Experimental Investigation of Cutting Forces in Ti-6Al-4V Alloys Using Rotary Ultrasonic Machining

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***Abstract*:** *The recent developments in advanced materials such as titanium alloy (Ti-6Al-4V) and their increased engineering applications have led to advances on manufacturing processes. However, widespread utilization of these materials has been hindered by high machining cost and poor surface finish. Since, difficult-to-machine materials such as Ti-6Al-4V are very hard, tough, and possessed high impact resistance, their machinability is low and sometimes impossible with traditional machining processes. Recently, Rotary Ultrasonic Machining (RUM) has attracted total attention for machining DCM.*

The ultimate goal of this research is to enhance machining of Ti-6Al-4V using of RUM process. The experiment has been designed using Taguchi approach to find signal-to-noise (S/N) ratios. The results of this work identify that the cutting forces increase significantly with increase in coolant pressure, vibration amplitude, depth of cut and feed rate while decrease with increase in spindle speed.

Keywords: *Ultrasonic, Machining, Titanium, Taguchi, Cutting, Forces.*

1. Introduction

Titanium alloys are common, readily available engineering metals that compete directly with special type of steels, copper alloys, nickel based alloys and composites.

Titanium alloys have unique characteristics including its attractive strength-to-density ratio and exceptional corrosion resistance. Therefore, they have increasingly been used in many applications such as spacecraft, hydrocarbon processing, power generation, nuclear waste storage and processing, sea applications, medical implants and surgical devices and in many other applications [1, 2]. However, major disadvantage of titanium alloys is their low thermal conductivity. As a result, the heat generated during machining will be dissipated in low rate. So, the machining area temperature will increase rapidly during machining which cause an increasing of the tool temperature as the tool is in contact with the machining area, for example in machining of Ti-6Al-4V the tool is absorbed about half of that generated heat in machining area. Titanium alloys considered as difficult-to-machine material (DCM). Hence, non-traditional machining processes are required to operate these materials [3-5].

In recent years, many non-traditional machining processes have been applied to machining of Ti-6Al-4V, but even these processes face many limitations such as poor surface finish, inaccurate dimensions, etc. However, Rotary Ultrasonic Machining (RUM) can be an alternative to machining titanium and its alloys [6-9]. RUM is a hybrid machining approach that combines two material removal mechanisms, namely, diamond grinding and ultrasonic machining. In RUM, depth of cut can be maintained due to the stability of the tool in horn and also no cutting forces are present between the tool and work piece. Moreover, use of cutting fluid in RUM ensures heat transfer efficiently through the workpiece instead of the heat concentration in the contact area between cutting tool and workpiece. One of the side effects of the titanium is that the reaction with cutting tool,

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In RUM this side effect is prevented because the cutting tool doesn't contact workpiece during machining. Moreover, RUM is better than other non-traditional processes in terms of simplicity, cost of tooling besides providing better stability and control.

Cutting forces is determined highest stress and deflection in workpiece and machine respectively, beside to its effect in the damage of the tool. Therefore the cutting force has more concern in machining. Moreover, cutting forces are directly related to cutting temperature, surface roughness, workpiece accuracy, and surface residual stress, etc. Several studies have been found in measurement of average or maximum cutting force with the direction of feed rate and tool axial direction. Relationship between cutting forces and spindle speed has been absorbed in many research studies [10-16], the relationship between the cutting forces and feed rate has been also studied [10,12,15-17], during RUM of titanium alloy (Ti-6Al-4V) and other materials such as Ceramic Matrix Composites, silicon carbide SiC, alumina ceramic (Al2O3), dental ceramic, and stainless steel materials. It was also found that ultrasonic vibration power has significant effect on cutting force [13, 18, 19]. Lower cutting forces are produced when larger abrasive grit size, a higher abrasive concentration is used [14].Tools with different levels of abrasive sizes ranging from fine to large were also studied as one of process parameters of Rotary Ultrasonic Face Milling on magnesia-stabilized Zirconia material [20]. Nath and Rahman [21] found that the important parameters influence the ultrasonic cutting mechanism. However, the effect of these parameters to the cutting forces has been not clearly established. Liu et al [22] introduced a model of cutting force for brittle materials in RUM. They predicted relationships between the cutting forces and input parameters.

The literature review of previous researches show that, most of the research works were carried out on investigations of the capability to machine hard and brittle materials by stationary USM and drilling operation of RUM process. Few research studies were found in milling operation of RUM process In addition, few process parameters of RUM have been investigated.

This paper introduce an experimental investigations of process parameters including vibration frequency (*F*), vibration amplitude (*A*), spindle speed (*S*), feed rate (*Fr*), depth of cut (*D*) and coolant pressure (CP) on the cutting force of Ti6Al4V in RUM. The selection of optimum parameters for machining Ti-6Al-4V in RUM process, to obtain minimum cutting force, is achieved based on Taguchi's approach.

2. Materials and Methods

Ti-6Al-4V in cylindrical form (20mm dia. and 15 mm height) is used in this study. Mechanical properties of Ti-6Al-4V materials can be found in Table 1 [23].

TABLE 1: Mechanical properties of Ti6Al4V

Property	Unit	Value
Tensile strength	MPa	929 -1,014
Thermal conductivity	W/(m×K)	21
Melting point	ºK	1,941 ± 285
Density	Kg/m3	4,510
Vickers hardness	GPa	3.5

Diamond milling cutters of 4 mm outside diameter and wall thickness of 1.5mm and a grain size of D91= 16.2 nanometres for the diamond abrasives are involved in this experimental work. These cutters have been provided by SCHOTT Company [24].

Among the six process parameters, CP factor have two levels while each of the remaining parameters consists of three levels. These parameters, given in Table 2, and their respective levels have been selected based on preliminary experiments and studies in literature. It has been found that above selected parameters are critical to assess machining characteristics in terms of cutting forces.

TABLE 2: Main factors and levels of experiment for Ti-6Al-4V

Level	Parameter					
	CP (bar)	F (kHz)	A (%)*	S (rpm)	D (mm)	Fr (mm/min)
1	15	20	50	2000	0.025	50
2	25	25	60	4000	0.05	100
3	---	30	70	6000	0.075	150

*Vibration power supply controls the amplitude of ultrasonic vibration

The cutting tests have been conducted on RUM, (DMG Ultrasonic 20 Linear Machine) [25]. DMG's Ultrasonic 20 linear consisted of a 5-axis configuration that enables conventional multi-axis milling.

The experimental setup of the present work consists mainly of an ultrasonic spindle system, a data acquisition system, and a coolant set-up as shown in the Figure 1.

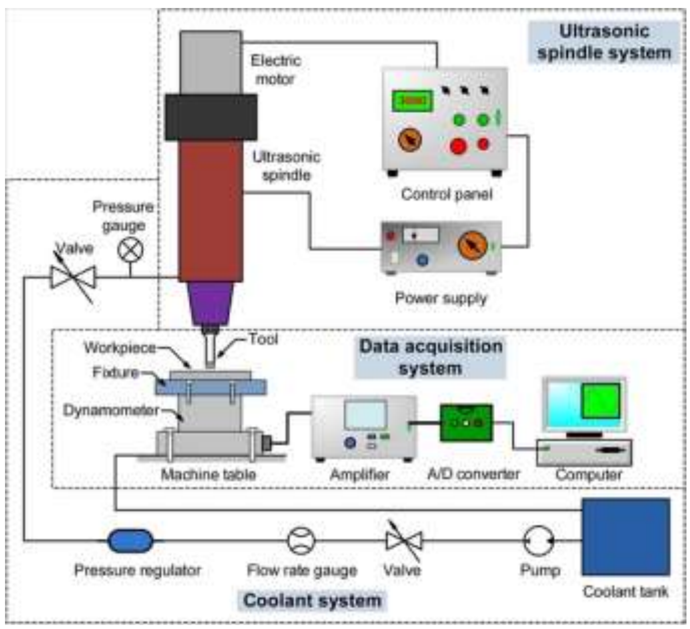

Fig. 1: Experimental set-up on a RUM

During RUM, cutting forces in F_x, F_y and F_z have been measured by KISTLER milling 9257 dynamometer. F_x and F_y represents forces in feed rate direction whereas F_z represent force in tool axial direction. The maximum value of these forces in three directions for each of the machining conditions has been used to study influences of process parameters on the cutting force. Different factors and responses of RUM have been analyzed and described in the following sections.

Normality test is used to generate a normal probability plot and to perform hypothesis test in order to examine whether or not the collected data follows a normal distribution.

Taguchi analysis, a highly fractional factorial design that provides maximum information using least number of experiments [26], is based on S/N ratio. In Taguchi method, a loss function has been defined to compare experimental and desired value of a performance characteristic [27]. By maximizing the S/N ratio, the loss function can be minimized and hence, the objective function can be optimized. In a particular Design of Experiment problem, there can be three different types of performance characteristics namely smaller-the-better, higher-the-better and nominal-the-best. The selection of an appropriate S/N ratio is very important for optimization of the performance characteristics [28].

In the present research, smaller-the-better type situation has been selected as objective function for cutting forces needs to be minimized. In Smaller-the-better type problem quality characteristic is continuous and non-negative and its most desirable value is zero. There is no adjustment factor to be used in this case as well; the objective function can be expressed as follows:

$$\eta = -10\ log_{10}\{\frac{1}{n}.\sum_{1}^{n} y_i^2\} \quad (1)$$

S/N ratios for each factor and level, $SN_{P,L}$, are calculated using Eq (2):

$$S/N_{P,L} = \frac{\sum_{\forall P,L} S/N_i}{NL_p} \quad (2)$$

Where**:** *p* = factor, L = level, S / Ni = S/N for experiment *i*, and NLp = number of levels of factor *p*. Range (Δ) of S/N for each parameter. Pi = *i-th* factor. Δ is calculated by:

$$Range\ (\Delta) = S/N_{P,L}\ max - S/N_{P,L} \quad (3)$$

With analysis of S/N ratio, the effect of the main factors and their interaction respective to cutting force has been studied.

Taguchi orthogonal array has been used to design experiments because it significantly reduces number of experiment combination and save lot of time and effort. Orthogonal tables can be identified as L_x (Z_y), where y is the number of process parameters, *Z* is the number of level settings and *x* is the number of runs. Two replications have been utilized for each experiment in order to increase experiment accuracy. Depending on some previous experiments, literature survey and requirements of this study, Taguchi's L36 orthogonal array has been selected for designing experiments. Table 3 shows orthogonal array of experiments for Ti-6Al-4V.

Table 3: Part of L36 Orthogonal Array of the Experiment of Ti-6Al-4V.

Exp. no.	CP	F	A	S	D	Fr
1	15	20	50	2000	0.025	50
2	15	25	60	4000	0.05	100
3	15	30	70	6000	0.075	150
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
35	25	25	50	4000	0.075	50
36	25	30	60	6000	0.025	100

3. Results and Discussion

The experimental results of cutting forces responses, (F_x, F_y and F_z), have been shown in Figure 2 (a-c). It is found that among maximum values of F_z, F_x and F_y , minimum value have been found for F_z which is 175.78N while for F_y and F_x, values are 53.71 and 39.06 N respectively.

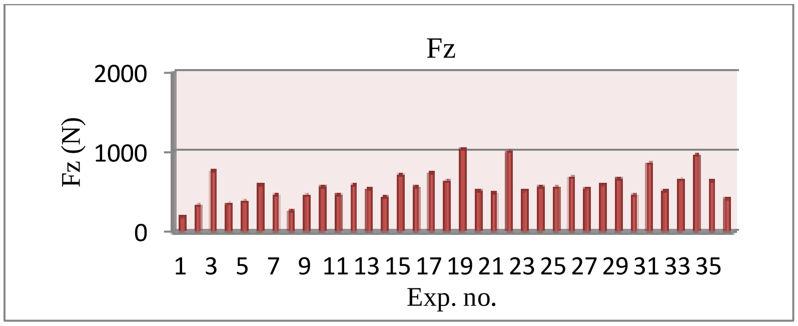

Fig. 2 (a): Fz

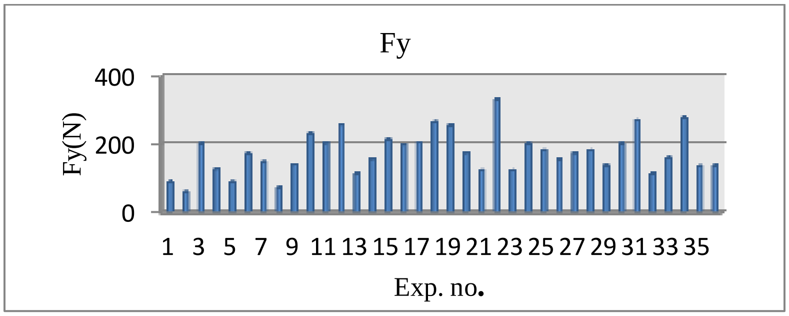

Fig. 2 (b): Fy

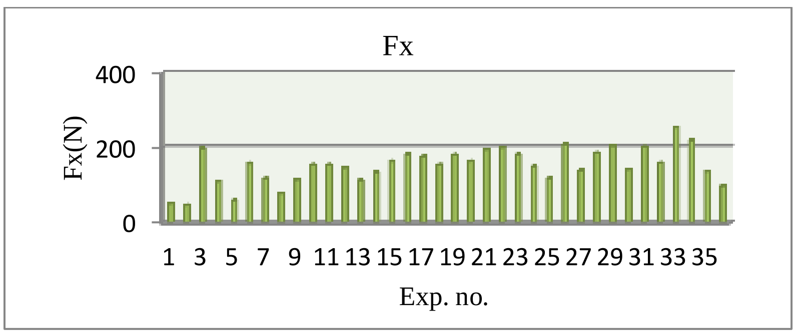

Fig. 2 (c): Fx

Normality test has been performed to examine whether observations follow normal distribution or not. It can be seen from residual plots of F_z, F_y, F_z (Figures 3(a-c)) that there is nothing unusual and data is normally distributed.

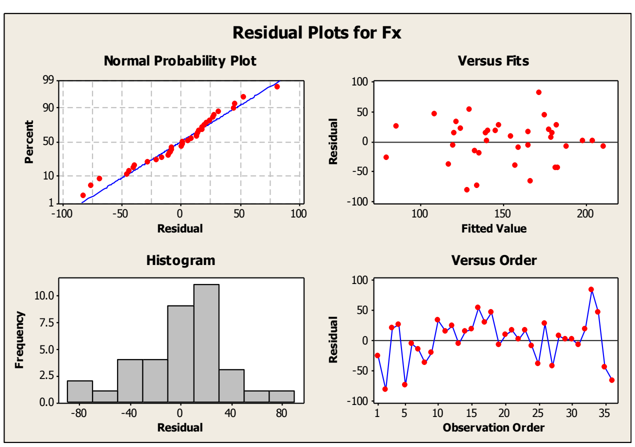

Fig. 3a: Residual Plots for Fx

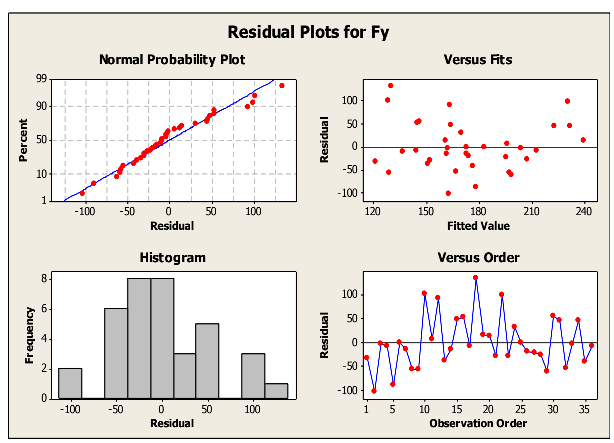

Fig. 3b: Residual Plots for Fy

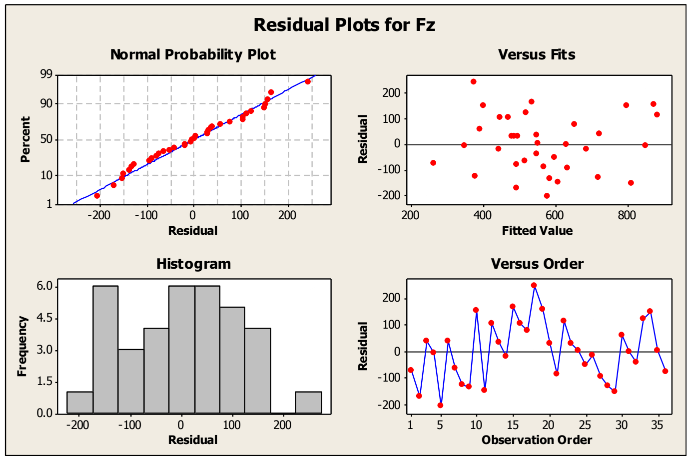

Fig. 3c: Residual Plots for Fz

S/N ratios have been calculated using Eq. (1), as cutting forces have to be minimized. The main effect of different factors on equivalent force has been shown in Figure 4.

From the main effect plot (Fig.4), it has been found that coolant pressure of 15bar, vibration frequency of 25 kHz, vibration amplitude of 50%, rotational speed of 6000rpm, depth of cut 0.025mm, and feed rate of 100 mm/min, resulted into minimum equivalent force .

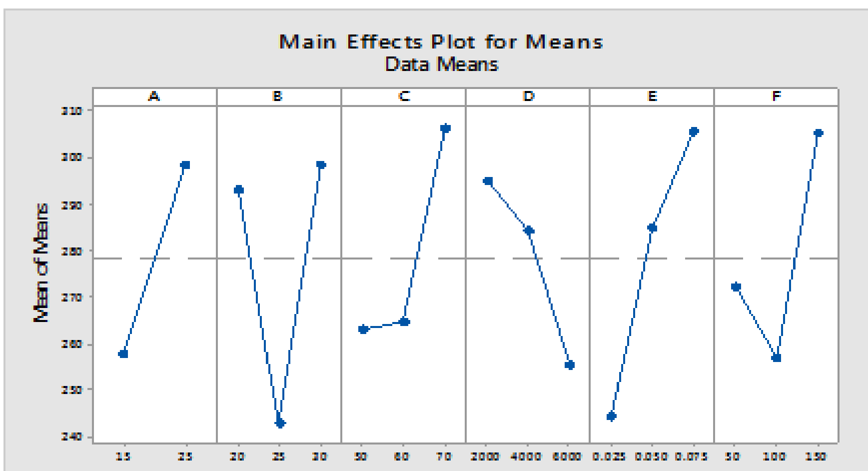

Fig. 4: Main effect plot for Equivalent Cutting force

4. Conclusions

Rotary Ultrasonic Machining (RUM) process has been implemented to machine Titanium Alloy (Ti-6Al-4V). The influence of RUM parameters has been studied to determine their effect on cutting force. Conclusions of this study can be concluded in the following points.

- Coolant pressure has significant effects on cutting forces. Cutting forces increases with increases in coolant pressure. Vibration frequency of 25 kHz has resulted in minimum cutting force.
- Vibration amplitude has higher significant effects on cutting forces, and cutting forces increase with increases in amplitude.
- Spindle speed has significant effects on cutting force. It has also been observed that with increase in spindle speed, cutting forces decreases.
- Feed rate and depth of cut have significant effects on cutting forces, cutting forces increase significantly with increase in feed rate and decrease in depth of cut.

- Finally, combination of a coolant pressure of 15 bar, a spindle speed at 6000rpm, a feed rate at 50mm/min, a frequency at 25 kHz, an amplitude of 50%, and depth of cut at 0.025mm produced optimum results which provide minimum values of cutting force components F_z, F_y, and F_x at 175.78, 53.71, 39.06 N, respectively.

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