Investigation of tool wear and surface roughness on machining of titanium alloy with MT-CVD cutting tool

Kalipada Maity* and Swastik Pradhan
Department of Mechanical Engineering, National Institute of Technology, Rourkela, Odisha, India, 769008
*kpmaity@gmail.com

Abstract
In this study, machining of titanium alloy (grade 5) is carried out using MT-CVD coated cutting tool. Titanium alloys possess superior strength-to-weight ratio with good corrosion resistance. Most of the industries used titanium alloy for the manufacturing of various types of lightweight components. The parts made from Ti-6Al-4V largely used in aerospace, biomedical, automotive and marine sectors. The conventional machining of this material is very difficult, due to low thermal conductivity and high chemical reactivity properties. To achieve a good surface finish with minimum tool wear of cutting tool, the machining is carried out using MT-CVD coated cutting tool. The experiment is carried out using of Taguchi L_{27} array layout with three cutting variables and levels. To find out the optimum parametric setting desirability function analysis (DFA) approach is used. The analysis of variance is studied to know the percentage contribution of each cutting variables. The optimum parametric setting results calculated from DFA were validated through the confirmation test.
Keywords: Titanium alloy, Tool wear, Surface roughness, Desirability function analysis, Analysis of variance

1. Introduction

In most of the manufacturing industries such as aerospace, automobile, marine and bio-medical sector the uses of titanium alloy component are in high demand. The demand of titanium alloy is high due to its inherent properties of high strength to weight ratio, good corrosion resistance and is able to sustain at high temperature by retaining its high strength [1, 2]. However, conventional machining of titanium alloy is challenging task. It falls under the category of difficult to cut material. Due to its low modulus of elasticity, low thermal conductivity and high chemical reactivity properties [3, 4]. Therefore, machining of titanium alloy leads to decrease the tool life of the cutting tool. The tool wear rate increases rapidly, thus, decreases the surface finish of the machined surface. It is difficult to machine titanium alloy at high cutting speed, feed and depth of cut, due to the generation of high temperature. Hence, machining of titanium alloy with the proper cutting tool and appropriate cutting conditions is important. To achieve a better surface finish with less tool wear rate is the major challenge led by the manufacturing industries. During machining, multiple criteria have to be satisfied such as time-saving, low machining, and material cost, the number of trials should be minimized. In such situations, it is difficult to find out the best possible combination of the cutting variables with satisfying all the output criteria. To overcome such type of problems, researchers have suggested various types of experimental layout design having less number of trial runs. They have also suggested multi-objective optimization approach and techniques such as Grey relational analysis (GRA), Principal component analysis (PCA), Response surface methodology (RSM) and desirability function analysis (DFA) find the best possible combination of the cutting variables with satisfying all the output criteria [5-7]. Such as, Lin optimized the EDM process through orthogonal array design with the GRA optimization method. Result obtained from the method impressively improved EDM process [8]. Nihat Tosun studied the effect of cutting variables on surface roughness and burr height during the drilling operation. The responses are optimized through grey relational analysis approach. Results indicate that, this approach can be successfully applied to the many other machining process in which multiple response criteria have to be optimized [9]. Ramanujam et al. studied the effects of surface roughness and power consumption during machining of Al-15%SiCp composites. The optimum cutting variables with desired responses were obtained by using desirability function analysis. It is observed that, the performance characteristics of the output responses were improved combinedly by using the DFA method [10]. Singh et al. studied the effect of turning parameter for Cr2O3 doped zirconia toughened alumina cutting insert during machining of AISI 4340 steel. The optimum cutting condition for the minimum tool failure and maximum tool life was found using desirability function optimization. The optimum cutting condition was cutting speed of 420 m/min, feed rate of 0.12 mm/rev and depth of cut of 0.5 mm [11]. Bouzid et al. also studied the flank wear and tool lifespan during finish turning of AISI 304 stainless steel using the desirability function method. The optimum setting for composite desirability was found v1-f1-t1 for flank wear, surface roughness and v1-f-for lifespan [12]. Chabbi et al determined the optimum cutting conditions based on the response surface methodology and desirability function approach leading to minimum surface roughness, cutting power, cutting force and maximum productivity, for turning of polyoxymethylene polymer using cemented carbide cutting tool [13]. Most of the research work had been carried out using various multi-objective optimization approaches for achieving best cutting condition with a satisfying performance characteristic for all the responses. Thus, the using of coated cutting inserts with the combination of different cutting conditions as per the design layout and finally obtaining the optimum cutting conditions through multi-objective optimization method will furnish the machinability of the titanium alloy. Hence, in this study, MT-CVD cutting insert with TiN/TiCN/Al_2O_3/TiN coating is used to machine the titanium alloy. To reduce the trails run during machining of titanium alloy the taguchi orthogonal array layout with three cutting variables and levels is selected. DFA method is used to find out the optimum parametric setting for low surface roughness and tool wear during machining of titanium alloy using MT-CVD coated cutting tool. Further, ANOVA analysis has been performed to identify the most influencing cutting parameter. The validation of predicted optimum parameter setting is conducted with the confirmation test.

2. Experimental details

The experiment is carried out on the NH 26 HMT lathe machine. The spindle speed of the machine varied between 45 to 1020 RPM with 11 kW spindle power. The experiment is designed as per the Taguchi L_{27} orthogonal array method. The cutting variables selected for machining are cutting speed, feed, and depth of cut. The variations in the level of the cutting variables are shown in Table 1.

IOP Conf. Series: Materials Science and Engineering **346** (2018) 012053 doi:10.1088/1757-899X/346/1/012053

Table 1. Cutting variables with three levels

Cutting parameter	Levels of the cutting parameter		
	1	2	3
Cutting speed (m/min)	43	73	124
Feed rate (mm/rev)	0.04	0.08	0.16
Depth of cut (mm)	0.4	0.8	1.6

Titanium alloy of grade 5 is considered as the workpiece. The machining of this material is very difficult due to its low thermal conductivity properties. It possesses highly chemically reactive properties due to this the machining of this alloy is difficult using coolant. Certain coating material of the cutting tool also reacts during machining. Hence, it's a challenging task to machine the titanium alloy in the conventional machining process. The diameter of the workpiece is 50 mm to 600 mm length. The properties of titanium alloy are shown in the Table 2. The experimental setup of the machining operation is shown in the Figure 1.

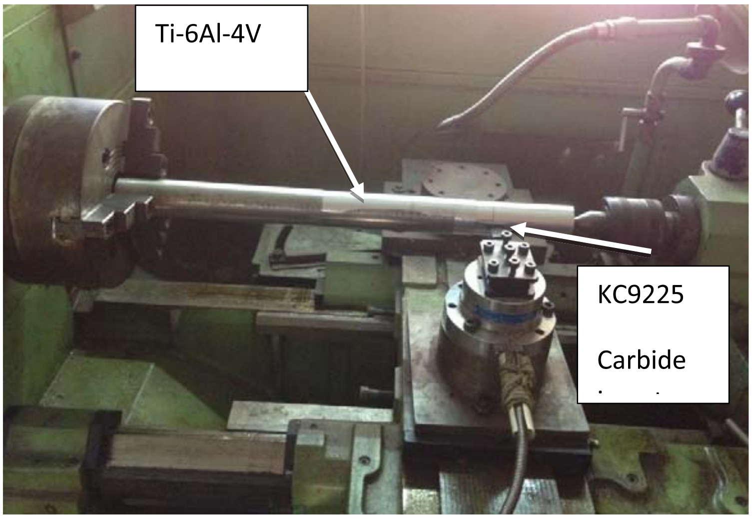

Figure 1. Experiment setup

Table 2. Chemical composition and mechanical properties of titanium alloy (grade 5) [14]

Properties	Density (g/cm3)	Tensile strength (Mpa)	Yield strength (Mpa)	Thermal Conductivity (W/m˚C)	Hardness (HRC)
	4.42	950	900	6.7	36

Multi-layered K-MTCVD coated cutting tool is selected for the machining of titanium alloy. The material of the cutting inserts is cobalt-enriched carbide. This cutting insert is specially designed for counterattacking the depth of cut, notching and burr formation during machining. The coating on the cutting inserts is done through chemical vapour deposition (CVD) process. The coating materials used for coating are TiN/TiCN/Al2O3/TiN. This grade of cutting inserts has a well polished edge that minimizes the formation of build-up edges and ensures the superior finish on

the machined surface. The manufacturer grade of the cutting insert is KC9225. The style of the cutting inserts is SNMG with 432 insert size. In this experiment, square shape types cutting inserts with a positive rake angle of 6 °is used for machining of Ti-6Al-4V. The tool holder used to hold the cutting inserts in the right-hand turning operation is of ISO coding “PSBNR 2020K12” with “P” clamping system.
After machining is performed as per the L_{27} layout, the surface roughness and tool wear are measured by using Taylor/Hobson Surtronic 3+ surface roughness tester and optical microscope respectively. The image of the measuring instrument is shown in the Figure 2 (a) and (b).

(a) Taylor/Hobson Surtronic 3+ surface roughness tester

(b) Optical microscope

Figure 2. Measuring Instrument

The experiment conducted as per the Taguchi L_{27} orthogonal array layout. The experimental layout with the cutting parameters and the results obtained after the machining i.e. surface roughness and tool wear are tabulated in Table 3.

Table 3. Orthogonal L_{27} experimental run with results

Run	Cutting Parameter level			Experiment value	
	Cutting speed (v)	Feed (f)	Depth of cut (d)	Surface roughness	Tool wear
1	43	0.04	0.4	0.66	0.444
2	43	0.04	0.8	0.82	0.203
3	43	0.04	1.6	0.94	0.164
4	43	0.08	0.4	1.06	0.289
5	43	0.08	0.8	1.36	0.152
6	43	0.08	1.6	1.38	0.293
7	43	0.16	0.4	0.86	0.186
8	43	0.16	0.8	1.04	0.179
9	43	0.16	1.6	1.42	0.281
10	73	0.04	0.4	1.6	0.285
11	73	0.04	0.8	0.76	0.144
12	73	0.04	1.6	1.48	0.302
13	73	0.08	0.4	1.04	0.372
14	73	0.08	0.8	1.04	0.113

15	73	0.08	1.6	1.32	0.268
16	73	0.16	0.4	1.06	0.442
17	73	0.16	0.8	1.32	0.364
18	73	0.16	1.6	1.58	0.315
19	124	0.04	0.4	1.16	0.225
20	124	0.04	0.8	1.06	0.263
21	124	0.04	1.6	1.36	0.397
22	124	0.08	0.4	1.18	0.388
23	124	0.08	0.8	1.18	0.351
24	124	0.08	1.6	1.34	0.31
25	124	0.16	0.4	1.06	0.359
26	124	0.16	0.8	1.6	0.993
27	124	0.16	1.6	1.58	0.359

3. Result and discussion

3.1. Desirability function analysis combined with Taguchi method

Derringer and Suich [15, 16] find out this useful approach to optimize the multiple responses. This procedure introduced the concept of desirability functions. This desirability function is also known as objective functions. The objective function transforms the surface roughness and tool wear value into a scale-free value called as an individual desirability index. Than, the individual desirability index is calculated using Equation 1. After that, the calculation of the composite desirability d_G is done using Equation 2. The optimal parametric setting for lower surface roughness and tool wear is selected based on calculated composite desirability. The highest value of the composite desirability signifies the optimal parametric setting for low surface roughness and tool wear.

$$d_i = \begin{cases} 1, & x \le x_{\min} \\ \left(\dfrac{x - x_{\max}}{x_{\min} - x_{\max}} \right)^r, & x_{\min} \le x \le x_{\max},\ r \ge 0 \\ 0, & x \ge x_{\min} \end{cases} \tag{1}$$

Where, d_i represents the individual desirability index, $x_{\min}$ and $x_{\max}$ are the lowest and highest values of x. The target to be minimized and it is denoted by x . r depicts the weight, and the weight values are expressed as per the requirement of the decision maker.

$$d_G = \left(d_1^{w_2} \times d_1^{w_2} \times .... \times d_i^{w_i} \right)^{1/w} \tag{2}$$

where w_i represents the weight assigned to each response, w is the sum of all individual weights. The value of d_G closer to 1 is assumed to be the optimal parametric setting of corresponding input parameters. The individual desirability index of the surface roughness, tool wear and the overall desirability index for each experimental data sets are shown in Table 4.

Table 4. DFA calculated data

Run	Individual Desirability F (di)		Composite desirability function
	Surface roughness	Tool wear	
Units	di (Ra)	di (Tool wear)	dG
1	1.000	0.624	0.889
2	0.830	0.898	0.929
3	0.702	0.942	0.902
4	0.574	0.800	0.823
5	0.255	0.956	0.703
6	0.234	0.795	0.657
7	0.787	0.917	0.922
8	0.596	0.925	0.862
9	0.191	0.809	0.627
10	0.000	0.805	0.000
11	0.894	0.965	0.964
12	0.128	0.785	0.563
13	0.596	0.706	0.805
14	0.596	1.000	0.879
15	0.298	0.824	0.704
16	0.574	0.626	0.774
17	0.298	0.715	0.679
18	0.021	0.770	0.358
19	0.468	0.873	0.799
20	0.574	0.830	0.831
21	0.255	0.677	0.645
22	0.447	0.688	0.744
23	0.447	0.730	0.756
24	0.277	0.776	0.681
25	0.574	0.720	0.802
26	0.000	0.000	0.000
27	0.021	0.720	0.352

The highest composite desirability value, i.e. 0.964 in the Table 4 corresponds to the optimal parametric setting. The optimal parametric setting is found to be cutting speed at 74 m/min feed at 0.04 mm/rev and depth of cut at 0.8 mm. The surface roughness and tool wear at that particular setting are 0.76 microns and 0.144 mm respectively.

The response means of the composite desirability according to the cutting variables and their level is calculated and tabulated in the Table 5. The difference between the maximum and minimum value of the composite desirability of each cutting variable is calculated to reveal the significance of the cutting variables on the responses. It is observed that, the responses are highly influenced by cutting speed followed by feed and depth of cut.

Table 5. Response table for the composite desirability

Machining parameter	Average composite desirability		
	Cutting speed	Feed	Depth of cut
Level 1	0.8126	0.7246	0.7288
Level 2	0.6362	0.7502	0.7335
Level 3	0.6233	0.5974	0.6098
Max-Min	0.1893	0.1528	0.1237
Rank	1	2	3
Total Mean of the composite desirability			0.69069

Analysis of variance (ANOVA)

Analysis of variance is a technique to obtain the contribution of each cutting variables on the output responses. The purpose of the ANOVA analysis is to found out the highest influencing cutting variables, as well as to know percentage contribution of the cutting variables on the responses. [17]. The results of the ANOVA analysis for surface roughness and tool wear are tabulated in Table 6 and Table 7. From the ANOVA analysis, it can be observed that, the surface roughness is highly influenced by depth of cut followed by cutting speed and feed with 25.35 %, 13.66 % and 8.73 % respectively. Whereas, the tool wear is highly influenced by cutting speed by 17.85 %. The ANOVA analysis for the composite desirability is carried out, to know the effect of cutting variables on both the responses.

Table 6. Analysis of Variance for the surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	Percentage contribution
Cutting speed	2	0.2841	0.2841	0.14206	4.85	13.66
Feed	2	0.1815	0.1815	0.09076	3.1	8.73
Depth of cut	2	0.5272	0.5272	0.26359	8.99	25.35
Cutting speed*feed	4	0.3476	0.3476	0.08691	2.96	16.72
Cutting speed*depth of cut	4	0.1737	0.1737	0.04343	1.48	8.35
Feed*depth of cut	4	0.3306	0.3306	0.08266	2.82	15.90
Residual Error	8	0.2345	0.2345	0.02932		
Total	26	2.0793				

Table 7. Analysis of Variance for the tool wear

Source	DF	Seq SS	Adj SS	Adj MS	F	Percentage contribution
Cutting speed	2	0.161038	0.20137	0.080519	3.32	17.85
Feed	2	0.095837	0.12055	0.047919	1.98	10.62
Depth of cut	2	0.007074	0.08853	0.003537	0.15	0.78
Cutting speed*feed	4	0.115986	0.31397	0.028996	1.2	12.86
Cutting speed*depth of cut	4	0.175335	0.24932	0.043834	1.81	19.43
Feed*depth of cut	4	0.152879	0.37054	0.03822	1.58	16.94
Residual Error	8	0.194088	0.28133	0.024261		
Total	26	0.902237				

Referring to Table 8, it can be observed that, both surface roughness and tool wear are highly influenced by cutting speed with the percentage contribution of 12.39 %.

Table 8. Analysis of Variance for the composite desirability

Source	DF	Seq SS	Adj SS	Adj MS	F	Percentage contribution
Cutting speed	2	0.20137	0.20137	0.10068	2.86	12.39
Feed	2	0.12055	0.12055	0.06027	1.71	7.42
Depth of cut	2	0.08853	0.08853	0.04426	1.26	5.45
Cutting speed*feed	4	0.31397	0.31397	0.07849	2.23	19.31
Cutting speed*depth of cut	4	0.24932	0.24932	0.06233	1.77	15.34
Feed*depth of cut	4	0.37054	0.37054	0.09263	2.63	22.79
Residual Error	8	0.28133	0.28133	0.03517		
Total	26	1.6256				

Also, it can be justified from the response table that the cutting speed is the most affecting cutting variable followed by feed and depth of cut respectively.

3.2. *Confirmation test*

The confirmation test is carried out to validate the optimum cutting parametric setting. The improvement of the performance characteristics of the optimum parametric setting is obtained with respect to the initial cutting condition. The predicted composite desirability of the optimum parametric setting is calculated using Equation 3 [10].

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q}\left(\overline{\gamma_i} - \gamma_m\right) \quad (3)$$

Where, $\hat{\gamma}$ is the predicted composite desirability, γ_m is the total mean of the composite desirability value, $\overline{\gamma_i}$ is the mean of the composite desirability value at the optimum level and q is the total number of machining parameter considered for the machining operation. The confirmation test is shown in the Table 9.

Table 9. Confirmation test

	Initial machining parameters	Optimal machining parameters	
	Experiment	Experiment	Prediction
Setting Level	v2f2d3	v2f1d2	v2f1d2
Surface roughness	1.32	0.76	
Tool wear	0.268	0.144	
Composite desirability value	0.704	0.964	0.853
Improvement in composite desirability value		0.26	

Referring to Table 9, it can be observed that, the predicted composite desirability is found to be 0.853. The surface roughness value of the optimum parametric setting is improved from 1.32 microns to 0.76 microns. The tool wear value of the optimum parametric setting is improved from 0.268 mm to 0.76 mm. An improvement of 0.26 in the composite desirability value is observed through DFA approach. The optimal cutting condition founded through the DFA method improved the machinability performance of the titanium alloy during machining with multi-layered coated carbide inserts.

4. Conclusion

In this study, the machining of titanium alloy is carried out using KC9225 cutting inserts. The experiment is done as per the L_{27} taguchi experiment design. The cutting variables cutting speed, feed and depth of cut were varied with three levels. DFA method is used to find out the optimal parametric setting. It is found that the optimal cutting condition found through the DFA method is cutting speed at 74 m/min feed at 0.04 mm/rev and depth of cut at 0.8 mm. It concluded that an improvement of 0.26 in the composite desirability value is observed through DFA Method during machining of titanium alloy with multi-layered coated carbide inserts. From ANOVA, it is observed that the cutting speed is most influencing cutting variables that combinedly affect the surface roughness and tool wear respectively.

5. References

[1] Ezugwu, E.O. and Z.M. Wang, *Titanium alloys and their machinability—a review.* Journal of Materials Processing Technology, 1997. **68**(3): p. 262-274.
[2] Arrazola, P.J., et al., *Machinability of titanium alloys (Ti6Al4V and Ti555. 3).* Journal of Materials Processing Technology, 2009. **209**(5): p. 2223-2230.
[3] Cui, C., et al., *Titanium alloy production technology, market prospects and industry development.* Materials & Design, 2011. **32**(3): p. 1684-1691.
[4] Revankar, G.D., et al., *Analysis of surface roughness and hardness in titanium alloy machining with polycrystalline diamond tool under different lubricating modes.* Materials Research, 2014. **17**(4): p. 1010-1022
[5] Maity, K. and S. Pradhan, *Study of Chip Morphology, Flank Wear on Different Machinability Conditions of Titanium Alloy (Ti-6Al-4V) Using Response Surface Methodology Approach.* International Journal of Materials Forming and Machining Processes (IJMFMP), 2017. **4**(1): p. 19-37.

[6] Khan, A. and K. Maity, *Parametric modelling of multiple quality characteristics in turning of CP titanium grade-2 with cryo-treated inserts.* International Journal of Materials and Product Technology, 2017. **54**(4): p. 306-331.
[7] Maity, K. and S. Pradhan. *Study of process parameter on mist lubrication of Titanium (Grade 5) alloy*. in *IOP Conference Series: Materials Science and Engineering*. 2017. IOP Publishing.
[8] Lin, J. and C. Lin, *The use of the orthogonal array with grey relational analysis to optimize the electrical discharge machining process with multiple performance characteristics.* International Journal of Machine Tools and Manufacture, 2002. **42**(2): p. 237-244.
[9] Tosun, N., *Determination of optimum parameters for multi-performance characteristics in drilling by using grey relational analysis.* The International Journal of Advanced Manufacturing Technology, 2006. **28**(5-6): p. 450-455.
[10] Ramanujam, R., R. Raju, and N. Muthukrishnan, *Taguchi multi-machining characteristics optimization in turning of Al-15% SiCp composites using desirability function analysis.* Journal of studies on manufacturing, 2010. **1**(2-3): p. 120-125.
[11] Singh, B., B. Mondal, and N. Mandal, *Machinability evaluation and desirability function optimization of turning parameters for Cr 2 O 3 doped zirconia toughened alumina (Cr-ZTA) cutting insert in high speed machining of steel.* Ceramics International, 2016. **42**(2): p. 3338-3350.
[12] Bouzid, L., et al., *Estimation and optimization of flank wear and tool lifespan in finish turning of AISI 304 stainless steel using desirability function approach.* International Journal of Industrial Engineering Computations, 2018. **9**(3): p. 349-368.
[13] Chabbi, A., et al., *Predictive modeling and multi-response optimization of technological parameters in turning of Polyoxymethylene polymer (POM C) using RSM and desirability function.* Measurement, 2017. **95**: p. 99-115.
[14] Satyanarayana, K., A.V. Gopal, and P.B. Babu, *Analysis for optimal decisions on turning Ti–6Al–4V with Taguchi–grey method.* Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2014. **228**(1): p. 152-157.
[15] Vojnovic, D., et al., *Simultaneaus optimization of several response variables in a granulation process.* Drug development and industrial pharmacy, 1993. **19**(12): p. 1479-1496.
[16] Naveen Sait, A., S. Aravindan, and A. Noorul Haq, *Optimisation of machining parameters of glass-fibre-reinforced plastic (GFRP) pipes by desirability function analysis using Taguchi technique.* The international journal of advanced manufacturing technology, 2009. **43**(5): p. 581-589.
[17] Hascalik, A. and U. Caydas, *Optimization of turning parameters for surface roughness and tool life based on the Taguchi method.* The International Journal of Advanced Manufacturing Technology, 2008. **38**(9): p. 896-903.