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Evaluating the Tool Wear Rate in Ultrasonic Machining of Titanium using Design of Experiments Approach

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Abstract**—**Ultrasonic machining (USM) is a non-traditional machining process being widely used for commercial machining of brittle and fragile materials such as glass, ceramics and semiconductor materials. However, USM could be a viable alternative for machining a tough material such as titanium; and this aspect needs to be explored through experimental research. This investigation is focused on exploring the use of ultrasonic machining for commercial machining of pure titanium (ASTM Grade-I) and evaluation of tool wear rate (TWR) under controlled experimental conditions. The optimal settings of parameters are determined through experiments planned, conducted and analyzed using Taguchi method. In all, the paper focuses on parametric optimization of ultrasonic machining of pure titanium metal with TWR as response, and validation of the optimized value of TWR by conducting confirmatory experiments.

Keywords**—**Ultrasonic machining, titanium, tool wear rate

I. INTRODUCTION

TITANIUM and its alloys are alternative for many engineering applications due to their superior properties such as chemical inertness, high strength and stiffness at elevated temperatures, high strength to weight ratio, corrosion resistance, and oxidation resistance. However these properties also make titanium and its alloys difficult to shape and machine into a precise size and shape. As a result, their widespread applications have been hindered by the high cost of machining with current technology [1]-[2]. Therefore, there is a crucial need for reliable and cost-effective machining processes for titanium and its alloys. Most cryogenic machining studies on titanium and its alloys have documented improved machinability when freezing the workpiece or cooling the tool using a cryogenic coolant. However, inherent weaknesses exist in these approaches [3].

Nontraditional machining processes such as electric discharge machining and laser beam machining have been applied to the machining of titanium and its alloys in recent times, but even these processes have their own limitations; the most prominent are the surface finish and dimensional inaccuracies besides their undesirable effects on the machined surface such as heat affected zone, recast layer and thermal stresses [4]. These adverse effects can lower the working life of the components critically. Ultrasonic Machining could be another alternative machining process that can be applied commercially to the machining of titanium; as this process is known to be free from all these adverse effects on the machined component, but there is critical lack of evidence for this aspect in the literature available till now. Hence, in the present investigation, ultrasonic drilling has been explored as an alternative machining method for pure titanium (ASTM Grade-I).

In USM, high frequency electrical energy is converted into mechanical vibrations via a transducer/booster combination which are then transmitted to an energy focusing as well as amplifying device: horn/tool assembly (fig.1). This causes the tool to vibrate along its longitudinal axis at high frequency [5]; usually above 20 kHz with amplitude of 12-50 μm. The power ratings range from 50-3000 W and a controlled static load is applied to the tool. Abrasive slurry, which is a mixture of abrasive material; e.g. silicon carbide, boron carbide or aluminium oxide suspended in water or some suitable carrier medium is continuously pumped across the gap between the tool and work (~25-60 μm). The vibration of the tool causes the abrasive particles held in the slurry to impact the work surface leading to material removal by microchipping [6].

Titanium and its alloys are alternative for many engineering applications due to their superior properties such as chemical inertness, high strength and stiffness at elevated temperatures, high strength to weight ratio, corrosion resistance, and oxidation resistance. However these properties also make titanium and its alloys difficult to shape and machine into a precise size and shape. As a result, their widespread applications have been hindered by the high cost of machining with current technology [1]-[3]. The machining characteristics for titanium and its alloys using conventional machining processes are summarized below [3]-[4]:

- Titanium and its alloys are poor thermal conductors. As a result, the heat generated when machining titanium cannot dissipate quickly; rather, most of the heat is concentrated on the cutting edge and tool face. About 50% of the heat generated is absorbed by into the tool while machining titanium alloy (Ti- 6Al-4V).
- During machining, titanium alloys exhibit thermal plastic instability that leads to unique characteristics of chip formation. The shear strains in the chip are not

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uniform; rather, they are localized in a narrow band that forms serrated chips.

- The contact length between the chip and the tool is extremely short (less than one-third the contact length of steel with the same feed rate and depth of cut). This implies that the high cutting temperature and the high stress are simultaneously concentrated near the cutting edge (within 0.5 mm).
- Serrated chips create fluctuations in the cutting force; this situation is further promoted when alpha-beta alloys are machined. The vibrational force, together with the high temperature, exerts a micro-fatigue loading on the cutting tool, which is believed to be partially responsible for severe flank wear.
- The surface finish achieved by a single machining process (no finishing operations) is poor.

Therefore, there is a crucial need for reliable and cost-effective machining processes for titanium and its alloys. Over the last few decades, there have been great advancements in the development of cutting tools, including coated carbides, ceramics, cubic boron nitride and polycrystalline diamond. These have found applications in the machining of cast iron, steels and high temperature alloys such as nickel based alloys and super alloys. However, none of these newer developments in cutting tool materials have had successful application in improving the machinability of titanium alloys. Most cryogenic machining studies on titanium and its alloys have documented improved machinability when freezing the workpiece or cooling the tool using a cryogenic coolant. However, inherent weaknesses exist in these approaches [3].

Hence, the present investigation is focused on exploring the use of USM as a viable alternative for machining pure grade of titanium.

II. MATERIALS AND METHODS

Commercially pure titanium (ASTM Grade-I) has been used as the work material in the present investigation. The chemical composition and other mechanical properties of the material are shown in table 1. Five type of tools made of High Carbon Steel, High Speed Steel, Cemented Carbide, Titanium (ASTM Grade-I) and titanium alloy (ASTM Grade-V) with straight cylindrical geometry (diameter 8 mm) were used in this investigation. All the tools except cemented carbide were made as one piece unit and attached to the horn by tightening the threaded portion of the tool with the horn. Tool of cemented carbide was prepared by silver brazing the tip with replaceable threaded part at 1200 F.

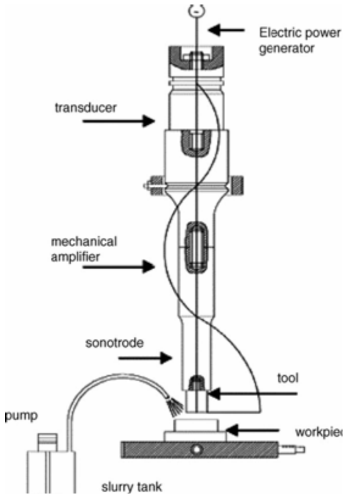

Fig. 1 USM Set Up

Three types of abrasive materials were used: silicon carbide, aluminium oxide and boron carbide. Three different grit sizes were selected for each abrasive material: 220, 320 and 500. Power rating of the ultrasonic machine was selected as another process parameter for this investigation as the effect of this parameter on tool wear rate in USM has not been explored to a significant extent by any researcher by now. Three levels of power rating were finalized from the pilot experimentation: 100 W, 250 W and 400 W. The process parameters and their levels selected for the final experimentation has been depicted in table 2.

TABLE I
CHEMICAL COMPOSITION OF TITANIUM

Chemical composition (by weight %) of Titanium (ASTM Grade I)						
O	N	C	H	Fe	residual	Ti
0.2	0.03	0.08	0.01	0.2	0.4	99.1
Yield Strength 220 MPa Ultimate strength 340 MPa Mod. of elasticity 103 GPa	Density 4.51 g/cm^3 Hardness 115 HV					

The experiments were conducted on an ‘AP-500 model Sonic-Mill’ ultrasonic machine. The complete setup is divided into the four sub systems; power supply, Mill module unit, slurry re-circulating system and Workpiece. To measure the tool wear rate (TWR), the time taken for drilling each hole was recorded using stop watch. The tool was weighed before and after drilling each hole using electronic balance. The weight loss for drilling each hole was thus recorded. The TWR was calculated by taking the ratio of weight loss of tool per hole to the drilling time per hole.

TABLE II
PROCESS PARAMETERS AND THEIR LEVELS

Symbol	**Parameter**	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
A	Tool	HCS	HSS	Titanium	Ti alloy	Carbide
B	Abrasive	Alumina	SiC	Boron Carbide		
C	Grit Size	220	320	500		
D	Power Rating	100	250	400		

Constant parameters

Frequency of vibration	20 KHz
Static load	1.63 Kg
Amplitude of vibration	25.3-25.6 µm
Depth of cut	1 mm
Thickness of workpiece	10 mm
Slurry Concentration	25%
Tool Geometry	Straight cylindrical with diameter 8 mm
Slurry Temperature	28° C (ambient room temperature)
Slurry Flow rate	$36.4\text{x}10^3$ mm^3/min
Slurry Media	Water

III. EXPERIMENTATION

Before finalizing a particular orthogonal array for the purpose of designing the experiments, the following two things must be established [7]:

1. The number of parameters and interactions of interest
2. The number of levels for the parameters of interest

In the present investigation, four different process parameters have been selected as already discussed. The tool material factor has five levels whereas all other parameters such as abrasive type, grit size and power rating of the machine have three levels each. Hence, L-18 array (in modified form) was selected for the present investigation. L-18 array has a special property that the two way interactions between the various parameters are partially confounded with various columns and hence their effect on the assessment of the main effects of the various parameters is minimized. It is not possible to assess the possible two factor interactions in L-18 array but the main effects of different process parameters can be assessed with reasonable accuracy. According to the scheme of the experimentation outlined in the L-18 OA (table 3), holes were drilled in the work pieces which were prepared in the form of circular discs with thickness of 10 mm and diameter of 34 mm.

Each trial was replicated twice, hence, three holes were drilled for each of the eighteen trial runs and moreover, all the fifty four trial runs in all were executed in completely randomized fashion to reduce the effect of experimental noise to the maximum possible extent. The flow rate of the abrasive slurry was maintained constant at a value of $36.4 \text{ x } 10^3$ mm^3/min. To avoid any possibility of dullness of the edges of the abrasive grains, a large volume of slurry was prepared.

Evaluation of S/N Ratios

The S/N ratio is obtained using Taguchi's methodology. Here, the term 'signal' represents the desirable value (mean) and the 'noise' represents the undesirable value (standard deviation). Thus, the S/N ratio represents the amount of variation present in the performance characteristic.

TABLE III
CONTROL LOG FOR EXPERIMENTATION BASED ON L-18 OA

Exp No.	**A: Col. 1 Tool**	**B: Col. 2 Abrasive**	**C: Col. 3 Grit Size**	**D: Col. 4 Power Rating**
1	HCS	Alumina	220	100
2	HCS	SiC	320	250
3	HCS	B$_4$C	500	400
4	HSS	Alumina	220	250
5	HSS	SiC	320	400
6	HSS	B$_4$C	500	100
7	Titanium	Alumina	320	100
8	Titanium	SiC	500	250
9	Titanium	B$_4$C	220	400
10	Titanium alloy	Alumina	500	400
11	Titanium alloy	SiC	220	100
12	Titanium alloy	B$_4$C	320	250
13	Carbide	Alumina	320	400
14	Carbide	SiC	500	100
15	Carbide	B$_4$C	220	250
16	HCS	Alumina	500	250
17	HCS	SiC	220	400
18	HCS	B$_4$C	320	100

Depending upon the objective of the performance characteristic, there can be various types of S/N ratios. Here, the desirable objective is lower values of tool wear rate. Hence, the Lower-the-Better (LB) type S/N ratio was applied for transforming the raw data. The Computed values of S/N have been summarized in table 4.

Main Effects due to Parameters

The main effects can be studied by the level average response analysis of raw data or of S/N data. The analysis is done by averaging the raw and/or S/N data at each level of each parameter and plotting the values in graphical form. The level average responses from the raw data help in analyzing the trend of the performance characteristic with respect to the variation of the factor under study. The level average response plots based on the S/N data help in optimizing the objective function under consideration. The peak points of these plots correspond to the optimum condition. The main effects of raw data and those of the S/N ratio are shown in Fig. 2.

Analysis of Variance (ANOVA)

The percentage contribution of various process parameters on the selected performance characteristic can be estimated by performing ANOVA. Thus, information about how significant the effect of each controlled parameter is on the quality characteristic of interest can be obtained.

TABLE IV
EXPERIMENTAL RESULTS FOR TWR AND S/N RATIO

Exp No.	TWR (mg/min) R1	R2	R3	Avg. TWR (mg/min)	S/N Ratio (dB)
1	3.87	4.13	3.56	3.85	11.73
2	4.85	5.28	4.57	4.90	14.13
3	6.56	6.30	7.00	6.62	16.43
4	3.20	3.00	3.36	3.19	10.08
5	8.16	8.08	8.25	8.16	18.24
6	1.88	1.64	1.97	1.83	5.24
7	0.57	1.33	0.54	0.81	0.23
8	1.40	1.89	1.21	1.50	3.68
9	6.00	6.50	5.77	6.09	15.70
10	0.95	0.62	0.87	0.81	1.67
11	0.72	0.72	0.56	0.67	3.47
12	1.86	1.95	1.78	1.86	5.25
13	7.75	7.95	8.26	7.99	18.05
14	5.12	5.06	5.50	5.23	14.37
15	9.37	9.88	9.10	9.45	19.51
16	1.45	1.70	1.40	1.52	3.65
17	12.30	12.00	12.36	12.22	21.74
18	3.23	2.47	4.00	3.23	10.35

The total variation in the result is the sum of variation due to various controlled factors and their interactions and variation due to experimental error. The ANOVA for raw data and S/N data have been performed to identify the significant parameters and to quantify their effect on the performance characteristic. The ANOVA based on the raw data signifies the factors, which affect the average response rather than reducing variation. But ANOVA based on S/N ratio takes into account both these aspects and hence it is used here. The pooled ANOVA S/N data are given in table 5. The percentage contributions of significant process parameters towards the variation in TWR are shown in Figure 3.

TABLE V
ANOVA RESULTS FOR TWR (S/N RATIO)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	(%P)
Tool	4	556.3	556.3	139.04	17.47	0.001	**53.77**
Abrasive	2	99.4	99.4	49.7	6.23	0.028	**1.87**
Grit Size	2	98.4	98.4	49.2	6.17	0.029	**9.51**
Power	2	223.7	223.7	111.8	14.01	0.004	**21.67**
Error	7	55.8	55.8	8.0			**5.42**
Total	17	1033.6					

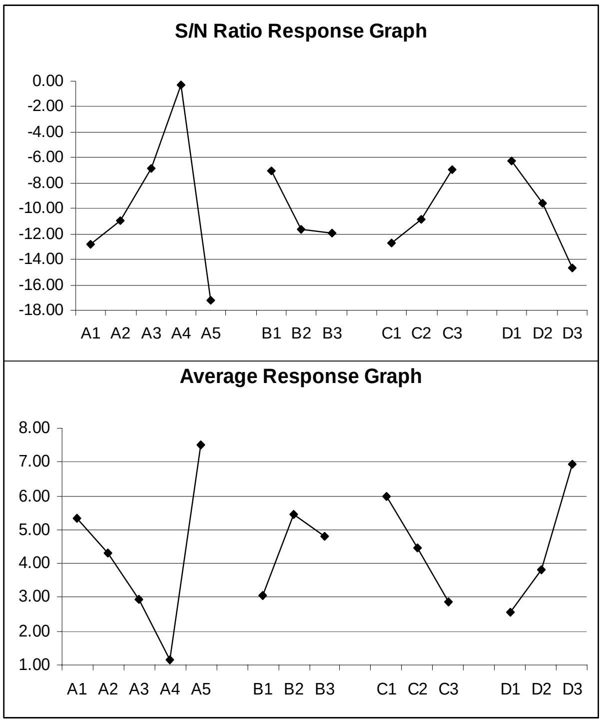

Fig. 2 Effects of process parameters on TWR-raw data and S/N ratio

IV. RESULTS AND DISCUSSION

It can be observed from fig. 2 that the tool material affects the rate of wear of the tool very significantly. Moreover, the different tool materials used in the experimentation can be ranked in the order of increasing tool wear rate as Ti alloy<Titanium<HSS<HCS<Cemented carbide. The lowest tool wear has been recorded for titanium alloy (ASTM Grade –V). This can be attributed to its excellent combination of high fracture toughness and optimum hardness (42 RC) from the point of view of USM process. Also the work hardening ability of this material has been found to be superior as compared to other materials used in this research. Hence, as a result of the repeated impacts of abrasive particles on the tool surface, it goes under significant amount of plastic deformation before fracture.

The type of abrasive used also puts a significant effect on tool wear rate for the different tool materials. It has been observed that use of Silicon carbide as abrasive results in more tool wear rate as compared to that achieved with the use of alumina. This can be explained on the basis of the relative knoop hardness of the abrasive grains. Silicon carbide is also having 50-60% more cutting power as compared to alumina. Hence, it promotes the increase in tool wear rate. The use of a coarser grit size promotes the increase in tool wear rate further (fig. 2). Use of coarse abrasive grains results in stronger impacts on the tool surface and hence the rate of fracture increases. Similar types of results have been reported by other researchers [8]-[10].

In the present investigation, the response variable is “Lower the Better” type characteristic. Therefore, lower values of TWR are considered to be optimal. It is clear from figure 1 that tool wear rate (TWR) is lowest at the fourth level of tool material parameter (A_4), first level of abrasive material parameter (B1), third level of the grit size (C3) and also the first level of power rating (D1). The main effects of the S/N ratio are also highest at these levels of the parameters that result in lowest tool wear rate. Hence, the process setting (A4B1C3D1) could be termed as ‘optimized process setting’ for tool wear rate under the range of parameters investigated. The concept of obtaining this optimized process setting through systematic planning and execution of experiments is known as ‘parametric optimization’. The data obtained by ANOVA test (table 5) also includes the percent contribution of various process parameters towards the variation in the response under consideration (TWR in this case). Tool factor emerges as the most significant (with a p value 0.001) followed by power rating. Abrasive material and grit size are almost equally significant as both assume the same p value. Tool factor contributes for 53.77 percent in the variation of TWR whilst contribution of abrasive factor is almost nil. Power rating emerges as another highly significant factor, with a percent contribution of 21.67 in the variation of TWR. The grit size factor is also marginally significant at 95% confidence level, with a percent contribution of 9.51.The percent contributions for various parameters have been plotted as shown in fig. 3.The Taguchi approach for predicting the mean performance characteristics and determination of confidence intervals for the predicted mean has been applied. Three confirmation experiments for TWR have been performed at optimal settings of the process parameters and the average value has been reported. The average values of the performance characteristics obtained through the confirmation experiments (three runs) must be within the 95% confidence interval, CI_{CE} (fixed number of confirmation experiments).

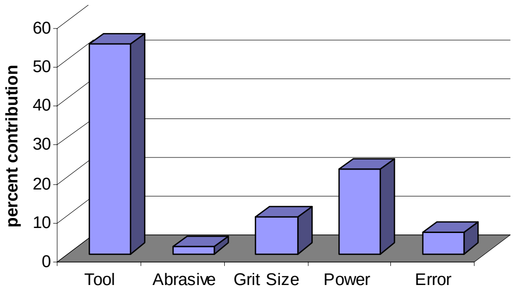

Fig. 3 Percent contributions of various factors

For TWR,The overall mean of the population is $\mu = 3.83$ (table IV)The predicted optimum value of TWR is calculated as,

$$\mu_{TWR} = (\mu A4+\mu B1+\mu C3+\mu D1) - (3\mu) = 0.45$$

For calculation of $CI_{CE,}$ the following equation [7] has been used:

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e)\left\{\frac{1}{n_{eff}} + \frac{1}{R}\right\}V_e}$$

F_{α} (1, f_e) = the F-ratio at a confidence level of (1-α) against DOF 1 and error degrees of freedom f_e
V_e = error variance for TWR
Effective DOF involved in calculation of mean = 10
N = total number of experiments
Hence $n_{eff} = 18/(1+10) = 1.64$
R = sample size for confirmatory experiments = 3
On putting all these values in the expression for CI_{CE}
$CI_{CE} = (0.09) \times 2 = 0.18$
The 95% confidence interval for μ_{TWR} is,
$CI_{CE} = 0.36<\mu_{TWR}<0.54$

Three experiments were conducted at the optimum settings of the process parameters to verify the validity of the optimized results. The mean values of the response (TWR) from these experiments have been found to be 0.425 mg/min, which is well contained by the confidence intervals, indicating the validation of the optimized results for TWR. The optimized results along with the confidence interval values have been summarized in table 6.

TABLE VI
OPTIMIZED PROCESS SETTINGS AND RESULTS

Parameter	**Optimized setting**	**Optimized value of TWR**
Tool Abrasive Grit Size Power Rating	Titanium alloy Alumina 500 (finest) 100 W (20%)	0.45 mg/min CI: $0.36<\mu_{TWR}<0.54$

V.CONCLUSIONS

The following conclusions can be withdrawn from this experimental work:

1. All the factors investigated have been found to be significant for their effect on tool wear rate. However, tool material factor has emerged as the most significant factor, followed by power rating of the USM equipment.
2. Abrasive type and grit size have been found to be almost equally significant as far as TWR is concerned.
3. The optimized process setting for achieving the optimal value of TWR has been identified. The confirmatory experiments conducted by using the optimized setting verified the validity of the optimized results.
4. The optimal value of TWR was established as 0.45mg/min, as experimentally verified.

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