JFET 23(2) (2016) 19-28

Journal of Faculty of Engineering & Technology

journal homepage: www.pu.edu.pk/journals/index.php/jfet/index

TAGUCHI BASED OPTIMIZATION OF MACHINING PARAMETERS TO CONTOL SURFACE ROUGHNESS USING TiAlN-COATED TUNGSTEN CARBIDE MILLING CUTTER

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Abstract

Surface roughness is one of the determinant factors that govern the quality of machined surfaces. This paper experimentally studies effect of machining parameters on surface roughness (R_a) for end milling of AISI 1045 workpiece using a TiAlN coated carbide milling cutter. Taguchi optimization method has been used to determine the optimal level of three control factors, namely, feed rate, spindle speed and depth of cut. Analysis of variance (ANOVA) demonstrates that the feed rate is the most significant parameter and contributes 47% for surface roughness. Finally, the contour plots of these three parameters have been analysed to determine the optimal ranges of control factors.

Keywords: Surface Roughness, TiAlN Coated End Mill, Taguchi Optimization Method, ANOVA

1. Introduction

The AISI 1045 steel is widely used in manufacturing industry. End milling is a commonly used machining process for AISI 1045 steel. The surface roughness obtained by end milling process is important and has a direct impact on wear resistance, strength, lubrication requirements, corrosion resistance and fatigue resistance of a machined component [1]. Meeting the requirement of tolerance and obtaining a reasonable quality of the cut for machined parts have become a challenge for manufacturing industry. The phenomenon of tool wear has practically put a limit on achieving a high degree of accuracy and surface finish. To obtain a high degree of surface finish, different coatings are applied on cutting tools. The purpose of these coatings is to improve the hardness, wear resistance, and life of cutting tools. Titanium (Ti) based coatings, with their higher hardness, lower wear coefficient and chemical inertness against corrosion, help to perform high speed milling under dry cutting conditions [2-5]. The concept of dry machining is gaining more attention from the researchers because the usage of coolants causes environmental pollution and biological problems to operators and contributes towards the total manufacturing cost [6]. In the list of Ti based coatings, the family of TiAlN is categorized as the self-lubricating coating that reduces the use of coolant in machining.

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oxidation resistance [2, 7-9]. The properties of Ti based hard coatings are listed in Table 1.

Table 1.Properties of Ti based hard coatings for cutting applications [2].

	TiN	TiCN	TiAlN
Composition (%)	50Ti-50N	50Ti-25C-25N	25Ti-25Al-50N
Hardness (kg mm^{-2})	2200-2500	2800-3200	2500-3000
Hardness at 800°C (HV 0.05)		1100	1400
Coefficient of penetration of heat (Ws$^{1/2}$/(m^{2}K))	8100	13900	6300
Thermal conductivity (Wm^{-1}K^{-1})	30	43	22
Oxidation resistance (°C)	500-600	400	800

Initially coatings were applied in single layer but the advancements in coating technology have made it possible to develop multi-layered coating depositions such as TiZrN, TiCrN, CrAlN, TiAlVN, TiAlZrN, and TiAlCN. The intent to develop multi-layered coating is to combine the suitable properties of different materials. The insertion of number of parallel interfaces hinders the dislocation movement and improves the toughness and hardness of the coating [10].

Many researchers have performed machining with coated tools while studying the effect of process parameters to control surface roughness in end milling operation. Da Silva et al. performed end milling of AISI 1047 steel by using TiAlN coated carbide inserts under wet and dry machining environments. Lower surface roughness was obtained at lower cutting speed and feed rate in the presence of cutting fluid at reduced flow rate [11]. In end milling of medium carbon steel S50C with TiAlN coated tool, surface roughness decreased with increase in spindle speed while higher values of axial depth of cut and feed rate result in increased surface roughness [12, 13]. Qinglong et al. studied the effect of cutting speed, feed rate, and radial depth of cut in hard milling of high strength steel 30Cr3 by using TiAlN coated tool. It was observed that cutting forces drop due to increase in cutting speed resulting in improved surface finish while higher values of feed rate and radial depth of cut give rise to cutting forces and tool wear which in turn increase roughness of machined surface [14]. Hameed et al. applied minimum quantity lubrication (MQL) for hard milling of AISI 4340 alloy steel using coated end mill and determined that feed rate is the highest contributing factor for surface roughness followed by cutting speed and radial depth of cut. The interactions of feed rate with radial depth of cut and cutting speed were also significant [15]. In another research, robust parameter design was employed to optimize process parameters such as feed per tooth, axial depth of cut, radial depth of cut, and cutting speed for end milling of AISI 1045 using TiN-coated carbide inserts. Experimental results suggested the use of lower feed per tooth, larger value of depth of cut, and smaller cutting speed to improve surface finish [16]. Costa et al. utilized normal boundary intersection method to optimize multiple response variables namely, surface roughness and material removal rate, in dry end milling of AISI 1045 using TiCN and TiN-coated carbide inserts. Feed per tooth and axial depth of cut were found out to be most significant factors [17]. It is clear from research work highlighted above that no significant work was performed on dry end milling of AISI 1045 using TIAlN coated tool. Researchers have shown that feed rate, depth of cut and, spindle speed are influential factors to control surface roughness for case of end milling.

In present study, multilayered TiAlN-coated tungsten carbide milling cutter is used to produce slots in AISI 1045 using Taguchi experimental design technique. Three control factors namely, feed rate, depth of cut, and spindle speed are varied in order to assess their effect on surface roughness (R_a value). R_a is the arithmetic average height of roughness profile, also known as centre line average (CLA). It is the most commonly used parameter to measure surface roughness of a machined component.

2. Experimental Design

Taguchi's experimental design technique was employed for the experimentation. Taguchi's method advocates the use of fewer experimental combinations as compared to that of the full factorial design of experiments. It is an efficient technique to determine the nature of variation in any manufacturing process. It also helps to cut short the product development cycle time thus increases the profit margin [18].

On the basis of literature review and initial tests on material, three control factors, with three levels each, were considered. Numerical values for each level of parameters are given in Table 2.

Table 2. Control factors and level values for experimental design.

Control factors	Level 1	Level 2	Level 3
Depth of cut (DOC) (mm)	0.5	0.9	1.3
Feed rate (FR) (mm/sec)	20	30	40
Spindle speed (SS) (rpm)	200	500	800

In this study, Taguchi orthogonal array L9 was selected for design of experiments. Each experiment was repeated three times and mean value of response variable was recorded.

3. Experimental Work

Experiments were conducted on First MCV 600 vertical machining center using a multilayered TiAlN-coated tungsten carbide milling cutter. Specifications of machining center and milling cutter are outlined in Table 3.

Table 3. Specifications

Machine Specifications		Cutter Specifications	
Maximum table load capacity	800kg	Material	Tungsten Carbide
Spindle speed	120-8000rpm	Diameter	8mm
Tool holding capacity	20 tools	No of Flutes	4
Machine weight	4100kg	Coating Material	TiAlN
Controller	Fanuc series	Coating Thickness	4 micron
Power rating	20kwA	Coating Method	Physical vapour deposition
Pneumatic pressure	5.5bars		

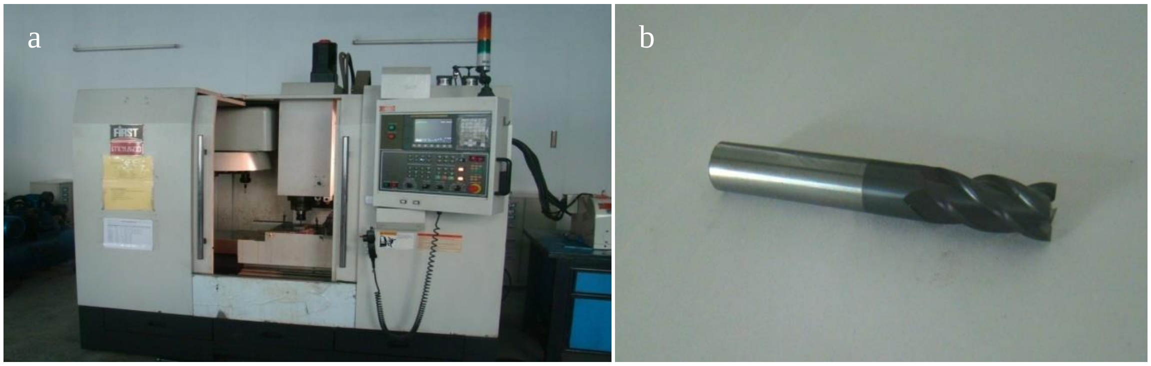

Figure 1. (a) First MCV 600 vertical machining center (b) Milling cutter

3.1. Workpiecematerial

The material of the work piece was AISI 1045. The dimensions of the workpiece were 115mm x 115mm x 20mm. The hardness of the material was 84HRB with a yield strength of 310Mpa. The modulus of elasticity of the specimen used was 200Gpa, approximately.

3.2. Measurement of surface roughness

Surface roughness (R_a) values were measured at five places along the length of each slot. Then a mean of these five values was recorded. Surtronic 25 portable roughness tester by Taylor Hobson was used. The cut of length of 0.8mm and evaluation length of 4mm were used for measuring surface roughness.

4. Results and Discussion

Twenty seven slots (three for each experimental run) having 8mm width and 50 mm length, were produced using CNC machining center. Experiments were carried out in a random order to incorporate the effect of variability in a better way. Each experiment was performed using a new tool in order to mitigate the effect of tool wear on surface roughness of workpiece. The mean values of surface roughness (R_a) against each experiment are shown in Table 4.

Table 4. Experimental results following L9 (33) orthogonal array

Experimental Run	Control factors and levels			Surface Roughness
	DOC (mm)	FR (mm/sec)	SS (rpm)	R_a (µm)
1	0.5	20	200	1.190
2	0.5	30	500	1.168
3	0.5	40	800	1.223
4	0.9	20	500	1.267
5	0.9	30	800	1.100
6	0.9	40	200	1.377
7	1.3	20	800	1.220
8	1.3	30	200	1.302
9	1.3	40	500	1.460

4.1. Main Effects Plot Analysis

To evaluate the trend of input parameter in relation to the performance characteristic, main effects plot analysis was carried out.

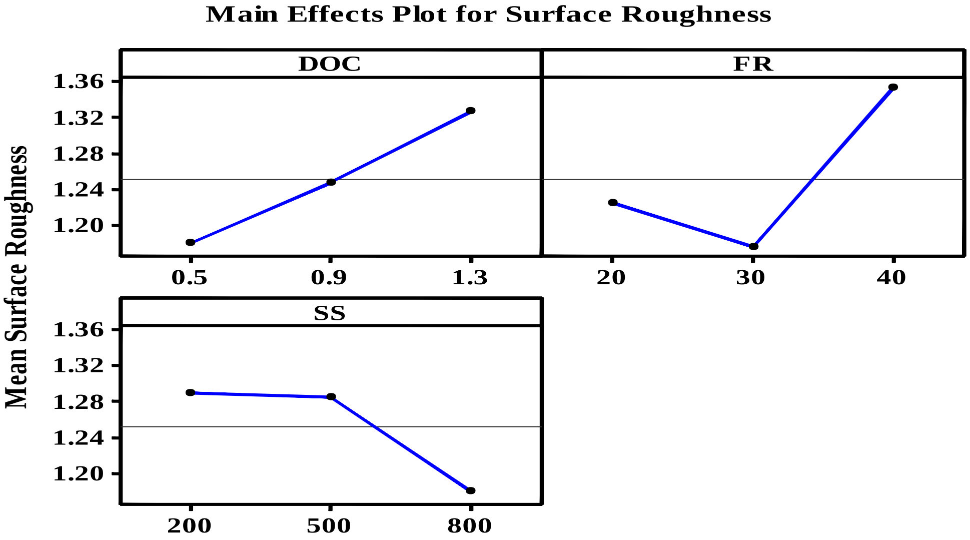

Figure 2. Main effect plot for surface roughness means

Main effects plots of mean values of surface roughness are shown in Figure 2. It is evident from Figure 2 that surface roughness increases with increase of depth of cut. This trend is most likely due to a large tear off of the material, associated with a high amount of material removal rate. When the rotating tool comes in contact with the target material, the shearing action is generated by two stimuli, i.e., the cutting force because of cutting edge, and, the force imparted due to the momentum of the cutting tool. When depth of cut is increased, the combination of these two stimuli may become unbalanced and the cutting action is predominantly due the force imparted by momentum that leads to the tearing action. This tearing action causes more roughness. Minimum value of surface roughness is obtained at level 1 (0.5mm DOC).

Feed rate provided the best results at level 2, i.e. 30mm/sec. The trend of feed rate can be explained on the basis of uncut chip thickness. At the lowest feed rate of 20mm/sec, the value of uncut chip thickness is smaller than the threshold value, i.e., the value where actual shearing action starts hence the phenomena of ploughing dominates rather than proper shearing which results into a higher value of surface roughness. At 30mm/sec, the value of uncut chip thickness presumably is within the acceptable limits of required uncut chip thickness of the machining regime, thus roughness decreases. At 30mm/sec, again the work piece roughness increases that may be attributed to a higher uncut chip thickness.

The third control factor, viz. spindle speed has shown almost similar values of response variable at level 1 and level 2, while at level 3 it provides the lowest value of surface roughness. Similar kind of trend of spindle speed has been observed by Ghani et al. while machining hardened steel AISI H13 using a TiN coated carbide insert [19]. This may be due to the reason that with the increase in spindle speed, the velocity of the chip is assumed to be faster. This reduces the contact time between the chip and the newly formed surface. Additionally, the tendency of chip to wrap back also reduces.

4.2. Signal-to-noise ratio

Signal-to-noise (S/N) ratio analysis was performed to evaluate the optimum level of each input parameter. Taguchi purposed that the influential factor for a particular performance characteristic may be categorized into two distinct groups: control factors and noise factors. Control factors are presumably under control while noise factors are uncontrollable [20]. Taguchi addresses those noise factors by defining the loss function. There exist six different S/N ratios, out which the smaller the better was chosen as the lesser value of surface roughness was the requirement. The relationships for loss function and the smaller the better S/N ratio are shown below:

$$Lij = \frac{1}{n}\sum_{k=1}^{n} Yij^2 \qquad (1)$$

$$\eta ij = -10 \log \left[\frac{1}{n}\sum_{k=1}^{n} Yij^2\right] \qquad (2)$$

Where Lij is the loss function of ith performance characteristic in jth experimental run andyij is the actual value of ith output parameter obtained in jth experimental run. The mean of the S/N ratio values for each level of each control factor are listed in Table 5.

Table 5. S/N ratios of responses

The smaller the better			
Level	DOC	FR	SS
1	-1.435	-1.760	-2.194
2	-1.887	-1.389	-2.130
3	-2.431	-2.605	-1.430
Delta	0.996	1.216	0.764
Rank	2	1	3

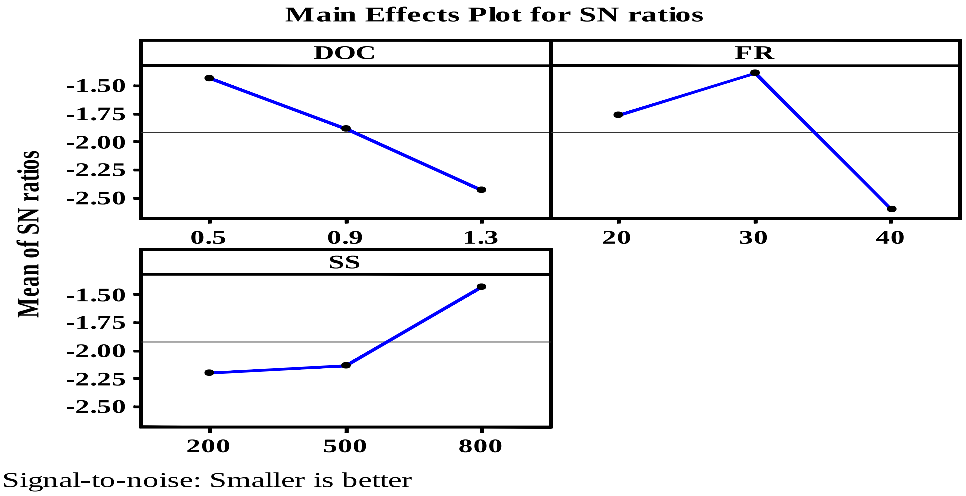

Figure 3. Main effect plot for surface roughness S/N ratios

For means of S/N ratios, the smaller the better characteristic was employed. The optimum values of S/N ratios were obtained at level 1(0.5mm) for depth of cut, at level 2 (30mm/s) for feed rate, and at level 3 (800 rpm) for spindle speed as shown in Figure 3.Therefore, the optimal experimental settings are at a depth of cut of 0.5mm, a feed rate of 30mm/sec and, a spindle speed of 800 rpm.

4.3. Confirmatory experiment

A confirmatory experiment was conducted with the model purposed optimum levels to evaluate the authenticity of the model. Signal-to-noise ratios at optimum levels of control factors can be approximated by the relationship given in eq. (3) [21].

$$\eta_{pre} = \eta_{om} + (\eta_{DOC} - \eta_{om}) + (\eta_{FR} - \eta_{om}) + (\eta_{SS} - \eta_{om}) \qquad (3)$$

η_{om} is the overall mean S/N ratio while η_{DOC}, η_{FR} and η_{SS} are S/N ratio values of depth of cut, feed rate and spindle speed respectively.
The result of the confirmatory experiment is presented in Table 6.

Table 6.Result of confirmatory experiment for R_a

	Starting input machining parameters	Prediction	Experimental
Level	DOC2, FR3, SS1	DOC1, FR2, SS3	DOC1, FR2, SS3
Ra (μm)	1.377	1.052	1.086
S/N (dB)	-2.779	-0.554	-0.831

It is evident from the result of confirmatory experiment that with the optimum levels settings of the control factors an improvement of 2.225dB was found in the S/N ratio for the surface roughness.

4.4. Analysis of variance (ANOVA) method

Analysis of variance is a statistical tool used to interpret experimental data and make necessary decisions [1]. In this research, ANOVA method is used (at a confidence level of 95%) to study the effects of control factors on surface roughness for milling operation. The results of ANOVA are shown in Table 7. The significance of each control factor is determined by p value i.e. confidence interval. The control factors having value less than 0.05 are considered to be the significant. Additionally the control factor significance is also gauged by F-value. According to Fisher a control factor having an F-value more than 4 is considered to be significant.

Table 7. Analysis of Variance for Ra, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Contribution
DOC	2	0.032181	0.032181	0.016090	39.93	0.024	30%
FR	2	0.050017	0.050017	0.025008	62.06	0.016	47%
SS	2	0.022931	0.022931	0.011465	28.45	0.034	22%
Error	2	0.000806	0.000806	0.000403			1%
Total	8	0.105934					

It is clear from Table 7, the parameter feed rate was the largest contributing factor to surface roughness followed by Depth of cut and spindle speed.

4.4. Contour Plots

The contour plots highlight the ranges of more influential control factors to achieve a desired value of response variable. Figure 4 indicates that the feed rate and depth of cut must be adjusted at 27-32 mm/sec and 0.7-0.9 mm, respectively to obtain minimum value (Ra< 1.1 μm) of surface roughness.

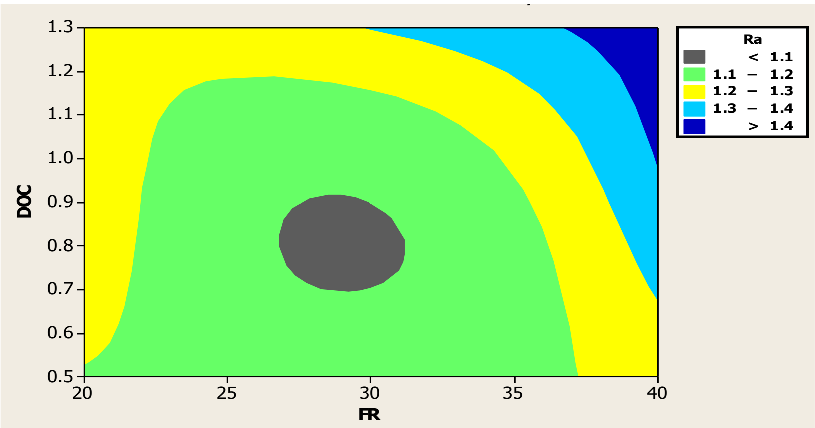

Figure 4. Contour plot of R_a vs. DOC and FR

5. Conclusions

In this research work Taguchi's experimental technique has been employed to find out the optimum parameters for dry end milling of AISI 1045 mild steel using TiAlN coated end mill. The results are analysed by using ANOVA, S/N ratio method and contour plots technique. The results can be summarised as follows:

- Main effect plot analysis indicates that small depth of cut, higher spindle speed and an intermediate value of feed rate yield lower surface roughness.
- S/N ratio analysis revealed that the optimum level of control factors for better surface roughness are level 1 (0.5mm) for depth of cut, level 2 (30mm/sec) for feed rate and level 3 (800 rpm) for spindle speed.
- Feed rate has proved to be the most influential parameter having a percentage contribution of 47% for surface roughness in dry end milling of AISI 1045
- Contour plot analysis shows that the optimal ranges for two most contributing factors are 27—32 mm/sec for feed rate and0.7 -0.9 mm for depth of cut.

The work can be extended by considering the effect of other control factors like different coating thicknesses, different coating compositions and tool vibrations etc., for better surface finish.

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