Research Article

Investigations for Statistically Controlled Tool Wear Solution of Titanium Alloys Using Ultrasonic Machining

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Abstract

The purpose of present work is to study process capability of ultrasonic machining (USM). Relationships between tool wear rate (TWR) and other controllable machining parameters (like: power rating; tool type; slurry concentration; slurry type; slurry temperature and slurry size) have been deduced. The results of study suggest that optimum TWR result based upon Taguchi model for USM process is under statistical control.

Keywords: Tool wear rate, Titanium alloys, Statistically controlled, Ultrasonic machining

Introduction

Titanium (Ti) and its alloys are branded as difficult-to-machine materials but have high utility in manufacturing sector.[1-4] Poor thermal conductivity of Ti alloys retard the dissipation of heat generated, creating, instead a very high temperature at the tool work-piece interface and adversely affecting the tool life.[5,6] Ti is chemically reactive at elevated temperature and therefore the tool material either rapidly dissolves or chemically reacts during the traditional machining process resulting in chipping, pre-mature tool failure and poor surface finish.[3] Compounding of these characteristics is the low elastic modulus of Ti, which permits greater deflection of the work piece and once again adds to the complexity of machining.[1] These properties also make Ti and its alloys difficult to machine into a precise size and shape.[7] As a result, their widespread applications have been hindered by the high cost of machining with current technology.[2] So the conventional machining processes are unable to provide good machining characteristics to Ti alloys.[5] Therefore, there is a crucial need for reliable and cost-effective machining processes for Ti and its alloys.[8] One of cost-effective machining methods for Ti and its alloys is Electric discharge machining process (EDM).[1] The material removal rate (MRR) is quite high using this process, however surface finish and dimensional accuracy is problematic area.[6,9] Now days another non-conventional machining process, ultrasonic machining (USM) has been successfully applied for machining of titanium and its alloys.[10,11] But the volume of material removal in this process is quite less.[12] For the USM, an approach to model tool wear rate (TWR) has been proposed and applied for Ti and its alloys.[13] In this TWR model for stationary USM, macro modeling concept has been used.[14] This model has been applied for predicting the TWR for pure Ti, (ASTM Gr.2) and Ti alloys, (ASTM Gr.5).[15,16] In this study the effect of controllable parameters (like: tool material, slurry type, slurry concentration, grit size, slurry temperature, and power density) were revealed with Ti work piece as noise factor. Table1 and 2 illustrates the chemical composition of pure Ti, (ASTM Gr.2) and Ti alloy, (ASTM Gr.5).

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Table 1.Chemical Analysis of Ti Pure (ASTM Gr.2)

C	H	N	O	Fe	Ti
0.006	0.0007	0.014	0.140	0.05	Balance

Table 2.Chemical Analysis of Ti Alloy (ASTM Gr.5)

C	H	N	O	Al	V	Fe	Ti
0.019	0.0011	0.007	0.138	6.27	4.04	0.05	Balance

The ultrasonic spindle kit consists of an ultrasonic spindle mounted with cylindrical horn of diameter 25.4mm and a power supply unit of 500W capacity. The amplitude of vibrations was fixed in range of 0.0253-0.0258mm with a frequency of 20 kHz +/- 200 Hz. The static load for feed rate was fixed at 1.636kg and slurry flow rate at 26.4L/min.

There are four sections in this article. Following this introduction section, design of experiment section describes the design of experiments using Taguchi technique. In the third section, observations have been made to investigate whether the USM process for machining of Ti alloys is under statistical control as regards to TWR is concerned. Conclusions are drawn up in the last section followed by references.

Design of Experiments

In this study, L18 orthogonal array of Taguchi design has been used to study the relationship between TWR and the controllable machining parameters.[17] Table 3 shows different control variables and their levels. The optimal conditions of control factors were obtained from experiments. For the analysis rd Expert™ software has been used. The output parameter studied as response variables for analysis is shown in Table 4.

Table 3.Control Variables and their Levels

No.	Control variables	Levels of Control variables						
		L	L 1	L 2	L 3	L 4	L 5	L 6
A	Tool	6	SS	HSS	HCS	WC	Di	Ti
B	Slurry concentration	3	15 %	20 %	25 %	-	-	-
C	Slurry type	3	B_4C	Si_4C	Al_2O_3	-	-	-
D	Slurry temperature	3	10°C	27°C	60°C	-	-	-
E	Power rating	3	30 %	60 %	90 %	-	-	-
F	Slurry size	3	220	320	500	-	-	-

The control log for experimentation is shown in Table 5. The best settings of USM for TWR are obtained at 450W power rating, with S.S tool and 500 grit-size slurry. These results well agree with experimental observations made otherwise.[8,15] This may be explained on the basis that ideal function selected was nominal the best type, so SS tool and 450W power rating were ought to come. Also, higher grit size must result in less TWR.[11,13]

Table 4.Response Variable (Output Parameter)

Name: Tool wear rate
Type: Nominal the Best (Ideal Function)
Response: TWR (gm/min)

Table 5.Control Log for Experimentation

Exp. No.	A	B	C	D	E	F
1	SS	15 %	B_4C	10ºC	30 %	220
2	SS	20 %	Si_4C	27ºC	60 %	320
3	SS	25 %	l_2O_3	60ºC	90 %	500
4	HSS	15 %	B_4C	27ºC	60 %	500
5	HSS	20 %	Si_4C	60ºC	90 %	220
6	HSS	25 %	l_2O_3	10ºC	30 %	320
7	HCS	15 %	Si_4C	10ºC	90 %	320
8	HCS	20 %	l_2O_3	27ºC	30 %	500
9	HCS	25 %	B_4C	60ºC	60 %	220
10	WC	15 %	l_2O_3	60ºC	60 %	320

11	WC	20 %	B_4C	10ºC	90 %	500
12	WC	25 %	Si_4C	27ºC	30 %	220
13	Di	15 %	Si_4C	60ºC	30 %	500
14	Di	20 %	Al_2O_3	10ºC	60 %	220
15	Di	25 %	B_4C	27ºC	90 %	320
16	Ti	15 %	Al_2O_3	27ºC	90 %	220
17	Ti	20 %	B_4C	60ºC	30 %	320
18	Ti	25 %	Si_4C	10ºC	60 %	500

The ideal function selected here is nominal the best type. The objective function to be maximized for present case is:

$Ŋ = 10 \log_{10} (\mu^2/\sigma^2)$

Where $_n$

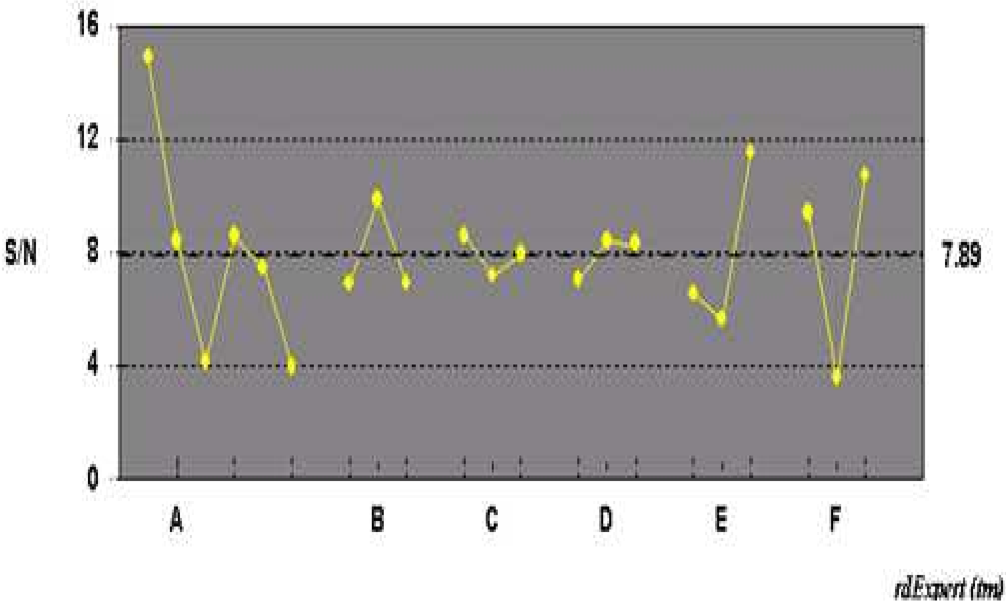
$\mu = 1/n. \sum y_i^{2\ i=1}\ _n$

$\sigma^2 = 1/ (n-1). \sum (y_i - \mu)^{2\ i=1}$

The optimization of the nominal-the-best problems can be accomplished in two steps:

1. Maximize 'ŋ' or minimize sensitivity to noise. During this step one can select the levels of control factors to maximize 'ŋ' while ignoring the mean.
2. Adjust the mean on target. During this step one can use the adjustment factor to bring the mean on target without changing 'ŋ'.

In general one should not attempt to minimize 'σ' and then bring the mean on target.[14] For analysis of TWR, signal to noise ratio (S/N) at different input parameters have been calculated (ref. figure1). Figure 2 shows 'Pie-chart' to understand percentage contribution of each factor affecting TWR. Based upon the proposed model for machining characteristics of titanium and its alloys using USM process verification experiments were conducted under the optimum conditions and starting conditions of input parameters. The data agrees very well with the predictions about the improvement in the S/N ratios and the deposition rate. Comparison of TWR results obtained shows improvement by 7%, even without introducing any other input. This means there will be less tool wear in USM of Ti and its alloys when working on optimized parametric settings, hence results in less down time and more productivity. The present results are valid for 90-95% confidence interval.



A: Tool, B: Slurry Concentration, C: Slurry type, D: Slurry temperature, E: Power rating, F: Slurry size

Figure 1.S/N Responses of TWR vs. Input Parameters

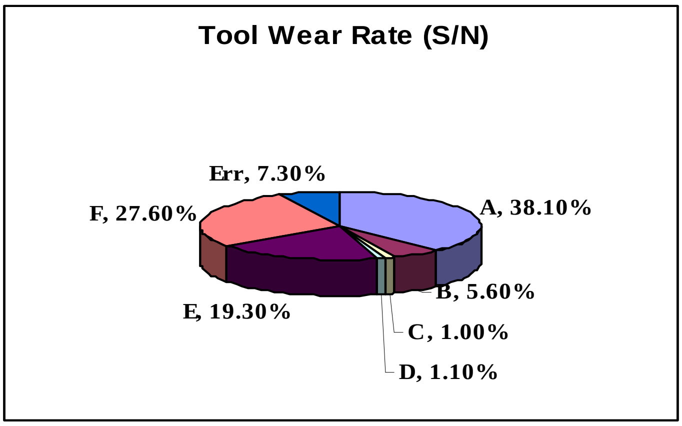


Figure 2.Pie Chart of TWR (S/N)

Statistical Analysis of TWR Based upon Taguchi Design

Further based on Taguchi design model for TWR, to understand whether the process is statistically controlled six samples of Ti alloy pieces were machined at best settings of input parameters for USM, (that is SS tool at 450W power rating and 500 grit size). The calculated values of TWR are shown in Table 6. Run chart (ref. figure3) for observed TWR has been developed from the results in Table 6.

Table 6.TWR Value at Best Settings of Input Parameters for USM

No.	Observations TWR (gm/min)	Mean	Above or below mean	Up or down
1	0.00894	0.008965	B	
2	0.00893	0.008965	B	D
3	0.00895	0.008965	B	U
4	0.00898	0.008965	A	U
5	0.00899	0.008965	A	U
6	0.00900	0.008965	A	U
MEAN	0.008965	0.008965	RUN=1	U and D=1

A=above the mean, B=below the mean, U=Up from previous reading, D=Down from previous reading

Now if the mean and standard of population that is having normal distribution is μ and σ respectively then for variable data X the standard normal deviation Z is defined as:

$$Z = \frac{(Xi - \mu)}{\sigma} \quad (1)$$

Where X_i is the variable data obtained, μ is the mean of data and σ is the standard deviation.[18]

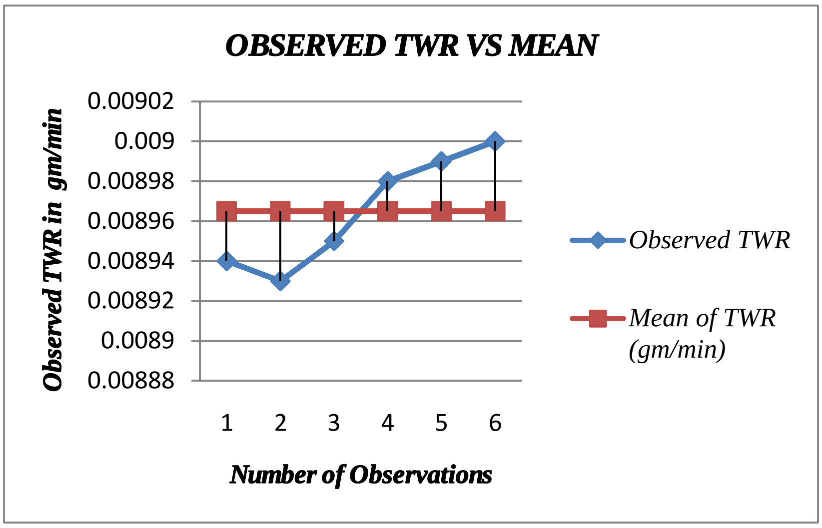


Figure 3.Run Chart for Calculated Values of TWR

Calculation for Z (standard normal deviate) above and below

$E\ (run)_{AB} = (\frac{N}{2} + 1)$ (2)

Where N is the number of observations and $E\ (run)_{AB}$ is the expected number of run above and below

$E\ (run)_{AB} = (\frac{6}{2} + 1) = 4$ (3)

$\sigma_{AB} = \sqrt{(N - \frac{1}{4})}$ (4)

Where σ_{AB} is the standard deviation of above and below

$\sigma_{AB} = \sqrt{(6 - \frac{1}{4})} = 1.118$ (5)

$Z_{AB} = \{RUN_{AB} - E(run)_{AB}\} / \sigma_{AB}$ (6)

Where RUN_{AB} is the actual number of run obtained above and below

$Z_{AB} = \frac{(1-4)}{1.118} = -2.6834$ (7)

$|\ Z_{AB}\ | = 2.6834$ (8)

$E\ (run)_{UD} = 2N - \frac{1}{3}$ (9)

Where N is the number of observations and $E\ (run)_{UD}$ is the expected number of run up and down.

$E\ (run)_{UD} = 2 \times 6 - \frac{1}{3} = 3.667$ (10)

$\sigma_{UD} = \sqrt{(16N - 29/90)}$ (11)

Where σ_{UD} is the standard deviation for up and down

$\sigma_{UD} = \sqrt{(16 X 6 - 29/90)}$ (12)

$\sigma_{UD} = 0.8628$ (13)

$Z_{UD} = \{RUN_{UD} - E(run)_{UD}\} / \sigma_{UD}$ (14)

$Z_{UD} = (1-3.667)/0.8628$ (15)

$Z_{UD} = -3.091$ (16)

$|\ Z_{UD}\ | = 3.091$ (17)

The critical value of Z is obtained by using Microsoft Excel software.

$Z_{crit} = NORMSINV\ (1-\alpha/2)$ (18)

Normally decision making is done with certain margin of error 'α' and taken as equal to 0.005 that is there can 5% chances in arriving at wrong conclusion.

Therefore, $Z_{crit} = 1.959963$ (19)

Now for decision making:

If $|\ Z_{AB}\ | > Z_{crit}$ OR /and $|\ Z_{UD}\ | > Z_{crit}$, then non-random pattern exist.

In the present case $|\ Z_{AB}\ |$ and $|\ Z_{UD}\ |$ are $> Z_{crit}$ indicates existence of non random pattern.

Now exercise of predicting various statistical or drawing conclusions should not be undertaken unless the normality of distribution has been verified. Even if one has a large data, superimposing of normal curve on the histogram it is more difficult task than it to be imagined. For histogram one require minimum of 50 observations, however more the better and for assessing whether the underlying distribution is normal or not becomes more difficult when the number of observations is fewer. For cumulative probability plot (Pi):

$Pi = (S.N-0.5)/N$ (20)

Where S.N is serial number of data observation arranged in ascending order, N is total number of observations in the data set. If the standard normal deviate follows normal distribution that has mean μ =0 and standard deviation σ =1, then:

$f(Z) = 1/\sqrt{(2\Pi e^{\frac{z^2}{2}})}$ (21)

The equation above follows normal probability curve and any date close to it also follows normal probability curve. The values of standard normal deviate were calculated using cumulative probability and dimensional values were arranged in ascending order as shown in Table 7. Based on Table 7 normal probability curve was drawn to predict the probability as shown in Fig. 4. As observed in figure4, the aforesaid data follows non random pattern and is under normal probability curve. So, there are very strong chances that the process is under statistical control however X-bar chart and R-bar chart cannot be drawn due to less number of observational data.

Table 7.Standard Normal Deviate and TWR in Ascending Order

No.	Pi (Cumulative probability)	Z (Standard normal deviate)	TWR value in gm/min
1	0.08333	-1.38299	0.00893
2	0.25	-0.67449	0.00894
3	0.416667	-0.21043	0.00895
4	0.58333	0.21043	0.00898
5	0.75	0.67449	0.00899
6	0.91667	1.382994	0.00900

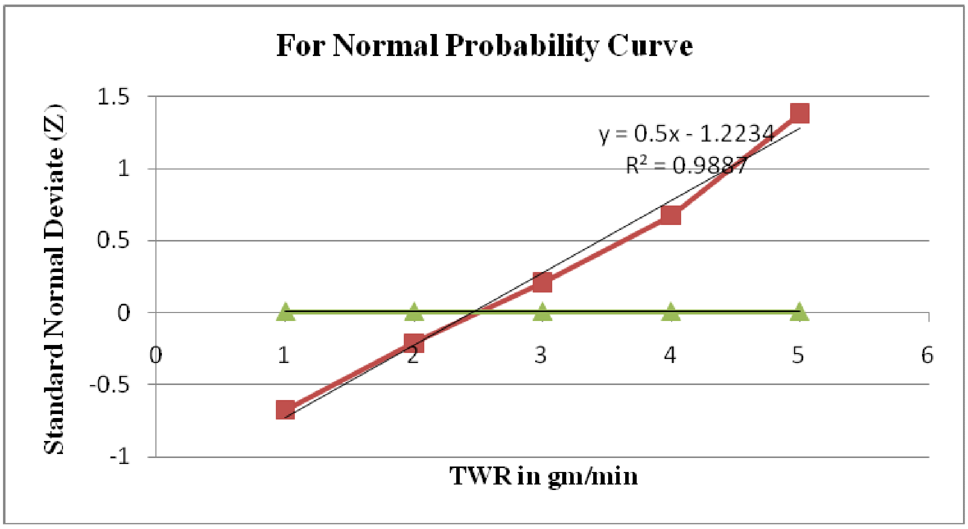


Figure 4.Normal Probability Curve (at best settings of USM)

Conclusion

Following conclusion has been drawn from the present study:

1. For TWR, type of tool and power rating are important factors followed by grit size of the slurry. The optimized results are obtained with SS tool at 450W power rating and 500grit size. The model developed shows close relationship between the experimental observations made otherwise.[12,13,15,16]
2. The adopted procedure is better as proof of model and for USM of other grades of Ti alloys, for which the cost of machining is high. The verification experiment reveals that on an average there is 7% improvement in TWR, for the selected work piece (TITAN15 and TIT.AN31).
3. The results of study suggest that at optimum TWR values based upon Taguchi design for machining of Ti alloys with USM; the process is under statistical control.

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