World Applied Sciences Journal 21 (Mathematical Applications in Engineering): 73-78, 2013
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2013.21.mae.99925

Empirical Modelling of Vibration in Micro End Milling of PMMA

[1]M.Y. Ali, [1]A.R. Mohamed, [1]A.A. Khan, [1]B. Asfana, [2]M. Lutfi and [3]M.I. Fahmi

[1]Department of Manufacturing and Materials Engineering,
International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia
[2]Perodua Manufacturing Sdn. Bhd., Sg. Choh, Locked Bag 226, 48009 Rawang, Selangor, Malaysia
[3]Perusahaan Otomobil Nasional Sdn. Bhd., HICOM Industrial Estate,
Batu 3, P.O. Box 7100, 40918 Shah Alam, Selangor, Malaysia

Abstract: This paper presents the vibration issue in micro end milling of of poly methyl methacrylate (PMMA) workpiece using integrated multi-process machine tools DT 110 (Mikrotools Inc., Singapore) with control parameter; spindle speed, feed rate and depth of cut. The vibration was measured using accelerometer (DYTRAN Instruments Inc., USA). The optimum solution for minimum average vibration is 64.3 Hz with spindle speed 2500 rpm, feed rate 2 mm/min and depth of cut 1.5 ìm. These micro end milling parameters are suitable to machine PMMA to get high precision. The analysis revealed that compared to spindle speed; the feed rate and depth of cut have highest influence on vibration during machining process.

Key words: Micro milling · Vibration · Dynamic issue · PMMA

INTRODUCTION

Micro end milling is one of the micro/meso mechanical manufacturing (M^4) technology that allows the production of micro parts including micro molds/dies and fully functional metal devices [1-3]. Most machining operations do not usually produce a high stability to the system and reduce the dimensional accuracy, increases surface roughness as well as limits the productivity of machining operation. Mostly, it is due to the vibration that occurs during machining process. Forced and self-excited vibrations can limit the cutting stability, tool breakage and machine tool damage [4-6].

Vibration is usually caused by repetition of forces in machines by rotation of imbalanced, misaligned, worn, or improperly driven machine components. The machine vibrates more strongly due to the repetition of forces that encourages the machine to vibrate. A repeating force can produce small resonance which initiates from the motion of machine components. This mild repeating force would not be creating problems until it begins to cause resonance that can lead to rapid and severe damage.

There are some researches done in establishing dynamic cutting force model and cutting system vibration model. The stability of a micro cutting process is sensitive towards feed rate. The result shows the transformation process of cutting system vibration conditions while the feed rate was changed from 0.2 ìm/t to 1.6 ìm/t. It is obvious that the range of vibration sharply increased when the feed rate changes from 0.2 ìm/t to 0.4 ìm/t. There is vital amount of energy of forced variation concentrated at the natural frequency (10.4 kHz) of the spindle. It corresponds to unstable cutting condition. On the contrary, the range of vibration sharply decreases when the feed rate changes from 1.2 ìm/t to 1.6 ìm/t [7]. However, the levels of vibration associated with micro end milling parameters such as spindle speed, feed rate and depth of cut are not fully studied as these vary case by case. Thus, the objective of this research is to study the level of vibration in micro end milling using various spindle speed, feed rate and depth of cut.

Experiment: L_{18} Taguchi's orthogonal array design was used as the experimental design to conduct 18 experiments which are shown in Table 1. The substrate used was PMMA since it is widely used in producing micro channel on flat plate [8] with dimension 50 mm x 50 mm x 10 mm. Tungsten carbide end mill with two flutes,

Corresponding Author: M.Y. Ali, Department of Manufacturing and Materials Engineering,
International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia.

Table 1: Experimental parameters of micro end milling

	Level			
Control Parameters	Factor	I	II	III
Spindle speed (rpm)	n	2000	2500	3000
Feed rate (mm/min)	f	2	4	6
Depth of cut (im)	d	0.5	1.0	1.5
Fixed Parameters:				
Workpiece material	PMMA (poly methyl methacrylate)			
Cutting tool	Two-fluted WC end mill			
Dimensions (mm)	Ø 0.8 x R0.05 x 6			

$\varnothing$ 0.8 mm of diameter was used as cutting tool [9,10]. The experiments were conducted using micro end milling of a multi-purpose miniature commercial machine tool, DT110 (Mikrotools Inc., Singapore). This machine is capable to be used for micro EDM, micro turning, micro milling and micro grinding for super finish MEMS devices [11].

The accelerometer (DYTRAN Instruments Inc., USA) with sensitivity of 100.7 mv/g was used as a sensor to detect the vibration on the micro end milling machine. Figure 1a shows the accelerometer attached to the outer spindle during the machining process in order to make sure that the vibration measurement is accurate. The Multi-channel orchestra system was used as an analyzer to analyze the vibration reading detected by the accelerometer which is shown in Figure 1b. It has 8 channels which can connect the cables to the accelerometer. The orchestra system allows 01 dB-Metravib software to display the result of vibration data (Figure 1c). 01 dB-Metravib has developed a modular PC-based measurement chain, similar to traditional stand-alone measurement systems. This generic approach also applies to sound level meters, tape recorders or multi-channel analyzers. First, the transducer transforms a physical phenomenon into an electrical input signal.

Fig. 1: Experimental setup (a) position of accelerometer, (b) multi-channel orchestra system and (c) vibration monitor with Metravib software.

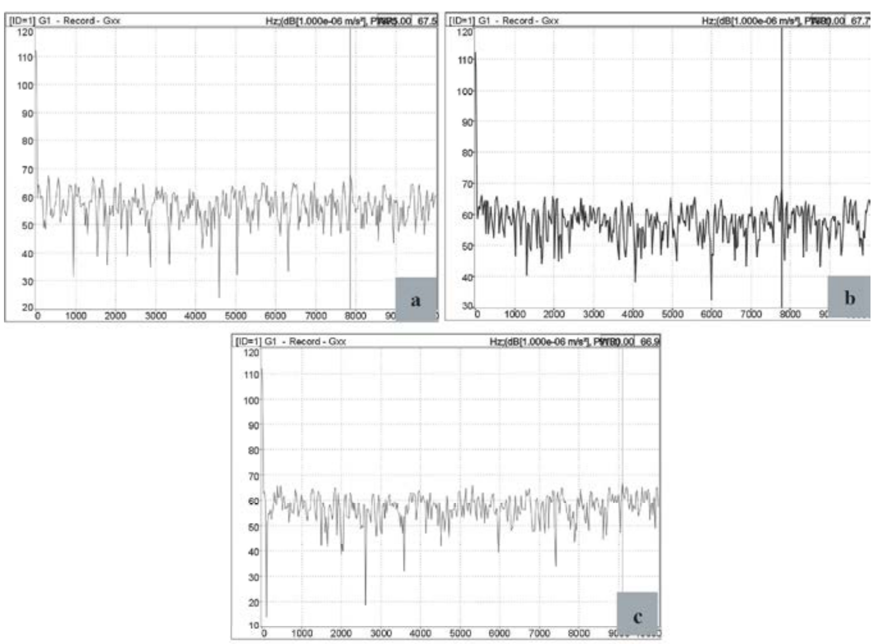

Fig. 2: Maximum peak of vibration for experiment 1 at a cutting distance of (a) 2 mm, (b) 4 mm and (c) 6 mm.

Then, the signal conditioning block transforms and/or amplifies the input signal for treatment in an acquisition unit. Control of the instrument and output of the results is required. Results such as a spectrum or time history graphs such as raw audio data, similar to a DAT recording or as a spectrum memory or set of Ln measurements may also be stored. Results are then available at the convenience of the user for post-processing operations similar to building acoustics calculations. Finally, the instrument may have an interface to a computer for further analysis and reporting.

Measurement of Vibration: Eighteen experiments were conducted to measure the vibration of micro end milling. For each experiment, three data were taken at 2 mm, 4 mm and 6 mm of cutting distance. The period for each reading taken is 10 seconds. The example of the data measurement of average vibration for experiment 1 is shown in Figure 2. Figure 2a shows the value of vibration for reading at 2 mm cutting distance with maximum value 67.5 Hz at 7.9 seconds. Further, Figure 2b shows the value of vibration for reading at 4 mm cutting distance with maximum value 67.7 Hz at 7.8 seconds. Meanwhile, in Figure 2c it shows the value of vibration for reading at 6 mm cutting distance with maximum value 66.9 Hz at 9.1 seconds. With these three data the average vibration value was taken. So, for experiment 1 the average vibration value is 67.4 Hz. These steps were repeated with the remaining 17 experiments.

ANALYSIS AND DISCUSSION

The vibration that had been measured using micro end milling with different spindle speed, feed rate and depth of cut, as tabulated in Table 2, were analysed. According to the Taguchi method, minimizing average vibration would be better for economy and precision manufacturing. So, smaller values of average vibration indicates the better machining performance which is referred as “smaller-the better” type problems. Figure 3 shows the graphs that indicate optimal combinations of micro end milling parameters with a maximum average vibration at spindle speed either three values; 2000 rpm, 2500 rpm, or 3000 rpm with feed rate 4 mm/min and depth of cut 1.5 µm. Analysis of variance (ANOVA) of average vibration is shown in Table 3. The model was developed with 95% confidence level. The Model F-value of 8.01 implies the model is significant. There is only a 0.17% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.05 indicate model terms *d, nd* and *fd* are significant.

ANOVA approach was used to check the adequacy of the model for average vibration. The analysis ultimately showed the main and interaction effects of the process variable on the response. The signal to noise ratio is key information in Taguchi experimental design and it proposed to maximize the performance of the target. Figure 4a shows the graph for spindle speed versus feed rate with constant depth of cut at 1.0 µm.

Table 2: Experimental result

	Parameters			Response	
Run	Spindle Speed (rpm)	Feed rate (mm/min)	Depth of cut (µm)	Average Vibration (Hz)	S/N Value
1	2000	2	0.5	67.4	-36.6
2	2000	4	1.0	65.7	-36.4
3	2000	6	1.5	66.3	-36.4
4	2500	2	0.5	67.2	-36.5
5	2500	4	1.0	65.4	-36.3
6	2500	6	1.5	66.8	-36.5
7	3000	2	1.0	66.5	-36.5
8	3000	4	1.5	64.2	-36.2
9	3000	6	0.5	65.1	-36.3
10	2000	2	1.5	65.2	-36.3
11	2000	4	0.5	65.3	-36.3
12	2000	6	1.0	66.1	-36.4
13	2500	2	1.0	66.6	-36.5
14	2500	4	1.5	65.4	-36.3
15	2500	6	0.5	65.2	-36.3
16	3000	2	1.5	64.4	-36.2
17	3000	4	0.5	66.6	-36.5
18	3000	6	1.0	65.7	-36.4

Table 3: ANOVA for response surface 2FI model of average vibration

Source	Sum of Square	Degree of Freedom (DF)	Mean Square	F Value	Prob > F
Model	11.33	6	1.89	8.01	0.0017
n	0.016	1	0.016	0.068	0.7986
f	0.95	1	0.95	4.03	0.0700
d	1.67	1	1.67	7.07	0.0222
nf	0.033	1	0.033	0.14	0.7162
nd	1.64	1	1.64	6.95	0.0231
fd	7.18	1	7.18	30.47	0.0002
Residual	2.59	11	0.24		
Cor Total	13.92	17			

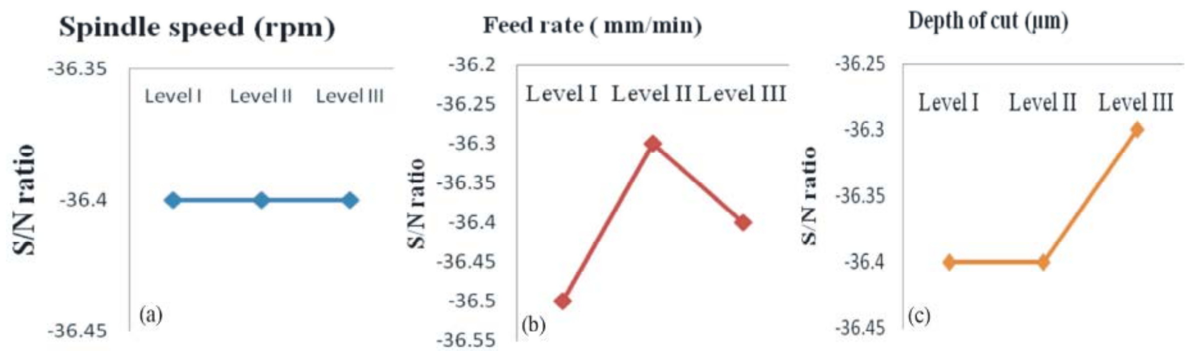

Fig. 3: S/N ratio curves of (a) spindle speed, (b) feed rate and (c) depth of cut for average vibration

From the graph, average vibration is maximum at the highest spindle speed and at the lowest feed rate. For further increase in feed rate and decrease in spindle speed, the average vibration starts falling slightly. Figure 4b shows the model graph for spindle speed versus depth of cut with constant feed rate at 4 mm/min. The graph shows the average vibration slightly decreases when the spindle speed increases at higher depth of cut. The average vibration is at highest frequency when the spindle speed is at maximum rpm with lowest depth of cut. Figure 4c is the model graph for feed rate versus depth of cut with constant spindle speed at 2500 rpm. From the graph, the average vibration slightly increases at lower value of feed rate as the value of depth of cut decreases. Further increases of feed rate make the average vibration to decrease with the increase of depth of cut. Thus, depth of cut and feed rate are the most affecting factors on vibration during the machining process since from the model, only a 0.02% chance that the "Model F-Value" could occur due to noise.

Optimization and Verification: The software has generated the possible solution for spindle speed, feed rate and depth of cut in response to average vibration in micro end milling process. The optimum solution to machine PMMA for lowest average vibration at 0.7 or 70.0% with desirable value of spindle speed 2500 rpm, feed rate 2 mm/min and depth of cut 1.5 ìm, with average vibration 64.3 Hz.

Based on the result, it is clear that the values are the best value to machine PMMA that gives highest desirability with lowest average vibration. Experiments were conducted for verification using results obtained from the optimization. The actual values obtained from the experiments were compared with the optimized results. Average vibration had been increased from 64.3 to 64.6 Hz with an error of 0.47%. The percentage error of average vibration is relatively small shows that the developed mathematical models significant to represent the relationships and useful to predict the performance characteristics to machine PMMA by micro end milling process. Final equation for this statistical model in terms of actual factors is expressed by Eqn (1) where; v is average vibration, n is spindle speed (rpm), f is feed rate (mm/min), d is depth of cut (µm).

$$V = 65.94 + 2.13 + 2.13\times10^{-3} n - 0.99 f + 1.73\times10^{-3} d - 6.84\times10^{-3} nd + 1.01 fd \quad (1)$$

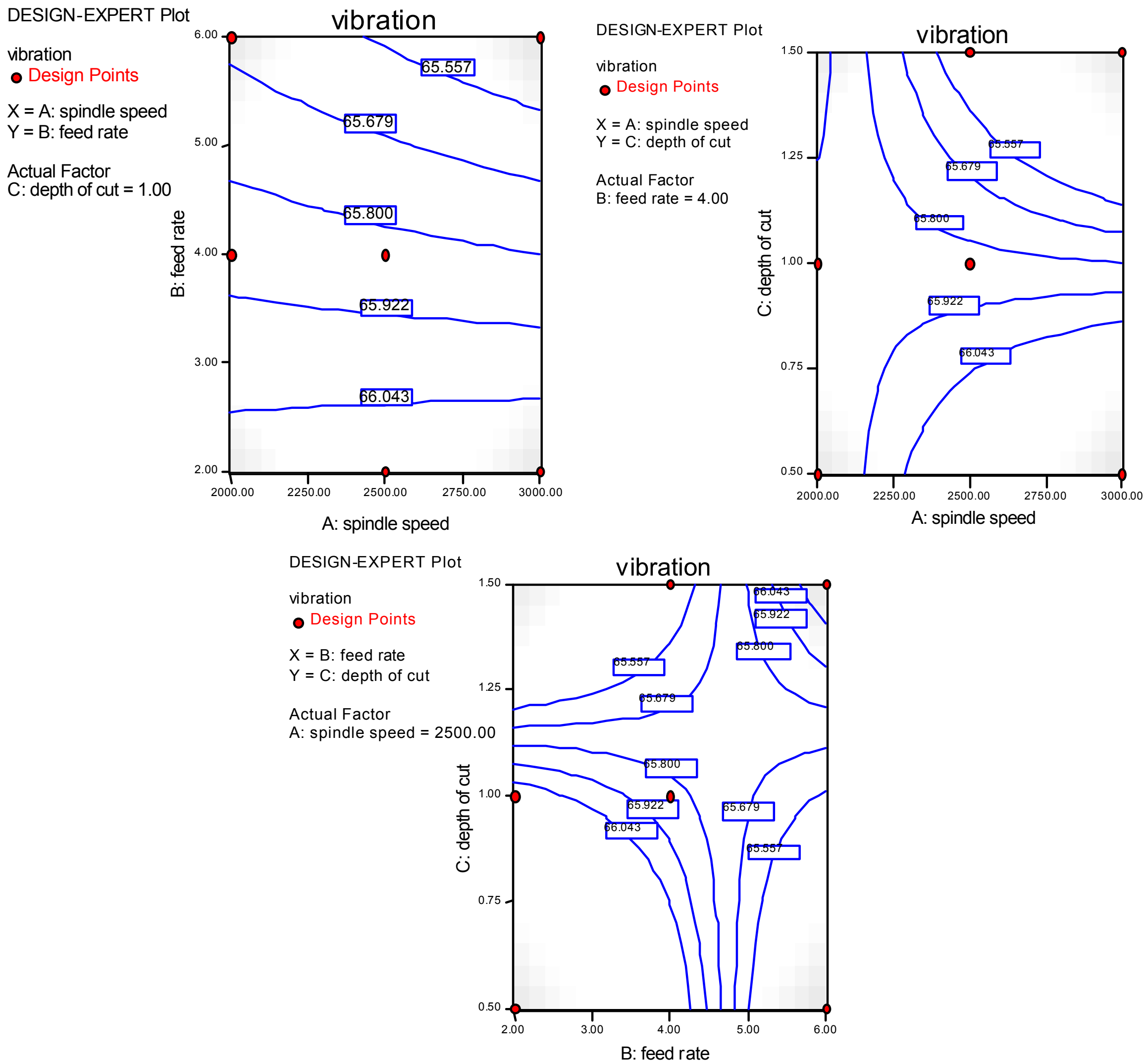

Fig. 4: Contour plot for average vibration (Hz) (a) spindle speed vs. feed rate with depth of cut 1 µm, (b) spindle speed vs. depth of cut with feed rate 4 mm/min and (c) feed rate vs. depth of cut with spindle speed 2500 rpm.

CONCLUSIONS

The purpose of this paper is to investigate the vibration issue of micro end milling of PMMA in using different parameters; spindle speed, feed rate and depth of cut. ANOVA approach was used for analysis of vibration and to obtain optimum solution of average vibration. The following conclusions can be made from this investigation.

- From ANOVA analysis it is observed that feed rate and depth of cut have highest influence on vibration during machining of PMMA. Whereas spindle speed has minimum effect of vibration.
- The minimum average vibration is found to be 64.3 Hz for spindle speed 2500 rpm, feed rate 2 mm/min and depth of cut 1.5 ìm which are considered to be the optimum parameters for micro end milling of PMMA.
- The verification of optimum parameters form minimum average vibration showed an error only 0.47%. As a result the developed mathematical model is significant to represent the relationship and useful to predict the performance characteristics to machine PMMA by micro end milling process.
- The model developed in this study is only valid for DT-110 micro milling machine and PMMA workpiece.

A verification check is to be performed to apply the model when using different machine or different workpiece materials.

ACKNOWLEDGMENTS

This research was funded by The Ministry of Higher Education, Malaysia under project FRGS12-074-0223. The authors are thankful to the Faculty of Engineering, International Islamic University Malaysia where the experimental studies were performed.

REFERENCES

1. Miao, J.C., G.L. Chen, X.M. Lai, H.T. Li and C.F. Li, 2007. Review of Dynamic Issues in Micro-End-Milling. International Journal Advance Manufacturing Technology, 31: 897-904.
2. Dhanorker, A. and T. Ozel, 2006. An Experiment and Modeling Study on Meso/Micro End Milling Process. ASME International Conference on Manufacturing Science and Engineering.
3. Rahman, M., A.S. Kumar and J.R.S. Prakash, 2001. Micro Milling of Pure Copper. Journal of Materials Processing Technology, 116: 39-43.
4. Filiz, S. and O.B. Ozdoganlar, 2011. A Three-Dimensional Model for the Dynamics of Micro-End Mills including Bending, Torsional and Axial Vibrations. Precision Engineering, 35: 24-37.
5. Hsieh, W.H., M.C. Lu and S.J. Chiou, 2011. Application of Back Propagation Neural Network for Spindle Vibration-Based Tool Wear Monitoring in Micro-Milling. International Journal Advance Manufacturing Technology, pp: 1-9.
6. Huang, B.W., P.P. Yu and J.H. Kuang, 2010. Using Finite Element Analysis on Dynamic Characteristics in a Micro Stepping Mill. World Academy of Science, Engineering and Technology, 70: 718-722.
7. Liu, X., M.B. Jun, R.E. DeVor and S.G. Kapoor, 2004. Cutting Mechanisms and Their Influence on Dynamic Forces, Vibrations and Stability in Micro-End Milling. Proceedings ASME International Mechanical Engineering Congress and Exposition.
8. Ali, M.Y., 2009. Fabrication of Microfluidic Channel using Micro End Milling and Micro Electrical Discharge Milling. International Journal of Mechanical and Materials Engineering, 4(1): 93-97.
9. Lee, S.W., 2006. Dynamic Analysis of a Mesoscale Machine Tool. ASME Journal Manufacturing Science and Engineering, 128: 194-203.
10. Popov, K., S. Dimov, A. Iivanov, D.T. Pham and E. Gandarias, 2010. New Tool-Workpiece Setting Up Technology for Micro-Milling. International Journal Advance Manufacturing Technoogy, 47: 21-27.
11. Ali, M.Y., A.R. Mohamed, B. Asfana, M. Lutfi and M.I. Fahmi, 2012. Investigation of Vibration and Surface Roughness in Micro Milling of PMMA. Applied Mechanics and Materials, 217-219: 2187-2193.