COMPARISON OF STATISTICALLY CONTROLLED MACHINING SOLUTIONS OF TITANIUM ALLOYS USING USM

R. Singh

Department of Production Engineering
Guru Nanak Dev Engg. College,
Ludhiana-141006 (Punjab), India;
Phone: +91 98722 57575, Fax: +91 161 2502700
Email:rupindersingh78@yahoo.com

ABSTRACT

The purpose of the present investigation is to compare the statistically controlled machining solution of titanium alloys using ultrasonic machining (USM). In this study, the previously developed Taguchi model for USM of titanium and its alloys has been investigated and compared. Relationships between the material removal rate, tool wear rate, surface roughness and other controllable machining parameters (power rating, tool type, slurry concentration, slurry type, slurry temperature and slurry size) have been deduced. The results of this study suggest that at the best settings of controllable machining parameters for titanium alloys (based upon the Taguchi design), the machining solution with USM is statistically controlled, which is not observed for other settings of input parameters on USM.

Keywords: ultrasonic machining; titanium alloys, Taguchi model, material removal rate, tool wear rate, surface roughness.

INTRODUCTION

The history of ultrasonic machining (USM) began with a paper by R.W. Wood and A.L. Loomis in 1927 (Singh and Khamba, 2006) and the first patent was granted to the American engineer Lewis Balamuth in 1945 (Singh, 2006). USM has been variously termed ultrasonic drilling, ultrasonic abrasive machining, ultrasonic cutting, ultrasonic dimensional machining, and slurry drilling (Singh and Khamba, 2006). However, from the early 1950s it was commonly known either as ultrasonic impact grinding or USM. The application of USM to the machining of hard and brittle material is well known, but hitherto less work has been reported for the machining of tough material. In the present work, the application of USM to tough materials has been explored. In this study titanium and its alloys has been selected based upon their industrial applications (Singh, 2006). These alloys are branded as difficult-to-machine materials but have high utility in manufacturing sector (Verma et al., 2003). They are alternatives 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) (Singh and Khamba, 2003). The poor thermal conductivity of titanium alloys retards the dissipation of generated heat, creating instead a very high temperature at the tool work interface and adversely affecting the tool life and surface finish (Dornfeld et al., 1999; Singh and Khamba, 2009a). Titanium is chemically reactive at elevated temperatures and therefore the tool material either rapidly dissolves or chemically

reacts during the traditional machining process, resulting in chipping, premature tool failure and poor surface finish (Verma et al., 2003). These properties also make titanium and its alloys difficult to machine into a precise size and shape (Singh and Khamba, 2004). As a result, their widespread applications have been hindered by the high cost of machining with current technology (Singh, 2006). So the conventional machining processes are unable to provide good machining characteristics to titanium alloys (Dornfeld, 1999). Therefore, there is a crucial need for reliable and cost-effective machining processes for titanium and its alloys (Singh and Khamba, 2007a). One of the cost-effective machining methods for titanium and its alloys is the electric discharge machining process (EDM) (Singh and Khamba, 2006). The material removal rate (MRR) is quite high using this process, however surface finish and dimensional accuracy are problematic (Benedict, 1987, Singh and Khamba, 2009a).

Now days another non-conventional machining process, USM has been successfully applied to the machining of titanium and its alloys (Thoe et al., 1998, Singh and Khamba, 2007b). But the volume of material removal in this process is quite less (Singh and Khamba, 2008). For stationary USM, an approach to model MRR, tool wear rate (TWR) and surface roughness (SR) has been proposed and applied for titanium and its alloys (Singh and Khamba, 2007b). In this Taguchi-based model for stationary USM, the macro modelling concept has been used. In a macro-model, the need to write a mathematical equation for developing relationships is bypassed (Singh and Khamba, 2009b, Taguchi and Konishi, 1987). The model developed is mechanistic in the sense that these parameters can be observed experimentally from a few experiments for a particular material and then used in the prediction of MRR, TWR and SR over a wide range of process parameters (Singh and Khamba, 2009b). This has been demonstrated for titanium and its alloys, where very good predictions have been obtained using an estimate of multi parameters. On the basis of this model, the relationships between the MRR, TWR, SR and the controlling machining parameters have been studied. These relationships agree well with the trends observed in experimental observations made by other investigators (Singh and Khamba, 2009a, Singh and Khamba, 2009b, Kumar et al., 2008, Kumar and Khamba, 2008). This model has been applied to predicting the MRR, TWR and SR for pure titanium, (ASTM Gr.2) and titanium alloy, (ASTM Gr.5). In this study the effect of six controllable parameters (tool material, slurry type, slurry concentration, grit size, slurry temperature, and power density) were examined, with titanium work piece as noise factor. Tables 1 and 2 illustrate the chemical composition of pure titanium, (ASTM Gr.2) and titanium alloy, (ASTM Gr.5) (Singh, 2006).

Table 1: Chemical analysis of pure Titanium (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 Titanium 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

Figure 1 shows the mechanism of tool wear in USM. The USM machine tool used for study was of 500 W capacity, which consists of an ultrasonic spindle kit, a constant pressure feed system and a slurry flow system (Singh, 2006). The ultrasonic

spindle kit comprises an ultrasonic spindle, mounted with cylindrical horn of ϕ25.4 mm, a power supply unit. The power supply converts 50 Hz electrical supply to high frequency 20 kHz AC output (Singh and Khamba, 2006). This was fed to the piezo-electric transducer located in the spindle. The transducer converts the electrical input into mechanical vibrations. The amplitude of vibrations was fixed in range of 0.0253-0.0258 mm with a frequency of 20 kHz +/- 200 Hz. The static load for the feed rate was fixed at 1.636 kg and the slurry flow rate at 26.4 L/min. The replaceable tools used for machining were solid tools made by silver brazing, having same area of cross-section, that is, Ø5 mm. For this model, an L18 orthogonal array of Taguchi design (Phadke, 1989) was used to study the relationship between MRR, TWR, SR and the controllable machining parameters.
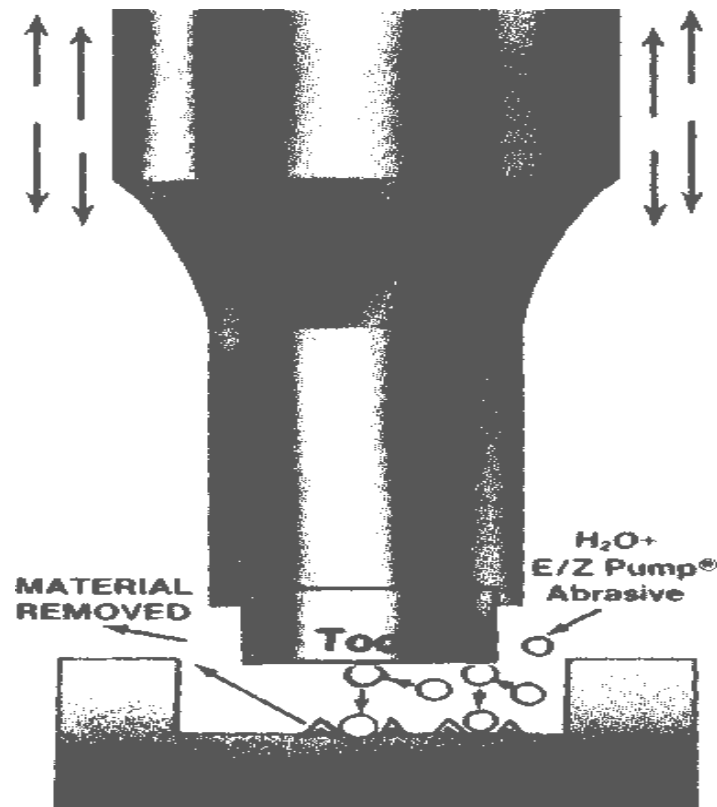

Figure 1: USM tool wear mechanisms (Singh and Khamba, 2006)

There are four sections in this paper. Following this Introduction, the design of experiment section describes the design of the experiments. In the third section, observations have been made to investigate whether the USM process for machining of titanium alloys is under statistical control as regards to MRR, TWR and SR is concerned. Conclusions are drawn in the last section, followed by references.

DESIGN OF EXPERIMENTS

The study presented in this paper is concerned primarily with obtaining the optimum system configuration with minimum expenditure of experimental resources. Table 3 shows different control variables and their levels. The best settings of the control factors were determined through experiments. For the analysis rd Expert ™ software was used. The output parameter

studied as response variables for analysis is shown in Table 4. The control log for experimentation is shown in Table 5.

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 conc.	3	15%	20%	25%	-	-	-
C	Slurry type	3	B_4C	Si_4C	Al_2O_3	-	-	-
D	Slurry temp.	3	10°C	27°C	60°C	-	-	-
E	Power rating	3	150 W	300 W	450 W	-	-	-
F	Slurry size	3	220	320	500	-	-	-

Table 4: Response variable (output parameter) (Singh and Khamba, 2007b)

Response No.	Response 1	Response 2	Response 3
Response name	MRR	TWR	S.R.
Response units	gm/min	gm/min	μm
Response type	Continuous	Continuous	Continuous

Table 5: Control log for experimentation

Exp. No.	A	B	C	D	E	F
1	SS	15%	B_4C	10°C	150 W	220
2	SS	20%	Si_4C	27°C	300 W	320
3	SS	25%	Al_2O_3	60°C	450 W	500
4	HSS	15%	B_4C	27°C	300 W	500
5	HSS	20%	Si_4C	60°C	450 W	220
6	HSS	25%	Al_2O_3	10°C	150 W	320
7	HCS	15%	Si_4C	10°C	450 W	320
8	HCS	20%	Al_2O_3	27°C	150 W	500
9	HCS	25%	B_4C	60°C	300 W	220
10	WC	15%	Al_2O_3	60°C	300 W	320
11	WC	20%	B_4C	10°C	450 W	500
12	WC	25%	Si_4C	27°C	150 W	220
13	Di	15%	Si_4C	60°C	150 W	500
14	Di	20%	Al_2O_3	10°C	300 W	220
15	Di	25%	B_4C	27°C	450 W	320
16	Ti	15%	Al_2O_3	27°C	450 W	220
17	Ti	20%	B_4C	60°C	150 W	320
18	Ti	25%	Si_4C	10°C	300 W	500

For analysis of MRR, TWR, and SR, the signal to noise ratio (S/N) at different input parameters has been calculated (Figures 2–4). The ideal function selected here is nominally the best type. The best settings of USM for MRR are obtained using the SS tool, 450 Wpower rating with boron carbide slurry. This may be because the SS tool yields a better tool–work combination as regards to work-hardening: its higher power rating (450 W) imparts a higher momentum to the abrasive particles, and boron-carbide

slurry is the hardest among the three slurries (Singh and Khamba, 2007b). As regards to TWR, the best settings of USM are obtained at 450 W power rating, with SS tool and 500 grit-size slurry. This may be explained on the basis that the ideal function selected was nominally the best type, so the SS tool and 450 W power rating ought to come. Also, the higher grit size (500 grit) must result in less TWR (Singh and Khamba, 2007b, Singh and Khamba, 2009b). For SR, slurry temperature is the most important, followed by slurry concentration and type of tool. Best settings are obtained at 25 ^{o}C at 25% concentration with SS tool. The selection of temperature and concentration setting may be explained on the basis that at this temperature and concentration neither sticking (because of freezing of slurry) nor evaporation took place, resulting in the maximum number of abrasive particles contributing in material removal mechanisms. The choice of SS tool is because of the selection of the ideal function as nominally the best type. Figures 5–7 show 'pie-charts' to understand the percentage contribution of each factor effect for MRR, TWR and SR. 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 MRR, TWR and SR results obtained shows improvement by 52%, 7%, and 32%, respectively, even without introducing any other input. The present results are valid for the 90%–95% confidence interval.

A: Tool, B: Slurry conc., C: Slurry type, D: Slurry temp.,
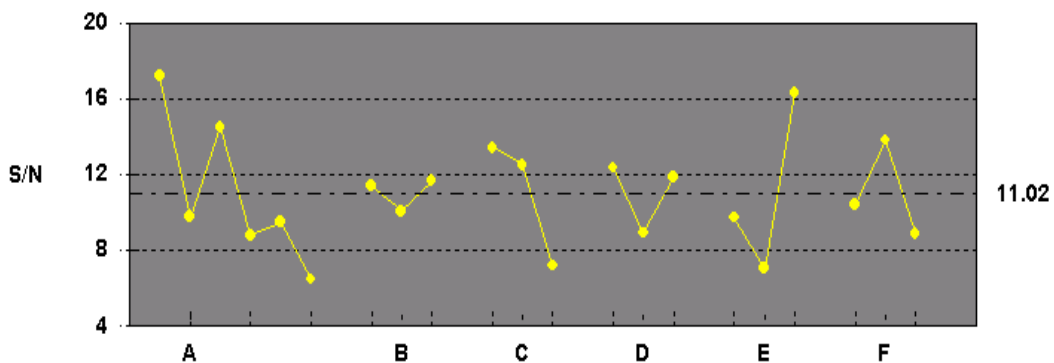E: Power rating, F: Slurry size

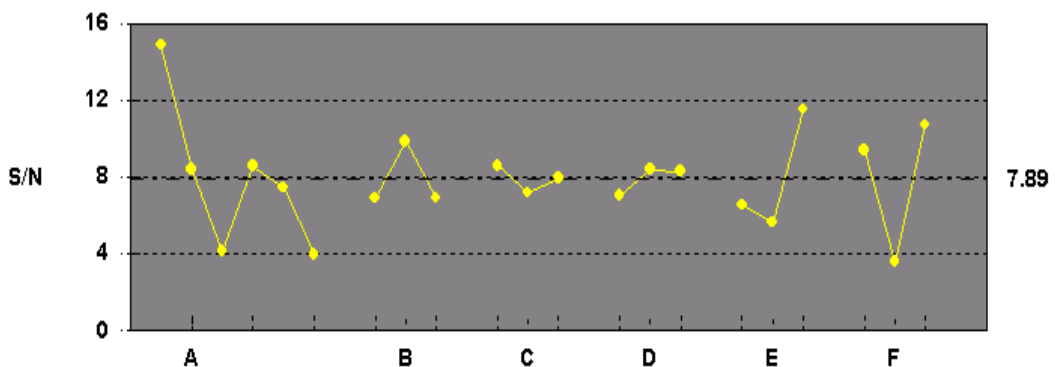Figure 2: S/N responses of MRR vs input parameters (Singh and Khamba, 2007b)

Figure 3: S/N responses of TWR vs input parameters (Singh and Khamba, 2007b)
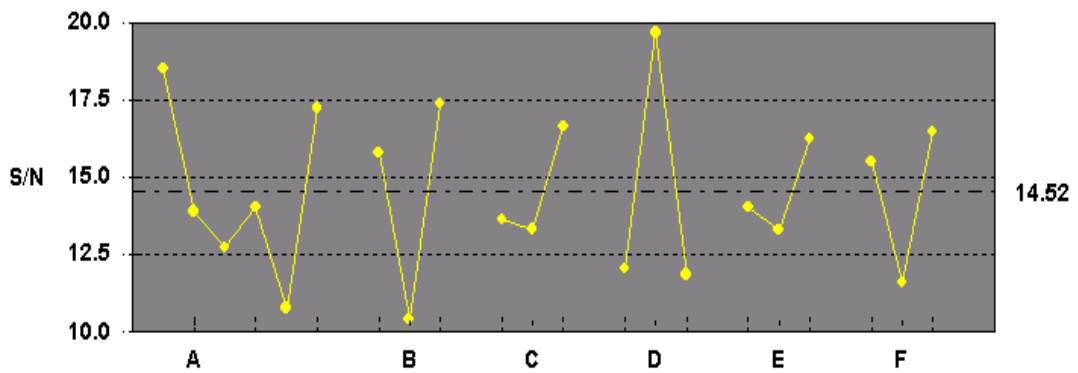
Figure 4: S/N responses of SR vs input parameters (Singh and Khamba, 2007b)
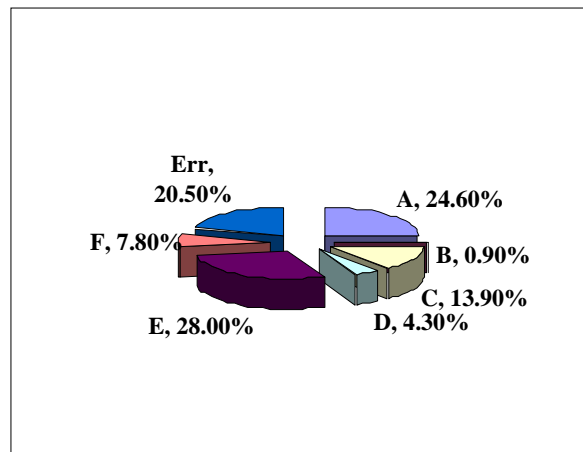

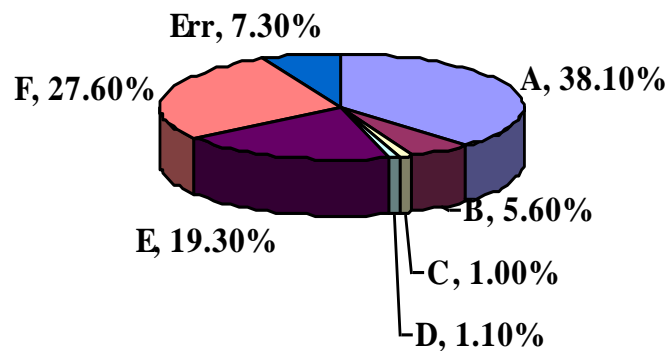Figure 5: Pie chart of MRR (S/N) (Singh and Khamba, 2007b)

Figure 6: Pie chart of tool wear rate (S/N) (Singh and Khamba, 2007b)

The optimal results for MRR are obtained with SS tool at 450 W power rating with boron carbide slurry. The optimal results for TWR are obtained with SS tool at 450 W power rating and 500 grit size. The optimal results for SR are obtained at 25 ^{o}C temperature, with 25% concentration using SS tool.
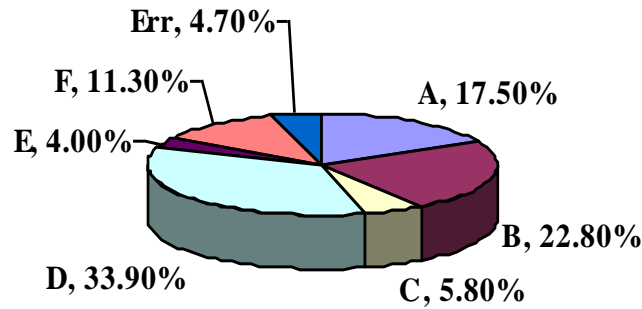
Figure 7: Pie chart of SR (S/N) (Singh and Khamba, 2007b)

STATISTICAL ANALYSIS

To understand whether the process (based on the Taguchi design model) is statistically controlled, 18 samples {6 samples × 3 (for each case of MRR/TWR/SR) = 18} of titanium alloy work pieces were machined at the best settings of the input parameters for MRR (using SS tool at 450 W power rating with boron carbide slurry), TWR (using SS tool at 450 W power rating and 500 grit size), and SR (at 25 °C slurry temperature, 25% concentration with SS tool) with USM. After calculation of MRR, TWR, and SR, the values obtained are shown in Table 6. Based upon the observations in Table 6, the run chart for calculated values of MRR, TWR and SR was developed (Figures 8–10). Now if the mean and standard deviation of a population that has the normal distribution is μ and σ respectively then for variable data X the standard normal deviate Z is defined as (Devor et al., 2005):

$$Z = \frac{X_i - \mu}{\sigma} \tag{1}$$

where: X_i is the variable data obtained, μ is the mean of data and σ is the standard deviation.

Table 6: MRR, TWR and SR value at best settings of input parameters for USM

S. No	Observations MRR (gm/min)	Observations TWR (gm/min))	Observations SR (μm)	Above or below MEAN	Up or Down
1	0.00500	0.00894	0.31	B	
2	0.00498	0.00893	0.29	B	D
3	0.00499	0.00895	0.30	B	U
4	0.00502	0.00898	0.32	A	U
5	0.00503	0.00899	0.33	A	U
6	0.00509	0.00900	0.34	A	U
Mean	0.00501	0.008965	0.315	RUN=1	U and D=1

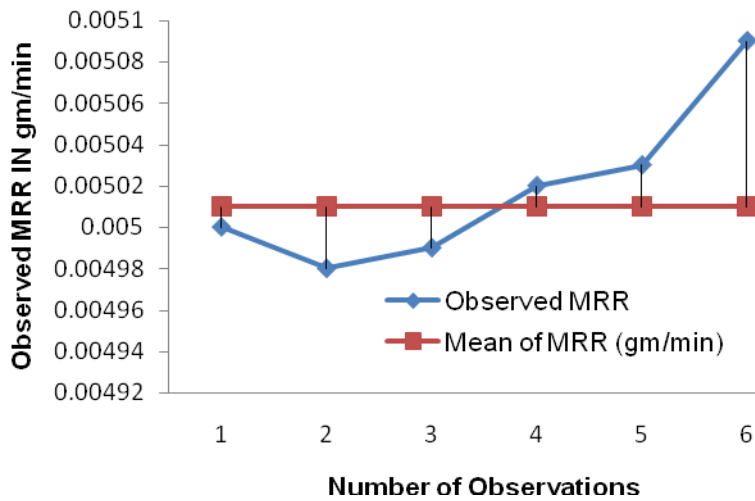A=above the mean, B=below the mean, U=up from previous reading, D=down from previous reading
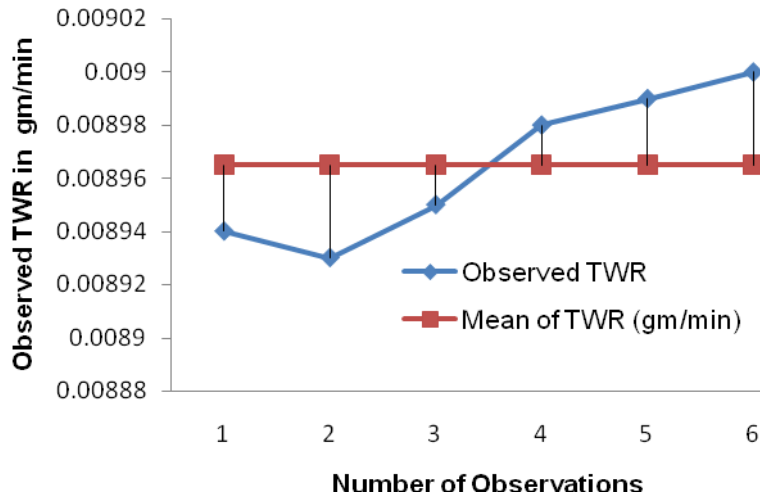
Figure 8: Run chart for calculated values of MRR

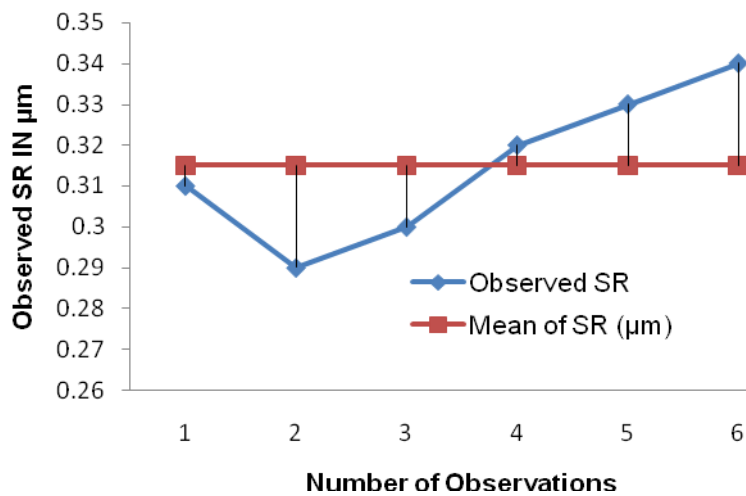
Figure 9: Run chart for calculated values of TWR

Figure 10: Run chart for calculated values of SR

Calculation for Z (standard normal deviate) above and below:

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

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

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

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

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

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

$$Z_{AB} = \left[\text{RUN}_{AB} - E(\text{run})_{AB}\right] / \sigma_{AB} \tag{6}$$

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

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

$$|Z_{AB}| = 2.6834 \tag{8}$$

$$E(\text{run})_{UD} = 2 \times N - \frac{1}{3} = 3.667 \tag{9}$$

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

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

$$\sigma_{UD} = \sqrt{16 \times N - 29 \times 90} \tag{11}$$

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

$$\sigma_{UD} = \sqrt{16 \times 6 - 29 \times 90} \tag{12}$$

$$\sigma_{UD} = 0.8628 \tag{13}$$

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

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

$$Z_{UD} = -3.091 \tag{16}$$

$$|Z_{UD}| = 3.091 \tag{17}$$

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

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

Normally decision making is done with a certain margin of error 'α' and taken as equal to 0.05, that is, that there can be 5% chances of arriving at a wrong conclusion.

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

Now for decision making:
If $| Z_{AB} | > Z_{crit}$ OR /and $| Z_{UD} | > Z_{crit}$, then a non-random pattern exists.

In the present case, $| Z_{AB} |$ and $| Z_{UD} |$ are $> Z_{crit}$, which indicates the existence of a non random pattern. Now the exercise of predicting various statistical properties 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 may be imagined. For a histogram, one requires a minimum of 50 observations, however the more the better and for assessing whether the underlying distribution is normal or not it becomes more difficult when the number of observations is fewer. For cumulative probability plot (Pi):

$$Pi = \frac{S.N - 0.5}{N} \qquad (20)$$

where $S.N$ is the serial number of the data observation arranged in ascending order, and N is the total number of observations in the data set. If the standard normal deviate follows the normal distribution that has mean $\mu = 0$ and standard deviation $\sigma = 1$, then

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

Equation 21 follows the normal probability curve and any data close to it also follows normal probability curve. The values of the standard normal deviates were calculated using cumulative probability and the dimensional values were arranged in ascending order as shown in Table 7. Based on Table 7, a normal probability curve was drawn to predict the probability as shown in Figures 11–13. As observed in Figure 5, the aforesaid data follows a non random pattern and is under the 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 the small number of observational data points.

Table 7: Standard normal deviates and response variable (MRR, TWR, SR) in ascending order

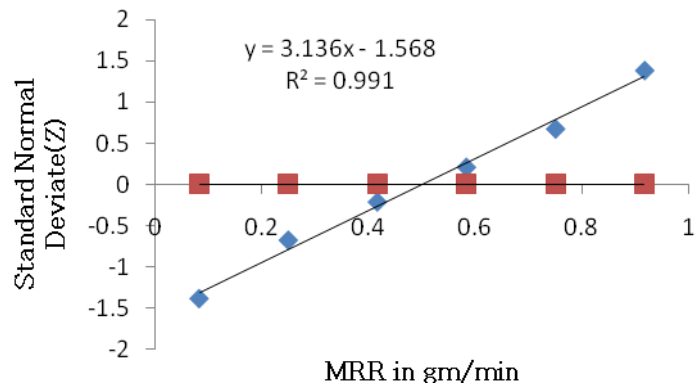| S. No	Pi (Cumulative Probability)	Z (Standard normal deviate)	MRR value in gm/min	TWR value in gm/min	SR value in µm
1	0.08333	-1.38299	0.00498	0.00893	0.29
2	0.25	-0.67449	0.00499	0.00894	0.30
3	0.416667	-0.21043	0.00500	0.00895	0.31
4	0.58333	0.21043	0.00502	0.00898	0.32
5	0.75	0.67449	0.00503	0.00899	0.33
6	0.91667	1.382994	0.00509	0.00900	0.34

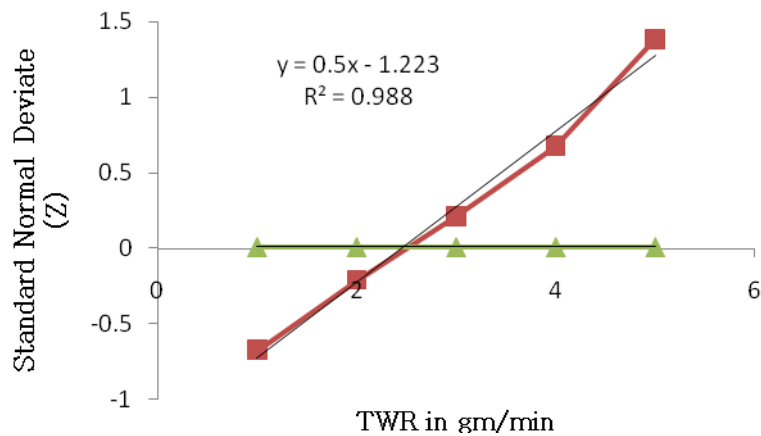Figure 11: Normal probability curve (at best settings of USM for MRR)

Figure 12: Normal probability curve (at best settings of USM for TWR)
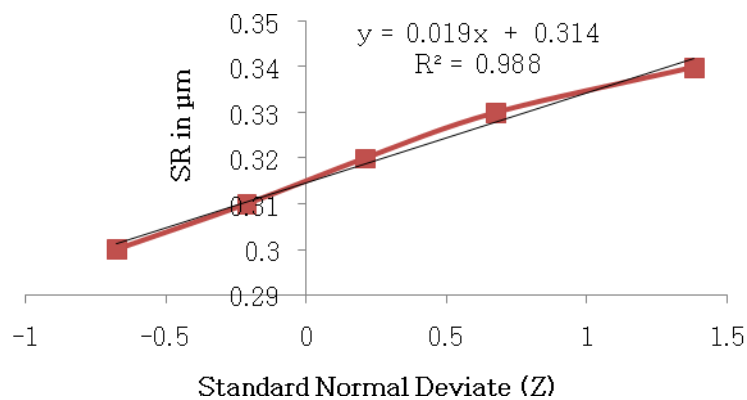

Figure 13: Normal probability curve (at best settings of USM for SR)

Now, again, to understand whether the process is statistically controlled (at other settings of control variables on USM for MRR, TWR and SR) eighteen more samples of titanium alloy pieces were machined based on Table 5. Further run charts of the

measured values were developed for eighteen sets of experiments corresponding to MRR, TWR and SR. Also the values of the standard normal deviates were calculated using cumulative probability and were arranged in ascending order. For these eighteen sets of observations, $| Z_{AB} |$ and $| Z_{UD} |$ are $< Z_{crit}$ indicating the existence of a random pattern. So, there are very strong chances that the process is not under statistical control at these settings of the control parameters.

CONCLUSIONS

The following conclusions may be drawn:

a) As regards to MRR, power rating and type of tool are important factors followed by slurry type.
b) The type of tool and power rating are important factors followed by grit size of the slurry for TWR.
c) The slurry temperature is the most important followed by slurry concentration and type of tool for SR.
d) The model developed shows a close relationship between the experimental observations made otherwise.
e) The adopted procedure is better as a proof of the proposed Taguchi based model and for USM of other grades of titanium alloys, for which the cost of machining is high.
f) Strong possibilities are observed for the process under statistical control as regard to MRR, TWR and SR is concerned at best settings of input parameters for USM of titanium and its alloys, which is not observed for all other settings of input parameters.

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