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Improving the Machined Surface of AISI H11 Tool Steel in Milling Process

Mohanad Kadhim Mejbel[†*], Mohanad Muzahem Khalaf[†], Ayad Mahmood Kwad[‡†]

[†] Middle Technical University, Technical Engineering College-Baghdad, Iraq.
[‡] Faculty of Electrical and Electronic Engineering (FKEE), Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia.

*Corresponding author E-mail: mohanad@mtu.edu.iq; mohanad@toc.edu.iq

ABSTRACT

Several challenges are faced by manufacturers producing the best surface finish, especially for the mold and die applications. Most of the mold and die materials are made from hardened steel (~40-60 HRC). The high strength of these materials reduced the capability of the conventional machining technique. High tool wear rate and poor machined surface are among the problems associated with traditional machining. To overcome these problems, this study proposed a hybrid machining process by adding axial ultrasonic vibration to the regular tooling system, namely ultrasonic vibration-assisted milling. Experimental work consisted of comparing ultrasonic vibration-assisted milling and conventional milling for different parameters, namely cutting speed, feed rate, and a milling depth of cut, to validate the proposed technique's effectiveness in enhancing the value of machined surface roughness for hardened AISI H11 tool steel. The milling tests revealed that axial ultrasonic-assisted vibration significantly improved the machined surface roughness with up to 89.7% reduction in Ra value than the conventional milling process with the same cutting conditions. The macroscopic observation of the machined surface showed that the surface produced from ultrasonic milling was uniform with a consistent peak to peak value which improved the surface finish.

KEYWORDS

Hybrid Machining; Ultrasonic Assisted Vibration Milling; Surface Roughness; Vickers microhardness.

INTRODUCTION

Conventional milling (CM) is somehow challenging to satisfy the growing requirements for machining high surface quality and excellent accuracy for the developing equipment of precision machinery, biological engineering, national defense, and aerospace industry. Milling processing assisted with ultrasonic vibration was introduced as an effective method. Ultrasonic vibration-assisted milling (UVAM) has been investigated for the last decade for its long cutting life, high efficiency, good cutting effect, extensive adaptability on materials. It is an emerging technique to obtain specific surface performance and biomimetic surface texture [1–8]. UVAM is an eco-friendly technique, newly developed to improve milling operation performance. In the late 1950s, cutting assisted with ultrasonic vibration was first introduced and analyzed in turning operations on a macro scale[9,10]. Cutting materials with ultrasonic vibration like glass, ceramics, and steel resulted in longer tool life, higher surface finish, and lower forces of cutting. Milling operations assisted with ultrasonic vibration have shown good promise to improve the surface finish and reduce cutting forces [9]. The intermittent cutting that happens only in a specific cutting parameter range reduces the UVAM's cutting forces [10,11].

Ultrasonic vibrations have been adopted in various orientations like cross-feed, feed, and axial directions; reducing cutting forces was achieved in all the cases [8,11–14]. Vibrations in the cross-feed direction produced a lower surface finish than feed and axial orientations because of the ironing effect [15]. Many researchers executed UVAM to the workpiece instead of the cutter [13,14,16]. Axial vibration to the workpiece results in a uniform machined surface finish as it provides the UVAM performance with more flexibility in any orientation, and it is considered more advantageous. In axial UVAM, in addition to the rotation of the milling cutter, the cutter vibrates axially with small amplitude and high frequency [9]. Previous experimental investigations revealed that implementing axial ultrasonic vibration reduces the cutter's wear, temperature, and forces of cutting [17–21]. Some significant studies in the scope of UVAM are briefly mentioned. Wickramarachchi and Maurotto[22] investigated the influence of axial vibration ultrasonic frequency for AISI 316L material using a cemented carbide tool in the end milling process. They reported that higher surface roughness resulted when the vibration frequency was increased. Residual stresses and tool wear as a point of view in UVAM was found to be unsuitable at a vibration frequency of 40 kHz.

The tool life of UVAM at 20 kHz was improved compared to higher frequencies at 60 kHz and 40 kHz. Shen et al. [12] conducted experimental tests using slot milling operation to analyze ultrasonic vibrations' influence in the feed direction experimentally. They compared CM and UVAM processes by calculating dimensional slot accuracy, chip morphology, surface roughness, and cutting forces. They concluded that milling operation was aided by ultrasonic vibration through performing intermittent cutting. Abootorabi Zarchi et al. [16] predicted the cutting forces by proposing an analytical model in ultrasonic-assisted milling. The provided ultrasonic vibrations in the workpiece considered a change in the undeformed thickness of chip formation. They validated their modelling results by experimental tests performed on stainless steel type AISI 420. Abootorabi Zarchi et al. [23] used ultrasonic-assisted side milling in their study and analyzed the influence of milling parameters on cutting forces experimentally. They reported a 42% decrease in cutting forces because of intermittent cutting. They revealed that the ultrasonic influence decreased at higher cutting speeds, and the machining behaviour approached CM. Li and Wang investigated the milling parameters influence on surface roughness and wear of tool in UVAM of tool steel type SKD61 [24].

They reported that axial ultrasonic vibration enhanced the burr height, surface finish, and reduced wear of the milling process tool. They also revealed that the influence of ultrasonic vibration decreased at a higher rotational speed. Elhami et al. [25] used ultrasonic vibration-assisted milling with concentrated plasma heating of the workpiece to study the milling parameters' effect on cutting forces of AISI 4140 hardened steel. They considered the influence of ultrasonic vibration on instantaneous chip thickness by proposing an analytical model. Their model predicted the reduction in cutting forces and temperature field in the workpiece because of thermal softening. Shen et al. [26] studied the effect of ultrasonic vibration on instantaneous chip thickness on AL6061 material using slot milling through experimental and analytical modelling. Tong et al. [27] investigated the surface microstructure of thin-walled titanium alloy parts using UVAM. They concluded that increasing the rotational speed provided a good surface finish compared to CM. Kurniawan et al. [28] used two different ultrasonic frequencies for surface texturing in their experimental and developed simulation modelling for measuring the machined surface roughness. They revealed that adopting the elliptical vibration texturing method in the milling process improved surface roughness.

Through the literature review, many researchers focused on surface roughness and surface texture when applying UVAM to the cutting tool or workpiece in cross-feed or feed direction, or both by adopting (ultrasonic elliptical vibration cutting)[10,29,30]. Because applying ultrasonic vibration, the trajectory and cutting motion is dramatically changed, but the cutting tool during the removal of material travelled on a 1D plane. More and more attention has attracted researchers in using axial ultrasonic vibration in recent years, which forces the cutter to travel in two planes, besides changing the cutting tool trajectory and motion[10]. Verma et al. [7,31] generated an analytical model considering a statistical model and an acoustic softening for cutting forces in UVAM. They found that applying ultrasonic vibration in the axial direction to the cutter has reduced the cutting forces due to the acoustic softening influence. Then, Verma et al. [32] introduced some experiments to investigate the surface roughness of AL 6063 by applying UVAM and investigated the influence of cutting parameters. It was concluded that surface roughness deteriorated at higher vibration amplitude, and the best surface roughness results obtained at low vibration amplitudes.

However, the mold and die industries' best-machined surface finish requirement is crucial to reduce the manual polishing process, costly and time-consuming[33]. Currently, the conventional milling (CM) process employed for the mold and die material (hardened steel with ~40-60 HRC) creates several challenges such as rapid tool wear, extreme machining temperature, high cutting force, and poor machined surface[8,13,14]. According to[34], UVAM is used for machining hardened steel is used to get a mirror machined surface and eliminate the manual polishing process. The cutter's vibration oscillation amplitude is altered by first incorporating the ultrasonic frequency to the rotating cutter, which imposes on the workpiece surface grains a static pressure, as then hammering effect is applied on the workpiece. Finally, surface finish is improved by decreasing the milling cutter's peak height, which produces a peening surface.

Furthermore, the transmitted oscillating vibration reduces the contact pressure between the workpiece and the cutter, decreasing the machining force and temperature that consequently improves the cutting tool life. Machining hardened steel material, surface roughness is the most crucial factor in obtaining a high-quality surface, dimensional accuracy of the machined workpiece, and good surface integrity. Upon the authors' best knowledge and from the literature review, no investigation was conducted to reveal axial UVAM parameters' influence on the surface finish of AISI H11 hardened steel. This work intends to conduct an experimental study to fulfil the research as mentioned earlier gap for evaluating the surface finish between axial UVAM and CM for different parameters, namely machining rotational speed, rate of feed, and depth of cut on hardened AISI H11 material, as such research is conducted for the first time. Also, macroscopic observation of the machined surface and subsurface hardness was employed to evaluate the cutting process's phenomena.

EXPERIMENTAL WORK

Machining experiments were conducted to evaluate machining parameters' effectiveness: depth of cut, feed rate, and cutting speed on machined surface roughness during slot milling using axial ultrasonic-assisted milling technique. AISI H11 tool steel with 48 ± 2 HRC hardness and 100 mm X 70 mm X 50 mm (LxWxH) dimension was used as a workpiece. Before machining tests were executed, vertical milling (facing) 0.5 mm of the raw material was skimmed down to remove any defects or surface problems from previous manufacturing processes. Details of the material, chemical compositions are mentioned in Table 1. All tests were done using a classical milling machine[34–36], and for the ultrasonic machining tests, an ultrasonic tool holder model HS-M2010 with a frequency of 20 kHz was used. The ultrasonic tool holder specifications are listed in table 2. 20 kHz electrical energy is used by converting the standard line voltage using a special power supply. This high-frequency electrical energy is converted into high-frequency, low amplitude vibration (mechanical motion) by a piezoelectric converter, transmitted and amplified to the cutting tool via the ultrasonic horn. As a result, the attached cutting tool and the horn vibrate axially (parallel with the spindle axis direction) around 20000 times per second without side-to-side movement. Figure 1 shows the mechanism for ultrasonic-assisted axial milling[38].

In vibration-assisted milling, the complex tooltip's trajectories might affect the cutting process resulting in a rugged surface. It was evident that the cutting tool trajectory assisted with ultrasonic vibration overlaps in some regions with the left contour of the surface by the previous path of cutting; thus, the edge of the cutting tool in these regions of overlapping will break off contact with the machined surface and chips having discontinuous type are generated. Periodical separation of workpiece-tool will occur as material parts have been removed due to previous cuts in the current cutting path. The cutting tool vibrates in an axial axis periodically as a sinusoidal signal within the cutting depth's central zone, resulting in a periodic separation between the machined surface and the cutting tool. However, the cutter is continuously in direct contact with the workpiece in CM. Hence, the tool motion fluctuation trajectory probably affects the machined surface topography and material removal in the UVAM process. Figure 2 illustrates the ultrasonic tool holder adopted in the experiments. A total of 27 runs of slot milling tests were performed using four flutes carbide, flat end mill with 12 mm shank diameter, and 30° helix angle as a cutting tool. All experiments were conducted in wet cutting conditions with the presence of cutting fluid. The cutting fluid is applied during the machining and was made of (1:10) phenol-water mixture.

Table 1. Chemical compositions of AISI H11

Element	C	Mn	Si	Cr	Ni	Mo	V	Cu	P	S	Fe
Content wt.%	0.41	0.29	0.85	4.91	0.22	1.26	0.52	0.31	0.013	0.014	Rem.

Table 2. Ultrasonic tool holder specifications

Model	HS-M2010
Weight	30 KG (Determined by the size of the horn)
Generator	Digital Generator
Working Time Control	24 Hours
Power Adjusting	Step or continuous
Switch	Handle or footswitch
Voltage	220 V
Output Power	1000 W
Frequency	20 kHz

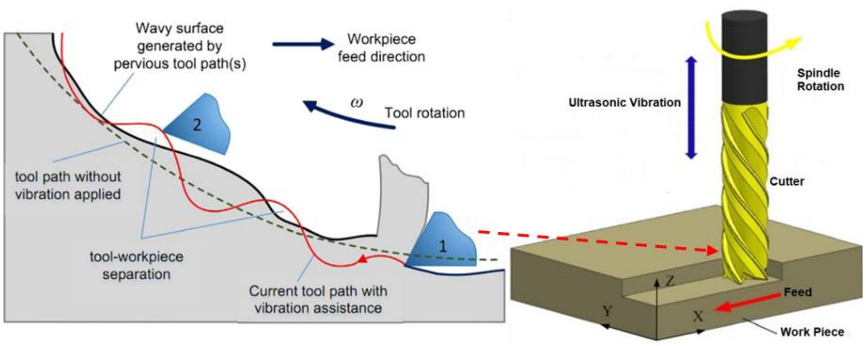


Figure 1. Mechanism of the ultrasonic-assisted axial milling[38].

In this study, the machining process was carried out using independent variables cutting speed, feed rate, and depth of cut. Details of the cutting parameter are mentioned in Table 3. Each single run test of the 100 mm length slot of the workpiece included two milling methods. The conventional milling method of the first half of the slot length (50 mm) was applied, and for the second half, the UVAM method was adopted during the second half of this single test run. The surface roughness of the machined slot was calculated by a surface roughness tester (Surfcom Touch 50, Zeiss-Germany) [34,37–41] at the middle line of the machined slot. The surface roughness tester equipment must be calibrated before reading the measurement[42–46]. Ra was taken immediately upon completing every slot milling machining test run the average arithmetic value of surface roughness. The measure was repeated five times on the horizontal (feed direction) axis at the middle line of the slot for every sample at random locations. The average arithmetic value of surface roughness, Ra, was calculated for both conventional and UVAM methods. The surface texture and 3D topography were measured using AFM (atomic force microscopy) (NTEGRA NT-MDT, Russia)[34–41]. Vickers microhardness was calculated using (HVS-1000, Laryree Technology Co. Ltd, China)[42,45,46].

Figure 2. Ultrasonic tool holder and its ultrasonic generator.

Table 3. Experiments run design.

Run No.	Speed (rpm)	Feed (mm/min.)	Depth of Cut (μm)	Conventional Milling Ra (μm)	Milling with Axial Ultrasonic Vibrations Frequency (kHz)	Amplitude (μm)	Ra (μm)
1	450	20	15	4.35	20	1	2.54
2	450	20	30	5.44	20	1	2.96
3	450	20	45	5.96	20	1	3.34
4	450	40	15	4.68	20	1	2.94
5	450	40	30	5.67	20	1	3.44
6	450	40	45	6.24	20	1	3.84
7	450	60	15	4.87	20	1	3.42
8	450	60	30	5.83	20	1	3.84
9	450	60	45	6.54	20	1	4.34
10	850	20	15	3.11	20	1	1.54
11	850	20	30	4.22	20	1	1.87
12	850	20	45	5.13	20	1	2.13
13	850	40	15	3.25	20	1	1.94
14	850	40	30	4.54	20	1	2.21
15	850	40	45	5.44	20	1	2.57
16	850	60	15	3.66	20	1	2.13
17	850	60	30	4.68	20	1	2.58
18	850	60	45	5.67	20	1	2.93
19	1450	20	15	1.32	20	1	0.14
20	1450	20	30	1.98	20	1	0.42
21	1450	20	45	2.75	20	1	1.12
22	1450	40	15	1.45	20	1	0.36
23	1450	40	30	2.12	20	1	0.68
24	1450	40	45	2.98	20	1	1.54
25	1450	60	15	1.56	20	1	0.65
26	1450	60	30	2.32	20	1	0.95
27	1450	60	45	3.15	20	1	1.97

RESULTS AND DISCUSSION

Surface Roughness

Figure 3 illustrates the measured average surface roughness values (Ra) of all the runs measured in the middle of the machined slots. The variation in surface roughness values was observed for different parameter cutting conditions. Surface roughness deteriorated when spinal speed decreased, increased rate of feed, and higher cut of depth. The obtained Ra values for ultrasonic vibration-assisted milling technique and conventional were in the range between 0.14 µm to 4.34 µm and 1.32 µm to 6.54 µm, respectively. One significant issue to be highlighted for all the UVAM experimental runs is that after applying ultrasonic vibration, a dramatic decrease in surface roughness values occurs compared to CM experiments. However, the revealed variations in the surface roughness values indicated that the surface roughness was dramatically affected by UVAM cutting parameters. Results show that run no. 19 (1 µm amplitude, frequency of 20 kHz, 15 µm depth of cut, 20 mm/min of feed rate, and rotational speed of 1450 rpm) produced the lowest surface roughness for both conventional and UVAM method with an average value of 1.32 µm and 0.14 µm respectively. An improvement of 89.7% of surface roughness using the UVAM technique was achieved, as illustrated in Fig. 3. Fig. 4 reveals the surface roughness measurement location, which happens perpendicular to the machined grooves for the best run result (run no. 19) with ultrasonic vibration.

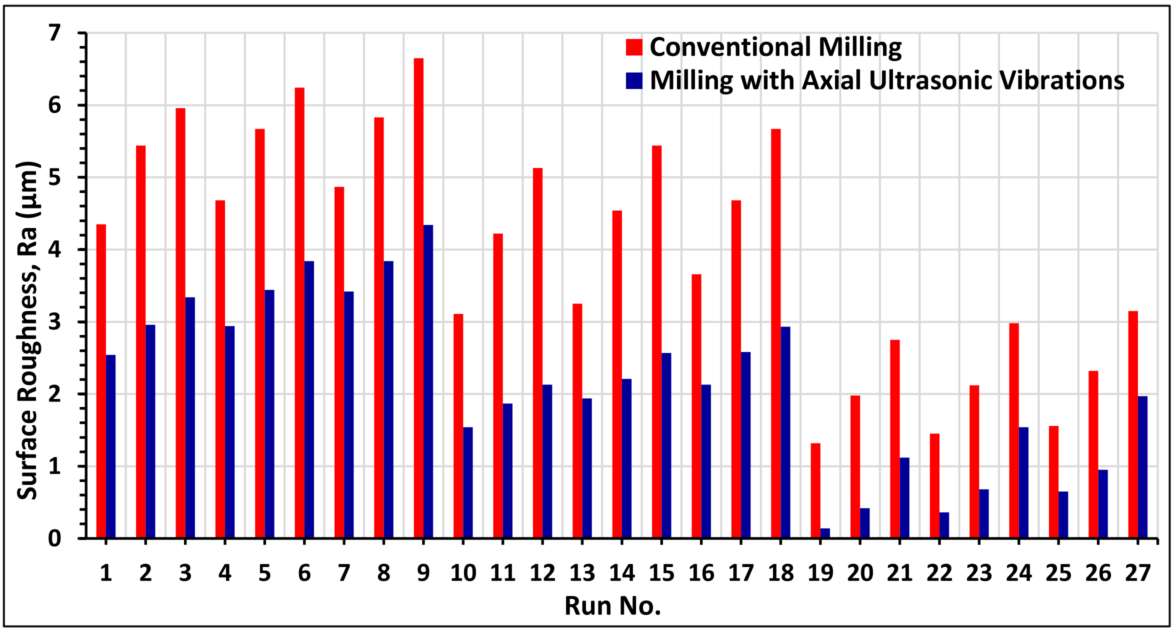


Figure 3. Surface roughness results for all runs.

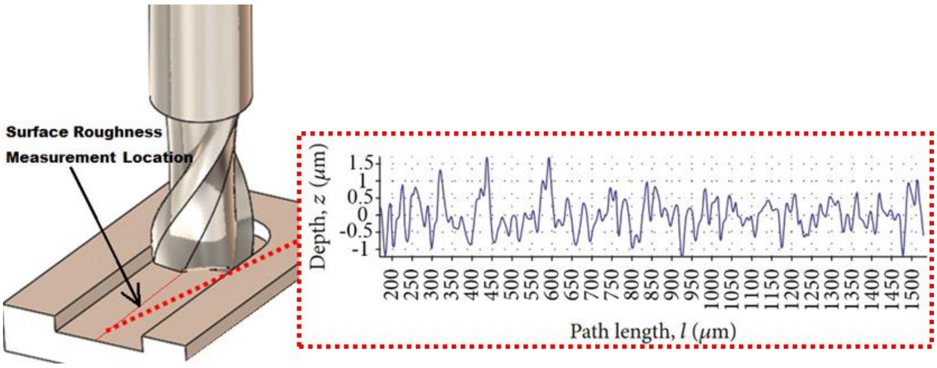
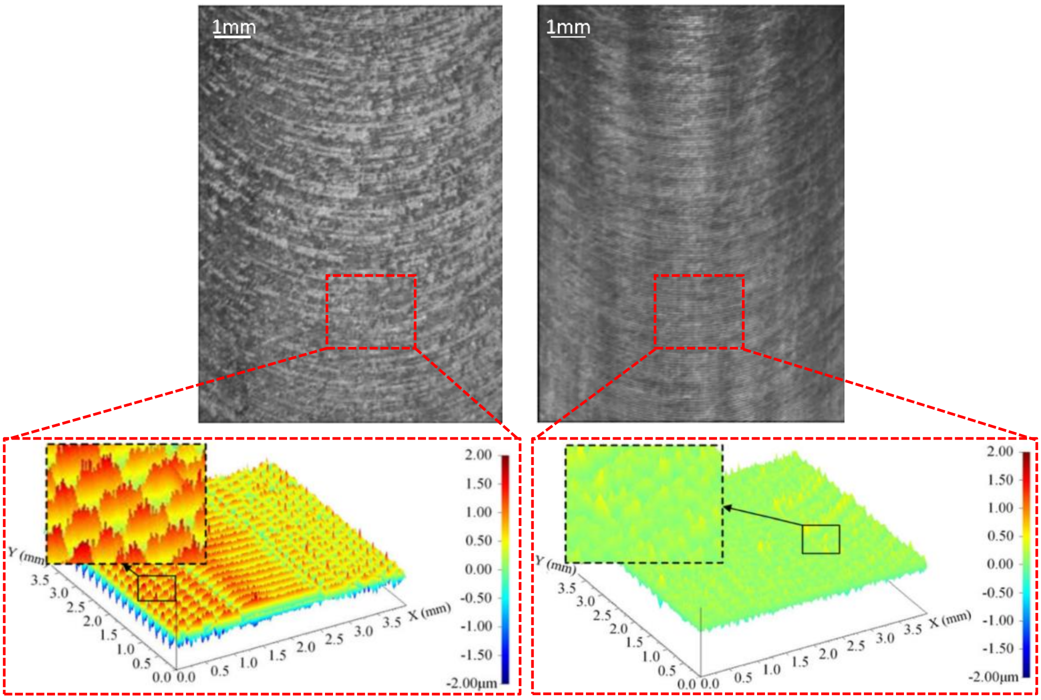


Figure 4. Surface roughness measurement perpendicular to the machined grooves for the best run result (run no. 19) with ultrasonic vibration.

The results also revealed that a smooth surface roughness could be produced using an optimal cutting parameter combination of UVAM. The surface finish was improved because of the applied ultrasonic vibration to the oscillating tool and the relative motion complexity. Ultrasonic vibration dramatically altered the tooltip's pattern trajectory, causing a regular and repeated separation of tooltips from the workpiece. In this experimental study, the cutting tool vibrates 20,000 times per second in an axial direction creating a hammering action on the machined surface, causing higher concentrated stress force on the new surface[30]. This concentrated stress force has improved the surface roughness magnitudes and reduced the peak height due to flattening the cutter marks left by the cutter's teeth.

Surface Topography

Based on the researcher's studies[2,9,30,47–51], surface topography finishing is positively affected by ultrasonic vibration. The topography and surface texture in UVAM are different from those of CM. Fig. 5 shows the macroscopic observation and their 3D topography of the machined surface for Run no. 19 between CM and UVAM. It can be observed that machined surface texture using UVAM has an excellent surface texture with smaller cutter feed marks than conventional machining. Irregular tool path, peaks, feed marks, and uneven valleys are much observed in the CM process, which results in irregular convex and concave surface finish. Extrusion, shear, and friction of tool-workpiece are factors that the removal of material depends on. However, on the finished surface in UVAM, several micro dimples and few feed marks are found, and they are regularly arranged. In this research, micro dimples formation over the machined surface results from the continuous instantaneously vibrating tool impacting the workpiece. The machined surface's topography generation is determined by the cutter travel, trajectory, and cutter geometry.



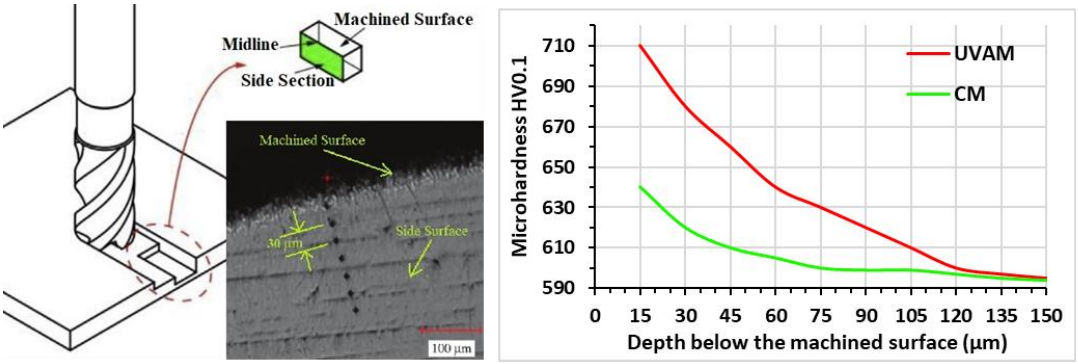
(a) (b)

Figure 5. Machined surface macroscopic images and their 3D topography for run no. 19 of (a) conventional milling on the left and (b) UVAM on the right.

Increasing the cutting speed, a better surface will be produced. This might be attributed to the particular vibration frequency and high rotational speed that affect the cutting tool's trajectory by lowering the cutting time. The generated machined surface cutter marks are less, as illustrated in Figure 5 (b). The machined surface created by the UVAM process was uniform and had a consistent peak to peak value which significantly improved the surface finish[29,30]. The cutter marks became more consistently scaly, uniform, and structured. A peening surface resulting from the localized stress force was observed, making the surface to be smoother and shiny, resulting from the ultrasonic machining. However, for the feed rate case, it was evident that increasing the rate of feed resulted in a rougher surface finish value. It is attributed to the increased thrust force that acts on the workpiece's surface, which affects machining stability, thus, leading to higher surface roughness.

Subsurface Microhardness

Work hardening occurs when subsurface layers plastically deform. The critical parameter affecting the machined surface tribological properties is surface microhardness. The specimen's surface microhardness for run no. 19 using both CM and UVAM techniques is illustrated in fig. 6. Fig. 6 (a) shows the scheme and principle behind Vickers microhardness measurement, where a load of 100 g for 10 seconds is applied to the indenter. Fig. 6 (b) shows that at the UVAM method, the subsurface microhardness near the outer machined surface is higher than CM. the significant plastic deformation induced by ultrasonic vibration in the UVAM method of the subsurface layer improves the work hardening of the machined surface. An intermittent cutting mechanism occurs when ultrasonic axial vibration is applied. Besides, reciprocating pressing characteristics, dynamic impulse, oscillation acceleration, linear vibration velocity, and considerable impact energy of the ultrasonic vibration all significantly affect the subsurface layer by generating severe plastic deformation, as discovered by Liu et al.[1] and Zhang et al.[2]. This can be attributed to the enhanced strain hardening resulting from mechanical effects through ultrasonic axial vibration.



(a) (b)

Figure 6. Distribution of Microhardness for run no. 19 below the machined surface in both UVAM and CM methods (a) Principle of microhardness measurement, (b) Values of microhardness.

CONCLUSIONS

This paper has demonstrated axial ultrasonic vibration on the rotating cutter, which significantly improves the machined surface condition. The presence of the axial ultrasonic vibration transmitted to the tip of the cutter creates a hammering action that flattens the cutter marks left by the cutter teeth. Also, both collaborative activities, i.e., rotating cutter and vibration impacts, increase the localized stress force on the surface, reducing the height of the peak, hence improving the value of surface roughness of the machined surface. The findings from this study reveal the following:

1) The interaction between the studied cutting parameters has significantly affected the Ra values.
2) Ra's surface roughness has been improved by up to 89.7% compared to the conventional milling process with the same cutting conditions.
3) The macroscopic analysis shows that the machined surface obtained using ultrasonic-assisted milling becomes consistently scaly, uniform, structured, shiny, and smooth compared to conventional machining.
4) The effect of frequency vibration and constant hammering process between cutter teeth and workpiece significantly influences surface roughness.
5) After applying ultrasonic vibration, a dramatic decrease in surface roughness values occurs compared to CM experiments.
6) Run no. 19 (1 µm amplitude, frequency of 20 kHz, 15 µm depth of cut, 20 mm/min of feed rate, and rotational speed of 1450 rpm) produced the lowest surface roughness for both conventional and UVAM method with an average value of 1.32 µm and 0.14 µm, respectively.
7) The machining cycle can be further improved to increase productivity.
8) The results can be used to improve the machining techniques for hardened AISI H11 tool steel material.

9) The vibration-assisted milling process is more complex than vibration-assisted turning processes.

10) Micro tool wear, VAM duty cycle, dynamic cutting forces, instantaneous uncut chip thickness, tool tip trajectory, etc. are difficult to obtain, so that precise dynamic and kinematic models are significantly required to guide the process of UVAM.

11) To the extend tool life and improve the machining performance, special milling tools for UVAM should be designed.

12) The combination of Hybrid machining technology with UVAM is key parameter to extend tool life, increase process reliability, allow very fine structures, and reduce the process forces.

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