DOI: 10.1007/s12541-012-0277-y

Optimizing the Cutting Parameters for Better Surface Quality in 2.5D Cutting Utilizing Titanium Coated Carbide Ball End Mill

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KEYWORDS: Cutting parameters, 2.5D cutting, Coated carbide ball end-mill, Surface quality

The 2.5D cutting operations are intended for creating NC programs for components with pockets, lugs, flat sections etc, for which, it is too time consuming to produce a 3D volume model of the component. A 2.5D machining processes can perform the cutting operation only in two of the three axes at a time, the movement of the cutter on the main planes before moves to the next depth produced a terrace-like approximation of the required shape. However, adopting the right cutting parameters could be an ideal solution to improve the product quality. This study focused on optimizing the cutting parameters for higher surface quality in 2.5D cutting utilizing titanium coated carbide ball end mill. These parameters include; machined surface inclined angle, axial depth of cut, spindle speed and feed rate. Taguchi optimization method is the most effective method to optimize the cutting parameters, in which the most significant response variables could be identified. The standard orthogonal array of L_9 (3^4) is used, while the signal to noise (S/N), target performance measurement (TPM) response analysis and analysis of variance (Pareto ANOVA) methods are carried out to determine which parameters are statistically significant. Finally, confirmation tests are carried out to investigate the optimization improvements.

Manuscript received: December 8, 2011 / Accepted: July 18, 2012

1. Introduction

Milling is a machining process where a surface is generated by continuous chip removal.[1] 2.5D cutting is one of the common milling operations especially in pocket and contouring milling operation. A 2.5D cutting possesses the capability to translate in all three axes but can perform the cutting operation only in two of the three axes at a time. The code for a 2.5D is significantly less than a 3D machining, while the 2.5D image is a simplified three-dimensional (x, y, z) surface representation that contains at most one depth (z) value for every point in the (x, y) plane. The 2.5D operations normally involve two types of processes, roughing and finishing process. During operation, the depth of cut remains constant and the cutter movement only interpolate two axes simultaneously which means that the cutter moves only on the main planes XY, YZ and ZX and then it moves to the next depth and repeated the same movement. A terrace-like approximation of the required shape is produced in a roughing process in order to remove the excess material. After the roughing has been done, a finishing process is used to transform the part to its final design shape with acceptable tolerance.[2] An extensive work has been done on 2.5D cutting operation such as a study in producing efficient cutter paths,[3] studying the cutter path patterns,[4] investigating cutter engagement functions in 2.5D milling operation,[5] cutting tool sizes for a 2.5D pocket etc. However, the demand for high quality focuses attention on the surface quality which is the surface condition of a workpiece after being modified by a manufacturing process.

The surface quality after machining processes correlates very closely with the cutting parameters and the tool geometries. These machining processes will only deteriorate the surface quality if the improper parameters are used, such as dull tools, too high feed speeds or depth of cut, improper cutting speeds, coolant or lubrication, or incorrect tool hardness. Hence, if the cutting conditions are not selected properly, the process may result in violations of machine limitations and part quality or reduced productivity. Therefore, it is important to understand the relationship between the cutting conditions and the surface quality of the machined part especially the surface roughness of the machined surface, because of its effect on product appearance, function, and reliability.

Surface roughness is defined as a group of irregular waves in the surface, measured in micrometers (μm). The roughness data obtained by measurement can be manipulated to determine the roughness parameter. There are many different roughness parameters in use, but R_a is the most common. Surface roughness is mainly affected by different controlled cutting parameters that can be setup in advance, such as spindle speed, feed rate, and depth of cut. However, it is also affected by other uncontrolled variables such as the mechanical properties of the workpiece material, the type of the cutter, and the vibration produced during the process.[6,7] In metal machining, the small increase in R_a value was thought to be due to the increased unbalance of the tool at the higher cutting speed together with possibly higher cutting forces leading to vibrational effects.[8,9] Apparently, there will be an increase in surface roughness value with increasing cutting speed up to certain value, however, the surface roughness will decreases with the further increased cutting speed as the feed rate/tooth (mm/tooth) value will be decreased consequently with the increase of the cutting speed.[10] Low depth of cut will consistently provide a low surface roughness.[11-13] Meanwhile, increasing feed rate will increase the surface roughness of a material.[14] This is due to the increase in maximum chip thickness caused by the increase in feed rate and depth of cut. However, in 2.5D cutting, the effect of these parameters need to be investigated, especially the way of inclined machined surface angle affecting the cutting speed as shown in Fig. 1. Increasing the machined surface angle, θ, will cause the distance, r, to decrease. Furthermore, the decreasing r will decreases the cutting speed since the tool diameter is directly proportional to the cutting speed leading to different surface integrity characteristics.

Following the literature above, for optimizing the cutting parameters for lower surface roughness in 2.5D cutting, this study has been conducted by anticipating, spindle speed, feed rate, depth of cut and machined surface inclined angles as control variables. The main objective of this research work is to find the best combination of these parameters in milling of carbon steel workpieces utilizing titanium coated carbide ball end mill to get lower surface roughness. The conventional method to achieve that is to use the “trial and error approach. However, due to the large number of experiments, the “trial and error” approach is very time consuming. Hence, a reliable systematic approach for optimizing the machining parameters is thus required. Taguchi optimization method is an efficient, effective, reliable and simpler approach, in which the response parameters affecting surface roughness can be optimized. The steps in the Taguchi optimization method include: selecting the orthogonal array (OA) according to the numbers of controllable factors, running experiments based on that OA, analyzing data, identifying the optimum parameters, and conducting confirmation test with the optimal levels of all parameters.[15]

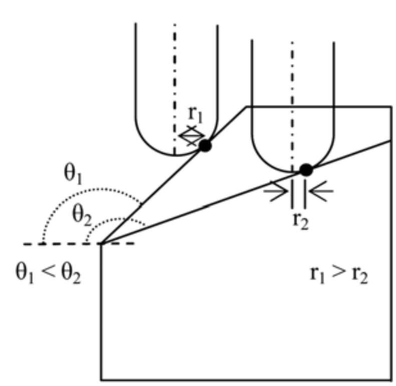


Fig. 1 Schematic of the tool position during machining

2. Design of Experiment

The most important thing of experiment design lies in the selection of control factors. All possible factors should be included, so that identification of non-significant variables could be done easily by Taguchi method, which is the best method to offer such facility. The control factors and experimental condition levels used are shown in Table 1. With the four control factors at three levels each, the Taguchi fractional factorial design used is the standardized orthogonal array $L_9(3^4)$. The levels of Factor A, and B, were chosen based on the result in preliminary experiment, while, both of the Factor C, and D levels are selected based on recommendations given by the tool manufacturer’s recommendation. The nine experiments with the details of combinations for each control factor (A-D) are shown in Table 2.

3. Experimental Setup and Procedure

After the orthogonal array has been selected, the second step in Taguchi optimization method is running the experiment based on that orthogonal array. The experimental setup used in this research is shown in Fig. 2. The machine used is a Five-axis CNC machining center (SPINNER U-620) built with Siemens controller. The tilting table integrated in the machine structure is useful for workpieces about 500 × 500 × 500 mm. The machine is designed for highest precision, best access to working area and top-value technical data as standard,

Table 1 Factors and levels used in experiments

Factors	Experimental Condition Levels (i)		
	1	2	3
A-Machined surface inclined angle (θ°)	100	110	120
B-Axial depth of cut (mm)	0.1	0.25	0.5
C-Spindle Speed (min^{-1})	3200	3700	4200
D-Feed Rate (mm min^{-1})	870	920	970

Table 2 L_9 (3^4) Orthogonal array

Experiment Level	Control factors and levels (i)			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

such as maximum spindle speed of 12000 min^{-1}, 32 tool changes, 11/29 kW spindle power (S6 40%) and chip-conveyor.

Tools selected to be used in the experiments are four flutes, 10 mm diameter titanium coated carbide with flat end mill and ball-nose end mill. One of the reasons of choosing these tools is high toughness and hardness due to ultra-fine grade and employing TiAlN coating. It is achieving good through a high oxidation temperature (1200ºC) with high hardness and provides superb performance for high speed dry cutting. The tool holder used is split collets type which is very popular on vertical milling machines. This type of split collets system is the collets chuck system where the tool slippage may be minimized. The workpiece material is S50C Medium Carbon Steel which has carbon content in between 0.3 and 0.55% carbon. The workpiece is a square block has the dimension of 60 × 60 × 60 mm. The chemical composition of work-material in percentage by weight is shown in Table 3.

To investigate the influence of the machined surface inclined angle on surface roughness in 2.5D cutting, the end milling test was carried out in two stages using the proposed experimental set-up and workpiece material. The first cutting stage is a rough cutting to prepare the stairs step inclined plane with different angles of 100, 110 and 120 degree. For each angle of 100, 110 and 120 degree, the effective radius would be 4.92, 4.70 and 4.33 mm, respectively. Based on this effective radius, the effective cutting speed can be obtained by the following equation:

$$V_e = \frac{\pi n D_e}{1000} \quad (1)$$

where D_e is the effective diameter and n is the spindle speed. In this first stage the end mill tool used is 10 mm diameter titanium coated carbide flat end mill. The tool Z-axis coordinate is sitting initially as shown in Fig. 3 (a), then the tool moves in +X direction to cut a stroke of 60 mm and in -Y direction with a fixed radial depth of cut of 5 mm until it reached 1 mm above the machined surface inclined angle as a leftover material for finishing process. After the end of the first cutting cycle the tool Z-axis coordinate has to be shifted in three different levels of axial depth of cut of 0.1, 0.25 and 0.5 mm to provide the feed motion while the cutting in +X and -Y direction is repeated to cut same stroke. Same tool shifts and cutting cycle is applied to complete the rough cutting to prepare the stairs step inclined plane with different angles of 100, 110 and 120 degree, as shown in Fig. 3 (b). The second cutting stage is a finish cutting to produce a flat smooth inclined surface to investigate the influence of the machined surface inclined angle on surface roughness in 2.5D cutting. In this cutting stage the end mill tool used is 10 mm diameter titanium coated carbide ball-nose end mill. The tool moves in +X and +Y direction to produce a flat smooth machined surface with different inclined angle, while, the tool Z-axis coordinate is shifted with a different axial depth of cut of 0.1, 0.25 and 0.5 mm, as shown in Fig. 3(c). These values are recommended by tool manufacturer for finishing process.

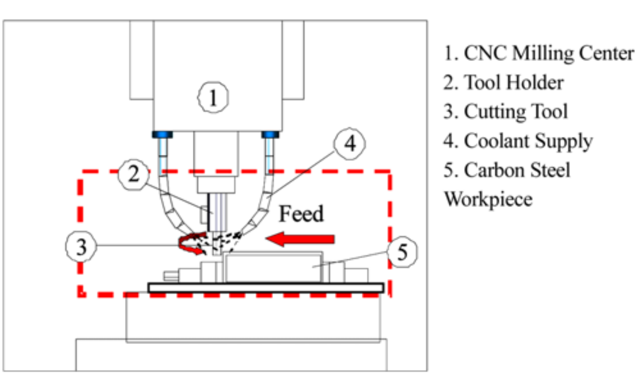


Fig. 2 Schematic diagram of the experimental set-up

Table 3 Chemical composition of medium carbon steel

C	Si	Mn	P	S
0.48 - 0.55	0.15 - 0.35	0.60 - 0.90	0.04	0.05

To control the temperature during cutting for better surface finish, the lubrication system is applied. The lubrication mode used in this research is high pressure flood coolant system that can provide flow rates up to 38 gallon per minute (gpm) at pressures from 50 to 2500 psi. High pressure coolant in machining centers provides better cooling, increased tool life, reduced friction, and also improved machined surface finishes. High pressure coolant removes chips from the machining process and reduces the re-cutting of chips problem. To measure the machined workpiece surface roughness R_a, a portable profilometer MarSurf PS1 Perthometer (Mahr, Germany) is used with 300 μm accuracy, 0.5 mm/s speed and five 0.8 mm sampling length. This perthometer offers metrology solutions with instrument designs that provide quick and simple measurement, yet comply with measuring standards. Measurements can be done on the spot after the machining process complete. Roughness was taken in the cutting direction (perpendicular to feed direction). Three reading were made in each specimen and a mean value was calculated for each specimen. The profilometer used for this measurement has been calibrated before we used to do the measurement using a standard specimen attached with the device and the measurement error is found to be 0.01 μm.

4. Experimental Results and Data Analysis

The experimental tests are carried out using the proposed experimental set-up. The measured surface roughness is summarized as

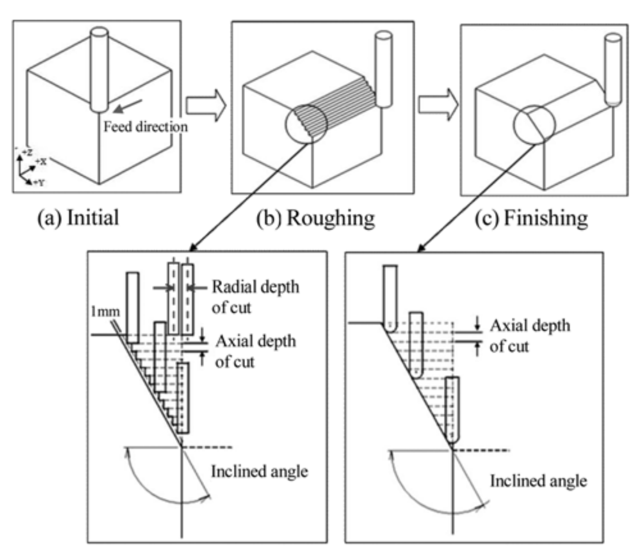


Fig. 3 Machining processes

three experimental runs for each test in Table 4. The procedure after the experimental runs is to analyze the results to optimize the parameters and to identify which process parameters are statistically significant. Analyzing data was conducted using S/N, TPM response analysis and Pareto ANOVA.

4.1 S/N and TPM Response Analysis

The methods for calculating the S/N ratio are classified into three main categories, depending on whether the desired quality characteristics are smaller the better, larger the better or nominal the better. In the case of surface roughness, the smaller values are always preferred. The equations for calculating the S/N ratio with smaller-the-better characteristics is as follows:

$$S/N_i = -10\log\left(1/n\sum_{j=1}^{n} y_j^2\right) \tag{2}$$

where, y_i is the individual measured surface roughness in first, second and third columns in Table 4, and n is the number of the individual measured. In this case, n = 3. The S/N values function shown in equation 2 is a performance measurement parameter to develop processes insensitive to noise factors. The degree of predictable performance of a process in the presence of noise factors could be defined from S/N ratio in which, for each factor, the higher the S/N ratio the better the result. The calculated S/N ratio and TPM values are summarized in Table 4, where TPM is the target performance measurement, which is equal to the average of the measured surface roughness at the same experimental level.

Furthermore, the TPM and S/N response data for surface roughness are calculated and summarized in Table 5. As for an example of TPM and S/N response calculation, A_i is the average of all TPM or S/N values corresponding to the same level of the control factor (A) in Table 4. In this case, (A) has three different levels (*i*) equal to 1, 2 or 3. The difference under A_i column is equal to the maximum minus the minimum of the S/N or TPM response values. Similarly, the S/N, TPM response values and the differences are calculated for B_i, C_i and D_i. The rank is given in order from the highest to the lowest difference values. The significance of each factor is determined based on the value of the difference of both S/N and TPM.

The desired "smaller the better criteria implies that the lowest surface roughness and TPM values would be the ideal result, while the largest S/N response would reflect the best response which results in the lowest noise. This is the criteria employed in this study to determine the optimal machining parameters. The S/N and TPM response graphs for selecting the best combination levels for minimum surface roughness is shown in Fig. 4.

Based upon the criteria of smaller TPM and larger S/N ratio, the axial depth of cut (Factor B) is found to be most significant factor affecting surface roughness, followed by machined surface inclined angle (Factor A), spindle speed (Factor C) and feed rate (Factor D). The lower axial depth of cut (B1, 0.1 mm), with higher machined surface inclined angle (A3, 120°), higher spindle speed (C3, 4200 min^{-1}) and lower feed rate (D1, 870 mm min^{-1}), are determined to be the best choices for obtaining the lowest value of surface roughness. Therefore, the optimal parameters for surface roughness are set as A3B1C3D1.

4.2 Pareto ANOVA: An Alternative Analysis

Pareto ANOVA is an alternative method used to analyze the data for process optimization. It exhibits the percentage of factor influence for each parameter in a very simple way. Pareto ANOVA for surface roughness is constructed in Table 6 using the S/N response data in Table 4. The summation of squares of differences (S) for each control factor is calculated such that, for example, S_A can be obtained by the following equation:

$$S_A = (A_1-A_2)^2+(A_1-A_3)^2+(A_2-A_3)^2 \tag{3}$$

Table 4 Results of measured surface roughness and calculated TPM and S/N ratio

Exp. level	Measured surface (μm)			TPM (μm)	S/N (dB)
	1	2	3		
1	0.415	0.416	0.420	0.417	7.597
2	0.614	0.659	0.755	0.676	3.368
3	1.097	1.181	1.175	1.151	-1.226
4	0.516	0.513	0.503	0.510	5.836
5	0.572	0.552	0.562	0.562	5.004
6	1.085	1.142	1.140	1.122	-1.004
7	0.382	0.350	0.340	0.357	8.927
8	0.539	0.544	0.565	0.549	5.202
9	1.047	1.044	1.045	1.046	-0.385

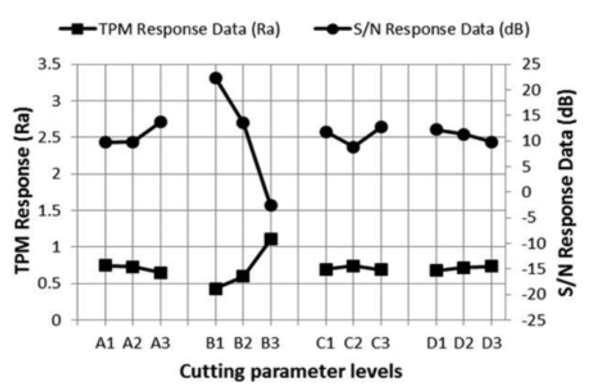


Fig. 4 TPM and S/N response graph

Table 5 The TPM and S/N response data

Level of input parameters (*i*)	TPM Response Data (μm)				S/N Response Data (dB)			
	A_i	B_i	C_i	D_i	A_i	B_i	C_i	D_i
Level 1 (*i* = 1)	0.747	0.427	0.696	0.675	9.7392	22.3615	11.7938	12.2164
Level 2 (*i* = 2)	0.731	0.595	0.743	0.718	9.8363	13.5741	8.8200	11.2911
Level 3 (*i* = 3)	0.650	1.106	0.690	0.736	13.7440	-2.6162	12.7057	9.8119
Difference	0.097	0.679	0.063	0.061	4.0048	24.9777	3.8857	2.4045
Rank	2	1	3	4	2	1	3	4

Similarly, S_B, S_C and S_D are calculated. The contribution ratio for each factor is calculated as the percentage of summation of squares of differences for each factor to the total summation of the squares of differences. A Pareto diagram is plotted using the contribution ratio, and the cumulative contribution.

For surface roughness analysis, as presented in Table 6, the significant factors are chosen from the left-hand side of the Pareto diagram. The best levels of factor combination for minimum surface roughness are obtained in: the axial depth of cut (B) 93.7%, the machined surface inclined angle (A) 3.0%, the spindle speed (C) 2.4%, and finally the feed rate (D) 0.9%. The recommended optimal parameters combination for best surface roughness is A3B1C3D1. This result is similar to the result obtained from S/N and TPM response analysis.

5. Discussion

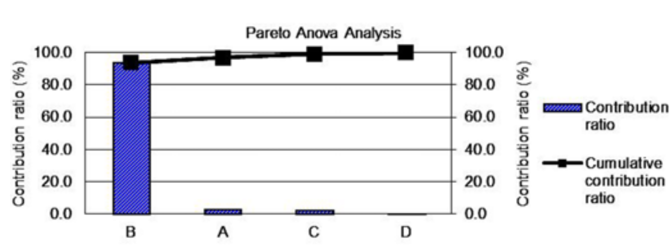
In this study, the measured surface roughness data were analysed using signal to noise (S/N), target performance measurement (TPM) and Pareto ANOVA response analysis to investigate the optimum parameters combination for higher surface quality. It was observed that, all analysis techniques delivered similar results such that the axial depth of cut (Factor B) is found to be most significant factor affecting surface roughness, followed by machined surface inclined angle (Factor A), spindle speed (Factor C) and feed rate (Factor D) as shown in Fig. 4. The increase of the machined surface angle, θ, will cause the distance, r (the radial depth of cut), to decrease as shown in Fig. 1. Furthermore, the decreasing radial depth of cut (r) will decreases the undeformed chip thickness and tool chip contact length, hence decreasing the amount of cutting forces required to remove a specified volume of material leading to lower surface roughness.

The surface roughness produced in milling operation depends on feed rate and depth of cut as well. The use of S/N ratio for selecting the best levels of combination for surface roughness (Ra) value suggests the use of low value of feed rate and depth of cut in order to obtain good finish. The greater the feed rate and depth of cut the larger the cross-sectional area of the uncut chip and the volume of the deformed workpiece. Consequently, the greater is the resistance of the workpiece to chip formation and the larger is the cutting force leading to a contact overload between the cutting tool and the workpiece producing bad surface quality. Further, it can be seen that the surface roughness decreases with the increase in cutting speed. So, the temperature rise softens the material aiding grain boundary dislocation and thus reducing the surface roughness.[12]

Furthermore, the lowest machined surface's roughness could be obtained by highest spindle speed of 4200 rpm (level 3). As cutting speed increases, machining becomes more adiabatic and the heat generated in the shear zone cannot be conducted away during the very short interval of time in which the material passes through this zone. This could be explained in terms of the velocity of chips that is faster at high cutting speed than at low cutting speed. This leads to a shorter time for the chips to be in contact with the newly formed surface of workpiece and the tendency for the chips to wrap back to the new face form is little as compared to low speed. The condition of seizure and sublayer plastic flow occurred at high speed and the term low-zone is used to describe secondary deformation in this range.[16,17] The time taken for the chips at this flow-zone for high speed cutting is short as compared to lower speed, as the velocity of chip is faster.

Table 6 Pareto ANOVA analysis

Level of input parameters (i)	S/N response data (dB)			
	A_i	B_i	C_i	D_i
Level 1 ($i = 1$)	9.7392	22.3615	11.7938	12.2164
Level 2 ($i = 2$)	9.8363	13.5741	8.8200	11.2911
Level 3 ($i = 3$)	13.7440	-2.6162	12.7057	9.8119
Total of summation	33.3194	33.3194	33.3194	33.3194
Sum of squares of differences (S)	$S_A = 31.3182$	$S_B = 963.2359$	$S_C = 24.7740$	$S_D = 8.8261$
Total summation of squares of differences $S_t = S_A + S_B + S_C + S_D$	1028.1542			
Contribution ratio (%)	3.0	93.7	2.4	100.0



Factor	B	A	C	D
Cumulative contribution ratio (%)	93.7	96.7	99.1	100.0
Optimum combination of significant factor levels	$A_3B_1C_3D_1$			

6. Confirmation Test

After the optimal levels of all control factors are identified, a confirmation test has been conducted using the optimal parameters A3B1C3D1 to validate the finding. The surface roughness obtained from the confirmation test is 0.313 μm. The result shows an improvement of 12.3% of the surface roughness compared with the results obtained from experiments shown in Table 4.

7. Conclusion

In this study the optimal cutting conditions for 2.5D cutting end milling was selected by varying cutting parameters through the Taguchi optimization method. The standard orthogonal array $L_9(3^4)$ is used and the data analysis is conducted using signal to noise ratio (S/N), target performance measurement (TPM) response analysis and analysis of variance (Pareto ANOVA) to determine the optimal cutting parameters for surface roughness. The experimental results indicate that the effect of axial depth of cut is found to be more significant than the other parameters like the machined surface inclined angle, spindle speed and feed rate. The lower axial depth of cut (B1, 0.1 mm), with higher machined surface inclined angle (A3, 120°), higher spindle speed (C3, 4200 min^{-1}) and lower feed rate (D1, 870 mm min^{-1}), are determined to be the best choices for obtaining the lowest value of surface roughness. Therefore, the optimal parameters for surface roughness are set as A3B1C3D1. The surface roughness obtained from the confirmation test under the optimal parameters indicated that Taguchi optimization method is an effective method for optimizing surface roughness in 2.5D cutting end milling. This was accomplished with a relatively small number of experimental runs.

ACKNOWLEDGEMENT

This research was supported by University of Malaya, Postgraduate Research Fund (PS133/2010B). The authors would also like to thank Mr. Chan Hann Tsong and Mr. Ahmad Fauzi for their assistance in experimental work.

REFERENCES

1. Black, J. T. and Kohser, R. A., “Materials and Processes in Manufacturing,” John Wiley & Sons, 2008.
2. Lee, Y. S. and Chang, T. C., “Application of computational geometry in optimizing 2.5D and 3D NC surface machining,” Computers in Industry, Vol. 26, pp. 41-59, 1995.
3. Pang, J. and Narayanaswami, R., “Multiresolution offsetting and loose convex hull clipping for 2.5D NC machining,” Computer-Aided Design, Vol. 36, pp. 625-637, 2004.
4. Yao, Z. and Gupta, S. K., “Cutter path generation for 2.5D milling by combining multiple different cutter path patterns,” International Journal of Production Research, Vol. 42, pp. 2141-2161, 2004.
5. Gupta, S. K., Saini, S. K., Spranklin, B. W., and Yao, Z., “Geometric algorithms for computing cutter engagement functions in 2.5D milling operations,” Computer-Aided Design, Vol. 37, pp. 1469-1480, 2005.
6. Hamdan, A., Sarhan, A. D., and Hamdi, M., “An optimization method of the machining parameters in high-speed machining of stainless steel using coated carbide tool for best surface finish,” The International Journal of Advanced Manufacturing Technology, Vol. 58, No. 1-4, pp. 81-91, 2012.
7. Ramanujam, R., Muthukrishnan, N., and Raju, R., “Optimization of cutting parameters for turning Al-SiC(10p) MMC using ANOVA and grey relational analysis,” Int. J. Precis. Eng. Manuf., Vol. 12, No. 4, pp. 651-656, 2011.
8. Saini, S., Ahuja, I., and Sharma, V., “Influence of cutting parameters on tool wear and surface roughness in hard turning of AISI H11 tool steel using ceramic tools,” Int. J. Precis. Eng. Manuf., Vol. 13, No. 8, pp. 1295-1302, 2012.
9. Sarhan, A. A. D. and Matsubara, A., “Compensation Method of the Machine Tool Spindle Thermal Displacement for Accurate Monitoring of Cutting Forces,” Materials and Manufacturing Processes, Vol. 26, No. 12, pp. 1511-1521, 2011.
10. Raju, K., Janardhana, G., Kumar, P., and Rao, V., “Optimization of cutting conditions for surface roughness in CNC end milling,” Int. J. Precis. Eng. Manuf., Vol. 12, No. 3, pp. 383-391, 2011.
11. Munawar, M., Chen, J.-S., and Mufti, N., “Investigation of cutting parameters effect for minimization of sur face roughness in internal turning,” Int. J. Precis. Eng. Manuf., Vol. 12, No. 1, pp. 121-127, 2011.
12. Zhang, J. Z., Chen, J. C., and Kirby, E. D., “Surface roughness optimization in an end-milling operation using the Taguchi design method,” Journal of Materials Processing Technology, Vol. 184, pp. 233-239, 2007.
13. Sayuti, M., Sarhan, A. D., Fadzil, M., and Hamdi, M., “Enhancement and verification of a machined surface quality for glass milling operation using CBN grinding tool-Taguchi approach,” The International Journal of Advanced Manufacturing Technology, Vol. 60, No. 9-12, pp. 939-950, 2012.
14. Ghani, J. A., Choudhury, I. A., and Hassan, H. H., “Application of Taguchi method in the optimization of end milling parameters,” Journal of Materials Processing Technology, Vol. 145, pp. 84-92, 2004.
15. Park, S. H., “Robust Design and Analysis for Quality Engineering,” Chapman & Hall, 1996.
16. El-Gallab, M. and Sklad, M., “Machining of Al:SiC particulate metal matrix composites Part II: Workpiece surface integrity,” Journal of Materials Processing Technology, Vol. 83, pp. 277-285, 1998.
17. Dogra, M., Sharma, V., Sachdeva, A., Suri, N., and Dureja, J., “Tool wear, chip formation and workpiece surface issues in CBN hard turning: A review,” Int. J. Precis. Eng. Manuf., Vol. 11, No. 2, pp. 341-358, 2010.