Quality Improvement of End Milled Slots using Titanium Nitride Coated Tools

Ahmed Raza Khan
Department of Industrial & Manufacturing Engineering, Rachna College of Engineering & Technology (Constituent College of UET Lahore), Gujranwala, Pakistan
ahmed.raza@uet.edu.pk

Muhammad Shahzad
Department of Industrial & Manufacturing Engineering, Rachna College of Engineering & Technology (Constituent College of UET Lahore), Gujranwala, Pakistan

Muhammad Awais Ahmad
Department of Industrial & Manufacturing Engineering, Rachna College of Engineering & Technology (Constituent College of UET Lahore), Gujranwala, Pakistan

***Abstract*—End Milling is a slot making operation which is extensively used in various industrial applications such as aerospace, automotive and dies molds making industry. Functioning of the parts manufactured in above mentioned industries is linked with the quality of the machined slots. This paper is aimed at investigating the quality of end milled slots taking into account different input process parameters whereas Titanium Nitride coated tools are employed for end milling operation. Quality of end milled slots is measured in terms of surface roughness and diameter error. Taguchi orthogonal array is used as the experimental design which resulted in better quality of end milled slots.**

Keywords— Machining; End Milling; Taguchi Method; Parametric Optimization

I. INTRODUCTION

Milling is a set of highly flexible machining operations that are capable of producing a number of geometries. End milling involves the application of a multi tooth cutter having smaller width as compared to the workpiece's width. Slots are generated using this operation and, therefore, this operation has become an important industrial machining operation in tool, dies, molds, aerospace and automotive industry [1- 4].

Cutting tool technology is improving day by day. High Speed Steel tooling loses its hardness at comparatively higher speeds due to elevated temperatures. However, coating of a suitable material enables the tool to be used at comparatively higher speeds. Higher speed of the spindle is used to get good finish machined parts. Therefore, surface finish of a machined part can be improved using coated tools. The technology of cutting tools is rapidly improving and this development is necessary to improve the wear resistance and performance of machining of difficult-to-cut materials. Improvement in performance can be achieved by increasing the strength of the cutting tools in terms of wear resistance [1].

Choudhry et al. [5] used application of Taguchi design of experiment to find the optimal conditions finishing for Titanium Nitride (TiN) coated carbide inserts. He found that a combination of high cutting speed, low feed and low depth of cut resulted in high finish mode of the work piece.

Azam et al [6] found that feed is the major contributing factor for surface roughness among cutting parameters using response surface design. High strength low alloy steel AISI 4340 was used as the work material whereas coated carbide tools were employed for machining on CNC lathe machine in the research study.

Zhou et al conducted a machining study on Inconel 718 using TiN coated CBN (Cubic Boron Nitride) tools and uncoated CBN tools. Coated tools were found to provide better finish surfaces at high cutting speeds as compared to uncoated CBN tools [7]. In another study on Titanium alloys, PVD (physical vapour deposition) coated TiN and TiAlN coated tools were found to provide good finish in a face milling operation [8].

Lima et al. [9] investigated machinability of hardened steel grade AISI 4340 while employing various cutting tools at different cutting conditions. Polycrystalline cubic boron nitride (PCBN) tools and coated carbide tools were investigated for machining of AISI 4340. He found that surface finish improves while increasing cutting speed upto an extent (120 m/min), after that the surface finish deteriorates. He further found that depth of cut has a minor contribution towards surface roughness.

The influence of physical vapor deposition (PVD) coated, CVD coated, and uncoated carbide tools, speed and feed on surface roughness were evaluated for AISI 1030, it was found that roughness of the surface decreased with increasing cutting speed. However, surface roughness was found to increase with increasing cutting speed. It was further found that feed rate has direct linear relation with surface roughness for both uncoated and coated carbide tools [10]. Suresh et al.[11] found that high cutting speed coupled with low feed rate resulted in low value of surface roughness during the machining of AISI 4340.

A good experimental design is necessary to find the relations between process parameters and performance measures. In this regard, different experimental methodologies were reviewed by Benardos and Vosniakos [12] to predict the value of surface roughness. It was further reported that Taguchi method and response surface methodology (RSM) are commonly employed methods to study surface roughness in machining. Sahin and Motorcu [13] used RSM to investigate the influence of cutting parameters on surface roughness using CBN tools for the turning of hardened steel grade AISI 1050, whereas Davim et al. employed Taguchi orthogonal array coupled with analysis of variance (ANOVA) to find the machinability of tool steel grade AISI D2 using ceramic inserts [14].

This paper is aimed at investigating the surface roughness and diameter error of end milled slots using Titanium Nitride coated tools. Taguchi method is employed to improve the quality of the slots.

II. MATERIALS AND EXPERIMENT SETUP

A. *Work Piece Details*

Three 25.4 mm (1-inch) thick plates of Brass with (130mm length and 400mm with) are employed for the presented work. The material is purchased from the market with the details of the chemical composition as given in TABLE I.

TABLE I. CHEMICAL COMPOSITION OF BRASS

Elements	Copper	Lead	Ferrous	Zinc
Composition (%)	60.00	2.50	0.35	37.50

B. *Machining Details*

End milling process is done on the work piece using vertical machining center[1].

The machine employed along with work piece used for experimentation is shown in Fig. 1 and Fig. 2.

Fig.1: Machine employed for end milling

The end mill used for the experimental work has the following specifications (TABLE II).

TABLE II. TOOL DATA

Tool characteristics	Characteristics employed
Base material	High Speed Steel (M2 grade)
Coated material	Titanium Nitride (TiN)
Coating depth	4 micron
Diameter of tool	12mm
Helix angle	30^o

Three repetitions are done for each experiment in order to ensure repeatability of experiments as is the general approach [15-17] with average values reported herein.

Fig. 3 shows the Titanium Nitride (TiN) coated End Mill employed for the experimental work.

Fig.2: End Milling on the vertical machining center

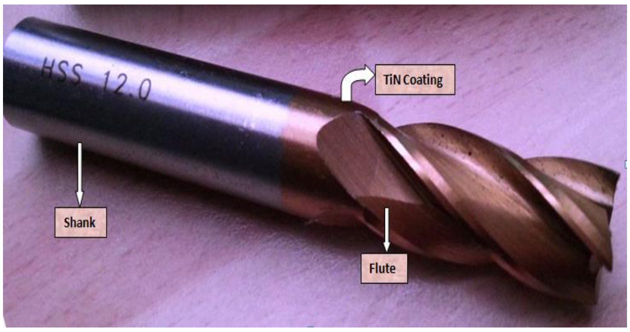

Fig. 3: Titanium Nitride (TiN) coated End Mill employed for the study

A slot is generated throughout the length of the work piece in each experiment. Fig. 4 shows the schematic of the slot generation on the work piece whereas Fig. 5 shows the pattern of the slots on the work piece after end milling process.

C. *Design of Experiments*

Experimental design is aimed to evaluate the influence of process parameters using Titanium Nitride (TiN) coated tools on quality of end milled slots taking different values of process parameters (spindle

[1] *MCV 720, Dah Lih Machinery Industry Co., Ltd., Taiwan*

speed, feed rate and depth of cut). Taguchi's orthogonal array L9 is used herein to evaluate the performance of coated tools. Thereafter, optimum levels are found for each process parameter. TABLE III shows the list of process parameters and the levels employed. Three levels are taken for each process parameter. Level 1 is the lowest value and level 3 is the highest value for each parameter investigated herein.

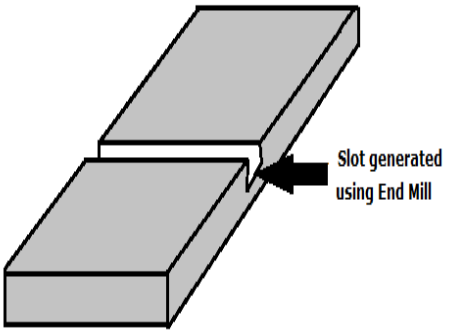

Fig. 4: Schematic of slot generation on the workpiece

Fig. 5: Pattern of slots after end milling process

TABLE III. PROCESS PARAMETERS AND LEVELS CHOSEN IN TAGUCHI ORTHOGONAL ARRAY L9

Process Parameters	Units	Working Range	Level-1	Level-2	Level-3
Spindle Speed (Ss)	rpm	900-2400	900	1800	2400
Feed rate (F_r)	mm/ min	800-1800	800	1200	1800
Depth of Cut (D_c)	mm	0.3-0.7	0.3	0.5	0.7

D. *Measurement Procedures*

Quality characteristics (performance measures) of end milled slots are evaluated in terms of surface roughness (Ra) and diameter error (Ed).

Fig. 6: Surface Profilometer employed for research work

Surface roughness is quantified by measuring surface roughness parameter "Ra" using surface profilometer (Surtronic S25, Taylor Hobson, United Kingdom). The profilometer employed for study is shown in Fig. 6. For each experiment, three readings are taken for each experiment with an evaluation length of 4.0 mm and a cut-off length of 0.8 mm and the average value isused herein.

Diameter error is the difference between the actual diameter (diameter of the slot machined) and the nominal diameter (diameter of the tool) [18]. Coordinate Measuring Machine (Chien Wei Precise Technology Co., Ltd., Taiwan) is used to find the actual diameter of the machined slot. Fig. 7 shows the Coordinate Measuring Machine employed for the study.

Fig. 7: Coordinate Measuring Machine (CMM) used for the measurement of axial and diameter error

A total of 4 different readings are taken along the same horizontal cross section of the slot and average value is taken. Thereafter, tool diameter (nominal diameter) is subtracted from average actual diameter to obtain the diameter error.

III. RESULTS, ANALYSIS AND DISCUSSIONS

A. *Results*

The results obtained for Taguchi orthogonal array L9 are shown in TABLE IV. Total 9 experiments are done whereas each row shows the experimental conditions (process parameters) and the quality dimensions (performance measures) measured for the experiment number.

TABLE IV. EXPERIMENTAL VALUES FOR THE MACHINING OF BRASS WITH TITANIUM COATED TOOL

No. of Exp.	Process parameters			Performance measures	
	S_s (rpm)	F_r (mm/min)	D_c (mm)	Ra (µm)	E_d (µm)
1	900	800	0.3	5.63	238.70
2	900	1200	0.5	6.85	265.10
3	900	1800	0.7	8.43	289.80
4	1800	800	0.5	4.08	145.70
5	1800	1200	0.7	5.95	175.50
6	1800	1800	0.3	5.26	156.40
7	2400	800	0.7	2.72	98.70
8	2400	1200	0.3	3.05	80.30
9	2400	1800	0.5	3.68	112.40

B. *Analysis and Discussions*

Signal to Noise Ratio analysis is done to find the influence of process parameters on quality dimensions (performance measures), namely surface roughness and diameter error, of slots end milled via Titanium nitride coated tools. Furthermore, optimum level of each process parameter is found for each performance measure. The type of the signal to noise ratio analysis used herein is “smaller the better” for “surface roughness” and “diameter error”. This indicates that the smallest values of the above stated performance measures are preferable. The formula for measuring “smaller the better” signal to noise ratio (SNR) is given in the Equation (1) [17].

$$\mathrm{SNR} = \eta = -10\log_{10}[\tfrac{1}{n}\textstyle\sum_{i=1}^{n} y_i^{2}] \quad (1)$$

Where SNR is represented by η and yi is the ith reading [xvi].

TABLE V shows signal to noise ratio values for surface roughness. The above formula is used to find the signal to noise ratio values for surface roughness at each level of the process parameters. The level that is providing the lowest value of signal to noise ratio without consideration of negative sign, in a column is the most preferable. In this regard, level 3 of the spindle speed is the optimum level because it provides the lowest value of the surface roughness.

TABLE V. RESPONSE TABLE (SIGNAL TO NOISE RATIOS) FOR SURFACE ROUGHNESS

Level	Ss	Fr	Dc
1	-16.747	-11.972	-13.039
2	-14.041	-13.963	-13.415
3	-9.898	-14.751	-14.233
Optimum level	-9.898	-11.972	-13.039
Delta	6.849	2.779	1.194
Rank	1	2	3

Similarly, level 1 of feed rate and depth of cut are found to be the optimum levels. Delta is the difference between the maximum and minimum value in a column of each process parameter. The highest value of Delta amongst all values of Delta is ranked as 1st. In this regard, spindle speed has the highest Delta value amongst feed rate and depth of cut, it is, therefore, ranked as first followed by depth of cut and feed rate. The high value of Delta represents the contribution of each process parameter. In this way, spindle speed is found to be the major contributing factor for surface roughness, whereas depth of cut is the least contributing factor. The results obtained from the table are plotted in Fig. 8. It can be seen that spindle speed is influencing the surface roughness of the end milled slots the most.

TABLE VI shows the signal to noise ratio values for diameter error at each level of the process parameter whereas the results from the table are plotted in Fig. 9.

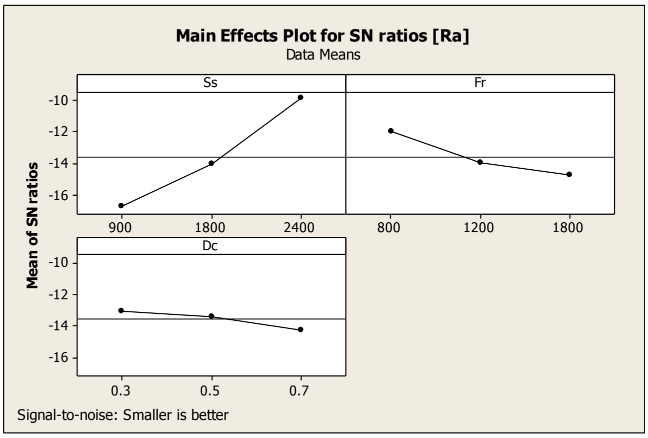

Fig. 8: Main effect plot (signal to noise ratios) for surface roughness

Spindle speed is found to be the major contributing factor for diameter error of end milled slots followed by depth of cut. Moreover, level 3 of spindle speed is found as the optimum level for diameter error whereas level 1 of feed rate and depth of cut is found as the optimum level for the diameter error of end milled slots.

TABLE VI. RESPONSE TABLE FOR (SIGNAL TO NOISE RATIOS) FOR DIAMETER ERROR

Level	(Ss)	Fr	Dc
1	-48.42	-43.57	-43.18
2	-44.01	-43.82	-44.25
3	-39.67	-44.71	-44.67
Optimum level	-39.67	-43.57	-43.18
Delta	8.76	1.14	1.49
Rank	1	3	2

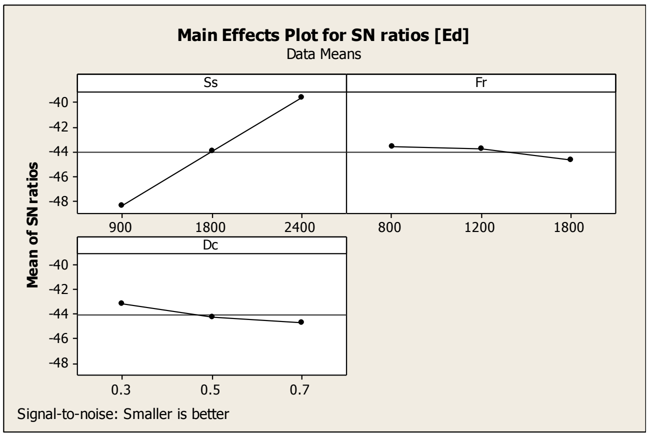

Fig. 9: Main effect plot (signal to noise ratios) for diameter error

In order to find the significance of the results obtained from signal to noise ratio analysis, analysis of variance (ANOVA) is done on signal to noise ratio analysis.

TABLE VII provides the results of ANOVA for surface roughness of end milled slots. A very low percentage contribution (0.81%) of residual error shows the significance of the analysis.

Moreover, ANOVA shows the percentage contribution of each process parameter. In this regard, spindle speed has a percentage contribution of 82.4%, whereas feed rate and depth of cut are found to influence the surface roughness by 14.21% and 2.58% respectively.

TABLE VII. ANOVA (SN RATIOS) FOR SURFACE ROUGHNESS

Process parameters	Defrees of freedom	Sequential Sum of Squares	Adjusted Sum of Squares	Adjusted Mean Squares	F-value	P-value	Percentage Contribution
Ss	2	71.3905	71.3905	35.6953	102.24	0.010	82.40024
Fr	2	12.3133	12.3133	6.1566	17.63	0.054	14.21224
Dc	2	2.2366	2.2366	1.1183	3.20	0.238	2.581525
Residual Error	2	0.6982	0.6982	0.3491	-	-	0.805875
Total	8	86.6387					

TABLE VIII shows the ANOVA for diameter error of end milled slots. Spindle speed is found to influence the diameter error at 94.19% whereas the contribution for feed rate and depth of cut is found to be 1.78% and 2.91%. A very low value of error (1.11%) is found for the signal to noise ratio analysis of diameter error.

The effect of Interactions is not taken due to the significance of the analysis. A very low value of residual error is found in the analysis (0.81% for surface roughness and 1.12% for diameter error)

TABLE VIII. ANOVA (SN RATIOS) FOR DIAMETER ERROR

Process parameters	Defrees of freedom	Sequential Sum of Squares	Adjusted Sum of Squares	Adjusted Mean Squares	F-value	P-value	Percentage Contribution
Ss	2	115.031	115.031	57.5157	84.23	0.012	94.1912
Fr	2	2.173	2.173	1.0866	1.59	0.386	1.779324
Dc	2	3.554	3.554	1.7771	2.60	0.278	2.910133
Residual Error	2	1.366	1.366	0.6828	-	-	1.118526
Total	8	122.125					

Because of the small amount of error present in the analysis of variance for surface roughness and diameter error, any possible interactions are not studied.

Regression modeling is done to formulate the process. In this regard, surface roughness of the end milled slots is found to follow the following equation.

$$Ra = 6.0169 - 0.00250994\ Ss + 0.00158333\ Fr + 2.63333\ Dc \quad (2)$$

Regression modeling is used to predict the values of surface roughness for each experiment. A relative error contribution is found for each experiment. TABLE IX shows the relative error for each experiment.

TABLE IX. FITS AND DIAGNOSTICS FOR SURFACE ROUGHNESS

Experiment No.	Experimental values	Predicted values	Relative error (%)
1	5.63	5.81	3.28
2	6.85	6.97	1.82
3	8.43	8.45	0.25
4	4.08	4.08	0.06
5	5.95	5.24	11.89
6	5.26	5.13	2.30
7	2.72	3.10	14.08
8	3.05	2.68	12.03
9	3.68	4.16	13.03

Average error comes to be 6.53% for the mathematical formulation.

Similarly, regression analysis is used to formulate the diameter error in terms of process parameters as shown in equation (3).

$$Ed = 295.7 - 0.112029\ Ss + 0.0248333\ Fr + 73.8333\ Dc \quad (3)$$

A relative error contribution is found for each experiment using equation (3) as shown in TABLE X. An overall average error comes to be 1.64%.

TABLE X. FITS AND DIAGNOSTICS FOR DIAMETER ERROR

Experiment No.	Experimental values	Predicted values	Relative error (%)
1	238.70	236.89	0.76
2	265.10	261.59	1.32
3	289.80	291.26	0.50
4	145.70	150.83	3.52
5	175.50	175.53	0.02
6	156.40	160.90	2.87
7	98.70	98.38	0.32
8	80.30	78.78	1.89
9	112.40	108.45	3.52

Confirmatory experiments are done to validate the finding of the regression analysis. Mathematical formulations are found to be in good agreement with the experimental values.

IV. CONCLUSION

End milling process is investigated for the quality improvement of slots using Titanium Nitride coated tools. Quality of the end milled slots is evaluated in terms of surface roughness (Ra) and diameter error. Three process parameters namely spindle speed, feed rate and depth of cut are taken for the study using Taguchi L9 orthogonal array as experimental design. Following conclusions are drawn after the study;

- For surface roughness, level 3 of cutting speed and level 1 of feed rate and depth of cut are found as the optimum levels. Moreover, cutting speed is found to be the major contributing process parameter with 82.4% followed by feed rate (14.21%) whereas depth of cut (2.58%) is found to be the least contributing factor for the selected range in ANOVA. Residual error is found to be 0.8% for ANOVA for surface roughness.
- For diameter error, level 3 of cutting speed and level 1 of feed rate and depth of cut are found as the optimum levels. Moreover, cutting speed is found to be the major contributing process parameter with 94.19% followed by feed rate (1.78%) whereas depth of cut (2.91%) is found to be the least contributing factor for the selected range in ANOVA. Residual error is found to be 1.12% for ANOVA for diameter error.
- Regression modelling provided useful linear mathematical equation for surface roughness and diameter error with an average error of 6.53% and 1.64% respectively.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Mr. Ijaz Hussain, Gujranwala Tools, Dies and Moulds Center (GTDMC), Gujranwala, Pakistan for providing facilities for the research work.

REFERENCES

1. M.P. Groover, “Fundamentals of Modern Manufacturing: Materials, Processes, and Systems”, John Wiley & Sons, 4th Edition, Chapter 23, 2010, pp. 525-526.

2. S. Kalpakjian, and S. R. Schmid, “Manufacturing Engineering and Technology,” Pearson Education, 6th Edition, Chapter 27, USA, 2009, pp. 659-668.

3. J. Paulo Davim, “Machining: Fundamentals and Recent Advances”, Springer Science & Business Media, 2008, chapter 8, pp. 225.

4. V. Sampat and U. Konada, “A novel approach to predict surface roughness in machining operations using Fuzzy set theory, ProQuest, 2007, chapter 2, pp. 4

5. I.A Choudhury, H.H Hassan, J.A. Ghani, “Application of Taguchi method in the optimization of end milling parameters”, Journal of Materials Processing Technology, Volume 145, Issue 1, 1 January 2004, Pages 84‑92

6. M. Azam, M. Jahanzaib, A. Wasim & S. Hussain, “Surface roughness modeling using RSM for HSLA steel by coated carbide tools”, International Journal of Advanced Manufacturing Technology, 2014, DOI 10.1007/s00170-014-6707-5

7. J. Zhou, V. Bushlya, P. Avdovic and J. E. Ståhl, “Study of surface quality in high speed turning of Inconel 718 with uncoated and coated CBN tools”, International Journal of Advanced Manufacturing Technology , vol. 58, 2012,pp. 141–151

8. N. Qiulin, M. Chen, W. Ming and Q. An, “Evaluation of the performance of coated carbide tools in face milling TC6 alloy under dry condition”, International Journal of Advanced Manufacturing Technology, vol. 64, (2013), pp. 623–631, DOI 10.1007/s00170-012-4043-1

9. J.G. Lima, R.F. Avila, A.M. Abrao, M. Faustino, J.P. Davim, “Hard turning: AISI 4340 high strength low alloy steel and AISI D2 cold work tool steel”, Material Processing Technology, vol. 169, 2005, pp. 388–395.

10. M. Nalbant, H. Gokkaya, I. Toktas, G. Sur, “The experimental investigation of the effects of uncoated, PVD- and CVD-coated cemented carbide inserts and cutting parameters on surface roughness in CNC turning and its prediction using artificial neural networks”, Robot Computer Integrated Manufacturing, vol. 25, 2009, pp.211–223

11. R. Suresh, S. Basavarajappa, G.L. Samuel, “Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool”, Measurement , vol. 45, No. 7,2012, pp. 1872–1884

12. P.G. Benardos, G.C. Vosniakos, “Predicting surface roughness in machining: a review”, International Journal of Machine Tools and Manufacture, vol. 43, 2003, pp. 833–844

13. Y. Sahin, A.R. Motorcu, “Surface roughness model in machining hardened steel with cubic boron nitride cutting tool”, International Journal of Refractory Met Hard Mater , vol. 26, 2008, pp. 84–90

14. J.P. Javim, F. Luis, “Machinability evaluation in hard turning of cold work tool steel (D2) with ceramic tools using statistical techniques”, Mater Des, vol. 28, 2007, pp. 1186–1191

15. A. Ikram, N.A. Mufti, M.Q. Saleem, A.R. Khan, “Parametric optimization for surface roughness, kerf and MRR in Wire Electrical Discharge Machining (WEDM) using Taguchi Design of Experiment” Journal of Mechanical Science and Technology, vol. 27, No. 7, South Korea, 2013, pp. 2133-2141

16. M.Q. Saleem, A.R. Khan, N.A. Mufti, “Performance Optimization of Electrical Discharge Machining (Die Sinker) for Al-6061 via Taguchi Approach”, Mehran University Research Journal of Engineering & Technology Pakistan, in press

17. A. Shah, N.A. Mufti, D. Rakwal, and E. Bamberg, “Material Removal Rate, Kerf, Surface Roughness of Tungsten Carbide Machined with Wire Electrical Discharge Machining”, Journal of Materials Engineering and Performance, vol. 20, No. 1, USA, 2011, pp. 71-76

18. T. Aized, M. Amjad, “Quality improvement of Deep Hole Drilling process of AISI D2”, International Journal of Advanced Manufacturing Processes, Volume 69, 2013, pp. 2493-2503