Application of Box-Behnken Method for Multi-response Optimization of Turning Parameters for DAC-10 Hot Work Tool Steel

Sunil Kumar, Saikat Ranjan Maity, and Lokeswar Patnaik

Abstract Turning parameters for cutting DAC-10 tool steel was optimized using surface response methodology (RSM). Turning was performed with TiAlN coated single point tool bit on CNC lathe. Cutting speed, feed rate, and depth of cut were considered as the cutting parameters and relative effect of process parameters on surface roughness and tool wear rate was analyzed. Outcomes revealed that feed rate and cutting speed are the governing parameters for surface quality and cutting speed for tool wear rate respectively. Optimization method confirms reasonable zone for responses and gives optimal condition for turning with cutting speed 150 m/min, feed rate 0.1 mm/rev and depth of cut 0.4 mm.

Keywords DAC-10 tool steel · Cutting speed · Feed rate · Depth of cut · Surface roughness · Tool wear rate

Abbreviations

CS	Cutting speed
FR	Feed rate
DOC	Depth of cut
Ra	Surface roughness
TWR	Tool Wear rate
FW	Flank wear
CNCLM	CNC lathe machine
DOE	Design of experiment

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1 Introduction

Turning is the oldest material removal process wherein a tool moves along the axis of the lathe to facilitate material removal in the form of chips. Surface characteristics of a product is the one of the essential attribute for determining the quality of the product. There are many applications which are directly affected by quality of surface such as tribological properties, aesthetic appearance, fatigue behavior of the product and corrosion resistance, etc.[1]. Right combination and level of turning parameters is important to get desirable surface finish with minimum tool wear rate. To improve the surface quality, CS needs to be increased. With rise in CS, TWR gets affected. Also, at lower CS, FW increases due to rubbing between tool flank and work material. Higher CS affects the crater wear which leads to tool breakage [2, 3]. Cutting fluid is widely used in machining process for cooling the tool and to improve surface roughness and machinability [4, 5]. Cutting speed can be increased upto 30% without having any effect on tool life [6].

Hard coating like TiC, TiN, and TiAlN minimize tool wear rate and improve surface roughness [7]. Thin coating is widely used on cutting and forming tools to improve the tool life and their performance. The PVD hard coating has a variety of applications. These coatings are used as protective layer for cutting tool, forming tool, gears and bearing [8, 9]. Tribological performance of TiAlN is superior to the TiN, AlCrN and TiCN [10, 11]. It is a third-generation coating among the ceramic hard coating [12]. Cutting speed is the major governing parameter for tool failure. Rise in temperature at higher cutting speed causes softening of outer layer which subsequently leads to delamination of the coating [13, 14].

L15 orthogonal array gives 15 sets of different combinations of cutting parameters for experiments. All 15 experiments were performed on CNCLM and the responses are measured. The experimental result was analyzed and optimal parameters are described.

2 Methodology

2.1 Material

In the present study, DAC-10 tool steel was used as work material. It is a hot work tool steel used for manufacturing of die casting die elements for their excellent heat crack and wear resistance at high temperatures. The chemical composition of the tool steel is C-0.3%, Si-0.3%, Mn-0.6%, Cr-5.2%, Mo-2.7 and V-0.9% [15].

2.2 Box-Behnken Design of Experiment

Turning was conducted on a CNCLM, total 24 number of experiments were performed including pilot experiments. Number of experimental run was designed by Box-Behnken DOE for L15 orthogonal array. CS, FR, and DOC were considered as the cutting parameter and their levels are tabulated in Table 1. Investigations were performed according to the experimental run and values of the responses were collected and tabulated in Table 2.

Table 1 Process parameters and their levels

S. No.	Process parameters	Level 1	Level 2	Level 3
1	CS (m/min)	150	200	250
2	FR (mm/rev)	0.1	0.15	0.2
3	DOC (mm)	0.4	0.6	0.8

Table 2 Experimental run and responses value

Run order	CS (m/min)	FR (mm/rev)	DOC (mm)	Ra (μm)	TWR (g/min)
1	150	0.2	0.6	2.4	0.0015
2	200	0.1	0.4	1.3	0.00175
3	200	0.15	0.6	1.9	0.00198
4	200	0.2	0.8	2.3	0.0022
5	200	0.15	0.6	1.8	0.00198
6	200	0.2	0.4	2.1	0.00211
7	150	0.15	0.4	1.7	0.00117
8	150	0.1	0.6	1.3	0.00139
9	200	0.1	0.8	1.7	0.00215
10	200	0.15	0.6	1.8	0.00212
11	250	0.1	0.6	1.1	0.00235
12	250	0.15	0.8	1.4	0.00252
13	250	0.15	0.4	1.2	0.00229
14	250	0.2	0.6	1.4	0.00244
15	150	0.15	0.8	1.9	0.00159

3 Results and Discussion

3.1 *Relative Effect of Cutting Parameter on Response*

Quality of surface is an important outcome of turning operation which is affected by FR and CS. Increase in CS and decrease in FR gives preferable surface finish. Figure 1a shows that better surface finish is obtained at 250 m/min CS and 0.1 mm/rev FR. Paengchit et al. [16] performed turning on AISI4140 steel with Al_2O_3 + TiC cutting tool to obtain the minimum Ra at CS 220 m/min and FR 0.06 mm/rev. Ibrahim et al. [17] performed machining on D2 steel and suggested that surface quality depends on CS and FR. Arefi et al. [18] conducted similar experiment on lead alloy and obtained similar consequences of CS and FR on Ra. Oehaia et al. [19] conducted machining of C62D cold rolled steel and found that higher CS and lower FR give better Ra. DOC also has an impact on Ra; surface quality improves with lower DOC. Combined effect of DOC and CS is expressed in Fig. 1b, it was observed that surface quality improves at 250 m/min CS and 0.54 mm DOC. Chandra et al. [20] has conducted an investigation on the consequences of process parameters on Ra of alloy steel and observed that Ra improve at higher CS and lower DOC. Surface quality reduces with lower FR and DOC as shown in Fig. 1c.

Tool wear affects the cost of production. Combined effect of process parameters are shown in Fig. 2a–c. TWR is directly affected by CS, FR, and DOC. With increase in CS, FR, and DOC, TWR also increases. Zheng et al. [21] had examined the wear behavior of TCVD-TiCN-Al_2O_3 coated tool for machining of 40CrNi2SiMoV steel

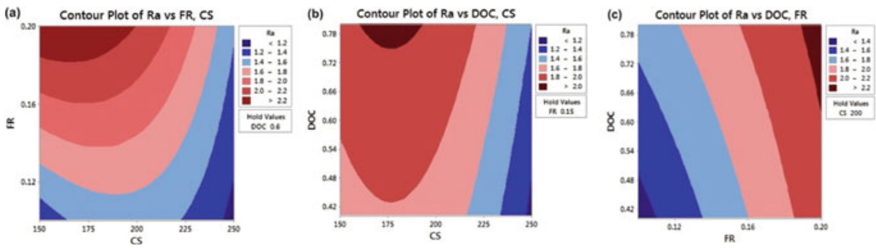


Fig. 1 Relative effect of cutting parameter on Ra

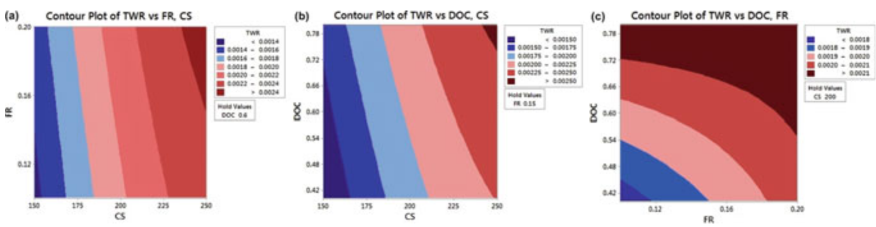


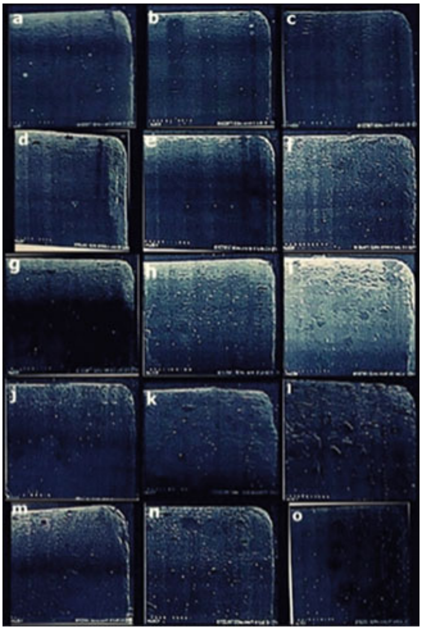
Fig. 2 Relative effect of cutting parameter on tool wear rate

and found that increase in CS and FR results increase in TWR. Similar experiments were performed by Korade et al. [22] on H21 tool steel and Thamizhmanii et al. [23] on titanium, stainless steel, and inconel, they found similar consequences of turning parameters on tool wear rate. Zhou et al. [24] had performed experiments on titanium alloy with Co10Ti3-CAT coated tool and found that tool wear reduces by 24% with decrease of CS, FR, and DOC. Kuntoglu et al. [25] investigated machining of AISI 1050 carbon steel and found that feed rate directly affects quality of machined surface. Similar experiment was done by Thiyagu et al. [26] and suggested the similar consequences of process parameter on TWR.

3.2 TWR Analysis

Worn surface of single point cutting tool was investigated using optical microscopy (OM). The OM images of worn tool tip were arranged according to the experimental run order (see Table 2). Figure 3a, g, h, and o are showing tool wear for the combination of different process parameters for which CS (150 m/min) is constant. The least TWR of 0.0015 g/min was observed at CS 150 m/min, FR 0.2 mm/rev and DOC 0.6 mm (Fig. 3a). A least TWR value of 0.00175 g/min was observed at CS 200 m/min, FR 0.1 mm/rev, and DOC 0.4 mm as expressed in (Fig. 3b) among the other combination of parameters where CS 200 m/min was kept constant. Worn surface of tools for these combinations are presented in Fig. 3b–f, i, j. Maximum

Fig. 3 Tool wear analysis



TWR of 0.00252 g/min was noticed at CS 250 m/min, FR 0.15 mm/rev and DOC 0.8 mm (Fig. 3l). Worn surfaces of tools after turning at highest CS (250 m/min) are shown in Fig. 3k–m, n.

Least TWR of 0.0015 g/min was observed at CS 150 m/min, FR 0.2 mm/rev, and DOC 0.6 mm among all the experimental runs. It was also noticed that TWR is directly proportional to CS and FR.

In addition, adhesion and abrasion are the main wear mechanism of the tool surface. Adhesive wear is due to high temperature generated at tool work interface under high pressure during cutting. This resulted in adhesion of small chips or fragments on to the tool surface causing the coating to gets torn away by itself and adhere to the tool surface. On the other hand, presence of hard particles such as oxide compounds, built-up fragments along with nitrides are responsible for abrasive wear.

Further, flanking of coating was observed (see Fig. 3i, l and n) which is also responsible for tool wear. When the average flank wear reached to 300 µm of tool wear criterion then flanking becomes more apparent [27]. Similar observations were found in a study by Bhatt et al. [28].

3.3 Examination of Data and Acceptability of the Model

Residual plot for Ra and TWR is presented in Fig. 4a and b respectively. Errors are normally distributed as the residual fall in straight line. Acceptability of responses is tabulated in Table 3. Value of R^2, R^2 (adj) shows that models fits the data, which reinforces the expectation capacity of the model. R^2 (pred) values are well above 95%, which build them fit for forecasting the solution.

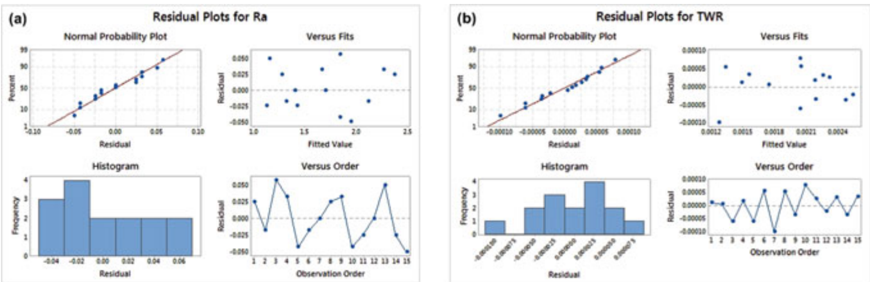


Fig. 4 Residual plot of Ra and tool wear rate

Table 3 Process parameters and their levels

Response	Standard deviation	R^2 (%)	R^2 (adj) (%)	R^2 (pred) (%)
Ra	0.0462910	99.23	98.65	97.24
TWR	0.00000636	98.41	97.53	95.53

Table 4 ANOVA for responses

Response	Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	*F*	*P*
Ra	Model	6	2.20019	99.23	2.20019	0.366698	171.13	0
	Error	8	0.01714	0.77	0.01774	0.002143		
	Total	14	2.21733	100.00				
TWR	Model	5	0.000002	98.41	0.000002	0.00	111.42	0
	Error	9	0.00	1.59	0.00	0.00		
	Total	14	0.000002	100.00				

3.4 Anova

Analysis of variances for the responses is tabulated in Table 4. P is <0.05 for responses and F-value is remarkable at 95% confidence limit. It established that the generated model is sufficient. Expected value and measured data are also acceptable.

3.5 Optimization of Parameter

Optimized cutting parameter for the responses is shown in Fig. 5. TWR and Ra are minimum at the initial value of all three parameters which fulfils the condition of

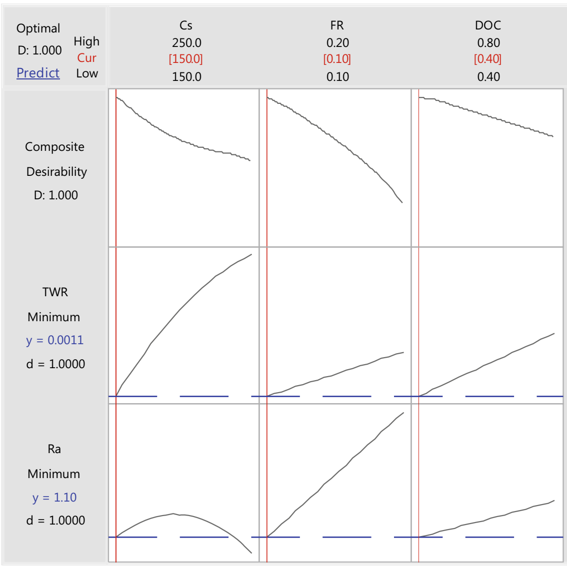


Fig. 5 Optimization of parameter

optimization. The optimal values of cutting parameters are 150 m/min CS, 0.1 mm/rev FR and 0.4 mm DOC.

4 Conclusions

This study has furnished an approach of Box-Behnken design for experiment and optimize the turning process parameters for cutting DAC-10 tool steel. Following conclusions are drawn:

- The contour plots show that CS and FR are the most influencing parameter for surface roughness. Surface quality enhances with increase in CS and decrease in FR.
- CS is the most influential parameter for determining TWR. Increase in CS leads to increase in TWR whereas FR and DOC have least effect on TWR.
- The optimized parameters were CS 150 m/min, FR 0.1 mm/rev, and DOC 0.4 mm for smaller Ra and TWR for turning of DAC-10 tool steel with TiAlN coated tool.
- P value less than 0.05 suggests the authenticity of the model.

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