Taguchi Analysis on Cutting Forces and Temperature in Turning Titanium Ti-6Al-4V

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Abstract *- Titanium alloy machining is hindered basically due to its high chemical reactivity and low thermal conductivity. The present work is focused on investigating the effect of process parameters on machinability performance characteristics and there by optimization of the turning of Titanium (Grade 5) based on Taguchi method. The cutting speed, feed and depth of cut were used as the process parameters where as the cutting force and temperature ware selected as performance characteristics. The L9 orthogonal array based on design of experiments was used to conduct experiments. The degree of influence of each process parameter on individual performance characteristic was analyzed from the experimental results obtained using Taguchi Method. The cutting speed was identified as the most influential process parameter on cutting force and temperature.*

Key words *- Titanium alloy machining, Taguchi method, ANOVA.*

I. INTRODUCTION

The knowledge of cutting forces, tool wear and temperature developed in various machining processes under given cutting conditions is being a dominating criterion of material machinability, to both the designer-manufacturer of machine tools, as well as to user. Nowadays manufacturing industries are constantly focused on lower cost solutions with reduced lead time and better surface quality in order to maintain their competitiveness and efficiency. Newly developed cutting tool grades are intended to permit multipurpose use in roughing and finishing applications for a wide range of workpiece materials. The new developments and improvements in coating technologies have produced more wear resistant tools. Coated tools used for metal cutting must possess a combination of abrasion wear resistance and chemical stability at high temperature to meet the demands of the application.

Metal cutting operations require tool materials that can withstand the extreme conditions produced during machining. Common problems that all cutting tools face: wear at the cutting edge, heat generated during the cutting process and thermo mechanical shock. Characteristics that allow tool materials to stand up during the cutting process include hardness, toughness, wear resistance, and chemical stability. Cutting force is important in machining because they provide unique signature of the mechanics of machining. It plays a primary role in determining the energy consumed and machining power required for the process, tool and workpiece deflections. There have been many studies concerning the effect of cutting parameters such as speed, feed, depth of cut, etc. and tool geometry on cutting forces while machining different materials [1-4].

Titanium alloy machining is hindered basically due to its high hardness, high chemical reactivity and its low thermal conductivity results in higher cutting forces than usual and generating high temperature. Of this generated heat, about 80% is retained in the tool and 20% is taken away by the chip [5]. Machining of titanium alloys at higher cutting speed will also cause rapid chipping at the cutting edge which lead to the catastrophic failure of inserts [6]. This is due to the concentration of temperature generated at the cutting edge closer to the nose of the inserts. The heat effected zone is very small when machining titanium alloys lead to high temperatures and can cause physical chemical phenomena which exacerbate tool wear at the rake.

Cutting temperature is an important factor in the machining operations as it strongly influences the cutting forces, tool life and the workpiece surface integrity. Higher cutting temperatures decrease the yield strength of the workpiece material, making it more ductile. This results a decrease in cutting forces and hence improve the machinability of the material. However, increased workpiece surface temperatures cause problems like white layer formation and reduced tool life [8].

In the present work, turning experiments were conducted on a lathe with coated tungsten carbide cutting tools for the machining of titanium alloy (Ti-6Al-4V). The L9 orthogonal array based on design of experiments was applied to plan the experiments, by selecting three controlling factors namely, the cutting speed (*v*), feed (*f*) and depth of cut (*d*). The Taguchi analysis is applied to examine how these cutting factors influence the cutting force (F_z) and temperature (θ). An optimal parameter combination was then obtained using the experimental results. Furthermore, analysis of variance (ANOVA) was also carried out to examine the most significant factors for the F_z and θ in the turning process.

II. EXPERIMENTAL DETAILS AND RESULTS

The turning experiments were carried out on a precision lathe setup using coated tungsten carbide cutting tools for the machining of titanium alloy (Ti-6Al-4V) bar, which is 30 mm in diameter and 180 mm in length. The chemical composition and mechanical properties of the workpiece material are listed in Table I.

TABLE I. CHEMICAL AND MECHANICAL PROPERTIES OF TITANIUM ALLOY (TI-6AL-4V)

Chemical composition	*C*	*V*	*Al*	*Fe*
wt %	0.002	3.99	6.01	0.037
Mechanical properties	*Density (g/cm3)*	*Tensile strength (MPa)*	*Thermal conductivity (W/moC)*	*Hardness (HRC)*
	4.42	950	6.7	36

Coated carbide tool materials are employed in the machining of titanium alloys due to their improved performance in terms of tool wear relative to other tool materials [9]. Coated titanium nitrate TiN inserts, along with the tool holder PCLNR 2020 M12 (Tool geometry: approach angle: 95^0, back rake angle: -6^0 and inclination angle: -6^0) were used in the present investigation.

In full factorial design, the number of experimental runs exponentially increases with the increase in the number of factors as well as their levels. This results in a huge experimentation cost and considerable time period [10]. In order to compromise these two adverse factors and also to search for the optimal process condition through a limited number of experimental runs, Taguchi's L_9 orthogonal array consisting of 9 sets of data was selected. Experiments were conducted with the process parameters, given in Table II.

TABLE II. CUTTING PARAMETERS AND THEIR LIMITS

Cutting parameter	Notation	Units	Level of factor		
			1	2	3
Cutting speed	*v*	m/min	45	60[a]	75
Feed	*f*	mm/rev	0.25	0.30[a]	0.35
Dept of cut	*d*	mm	0.5	1.0[a]	1.5

The response variables measured were cutting forces and temperature. The Cutting forces generated during machining trials were measured using piezoelectric tool post dynamometer (Kistler, 9272). The force signals generated during machining were fed into a charge amplifier (Kistler, 5070) connected to the dynamometer. This amplifier converts the analogue signal to digital signal that was continuously recorded by the data acquisition system connected to the charge amplifier. One of the cutting force signals obtained for *v* = 60 m/min, *f* = 0.35 mm/rev and *d* = 0.5 mm using DynoWare software is shown in Fig.1. The temperature was measured using infrared temperature measuring equipment (KM 690) for every pass at the interface of tool tip and workpiece. Based on Taguchi L_9 orthogonal array consisting 9 sets of coded conditions and the experimental results for the responses of F_z and θ are shown in Table III.

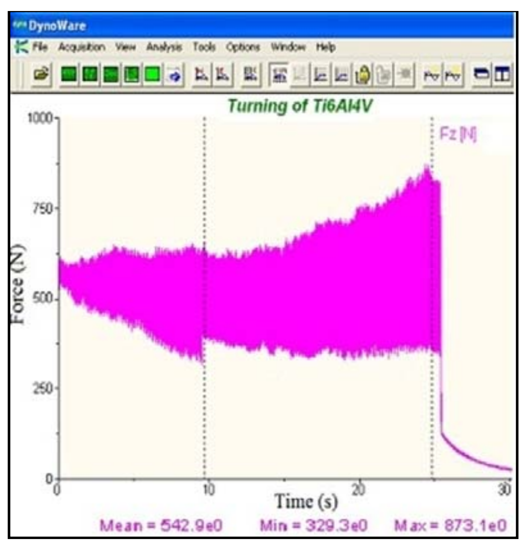

Fig. 1 : Cutting force signal from dynoWare

TABLE III. ORTHOGONAL ARRAY L9 OF THE EXPERIMENTAL RUNS, RESULTS AND CORRESPONDING S/N RATIOS

Run No.	Parameter level			Experimental results		S/N Ratio	
	v	*f*	*d*	F_z (N)	θ(^oC)	F_z (N)	θ (^0C)
1	1	1	1	560	213	-54.96	-46.568
2	1	2	2	687	217	-56.74	-46.729
3	1	3	3	762	190	-57.64	-45.575
4	2	1	2	769	215	-57.72	-46.649
5	2	2	3	891	279	-58.99	-48.912
6	2	3	1	873	273	-58.82	-48.723
7	3	1	3	925	299	-59.33	-49.513
8	3	2	1	820	290	-58.28	-49.248
9	3	3	2	890	315	-58.99	-49.966

III. ANALYSIS OF RESULTS

A. *Analysis of S/N ratio*

In Taguchi method, the term ‘signal’ represents the desirable value (mean) for the output characteristic and the term ‘noise’ represents the undesirable value for the output characteristic. Taguchi uses S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available depending on the type of characteristics i.e., higher-the-better, lower-the-better and nominal-the-better. The S/N ratio □ is defined as

$$□ = -10 \log (M.S.D) \quad (1)$$

where M.S.D. is the mean-square deviation for the output characteristic.

As mentioned, there are three categories of quality characteristics, i.e. the lower-the-better, higher-the-better and nominal-the-better. Typically, smaller values of F_z and θ are desirable for any machining operation. Thus, smaller the better criteria for F_z and θ were selected during the present work. The mean-square deviation (M.S.D.) for smaller-the-better quality characteristic can be expressed as:

$$M.S.D = 1/m \, \Sigma \, T_i^2 \quad (2)$$

where m is the number of tests and T_i is the value of F_z and θ of the i^{th} test.

Table III shows the experimental results for F_z, θ and the corresponding S/N ratio using Equations (1) and (2). Since the experimental design is orthogonal, it is then possible to separate out the effect of each cutting parameter at different levels. For example, the mean S/N ratio for the cutting speed at levels 1, 2 and 3 can be calculated by averaging the S/N ratios for the experiments 1–3, 4–6 and 7–9 respectively. The mean S/N ratio for each level of the other cutting parameters can be computed in a similar manner. In addition, the total mean S/N ratio for all nine experiments are also calculated and listed in Table IV and Table V. Regardless of the lower-the-better or the higher-the-better quality characteristic, the greater the S/N ratio corresponds to the smaller variance of the output characteristics around the desired value.

TABLE IV. S/N RESPONSE TABLE FOR F_Z

Cutting parameter	S/N Response for force Fz (N)			
	Level 1	Level 2	Level 3	Max-Min
v	-56.45	-58.51	-58.86	2.54
f	-57.34	-58.00	-58.48	1.27
d	-57.23	-57.82	-58.65	1.42
	Average value = -57.90			

TABLE V. S/N RESPONSE TABLE FOR Θ

Cutting parameter	S/N Response for Temperature (θ)			
	Level 1	Level 2	Level 3	Max-Min
v	-46.29	-48.10	-49.58	3.29
f	-47.58	-48.30	-48.09	0.72
d	-48.18	-47.78	-48.000	0.40
	Average value = -35.26			

B. *Analysis of varience*

Analysis of variance (ANOVA) was introduced by Sir Ronald Fisher [11]. This analysis was carried out for a level of significance of 5%, i.e., for 95% level of confidence. The purpose of ANOVA is to investigate which turning parameter significantly affects the performance characteristics [12]. Table VI shows the results of ANOVA for F_z. It is found that cutting speed and depth of cut are significant cutting parameters affecting cutting force. Therefore, based on S/N ratio and ANOVA analyses, the optimal cutting parameters for cutting force are the cutting speed at level 1, the feed at level 1 and the depth of cut at level 1. Table VII shows the results of ANOVA for θ. The contribution order of the cutting parameters for temperature is cutting speed, then depth of cut and then feed rate. The optimal cutting parameter combination for temperature are the cutting speed at level 1, the feed rate at level 1 and the depth of cut at level 2.

TABLE VI. RESULTS OF ANOVA FOR F_Z

Symbol	Parameter	DOF	SS	MS	F	P (%)
v	Speed	2	11.335	5.668	12.854	63.887
f	Feed	2	2.464	1.232	2.794	13.885
d	Depth of cut	2	3.062	1.531	3.472	17.257
Error		2	0.882	0.441		4.971
Total		8	17.743			100

TABLE VII : RESULTS OF ANOVA FOR Θ

Symbol	Parameter	DOF	SS	MS	F	P (%)
v	Speed	2	16.241	8.121	5.177	79.458
f	Feed	2	0.823	0.412	0.262	4.027
d	Depth of cut	2	0.239	0.119	0.076	1.167
Error		2	3.137	1.568		15.347
Total		8	20.440			100

C. *Confirmation tests*

The optimal parameter combination for achieving minimum cutting force (F_z) and temperature (θ) was obtained as $v_1f_1d_1$ and $v_1f_1d_2$ respectively using Taguchi technique. Therefore, above set of combination i.e., corresponding speed, feed and depth of cut for F_z and θ for turning operation was treated as a conformation test to conduct the experiments.

Table VIII shows the comparison of the predicted cutting force with the actual cutting force using optimal cutting parameters. A good agreement between the predicted and actual force values has been observed. The increase of the S/N ratio from initial cutting parameters to the optimal cutting parameters is 3.52 dB, which indicate that the cutting forces can be reduced by machining at optimum process parameters. Table IX shows the comparison of values of predicted temperature and the actual temperature values. The increase of the S/N ratio from initial cutting parameters to the optimal cutting parameters is 11.8 dB, which indicate that the Temperature can be reduced by machining at optimum process parameters. In other words, the experimental results conforms the design and analysis for optimizing the cutting parameters through this approach.

TABLE VIII : RESULTS OF CONFORMATION EXPERIMENT FOR F_Z

	Initial cutting parameters	Optimal Machining Parameters	
		Prediction	Experiment
Level	$v_2f_2d_2$	$v_1f_1d_1$	$v_1f_1d_1$
F_z (N)	840	579	560
S/N ratio(dB)	-58.48	-55.25	-54.96

Improvement of S/N ratio =3.52 dB

TABLE IX: RESULTS OF CONFORMATION EXPERIMENT FOR Θ

	Initial cutting parameters	Optimal Machining Parameters	
		Prediction	Experiment
Level	$v_2f_2d_2$	$v_1f_1d_2$	$v_1f_1d_2$
θ (^oC)	260	192	216
S/N ratio(dB)	-48.30	-45.67	-46.68

Improvement of S/N ratio =11.8 dB

IV. CONCLUSIONS

This paper discussed an application of the Taguchi method for optimizing the cutting parameters in turning operation. As shown in this study, the Taguchi method provides a systematic and efficient methodology for the design and optimization of cutting parameters with far less effort than would be required for most optimization techniques. It has been shown that cutting force and temperature were reduced significantly for turning operation by conducting experiments at the optimal parameter combination and also by analyzing S/N ratio. The conformation experiments were also conducted to verify the optimal combination of parameters obtained. Good agreement between the predicted and actual values for Force and temperature has been observed.

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