Multi-objective Optimization of Process Parameter During Dry Turning of Grade 5 Titanium Alloy with Carbide Inserts: Hybrid Fuzzy-TOPSIS Approach

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1 Introduction

Titanium alloy is one of the most widely used metals in the industrial sectors. The high strength to weight ratio properties allows it to sustain in the manufacturing field. Nowadays, most of the durable and wear resistance components are made by using titanium alloy. Titanium alloy is amplifying its uses in every field of engineering and technology such as rotors, compressor blades, engines, frames and hydraulic system components. Above 50% of the aircraft components are made from the titanium grade 5 alloy. Due to the diversity properties in terms of non-toxicity and adaptability, it has increased its application towards making of the aircraft, armor plating, naval ship, landing gear and some of the medical–surgical equipment and implants. Nowadays, its unique quality of biocompatibility is also helping towards the computed tomography (CT) and magnetic resonance imaging (MRI) [1]. But mostly difficult and challenging task that arises during manufacturing of components using titanium alloy is its machining. As it is chemically reactive and less thermally conductive, it very difficult and a challenging task to machined. The adhesion and welding tendency of the titanium alloy with the chips flowing out during machining deteriorate the surface finish of the product and also the power, cutting force, tool wear and temperature required during machining increased [2–5]. Most of the researcher reveals

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that manufacturing cost of the components goes on increasing as the number of cutting inserts increase due to high tool wear rate [6]. At high temperature and lower DOC, the chips get chemically active and react with the cutting tool material and the machined surface [7–9]. Some of new techniques are involve to reduces the surface roughness and improve tool life of the cutting insert such as applying high-pressure coolant at the workpiece and cutting tool interface [10, 11]. Using of duplex liquid nitrogen jet of cooling [12], where one jet aims at tool–chip interface and second one at tool–work interface [13]. Fitzsimmons et al. [14] suggested that, for general practice, straight cemented carbides were the best cutting tool material for machining of titanium alloy. Researchers also revealed that, to achieve good machinability a good combination of process parameter through various multi-optimization techniques is also required. Some of the researchers also performed various types of optimization techniques to achieve a better combination of process parameter such as responses surface methodology, principal component analysis, grey relational analysis and desirability function analysis [15–17]. In this investigation, a multi-objective optimization technique is used to optimize the tool wear (TW), chip reduction coefficient (CRC) and surface roughness (SR) by finding out the optimal setting of the process variables with Cs, F and DOC during machining titanium alloy with K313 carbide insert. Further, the most significant process variable affecting the response has found by performing analysis of variance (ANOVA).

2 Experimentation Details

Left-hand dry turning operation of the titanium alloy was performed with cemented carbide inserts of Wida-made and model number K313. Taguchi L9 orthogonal array is designed to reduce the experimental cost and number of experimental runs. This experiment is done with a high precision lathe machine (Model No NH26 HMT). Ti–6Al–4V round bar of 600 mm length and 50 mm diameter. The process parameter considered for machining were F (0.04, 0.08 and 0.16 mm/rev), Cs (40, 65 and 112 m/min) and DOC (0.4, 0.8 and 1.6 mm). The FW, SR and CRC are measured with surface roughness tester (Make: Taylor/Hobson Surtronic 3+) and tool-maker's microscope.

3 Fuzzy-TOPSIS Multi-objective Optimization Method

TOPSIS method is one of the suitable optimization techniques that deals with the multi-response problem related to the manufacturing sector. The longest distance and the shortest distance from the ideal solutions gives the most suitable option from rest of the runs [18, 19]. The linguistic variables are given important weights within 0–1 interval by triangular fuzzy number as given in Table 1. The weights assigned by the four decision makers are given in Table 2. The aggregated fuzzy weights are

Table 1 DM responses for machining responses

Machining responses	Decision makers (DM)			
	DM-1	DM-2	DM-3	DM-4
Flank wear	L1	L3	L2	L1
RA	L1	L2	L2	L3
CRC	L1	L3	L2	L1

Table 2 Linguistic variables

Importance fuzzy weights	
Lowest (L1)	(0, 0, 0.1)
Lower (L2)	(0, 0.1, 0.3)
Low (L3)	(0.1, 0.3, 0.5)
Medium (M)	(0.3, 0.5, 0.7)
High (H3)	(0.5, 0.7, 0.9)
Higher (H2)	(0.7, 0.9, 1)
Highest (H1)	(0.9, 1, 1)

Table 3 Aggregated fuzzy weights assigned to the responses

Machining responses	Fuzzy weights		
Flank wear	0.025	0.1	0.25
Ra	0.025	0.125	0.3
CRC	0.025	0.1	0.25

specified in Table 3. Equation 1 helps to develop normalized performance matrix [20].

$$X_{mn} = \frac{a_{mn}}{\sqrt{\sum_{m=1}^{9} a_{mn}^2}} \tag{1}$$

where the a_{mn}, m and n are the experimental runs and responses, respectively, and X_{mn} symbolizes the normalized values as in Table 4. The weights of the responses were multiplied with the corresponding normalized performance matrix. The ideal value set (H^+) and (H^-) were calculated using Eqs. 2 and 3, respectively.

$$\begin{aligned} H^+ &= [[\max(h_{mn}), n \in M] or [\min(h_{mn}), n \in M], m = 1, 2, 3, \ldots 9] \\ &= h_1^+, h_2^+, h_3^+, \ldots h_9^+ \end{aligned} \tag{2}$$

$$\begin{aligned} H^- &= [[\min(h_{mn}), n \in M] or [\max(h_{mn}), n \in M], m = 1, 2, 3, \ldots 9] \\ &= h_1^-, h_2^-, h_3^- \ldots h_9^- \end{aligned} \tag{3}$$

Table 4 Normalized performance matrix

Run no.	Process parameters			Normalized values			Ideal solution		Closeness coefficient	S/N ratio
	A	B	C	Flank wear	Ra	CRC	dm^+	dm^-	C+	SNRA1
1	1	1	1	0.00023	0.018	0.324	0.096	0.352	0.784	−2.109
2	1	2	2	0.00056	0.346	0.098	0.159	0.289	0.644	−3.819
3	1	3	3	0.00063	0.166	0.136	0.093	0.356	0.792	−2.021
4	2	1	2	0.00114	0.036	0.324	0.105	0.344	0.765	−2.317
5	2	2	3	0.00119	0.492	0.116	0.232	0.216	0.482	−6.334
6	2	3	1	0.00071	0.073	0.098	0.037	0.412	0.917	−0.751
7	3	1	3	0.00025	0.071	0.681	0.254	0.194	0.433	−7.268
8	3	2	1	0.00159	0.051	0.145	0.045	0.404	0.899	−0.920
9	3	3	2	0.01382	0.173	0.065	0.074	0.374	0.833	−1.583

The distance between the ideal solutions was estimated. Finally, proximity of all experimental value of the ideal solution for the response was derived from the closeness coefficient. The closeness coefficient is calculated using Eq. 4. The ideal solutions and the closeness coefficients are tabulated in Table 4.

$$C_c = \frac{d_m^-}{d_m^- + d_m^+} \tag{4}$$

4 Results and Discussion

Since the experimental run is done as per the L9 orthogonal array the optimal parametric setting has been predicted by using statistical software Minitab trail version 18 software. Figure 1 portrays the main effects plot of the responses. The optimum parametric setting found from the Fig. 1 of main effects plot is F at 0.16 mm/rev, Cs at 40 m/min and DOC at 0.4 mm. Predicted S/N ratio along with mean value for the optimal solution is found to be 0.6652 and 0.9988, respectively. ANOVA is performed to find out each process parameter percentage contribution on the responses and to know the most influencing process parameter. From Table 5 ANOVA, it is observed that DOC has the percentage contribution of 55.6%, accompanied by feed of 25.3% and cutting speed of 1.41%. DOC is the most important process parameter trailed around with feed and cutting speed. Fig. 2 portrays that decreasing the DOC

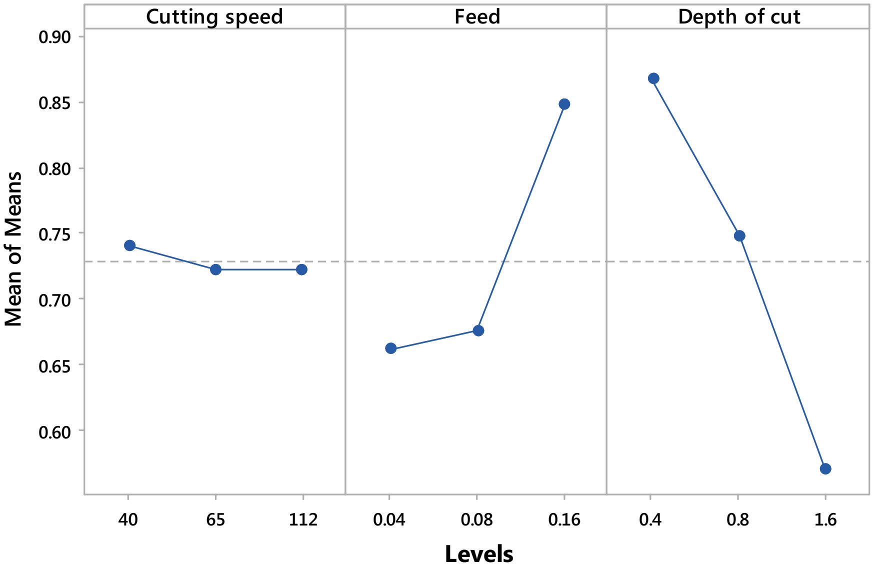

Fig. 1 Main effect plot for closeness coefficient

Table 5 ANOVA for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	% contribution
Cs (m/min)	2	0.6188	0.6188	0.3094	0.08	1.42
F (mm/rev)	2	11.0429	11.0429	5.5214	1.43	25.32
DOC (mm)	2	24.2491	24.2491	12.1245	3.15	55.60
Residual error	2	7.7012	7.7012	3.8506		
Total	8	43.612				

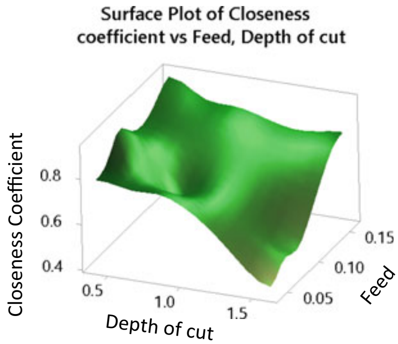

Fig. 2 3D surface plot of closeness of coefficient with feed and depth of cut

and increasing the feed the closeness coefficient increased. Actually, the tool wear occurred at a high-speed cutting, since at this instance the adhesion of chip to the workpiece takes place. Thus, increases in feed rate affect the tool wear. Temperature formation in chip–tool interface is also high. At this time, more the DOC the more will be adhesion, which leads to an increase in the tool wear. Increase in wear of tool reduces the surface finish of the newly machined surface and thus increases the surface roughness. The chip cross section increases with feed and the increase in cutting speed increase the temperature between the tip of the cutting inserts and workpiece. An excessive heat is generated in the interface of chip and tool due to increase in the friction.

5 Conclusion

An attempt was made to search the optimum parameter setting with the process variables i.e., F, DOC and Cs using a hybrid fuzzy-TOPSIS method while machining titanium alloy with uncoated carbide inserts. Based on the analysis of fuzzy-TOPSIS method and the predicted closeness coefficient, the optimum parametric setting was established as Cs at 40 m/min, DOC at 0.4 mm and feed at 0.16 mm/rev. The DOC was found to be the most influencing process variable.

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