ROTARY ULTRASONIC ASSISTED MACHINING OF MOULD AND DIE MATERIAL

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ABSTRACT: The high strength properties of hardened steel AISI D2 material (~51 HRc) have created problems to the conventional machining process; poor machined surface, high cutting force, extreme machining temperature and rapid tool wear. In order to solve the discrepancies in machining the material, this paper proposed a hybrid machining process technique that combined a high frequency ultrasonic vibration (~20 kHz) with the rotating end mill. An in-house ultrasonic tool holder that fitted the CNC machine spindle was developed to perform the ultrasonic assisted machining process. A set of experimental work was conducted to evaluate the improvement of the ultrasonic vibration in the cutting process. The evaluation included the effects of machining parameter namely cutting speed, feed rate, depth of cut, ultrasonic frequency and vibration amplitude in improving the surface roughness value for machining hardened AISI D2 material. The analytical results demonstrated that the presence of the ultrasonic vibration was able to improve the machined surface roughness in that up to 80% reduction in Ra value was observed as compared to the conventional machining process within the same cutting conditions.

KEYWORDS: *Hardened Steel; Hybrid Machining Process; Surface Roughness; Precision Machining*

1.0 INTRODUCTION

Hardened steel material is commonly used for mould and die applications. For such aforementioned applications, the material is typically produced by a machining process [1]. Mould and die component is generally machined by end milling process followed by a manual polishing process to obtain the required surface finish value [2]. In mould and die application, the surface roughness value is a critical aspect as it will affect the product performance. Surface roughness is defined as a surface topography and measured by the irregularities in the direction of the normal vector of a real surface compared to its ideal form. However, the machinability rating for hardened steel material is very poor that reflects the surface roughness values [3]. Apart from that, other common problems encountered during the machining of hardened steel material are high thrust force, excessive machining temperature and rapid tool wear [4]. Hence, the issues that relate to machining hardened material must be solved as to survive in the competitive manufacturing market.

Recently, an ultrasonic application to improve the machining process has gained great attention. Ultrasonic machining (USM) is the non-conventional machining process in which the material is removed from the surface by micro chipping hammering, aided by fine abrasive grains in a water slurry which vibrates between 20-40 kHz with 12-75 μm of amplitude [5-6]. Unlike the normal USM process, the mechanics of material removal mechanism rotary ultrasonic assisted machining (RUAM) are the combination between ultrasonic frequency vibration amplitude and rotating end mill cutter. The amalgamation between both actions causes the cutter to shear whilst periodically vibrate perpendicular to the work surface at a constant feed [7-8]. Figure 1 depicts the mechanics of RUAM material removal process.

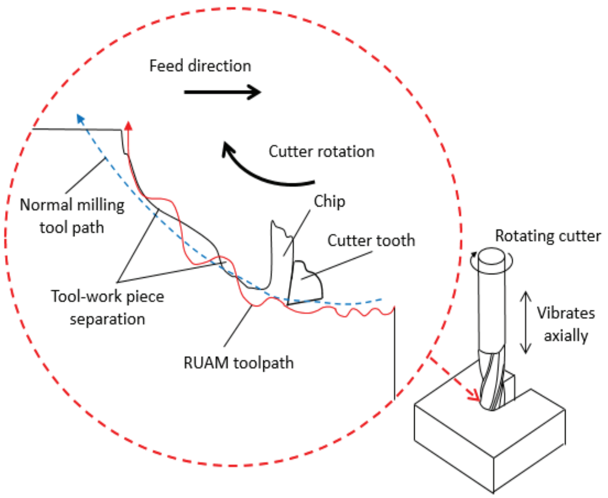


Figure 1: Mechanics of RUAM material removal process

Currently, RUAM is employed for shaping hard and brittle material such as ceramics, hardened steel and composites materials [9]. Unlike the normal USM process, the abrasive slurry in the RUAM process is replaced by a metal bonded diamonds abrasives tool that vibrates ultrasonically and rotates with constant pressure pressed against to the work piece surface [10]. The literature shows that employing the ultrasonic vibration with machining such as milling, turning and drilling is able to maximize the material removal rate, decrease the machining forces and improve the surface finish by reducing the peak height produced from the milling cutter. Suzuki [11] employed an elliptical ultrasonic vibration machining technique of hardened steel material. They found the reduction in machined surface roughness value as compared to the conventional milling process. In a similar experimental work, Moriwaki et al. [10] recorded an improvement of surface roughness value of 0.11 µm Ra using cutting speed of (523 mm/min), depth of cut (10 µm) and feed (57 µm) respectively for machining hardened steel material (HRC 50). They observed that employing the ultrasonic vibration can decrease the peak height produced from the milling cutter tool. In addition, the tool wear rate improvement on a single crystal diamond tool is also observed.

Although several researchers have claimed on the success of RUAM in improving the machined surface roughness value for hardened material, a long process cycle needs to be completed for the machining process which is not practical such as slow feed travel and low machining depth. Hence, this paper was to improve the cycle time by investigating the effects of cutting parameter for RUAM process at high level.

2.0 METHODOLOGY

The experiment work was performed to investigate the effectiveness of applying ultrasonic frequency directed to the rotating tool on machining hardened steel material. Machined surface roughness value, Ra was taken as a response performance. Slot milling test with different parameter values such as speed, feed rate and axial depth of cut were performed to compare between the presence and absence of ultrasonic vibration using HAAS VF-1 3 axis vertical CNC milling machine. The work piece material employed in this study was hardened AISI D2 cold work tool steel (~51 HRc) with 100 x 100 x 20 mm dimension of width, height and length respectively. Table 1 depicts the details of AISI D2 material composition. The work piece surface was skimmed down to 0.5 mm as to remove any surface problems or defects from previous manufacturing process [12]. Figure 2 and Table 2 depict the rotary ultrasonic assisted milling setup and the slot milling cutting parameter conditions respectively. Two flutes solid carbide ball nose mill with K20 micro grain, 5 mm diameter, 35 helix angle degrees and 50 mm length were used in the experiment.

Table 1: AISI D2 material composition

Chemical Composition	C	Si	Mn	Cr	Mo	V
	1.55	0.3	0.4	11.8	0.8	0.5

Table 2: Slot milling parameter conditions

Parameter	**Setting**
Cutting speed (rev/min)	30to 150
Feed rate (mm/min)	5 to 45
Depth of cut (μm)	10 to 30
Frequency of vibration (kHz)	20 to 27
Amplitude (μm)	1 to 3

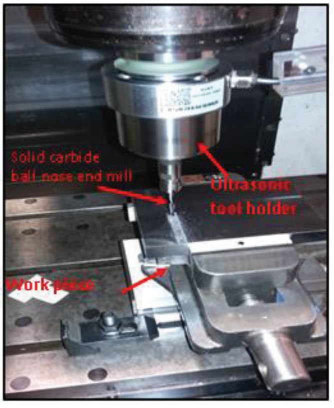


Figure 2: Ultrasonic assisted milling setup

Mitutoyo Surftest SJ-301 was used to analyze the machined surface roughness of both techniques. The peaks and valleys of the surface were measured using Ra parameter (arithmetical mean deviation of the assessed slot) at a location shown in Figure 3. Maximum value of Ra was taken for each slot and average value was calculated as the input to surface roughness response. In addition, stereo microscope was used for the macroscopic observation of machined surface.

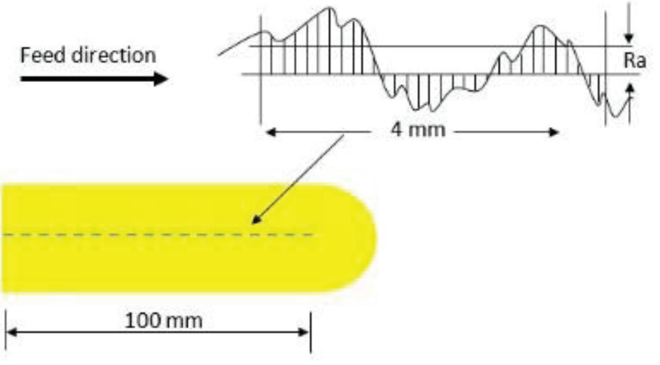


Figure 3: Surface roughness measuring location

3.0 RESULTS AND DISCUSSION

3.1 Surface Roughness Results and Analysis

The ultrasonic machining has been recently applied in mould and die industry for finishing of various precision parts such as mirror surface finishing of mould and die materials. The ultrasonic vibration presence in the rotating cutting tool can improve the surface roughness value up to 89 %. The incorporation of the ultrasonic vibration creates an imposed static pressure on the work piece surface grains, in which the work piece surface is hammered into, and finally a peening surface is produced that improves the surface finish by reducing the peak height produced from the milling cutter.

Table 3 and Figure 4 depict the measured surface roughness values of all the runs. The variation in surface roughness values were observed for different parameter levels condition.

Table 3: Experimental results

Run	Speed (RPM)	Feed mm/m	DOC (μm)	Freq. (kHz)	Amp. (μm)	Ra (μm)
1	90	45	10	23	2	2.15
				No Ultrasonic		5.58
2	90	25	30	20	1	4.54
				No Ultrasonic		5.07
3	90	25	30	20	2	3.15
				No Ultrasonic		5.04
4	150	45	20	20	1	4.59
				No Ultrasonic		5.14
5	150	45	20	20	2	3.57
				No Ultrasonic		5.16
6	90	5	20	27	1	1.60
				No Ultrasonic		1.87
7	90	5	20	27	2	1.84
				No Ultrasonic		1.89
8	150	25	10	27	3	2.88
				No Ultrasonic		3.82
9	150	25	10	27	2	3.24
				No Ultrasonic		3.85
10	90	45	10	23	3	2.86
				No Ultrasonic		5.55
11	30	5	10	20	1	3.62
				No Ultrasonic		4.02
12	30	45	30	27	1	3.06
				No Ultrasonic		6.31
13	150	5	30	23	2	0.91
				No Ultrasonic		1.93
14	150	5	30	23	1	0.35
				No Ultrasonic		1.94
15	30	5	10	20	3	2.60
				No Ultrasonic		4.04
16	30	5	10	20	3	3.66
				No Ultrasonic		5.54
17	30	5	10	20	2	2.94
				No Ultrasonic		4.00
18	30	25	20	23	1	5.50
				No Ultrasonic		6.37

19	30	45	30	27	3	3.25
				No Ultrasonic		6.65
20	30	25	20	23	3	5.28
				No Ultrasonic		6.49
21	30	25	20	23	3	4.86
				No Ultrasonic		6.10
22	150	5	30	23	3	0.70
				No Ultrasonic		1.95
23	150	45	20	20	3	2.91
				No Ultrasonic		5.14
24	90	25	30	20	3	2.72
				No Ultrasonic		5.03
25	150	25	10	27	1	0.78
				No Ultrasonic		3.86
26	90	5	20	27	3	0.19
				No Ultrasonic		1.81
27	30	25	20	23	2	5.15
				No Ultrasonic		6.22

The obtained Ra values for ultrasonic technique and conventional were in the range between 0.19 µm to 5.50 µm and 1.81 µm to 6.65 µm respectively. One major thing to be highlighted from the result is for all of the RUAM experimental runs, the surface roughness values are dramatically decreased after ultrasonic vibration was applied compared to the conventional milling process. In addition, variations seen in the values indicated that RUAM cutting parameter had a significant effect on the response values (surface roughness). It can be observed that the combination of runs no. 26 (Speed of 90 rpm, 5 mm/min feed rate, 20 µm depth of cut, frequency of 27 kHz and 3 µm amplitude) produced the lowest surface roughness with an average value of 0.19 µm as shown in Figure 4.

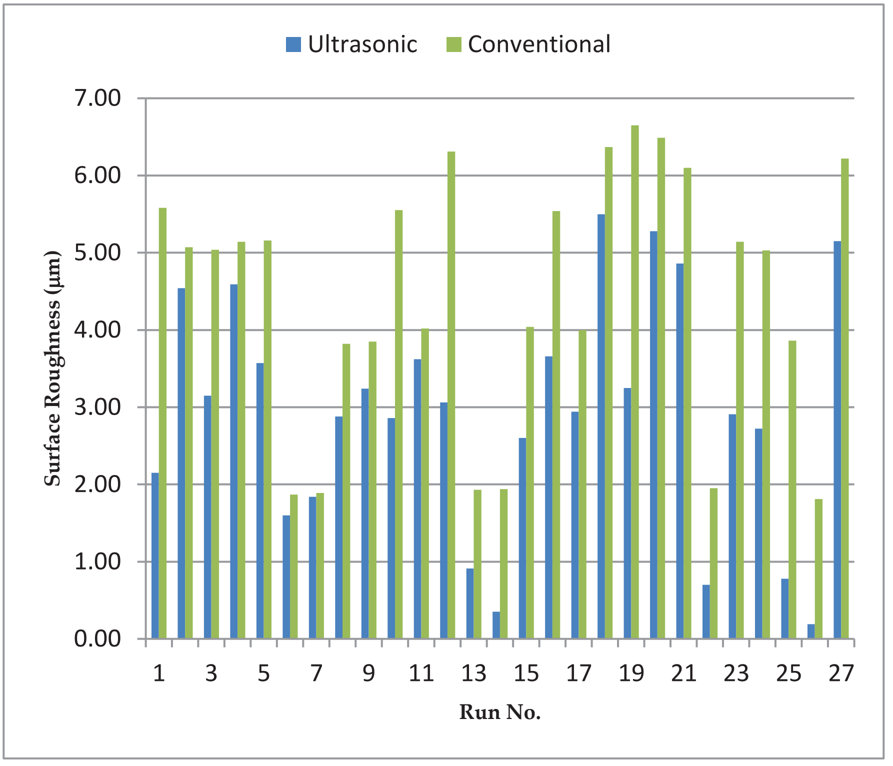


Figure 4: Surface roughness results between RUAM and conventional machining

The results showed that an optimal combination of RUAM cutting parameter could produce a smooth surface roughness and for this case it provided a deterioration of surface roughness due to the complexity of the relative motion between the tool and the work piece after ultrasonic vibration was applied. It is very clear that ultrasonic vibration greatly changed the movement pattern of tool tips, causing the tool tips to separate from the work piece repeatedly and regularly [13]. In this RUAM experimental work, the tool produced nearly 20-27 kHz vibrations in the axial direction within 1 s, creating small tool marks on slot bottom surface than that in the conventional milling process. Hence, an addition of the ultrasonic movement in axial direction creates a hammering action that increases the localized stress force on the surface [14-15].

This localized stress has flattened the cutter marks left by the cutter teeth, thus, reducing the peak height and improving the surface roughness values as depicted in Figures 5 and 6.

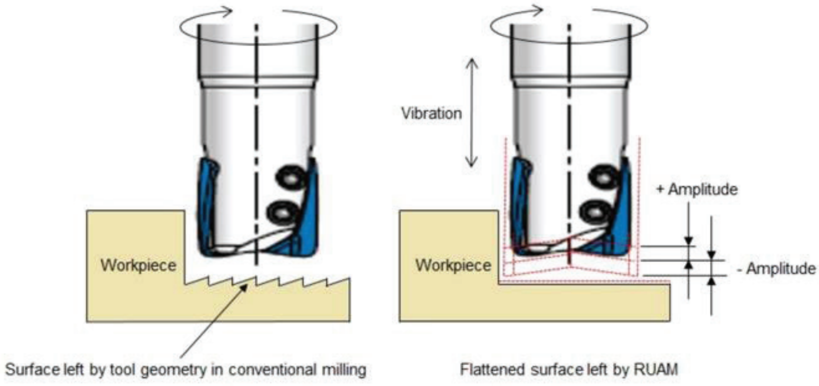


Figure 5: Comparison of machined surface between conventional and RUAM

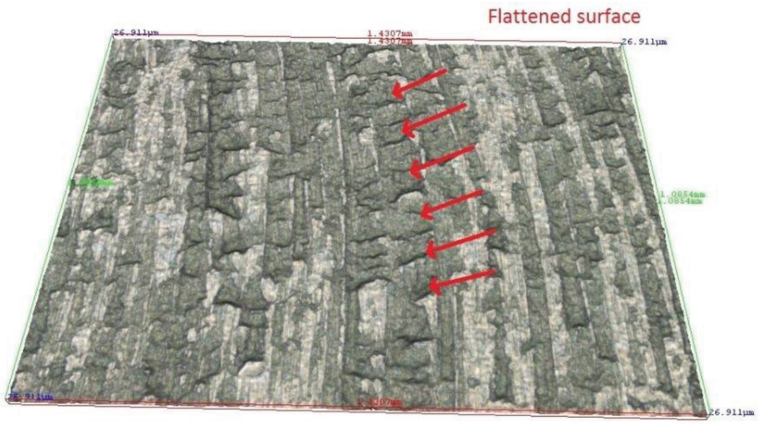


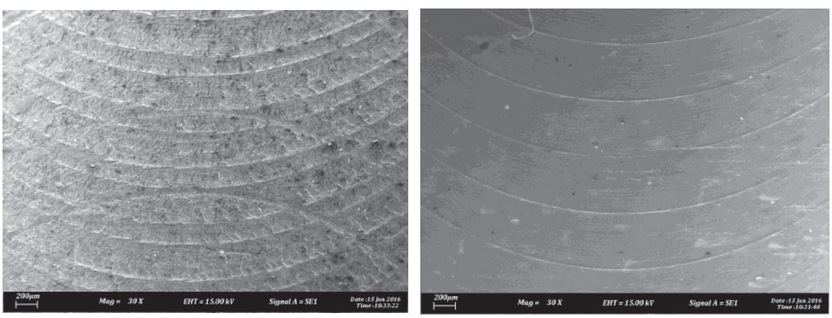
Figure 6: Machined surface topography for RUAM in the flattened surface

ANOVA was performed to further investigate on the effects of each parameter towards the surface roughness results (Table 4). The ANOVA tests showed that the generated model was significant, with p-value of <0.0001 and F-value of 27.03 indicating that there was only a 0.01% chance that the model could occur due to the noise. In addition, p-value less than 0.0500 indicated that the model terms were significant and in this case, the strongest machining parameter factor that affected the surface roughness value in the design space were speed, feed, ultrasonic frequency followed by ultrasonic amplitude. The R-Squared of 0.74 was in a reasonable agreement with the Adj R-Squared of 0.71 showed the adequacy of the model in predicting the response in the design space.

Table 4: ANOVA results

Source	Sum of Squares	DF	Mean Square	F Value	p-value
Model	118.19	5	23.64	27.03	< 0.0001
A	40.03	1	40.03	45.78	< 0.0001
B	49.16	1	49.16	56.21	< 0.0001
C	0.32	1	0.32	0.37	0.4482
D	7.17	1	7.17	8.19	0.8849
E	0.19	1	0.19	0.22	0.5139
Residual	41.97	48	0.87		
Pure Error	2.53	20	0.13		
Total of mean corrected	160.16	53			

It can be seen that by increasing the cutting speed and ultrasonic frequency, a better surface will be produced. One of the possible reasons is high spindle speed and certain vibration frequency will affect the exact tool trajectory by shortening the cutting period, producing less cutter marks on the machined surface as shown in Figure 7 (b). It can be clearly observed that machined surface produced from RUAM was uniform and had a consistent peak to peak value which significantly improved the surface finish. The cutter marks became more consistently scaly, uniform and structured. In addition, a peening surface resulting from the localized stress force was clearly observed which made the surface to be smooth and shiny, resulting from the ultrasonic machining as shown in Figure 7 (a) and (b). However, for the case of feed rate, surface roughness value increased as feed rate increased. This is due to the rise of thrust forces which act on the work piece surface that affect the machining stability, thus, increasing the roughness value.



(a) (b)

Figure 7: Cutter marks formation for (a) conventional milling and (b) RUAM

4.0 CONCLUSION

This paper has demonstrated the presence of ultrasonic vibration on the rotating cutter which significantly improves the machined surface condition. The presence of the ultrasonic vibration transmitted to the tip of the cutter creates a hammering action that flatten the cutter marks left by the cutter teeth. In addition, both combined actions i.e. rotating cutter and vibration impact increase the localized stress force on the surface which reduce the peak height, hence, improving the surface roughness value. The findings from this study reveal that the interaction between the study cutting parameter has significantly affected the Ra values. Hence, the machining cycle can be further improved to increase productivity. The macroscopic analysis shows that the machined surface obtained using an ultrasonic assisted milling becomes consistently scaly, uniform, structured and smooth compared to the conventional machining due to the effect of frequency vibration and constant hammering process between cutter teeth and work piece. The outcomes from the results can be used to improve the machining techniques for hardened AISI D2 tool steel material.

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REFERENCES

[1] E. Budak, I. Lazoglu, and B. U. Guzel, "Improving cycle time in sculptured surface machining through force modeling", *CIRP Annals,* vol. 53, no. 1, pp. 103–106, 2004.

[2] R. Izamshah, M. Zulhairy, M. Kasim, M. Hadzley, M. Amran and M. Amri and Sivarao, "Cutter path strategies for shoulder milling of thin deflecting walls", *Advanced Material Research*, vol. 903, pp. 175–180, 2014.

[3] E. Shamoto, N. Suzuki, E. Tsuchiya, Y. Hori, H. Inagaki and K. Yoshino, "Development of 3 DOF ultrasonic vibration tool for elliptical vibration cutting of sculptured surfaces", *CIRP Annals,* vol. 54, no. 1, pp. 321–324, 2005.

[4] R. Suresh, S. Basavarajappa, V.N. Gaitonde, G.L. Samuel, and J. Paulo Davim, "State-of-the-Art research in machinability of hardened steels", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 227, no. 2, pp. 191–209, 2013.

[5] B. C. Routara, A. K. Sahoo, A. K. Rout, and D. N. Thatoi, "Optimization of multiple performance characterstic in ultrasonic machining process using grey relational analysis", in Proceedings of the International Conference on Mechancal Engineering, Dhaka, Bangladesh, 2011, pp. 18–20.

[6] W. L. Cong, Z. J. Pei, N. Mohanty, E. Van Vleet, and C. Treadwell, "Vibration amplitude in rotary ultrasonic machining: a novel measurement method and effects of process variables", *Journal of Manufacturing Science and Engineering*, vol. 133, no. 3, pp. 034501-1–034501-5, 2011.

[7] R. P. Singh and S. Singhal, "Rotary ultrasonic machining of advanced materials: a review", *International Journal Technology for Research in Engineering*, vol. 2, no. 7, pp. 777–785, 2015.

[8] G. Ya, H. W. Qin, S. C. Yang and Y. W. Xu, "Analysis of the rotary ultrasonic machining mechanism", *Journal of Materials Processing Technology*, vol. 129, no. 1–3, pp. 182–185, 2002.

[9] H. Lian, Z. Guo, Z. Huang, Y. Tang and J. Song, "Experimental research of Al6061 on ultrasonic vibration assisted micro-milling", *Procedia CIRP*, vol. 6, pp. 561–564, 2013.

[10] T. Moriwaki, E. Shamoto, Y. Song and S. Kohda, "Development of a elliptical vibration milling machine", *CIRP Annals,* vol. 53, no. 1, pp. 341–344, 2004.

[11] N. Suzuki. (2011). *Ultraprecision sculpturing of hardened steel by applying elliptical vibration cutting* [Online]. Available: http://www.jspe.or.jp/wp_e/wp-content/uploads/isupen/2011 s/2011s-2-6.pdf

[12] M. S. Kasim, C. H. Che Haron, J. A. Ghani, and M. A. Sulaiman, "Prediction surface roughness in high-speed milling of inconel 718 under MQL using RSM method", *Middle-East Journal Science and Research*, vol. 13, no. 3, pp. 264–272, 2013.

[13] P. Guo and K.F. Ehmann, "An analysis of the surface generation mechanics of the elliptical vibration texturing process", *International Journal of Machine Tools and Manufacture,* vol. 64, pp. 85–95, 2013.

[14] X. Zhang, A. S. Kumar, M. Rahman, C. Nath and K. Liu, "Experimental study on ultrasonic elliptical vibration cutting of hardened steel using PCD tools", *Journal of Materials Processing Technology,* vol. 211, no. 11, pp. 1701–1709, 2011.

[15] X. Zhang, K. Liu, and A. S. Kumar and M. Rahman, "A study of the diamond tool wear suppression mechanism in vibration-assisted machining of steel", *Journal of Materials Process Technology*, vol. 214, no. 2, pp. 496–506, 2014.