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Investigation on Improvement of Surface Roughness Using Rotary Ultrasonic Assisted Machining Technique for Hardened Steel Material

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ABSTRACT

Several challenges are faced by manufacturers producing best surface finish especially for the mould and die applications. In general, most of the mould and die material are made from hardened steel (~40-60 HRc). The high strength of these materials reduced the capability of the conventional machining technique. Poor machined surface and high tool wear rate are among the problems associated with the conventional machining of this material. To overcome these problems, this paper proposed a hybrid machining process by adding an ultrasonic transducer to the normal tooling system namely ultrasonic assisted machining (UAM). Experimental work consisted of a comparison between ultrasonic assisted machining and conventional machining for different parameters namely cutting speed, feed rate and machining depth in order to validate the effectiveness of the proposed technique in improving the surface roughness value for machining hardened AISI D2 material. 2 level factorial design with 3 factors was employed as the technique of design of experiment (DOE). The machining

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test showed that the presence of rotary ultrasonic assisted vibration significantly improved the machined surface roughness with up to 85% reduction in Ra value compared to the conventional machining process with the same cutting conditions. In addition, the macroscopic observation of machined surface showed that the surface produced from ultrasonic machining was uniform with consistent peak to peak value which improved the surface finish.

Keywords: *Hardened Steel, Ultrasonic Assisted Vibration Machining, Surface Roughness*

Introduction

In ~~a~~ mould and die industries, the requirement for best machined surface finish is crucial, in order to reduce the manual polishing process, which is costly and time consuming [1,3]. Currently, the conventional machining process employed for the mould and die material (hardened steel with ~40-60 HRc) creates several challenges such as poor machined surface, high cutting force, extreme machining temperature and rapid tool wear [4,6]. Hence, a hybrid machining process is proposed, namely ultrasonic assisted machining (UAM).

UAM is a combination of ultrasonic vibrations with normal machining and is used in machining of difficult to cut materials [7,9]. UAM involves the use of ultrasonic vibration frequency, ranging between 20-40 kHz that is transmitted to the rotating cutting tool. According to [10], ultrasonic assisted machining is used for machining hardened steel to get a mirror machined surface and to eliminate the manual polishining process. By first incorporating the ultrasonic frequency to the rotating cutting tool, the vibration oscillation amplitude of the tool is altered which imposes a static pressure on the workpiece surface grains where the workpiece surface is then, hammered into. Finally, a peening surface is produced that improves the surface finish by reducing the peak height produced from the milling cutter. Furthermore, the transmitted oscillating vibration also reduces the contact pressure between the cutting tool and the workpiece, thus reducing the machining force and temperature that consequently improving the cutting tool life. The surface roughness of machined surface improves from 0.60 μm to 0.26 μm (up to 57% reduction) when the ultrasonic assisted milling of hardened steel material is applied and when using solid carbide ball nose as the tool material [10]. In machining of hardened steel material, surface roughness is the most important factor to obtain a high quality of machined surface, dimensional accuracy of machined work piece and good of surface integrity [11].

This study was conducted to evaluate the surface finish between ultrasonic machining and conventional machining for different parameters namely cutting speed, feed rate and machining depth on hardened AISI D2 material. In addition to this, macroscopic observation of the machined surface was also employed to evaluate the phenomena of the cutting process.

Experimental Work

Machining experiment was conducted to evaluate the effectiveness of machining parameters namely cutting speed, feed rate and depth of cut on machined surface roughness during slot milling machining using rotary ultrasonic assisted machining. AISI D2 tool steel with 51 ± 2 HRc hardness and 125 mm X 100 mm X 19 mm (LxWxH) dimension was used. Before machining was executed, the raw material was skimmed down to 0.5 mm by vertical milling machine to remove any defect or any surface problems from previous manufacturing processes [12]. Details of the material chemical compositions are tabulated in Table 1. All tests were done using HAAS VF-1 3 axis CNC milling machine, and for the ultrasonic machining tests, a BT40 ultrasonic tool holder with a frequency of 23.83 kHz and amplitude of 2 μm was used. Figure 1 illustrates the ultrasonic tool holder. A total of 8 runs of slot machining tests was performed using 2 flutes carbide flat end mill with 6 mm shank diameter and 30° helix angle as cutting tools. Figure 2 shows the cutting tool used in the experiment. All experiments were conducted in dry cutting condition without the presence of any coolant and lubricants.

Table 1: Chemical compositions of AISI D2

Composition	**C**	**Si**	**Mn**	**Cr**	**Mo**	**V**
% weight	1.55	0.3	0.4	11.8	0.8	0.8

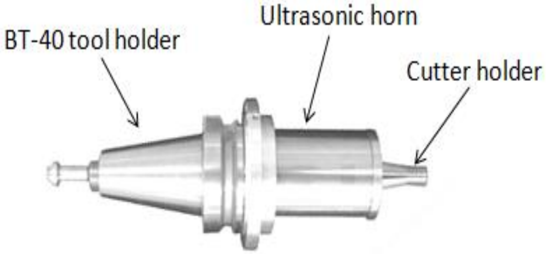


Figure 1: Ultrasonic tool holder

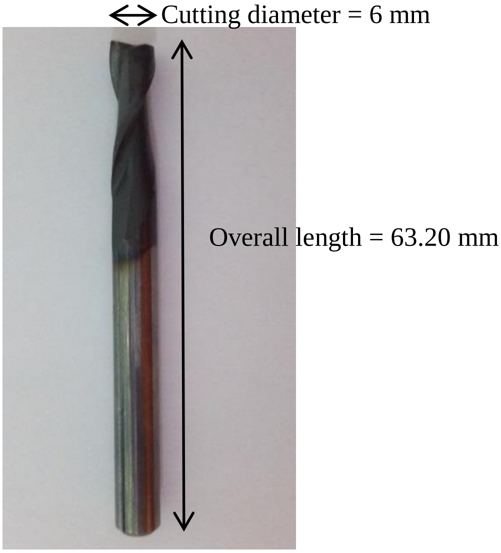


Figure 2: Cutting tool used in the experiment

The machining process was carried out for different parameters namely cutting speed, feed rate and machining depth of cut. A full factorial design of experiment with two levels of each factor was used and the independent variables were the cutting speed, feed rate and depth of cut. Details of the cutting parameter are tabulated in Table 2.

The surface roughness of the cutting slot was measured using a portable surface roughness tester (SJ 301). The surface roughness tester equipment must be calibrated prior to the reading of the measurement. The arithmetic average value of surface roughness, Ra was taken immediately upon the completion of every slot milling machining. The measurement was repeated 10 times on horizontal (feed direction) axis for every sample at random locations and the average of arithmetic value of surface roughness, Ra was calculated. After measuring the surface roughness, the macroscopic observation of machined surface was captured using optical microscope. 2 level factorial design was utilized as the design of experiment (DOE). Full factorial design is suitable to study the effect of cutting parameters on surface integrity (SI) [13]. In this study, the independent variables used were cutting speed (A), feed rate (B) and depth of cut (C), and a ‘maximum’ and ‘minimum’ setting on machining process were utilized to determine which had the greatest effect on cutting performance. Table 2 shows the two levels cutting parameters. From 2 level factorial design, 8 experimental runs were generated for the measurement of machining performance (surface roughness) analysis. Table 3 shows the full factorial design with 3 factors. Analysis of variance (ANOVA) in full factorial design was implemented to establish the influence of cutting parameters on output of surface integrity. The results of multiple regressions from the ANOVA were obtained and subsequently used to get an empirical model.

Table 2: Two levels cutting parameter

Level	**Cutting Speed (m/min)**	**Feed Rate (mm/min)**	**DOC (μm)**
Minimum	0.6	5	0.010
Maximum	3	100	0.012

Table 3: Full factorial design with 3 factors

Run	**Cutting Speed, *Vc* (m/min)**	**Feed rate, *f* (mm/min)**	**Depth of cut, *Ap* (μm)**
1	0.6	100	10
2	0.6	100	12
3	3	5	12
4	3	100	10
5	3	100	12
6	0.6	5	10
7	3	5	10
8	0.6	5	12

Results and Discussion

The measured machined surface roughness is tabulated in Table 4 and graphically presented in Figure 3. The results showed the observed surface roughness values for conventional machining ranged between 0.32 μm to 3.48 μm, whereas for the ultrasonic machining the surface roughness ranged between 0.27 μm to 1.11 μm. The finest and the lowest value of surface roughness was 0.27 μm at 3 m/min (cutting speed), 5 mm/min (feed rate) and 12 μm (depth of cut) with ultrasonic assisted machining. In addition, the machining parameters also affected the surface roughness value, hence requiring further investigation.

The results clearly showed the improvement of surface roughness values with the presence of ultrasonic vibration with up to 85% reduction in Ra value compared to the conventional machining process with the same cutting condition at Run 5 as shown in Table 4.

Table 4: The results of the surface roughness of machined surface with and without ultrasonic machining

Run	***Vc* (m/min)**	***f* (mm/min)**	***Ap* (μm)**	**Surface roughness, Ra (μm)**	
				Conventional	**Ultrasonic**
1	0.6	100	10	0.87	0.69
2	0.6	100	12	0.83	0.77
3	3	5	12	0.32	0.27
4	3	100	10	3.47	2.59
5	3	100	12	3.48	0.52
6	0.6	5	10	3.33	0.87
7	3	5	10	2.36	0.48
8	0.6	5	12	2.84	1.11

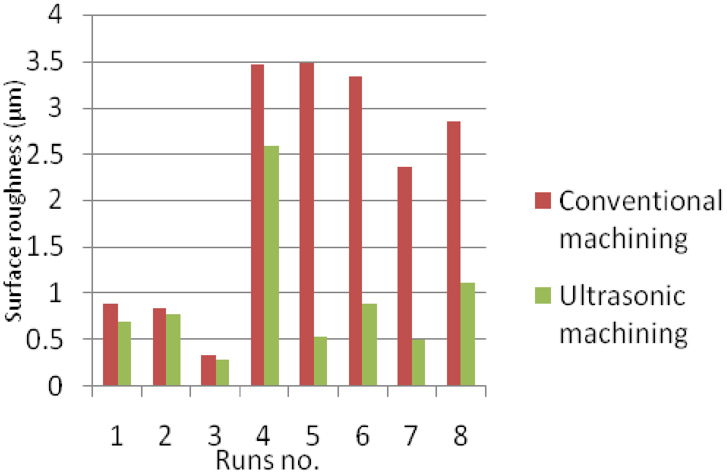


Figure 3: Comparison of surface roughness results between conventional machining and ultrasonic machining.

The data obtained from the experimental runs were analyzed. In order to find the influence of cutting parameters, data were analyzed using analysis of variance (ANOVA). ANOVA is a collection of statistical models used in order to analyze and determine the most significant factor that affects the surface roughness. In this study, the ANOVA with 5% significant level, *p* coefficient <0.050 was used to analyze and identify the influence of significant machining parameters in order to evaluate the machining performance such as surface roughness. The main effects and interaction effects were plotted from the ANOVA. While the range of surface roughness response was from 0.27 to 3.48 μm, the ratio of maximum response to minimum response was 12.8889. The main effects to be analyzed were the sum of square, degree of freedom (DF), mean square, F value, residual and total of mean corrected (Cor Total). Table 5 shows the analysis of variance (ANOVA) for response surface roughness in slot milling machining after transformation by full factorial analysis using square root (transformation by the Design Expert software). The model F-value of 3.95 implied that the model was significant.

Table 5: ANOVA Result for Surface Roughness (Ra) on Ultrasonic Machining

Source	**Sum of Square**	**DF**	**Mean Square**	**F-Value**	**Prob >F**	
Model	2.94	8	0.37	3.95	0.04343	*significant*
A	0.328	1	0.328	0.071	0.7978	
B	0.040	1	0.040	0.43	0.5331	
C	0.26	1	0.26	2.75	0.1413	
D	0.97	1	0.97	10.46	0.0144	
AB	1.37	1	1.37	14.76	0.0064	
AC	0.26	1	0.26	2.78	0.1392	
AD	0.025	1	0.025	0.26	0.6227	
BC	0.284	1	0.284	0.061	0.8116	
Residual	0.65	7	0.093			
Cor Total	3.59	15				

The probability F value that was derived from the mean square was converted into its corresponding p-value. The ANOVA analysis showed that the value of probability was small, Prob>F, near 4.343 % (p = 0.0062). In addition, when p<0.05, the relationship between surface roughness with cutting speed, feed rate and depth of cut was statistically significant. It has been shown that, the factors possessing the values less than 0.0500 of "Prob> F" indicate that the model terms are significant [14]. In this model, the parameters D and AB were significant model terms. The results of this study showed that cutting speed (A), feed rate (B) and ultrasonic assisted machining (D) were the main effects and strongly significant to the surface roughness value. The results of this study did not show that the depth of cut (C) was not affected and did not have significant effect on the surface roughness value when machining of hardened steel materials. However, the value of "Prob>F" was 0.0434 and less than 0.0500 which showed that model terms were statistically significant. The final statistical equation model was developed by ANOVA in terms of actual factors and is presented as follows in the form Equation (1):

$$\text{Surface roughness } (\mu m)_{ultrasonic} = 0.88472 + 0.88057A - 0.012574B + 0.043542C + 0.25596AB - 0.10602AC + 0.07280\,BC \quad (1)$$

This final statistical model depended on cutting speed and feed rate. The average error between the predicted value and an experiment was less than 10%, while the factor of determination for R-Squared and adjusted R-Squared was 81.86% and 61.12% respectively.

Figures 4 (a) and 4 (b) are the graphs of the 3 D response surface and contour plots. The surface roughness changed by the cutting speed and feed rate, while the depth of cut was constant. Hence, a higher cutting speed with lower feed rate can reduce the value of surface roughness. Figures 5 (a) and 5 (b) present the interaction between cutting speed and depth of cut on the surface roughness value when feed rate was constant. The lowest value of surface roughness can be achieved by increasing the depth of cut with lower cutting speed. Figures 6 (a) and 6 (b) show the estimated 3 D response surface and contour plots for surface roughness in relation to the machining parameters of feed rate and depth of cut. The value of surface roughness decreased with the decreasing of a feed rate and increasing of depth of cut. Therefore, the minimum value of surface roughness was obtained at low feed rate (5 mm/min) and high depth of cut (12 μm). This is due to the chip formed during machining operation by low feed was continuous and also tool-chips and workpiece-tool had less interaction which can reduce the friction of workpiece-tool interface [15]. Hence, the low feed rate can decrease the value of surface roughness and is in agreement with the results obtained by [11].

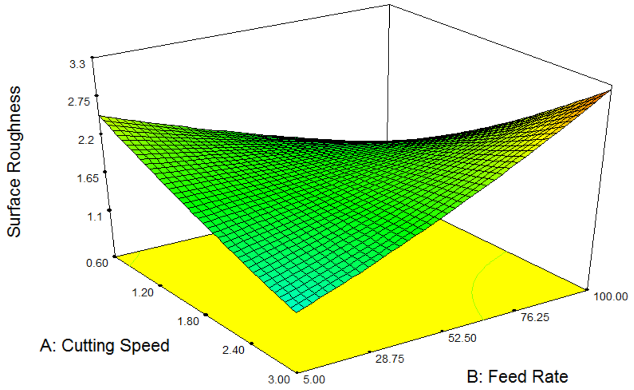


Figure 4: (a) 3D response surface graph shows two (2) machining parameters (cutting speed, feed rate) which affect the surface roughness

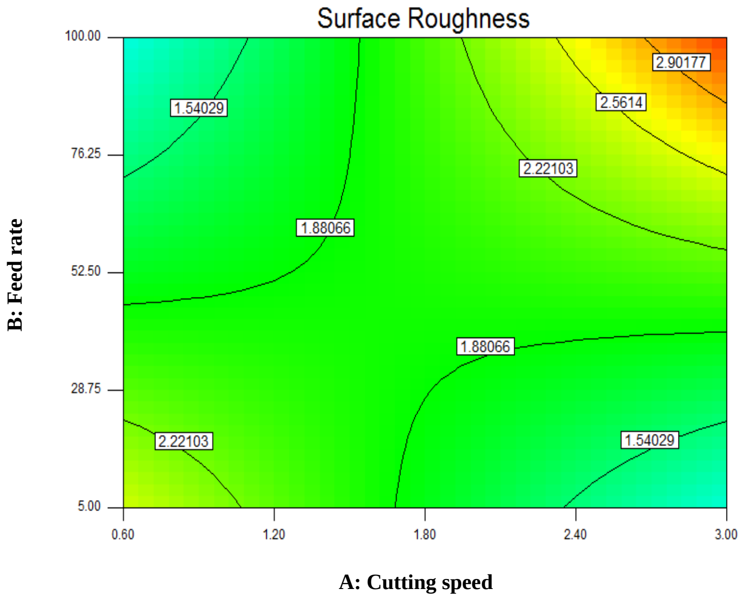


Figure 4: (b) Contour graph plots show the two (2) major factors affecting the surface roughness

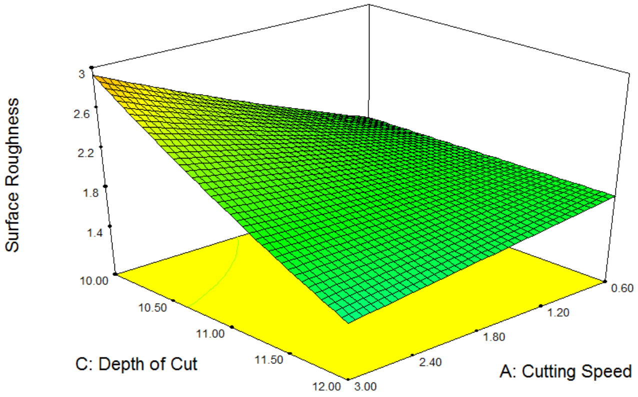


Figure 5: (a) 3D response surface graph shows two (2) machining parameters (cutting speed, depth of cut) which affect the surface roughness

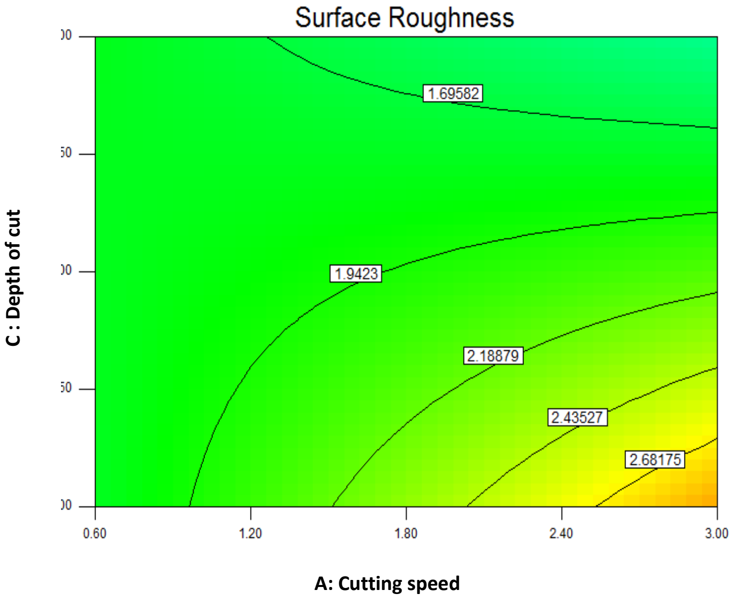


Figure 5: (b) Contour graph plots show the two (2) major factors which affect on surface roughness

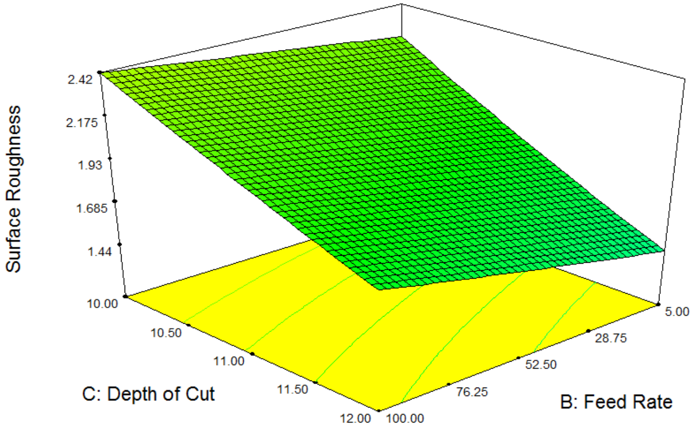


Figure 6: (a) 3D response surface graph shows two (2) machining parameters (feed rate, depth of cut) which affecting the surface roughness

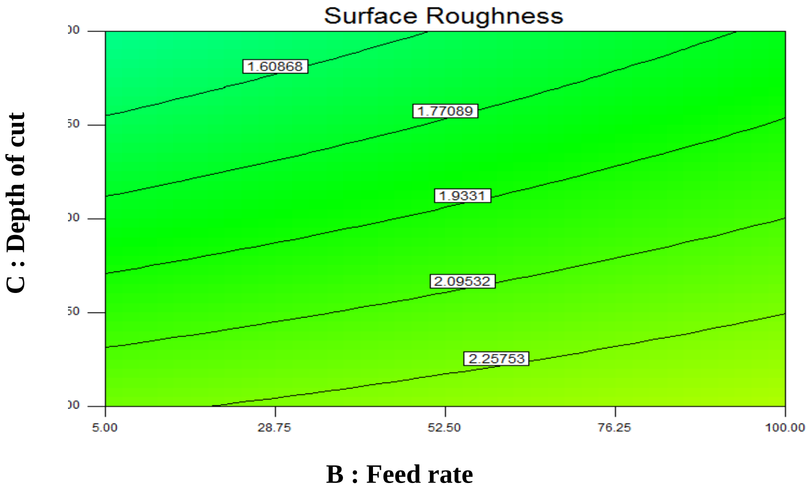


Figure 6: (b) Contour graph plots show the two (2) major factors which affect surface roughness

Figure 7 shows the normal plot of the residual graph for surface roughness generated by Design Expert. The normal probability plots of the residual graph indicate that the surface roughness value followed a normal distribution in a straight line. Distribution of data is good because all the points line up nicely. Figure 8 represents the predicted versus actual plots of response and is useful to detect outlier values that are predicted by the model and it shows that the model generated fits well with the observed values. It also shows a good agreement between the predicted values of surface roughness acquired from the model and actual experimental data.

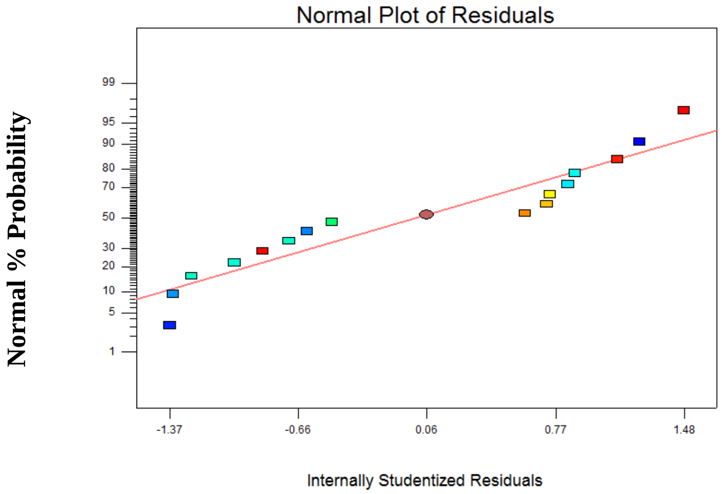


Figure 7: The normal plot of residual graph for surface roughness

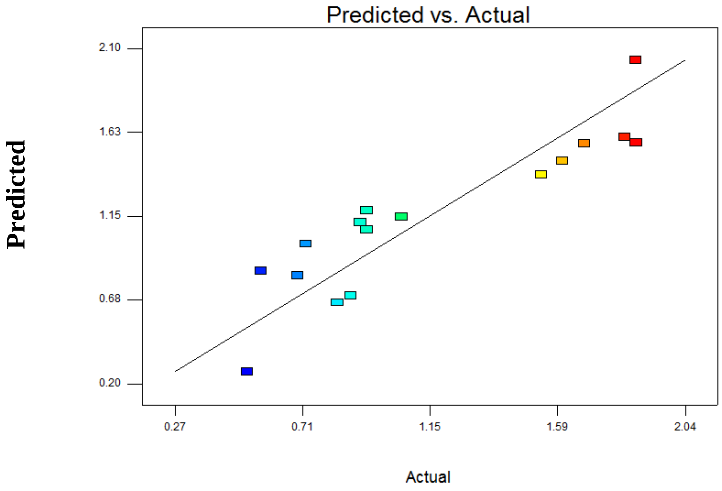
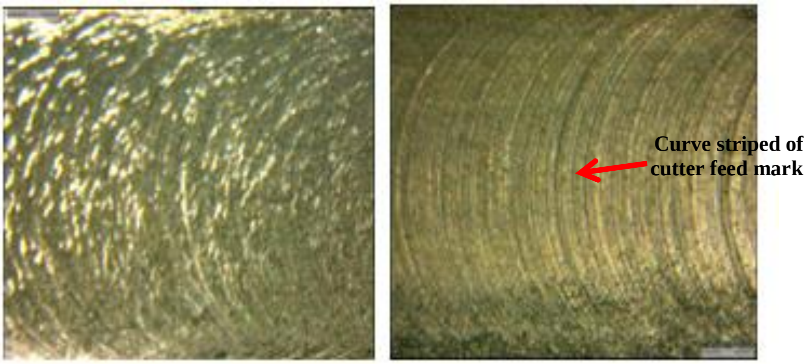


Figure 8: The predicted vs. actual graph for surface roughness

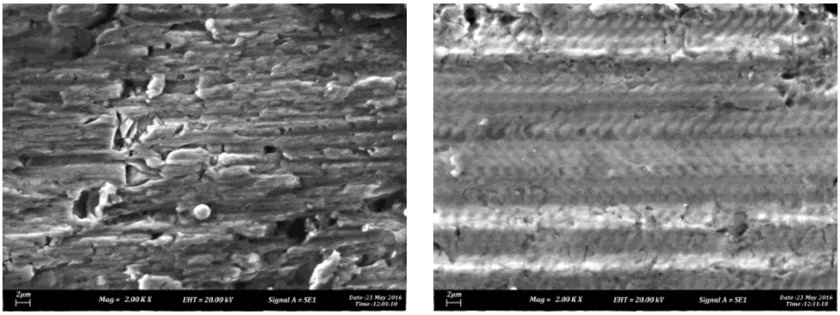
Figures 9 (a) and 9 (b) show the differences of macroscopic observation or macro surface profile in the conventional machining and the ultrasonic assisted machining of the hardened steel material using laboratory stereo microscope. The captured images from the macroscopic observation of machined surface show that the machined surface produced from the ultrasonic assisted machining was uniform with consistent peak to peak value which improved the surface finish as shown in Figure 9 (a) and 9 (b). They showed curve striped of cutter feed marks for conventional machining and ultrasonic assisted machining. The curve striped of cutter feed marks generated by ultrasonic assisted machining was consistent and had a low vibration with the smaller transverse marks compared to the conventional machining. The machined surface generated by the ultrasonic assisted machining was more shiny and luminous than what generated by the conventional machining. These results are in agreement with [16] findings which show that ultrasonic cutting generated by the smaller tranverse feed marks was caused by the low tool vibration compared to the common cutting.



a) Conventional machining b) Ultrasonic assisted machining

Figure 9: Macroscopic observation of machined surface of hardened steel material

The surface finish of machined surface can be obtained by measuring micro surface topography using Scanning Electron Microscopy (SEM) with comparison of conventional machining and ultrasonic assisted machining. Figures 10 (a) and 10 (b) present the SEM photos of the micro surface topographies of machined surface in conventional machining and in ultrasonic machining. The plastic deformation existed during the slot machining of hardened steel material. In addition, many shallow surface depressions (pits) appeared on the machined surface by conventional machining compared to rotary ultrasonic assisted machining. Rotary ultrasonic assisted machining offered machined surface which was very smooth with the consistency of feed mark. Hence, the surface quality in ultrasonic assisted machining is excellent compared to conventional machining. According to the SEM photos, we can be infered that machined surface and machining accuracy improve greatly by ultrasonic assisted machining compared to conventional machining.



(a) Conventional Machining (b) Ultrasonic assisted machining

Figure 10: The micro surface topographies by SEM with cutting speed, Vc = 3 m/min, feed, f = 100 mm/min, depth of cut, $A_p = 12\ \mu m$

Conclusion

This paper demonstrates that the presence of ultrasonic vibration on the rotating cutter significantly improves the surface roughness value. The improvement of surface roughness values with the presence of ultrasonic vibration is up to 85% reduction in Ra value compared to conventional machining process with the same cutting condition. The surface roughness values of machined surface in rotary ultrasonic assisted milling are better than conventional machining. This study has identified that the best selection of machining parameters with rotary ultrasonic assisted machining is 0.6 mm/min (cutting speed), 5 mm/min (feed rate) and 12 μm (depth of cut) with 0.27 μm of surface roughness value. The results of statistical analysis (ANOVA) show that cutting speed, feed rate and ultrasonic assisted machining are the main parameters that influence the surface roughness value. Macroscopic observation of machined surface has also shown that the machined surface generated from ultrasonic assisted machining is uniform with consistent peak to peak value which improves the surface finish. The phenomena of the cutting process by micro surface topography proves that machined surface by ultrasonic assisted machining is very smooth with the consistency of feed mark which contributes to the excellence of surface quality. This study also proves that rotary ultrasonic assisted machining successfully improves the machining accuracy with the reduction of Ra values and consistency of feed mark with the low tool vibration.

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