speed led to a decrease in cutting force and surface roughness, while an increase in the feed rate had an adverse effect, leading to higher values of both parameters.

(vi) Chips formed by UVAM were observed to have a half-turn shape, while those produced by CM were more helical in shape. Chips produced by UVAM were found to be thinner and shorter in comparison to CM.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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