Proceedings of the
International Conference on Mechanical Engineering 2007
(ICME2007) 29- 31 December 2007, Dhaka, Bangladesh

ICME07-AM-07

SURFACE ROUGHNESS ANALYSIS OF BERYLLIUM-COPPER ALLOY IN MICRO END MILLING

R. Mehfuz and M. Y. Ali*

Department of Manufacturing and Materials Engineering, Faculty of Engineering,
International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Malaysia.
*e-mail: mmyali@iiu.edu.my Fax: +60361964477

ABSTRACT

In this paper, the effect of feed per tooth and depth of cut during micro end milling of beryllium-copper alloy, a mold material, has been analyzed. Central composite design, a response surface method, was used to statistically analyze the influence of these process parameters on the surface roughness. The interaction effect of parameters was also discussed. Statistical models for micro-end-milling were established to predict the average (R_a), maximum (R_y) and ten-point (R_z) surface roughness. R_a was found strongly influenced by feed while, R_y was influenced by the interaction effects of feed and depth of cut. R_z was influenced by both feed and the interaction of feed and depth of cut. Surface roughness in the range of 0.10 - 0.20 μm was observed.

Keywords: Micro end milling, response surface methodology, surface roughness

1. INTRODUCTION

Miniaturization technologies are perceived as potential key technologies of the future that will bring a completely different approach of man-machine interaction with the physical world. Researchers all over the world are struggling to fabricate miniaturized products using various techniques at a reasonable cost; because the available lithography based micromachining is limited to simple geometries, material biased and not reproducible. Among the mechanical micromachining processes, micro end milling has shown great potentials in the fabrication of micro features. Its specialty includes the ability of fabricating micro features of wide varieties of materials with complex 3D geometries, which are not possible by lithography or etching processes. The injection molding mold or hot embossing master tool produced by micro end milling can be used economically in micro replication. The motivation comes from the translation of the knowledge obtained from the conventional process to the micro level. However, several macro rules are not applicable when machining in the micro/meso scale due to the size effect [1-2].

On the investigation of surface roughness of micro end mill surfaces, there are very few researches have been reported so far [3-4] though there are several researches have been conducted to explore the influence of different process parameters in conventional end milling. The mechanism behind the formation of surface roughness is very dynamic, complicated, and process dependent; hence, it is very difficult to calculate its value through theoretical analysis. Statistical mathematical models of first- and second-order polynomials were developed previously for conventional end milling [5]. A multiple regression model to predict the finish surface with 90% accuracy was also formulated [6]. Surface roughness prediction models were developed using design of experiment method and the neural network [7]. Some researchers used Taguchi design method for surface roughness optimization [8]. However, these above mentioned research works had been conducted using conventional end milling machine tool. These results were not equally fit for micro end milling with miniaturized machine tool.

In conventional end milling, surface roughness was primarily influenced by the cutting variables, work materials and tool geometry. Among the cutting variables, feed rate was most influential on the surface roughness. However, the surface generation mechanism in micro end milling was more complex, because of the size effect [9-10]. Due to the size effect, periodical cutting force developed chatter easily, while for high speed spindle vibration was common. These dynamic issues lead to premature tool failure. For this, good experimental design was especially require for micro end milling.

There are several experimental designs available including central composite design (CCD), Box - Behnken, Plackett Burman, full factorial etc. Among these CCD is the most popular response surface method (RSM), which requires less number of experiments providing minimum error. In the rotatable type of CCD, each factor is varied over five levels (-√2, -1, 0, +1, +√2). Due to its two end levels (-√2, +√2), known as axial points, CCD provides better curvature effect which is suitable for response models of second order. In this paper, CCD is used to analyze the influence of micromilling process parameters on the surface roughness of beryllium-copper (Be-Cu) alloy (Protherm). Integrated multi-process micromachining tool was used to perform the experiments. A series of microchannels were fabricated in order to characterize the process parameters affecting surface roughness. Experiments had been conducted for different feed values with different depth of cut.

2. EXPERIMENTAL DESIGN AND SETUP

In this paper, CCD of two micro end milling parameters, feed per tooth and depth cut were selected to analyze their effect on the surface roughness. Figure 1 shows the generation of a CCD for two factors experimental design. Experiments were conducted using the values generated by CCD, which is shown in Table 1.

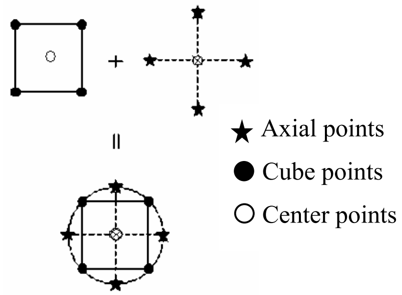


Fig 1: Central composite design (CCD) for two factors

Table 1: Levels of micro end milling factors

Parameter (unit)	Factor	Level				
		$-\sqrt{2}$	-1	0	1	$+\sqrt{2}$
		axial	cube	center	Cube	axial
Feed rate (μm/tooth)	A	0.38	1.00	2.50	4.00	4.62
Depth of Cut (mm)	B	0.07	0.09	0.14	0.18	0.20

Table 2: Surface roughness of the machined surface

No.	A (μm/tooth)	B (mm)	R_a (μm)	R_y (μm)	R_y (μm)
1	1.00	0.09	0.11	1.11	0.86
2	4.00	0.09	0.19	2.04	1.41
3	1.00	0.18	0.18	2.05	1.55
4	4.00	0.18	0.18	1.56	1.29
5	0.38	0.14	0.10	1.07	0.71
6	4.62	0.14	0.22	1.67	1.42
7	2.50	0.07	0.17	1.52	1.20
8	2.50	0.20	0.20	1.70	1.41
9	2.50	0.14	0.18	1.50	1.32
10	2.50	0.14	0.18	1.99	1.50
11	2.50	0.14	0.22	1.96	1.55
12	2.50	0.14	0.18	1.80	1.43
13	*0.50*	*0.13*	*0.12*	*1.26*	*0.92*
14	*0.80*	*0.13*	*0.12*	*1.23*	*1.03*
15	*2.00*	*0.13*	*0.18*	*1.81*	*1.36*
16	*3.50*	*0.13*	*0.21*	*1.79*	*1.35*
17	*4.40*	*0.13*	*0.21*	*1.86*	*1.45*

Table 2 shows the different runs of the experimental design. The first twelve runs were based on CCD, which are used to develop the models. In the last five experiments (13 to 17) random values of feed per tooth were chosen at a fixed depth of cut, which are used for model verification as discussed in section 4.0. Based on the experimented results, second order polynomial models were developed for average roughness R_a, maximum peak to valley height R_y and ten-point roughness R_z.

Integrated multi-process micromachining tool (DT-110: Mikrotools Inc. Singapore) was used for the experiments. It had the maximum spindle speed of 4000 rpm. Tungsten-carbide tool of 1 mm diameter and cutting speed of 3000 rpm were used. The tool had strong inner adhesion and high edge stability due to the presence of cobalt. The micro end mill tool was two fluted with standard geometry. Channels of 5 mm in length were fabricated in Be-Cu alloy (Be = 0.4 %, Ni = 1.8 % Cu = 97.8 %).

The surface roughnesses of the fabricated microchannels were inspected using a surface profiler (Mitutoyo, Surftest SV-500). The magnified images of the surface were inspected by scanning electron microscope (SEM, JEOL JSM-5600) after ultrasonic cleaning.

3. RESULTS AND DISCUSSION

The experimental results (run no 1 - 12) of all the responses, R_a, R_y and R_z, are tabulated in Table 2. Analysis of variance approach (ANOVA) is used to check the adequacy of the model. The analysis ultimately showed the main and interaction effects of independent variables, feed and depth of cut, on the response. Main effect was the direct effect of an independent variable on the response. Interaction effect was the joint effect of two independent variables on the response. In this paper, factor A (feed per tooth) and factor B (depth of cut) were the two main factors considered for the analysis of surface roughness. The interaction effect of these two factors was considered to obtain the relation of main factors. The second order quadratic effect of the comparatively significant variable, feed per tooth, was also included in the analysis. The statistical models developed by this analysis are:

$$R_a = -0.048 + 0.10f_t + 1.025d_c - 0.007f_t^2 - 0.296f_td_c \qquad (1)$$

$$R_y = -0.99 + 1.175f_t + 15.133d_c - 0.072f_t^2 - 5.26f_td_c \qquad (2)$$

$$R_z = -0.64 + 0.867f_t + 9.91d_c - 0.071f_t^2 - 3.0f_td_c \qquad (3)$$

where, f_t is the feed per tooth (μm/tooth) and d_c is depth of cut (mm).

Table 3, 4 and 5 show the results of ANOVA established for R_a, R_y and R_z respectively, using Design-Expert v 6, software for design of experiment. In Table 3, the Model F-value of 8.76 implies the model is significant. There is only a 0.74% chance that a "Model F-Value" this large could occur due to noise. In case of Be-Cu alloy, it is clearly seen that factor A is most influential on R_a by checking F-ratio and P-value. The P-value of factor A indicates the confidence level is 99.78%, which shows its strong influence. The P - value

Table 3: Analysis of variance for main and interaction effects on R_a

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.0124	4	0.0031	8.76	0.0074
A	0.0078	1	0.0078	22.00	0.0022
B	0.0013	1	0.0013	3.70	0.0957
A^2	0.0017	1	0.0017	4.82	0.0642
AB	0.0016	1	0.0016	4.52	0.0712
Residual	0.0025	7	0.0004		
Lack of Fit	0.0013	4	0.0003	0.80	0.5973
Pure Error	0.0012	3	0.0004		
Cor Total	0.015	11			

Table 4: Analysis of variance for main and interaction effects on R_y

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.95	4	0.24	6.06	0.0198
A	0.21	1	0.21	5.30	0.0548
B	0.064	1	0.064	1.63	0.2424
A^2	0.17	1	0.17	4.41	0.0738
AB	0.50	1	0.50	12.88	0.0089
Residual	0.27	7	0.039		
Lack of Fit	0.12	4	0.031	0.61	0.6849
Pure Error	0.15	3	0.050		
Cor Total	1.22	11			

Table 5: Analysis of variance for main and interaction effects on R_z

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	0.64	4	0.16	8.22	0.0088
A	0.21	1	0.21	10.81	0.0133
B	0.094	1	0.094	4.85	0.0635
A^2	0.17	1	0.17	8.76	0.0211
AB	0.16	1	0.16	8.47	0.0226
Residual	0.14	7	0.019		
Lack of Fit	0.11	4	0.026	2.66	0.2237
Pure Error	0.030	3	0.010		
Cor Total	0.77	11			

of B shows the confidence level is just above 90.0% and thus shows little influence on surface roughness. AB, the interaction effect, has the P-value of just below 94.0%, which shows better influence compare to B. The second order of A has better influence over R_a as it provides higher F and P values compared to factor B and AB. The "Lack of Fit F-value" of 0.80 implies the Lack of Fit is not significant relative to the pure error. There is a 59.73% chance that a "Lack of Fit F-value" this large could occur due to noise. The high P-value of lack of fit indicates the model is fit.

Table 4 shows the results of ANOVA established for maximum peak to valley height R_y. The Model F-value of 6.06 implies the model is significant. There is only a 1.98% chance that a "Model F-Value" this large could occur due to noise. The interaction effect AB is found most influential on R_y. The P-value of AB indicates the confidence level is 99.11%. The P-value of factor A shows the confidence level is just below 95.0% while the confidence level of the second order of factor A is just below 93.0%. Factor B has not much influence on R_y. The "Lack of Fit F-value" of 0.61 implies the lack of fit is not significant relative to the pure error.

Similarly the ANOVA table of ten-point roughness R_z is shown in Table 5. The Model is found significant where factor A, A^2 and AB are found as significant contributor to R_z. The model is also found fit.

Figure 2a shows the effect of factor A and factor B on average surface roughness, R_a. A is found as the strong influencer of R_a hence the profile of machined surface mainly depends on it. Thus, R_a increases along with the increase in feed, which is same as the conventional end milling. The distance between two adjacent profiles becomes larger when the feed value is increased. The value of surface roughness does not change a lot by altering the factor B though the increase in B increases R_a. The result obtained here is similar to the observation of Wang et al. [4].

Figure 2b shows the effects on maximum peak to valley height, R_y, where the interaction AB is found significant influencer of R_y. At lower value of factor B, with the increase in factor A, R_y increases. As factor B increases at increased value of factor A, R_y decreases. This phenomenon is quite different compare to conventional micro end milling. Similarly figure 2c shows the effect on ten-point roughness R_z, where the factor A and AB are found significant contributors for R_z. In a closer view it can be seen that all R_a, R_y and R_z curves are identical in some extent. In case of R_y and R_z, the decrease in surface roughness is visible from feed of 3 and 3.25 (μm/tooth) respectively. For R_a, the decrease in roughness occurs around a feed of 3.5 (μm/tooth). It indicates, after a particular feed value, surface roughness decreased. But the risk of tool failure increased. It had given similar trend to the work of previous researchers [4], though the reason was not discussed. It is assumed that the decrease in surface roughness was not a product of the kinematics (feed rate, depth of cut, speed), rather it was due to the dynamic behavior (less vibration and chatter) at high feed and depth of cut. This assumption was based on the works on dynamic behaviors in micromachining. The range of vibration was sharply

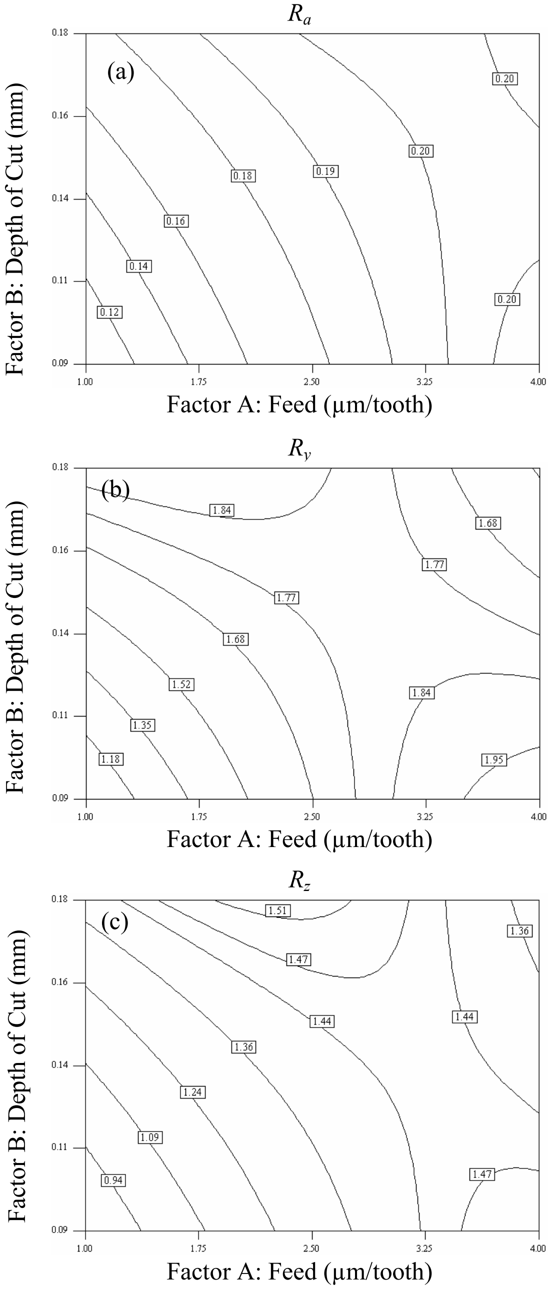
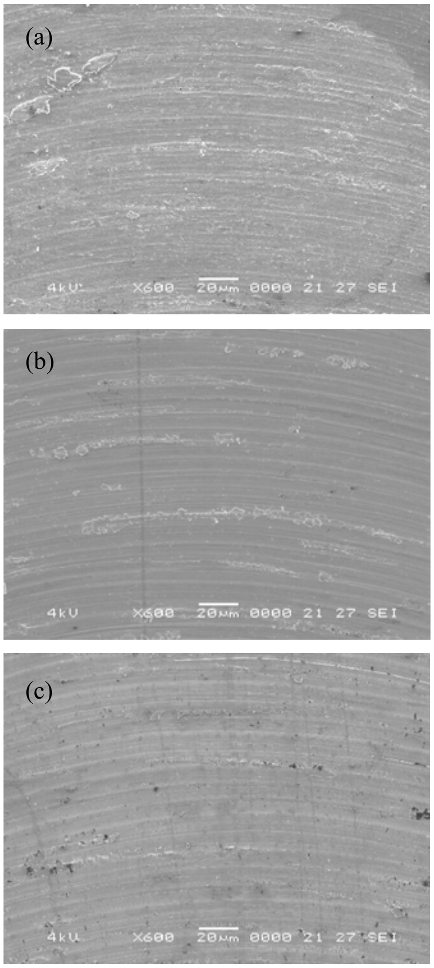


Fig 2: Effect of feed per tooth(factor A) and depth of cut(factor B) on a) R_a, b) R_y and c) R_z for cutting speed of 3000 rpm and tool dia of 1mm.

increased and then sharply decreased while the feed was changed from lower value to higher values [11]. Lower vibration at higher feed value thus reduced the cutting instability, which was favorable to surface quality.

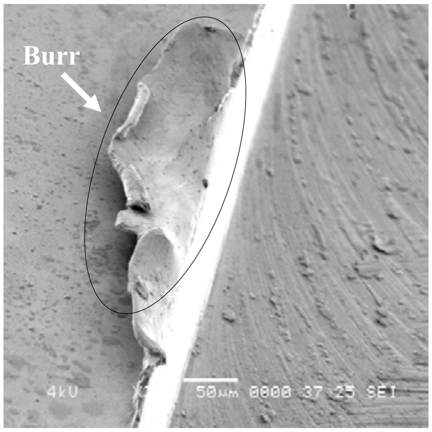


$R_a = 0.10$ µm
$R_y = 1.07$ µm
$R_z = 0.71$ µm

$R_a = 0.18$ µm
$R_y = 1.50$ µm
$R_z = 1.29$ µm

$R_a = 0.22$ µm
$R_y = 1.67$ µm
$R_z = 1.42$ µm

Figure 3: SEM micrograph of the surface profile of micro end milled surface when 1 mm tool dia, 3000 rpm spindle speed and 0.14 mm depth of cut with varying feed per tooth of (a) 0.38 µm/tooth, (b) 2.50 µm/tooth and (c) 4.62 µm/tooth.



Feed = 2.50 µm/tooth

Depth of cut = 0.14 mm

Figure 4: SEM micrograph of burr formation

The SEM images of the machined surface at different feed values are shown in figure 3. As the feed increased the milling mark is more visible. This happened because the distance between two adjacent peaks was larger as the feed value increased. In the machined samples, a significant amount of burrs were noticed. Figure 4 shows a sample with significant burrs. The formation of burr is often responsible for adjacent subsurface deformation, which is significant in micro end milling. This burr formation is a factor of work material properties, cutting conditions and tool geometry. Here the work material, Be-Cu alloy, is a ductile material which favored the formation of burrs. Moreover, cutting speed limitation of the machine was also responsible for the high burr formation. It was also noticed that burrs are more prominent in the tool-exit side of the machined slot,

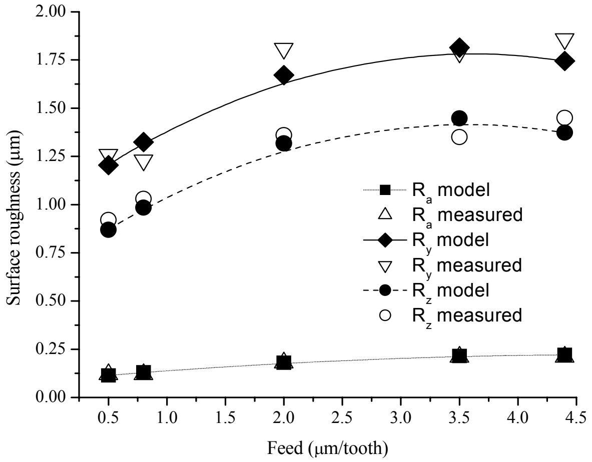


Figure 5: Comparison of predicted and measured surface roughness

which is similar to the observation of previous researchers [12].

4. MODEL VERIFICATION

In order to verify the models (Eqs. 1-3), five experiments (no. 13-17, Table-2) were conducted taking random value of different feed per tooth at a fixed depth of cut. Figure 5 compares the measured roughness, with the roughness value predicted by the models. Good agreement is seen for the predicted and measured R_a values; however, scattering of around 8.00% is observed for R_y and R_z values. Still the models show prediction with above 92.00% accuracy. Thus the model can be said as verified.

5. CONCLUSIONS

In this paper, surface roughness of Be-Cu alloy by micro end milling is discussed. Response surface methodology was used to analyze the experimental data. This study showed the followings:

1. The statistical models suggested that the feed per tooth was the significant factor that influences R_a greatly, while interaction effect of feed and depth of cut was found significant for R_y. Feed per tooth and interaction effect of feed and depth of cut both were found significant for R_z.
2. Effect of depth of cut as a single factor was not much influential to the surface roughness.
3. The best surface finish could be obtained by lowering the feed and depth of cut.
4. R_a was found near-linear function with respect to the feed per tooth, while R_y and R_z were found as a non-linear function.
5. Models were verified by experiment, which had shown above 90.0% prediction accuracy.
6. In this paper a constant cutting speed (3000 rpm) was maintained for limited maximum spindle speed capability. This low cutting speed is a contributor of high burr formation.

6. ACKNOWLEDGEMENT

The authors are thankful to Research Centre, International Islamic University Malaysia who provided the funding for this research under the grant LT35.

7. REFERENCES

1. Rahman, M., Kumar, A. S. and Prakash, J. R. S., 2001, "Micro-milling of Pure Copper", J. of Mat. Process. Technol. 116: 39-49.
2. Ehmann, K. F., DeVor, R. E. and Kapoor, S. G., 2002, "Micro/Meso-Scale Mechanical Manufacturing- Opportunities and Challenges", JSME/ASME Int. Conf. on Mat. Process., Vol. 1 pp. 6-13.
3. Lee, K and Dornfeld, D. A., 2004, "A Study of Surface Roughness in the Micro-End-Milling Process", Laboratory for Manufacturing Automation. Consortium on Deburring and Edge Finishing, University of California Berkley.
4. Wang, W., Kweon, S.H. and Yang, S.H., 2005, "A study on roughness of the micro-end-milled surface produced by a miniatured machine tool", J. of Mat. Process. Technol. 162–163(2005), 702–708.
5. Alauddin, M., Baradie, M., and Hashmi, M. S. J., 1995, "Computer-aided analysis of a surfaceroughness model for end milling", J. of Mat. Process. Technol., 55:123-127.
6. Lou, M. S., Chen, J. C. and Li, C. M., 1998, "Surface roughness prediction technique for CNC end-milling", Ind. Technol. 15 (1).
7. Fredj, N. B., Amamou, R., and Rezgui, M.A., 2002, "Surface Roughness Prediction Based upon Experimental Design and Neural Network Models", SMC IEEE 5.
8. Zhang, J. Z., Chen, J. C., and Kirby, E. D., 2007, "Surface roughness optimization in an end-milling operation using the Taguchi design method", J. of Mat. Process. Technol.184: 233–239.
9. Vogler, M. P., DeVor, R. E., and Kapoor, S. G., 2004, "On the Modeling and Analysis of Machining Performance in Micro-endmilling, Part I: Surface Generation," ASME J. Manuf. Sci. Eng., 126(4): 684–693.
10. Damazo, B. N., Davies, M. A., Dutterer, B. S., and Kennedy, M. D., 1999, "A Summary of Micro-Milling Studies," Proc. of 1st Int. Conf. and Gen. Meeting of the Euro. Soc. for Precision Engin. and Nanotech., Bremen, Germany, European Society of Precision Engineering, : 322–325.
11. Liu, X., Jun, M. B. G., DeVor, R. E., and Kapoor, S. G., 2004, "Cutting mechanisms and their influence on dynamic forces, vibrations and stability in micro-end-milling", In: Proc. of the ASME Int. Mech. Engin. Cong. and Expo. (IMECHE 2004), ASME Manufacturing Engineering Division, Anaheim, California.
12. Chu, C. H. and Dornfeld, D. A., 1999, "Tool Path Planning for Exit Burr Minimization by Estimating the Total Length of Primary Burrs," Int. J. Computer Integrated Mfg.