Ultrasonic Machining of Ti-6Al-4V Using Cryogenic Treated Tools

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Abstract

This paper presents an effective approach for the optimization of the ultrasonic machining process for titanium alloy (Ti6Al4V) with cryogenic treated tool material and evaluation of performance characteristics such as material removal rate and tool wear rate. The optimal setting of process parameters has been determined through experiment planned, conducted and analyzed using Taguchi method. The significant process parameters have also been identified and their effects on performance measures have been studied in detail. The microstructure of the machined surface has been studied using scanning electron microscopy. The predicted value for MRR and TWR at optimal parameter setting is 0.612 mm3/min and 0.174 mm3/min respectively and the experimental average value for MRR and TWR at optimal parameter setting is 0.697 mm3/min and 0.166 mm3/min. So the above mathematical prediction for MRR and TWR using MINITAB 14 is validated by confirmation experiment with error 0.328 and 0.061 respectively.

Keywords

Ultrasonic Machining (USM), Titanium Alloy, Cryogenic Treatment, Material Removal Rate, Tool Wear Rate, Taguchi Method

I. Introduction

Ultrasonic Machining (USM) is an advanced manufacturing technology used to machine electrically conductive as well as non-conductive materials such as diamond, glass, semiconductors, ceramics, quartz etc. Titanium and its alloys can be machined by electrical discharge machining, laser beam machining but these processes has its own limitations such as a proper surface finish, dimensional inaccuracies, recast layer and thermal stresses [1-2-3]. The highest strength to density ratio, resistance to heat and high corrosion resistance make it highly useful in various applications such as automotive, aerospace, human implants and protective armour on personnel carriers, naval ships and tanks. However the main reason for the demand of titanium in industries has been increased [4].

The Ultrasonic machining is an advance machining method that is used effectively for the machining of titanium alloy. The optimum parametric combinations like abrasive grit size, slurry concentration, power rating, tool feed rate and slurry flow rate for maximum MRR and minimum SR was obtained by CCD second-order rotatable design of ultrasonic drilling of hexagonal shaped hone on high alumina ceramics. The process performance i.e. MRR and SR were evaluated by using ANOVA [5]. Guzzo and Shinohara analyzed the abrasion of brittle and hard materials such as quartz are usually machined by USM [6]. Surface roughness and cutting force were analyzed during turning of titanium alloy. Proposed mathematical models were developed from two-level factorial experimentation to define the performance indicator within the limit of factors. Cutting speed, feed and depth of cut were the highly significant process parameters that impact on Ra and Fc [7]. The authors found that there was a linear relationship between MRR and hardness of cutting tool. During the USM, ample quantities of fluid used for cutting and efficient flow of slurry are necessary in order to remove the heat from the machining zone during machining of titanium alloy. Rigidity of tool joined in the horn ensures the proper maintenance for depth of cut. [8]. Singh and Khamba analyzed the USM of titanium alloy and pure titanium, to develop the mathematical model for USM responses [9]. During machining by USM, mechanical properties of work-piece play significant effect on performance characteristics such as MRR, TWR, and Ra. Singh and Khamba studied the USM of tough materials like titanium alloy [10]. From literature survey, it was found that significant machining was done by cooling the work-piece and tool at low temperature using a cryogenic treatment.

Cryogenic treatment is an eco-friendly, non-toxic and non-explosive technology. The effects on various types of steel and other material to investigate the process to optimize the parameters using various approaches have been used for cryogenic treatment. Cryogenic treatments of material produce the significant increases in wear resistance, hardness, toughness and produce the significant decrease in residual stresses, chemical degradation because retained austenite transforms into martensite [11]. To understand the behavior of distortion of the electrode and to establish the applications of liquid nitrogen in reducing distortion of the electrode during EDM of M2 grade high speed steel using cryogenically cooled copper electrode and conventional electrode [12]. To attain less wear resistance of 4140 steel, the deep cryogenic treated process parameters are optimized using analysis of variance. The four process parameters, namely hardening temperature, soaked period, temperature and period of tempering , are considered for the optimization and concluded that the hardening temperature play a significant role having percentage influence of 17.34% from other process parameters [13]. Nirmal et.al analyzed that the retained austenite after treatment was near 0%. The laboratory test on the lathe tool didn't indicate any effect on hardness of treated tool while on rapid facing test, it was discovered that cryogenically treated tool presented longer tool lives at different spindle speed and feed rates. Significant properties like fatigue behavior on the tool life due to variation in stresses and deformation in tool were analyzed and concluded that cryogenic treatment constraint the fine carbide and displacement of martensite for maximum fatigue load results maximum tool life [14]. The cryogenic treatment to conventionally machined Ti-6Al-4V alloy was carried out to evaluate the cutting temperature to machine different alloys under a different set of cooling conditions. Jet liquid nitrogen was used to provide the cooling at cutting interface and results of various cooling approaches were found [15]. The study concluded that, applying liquid nitrogen near to the cutting tool edge has a tendency to reduce the tool temperature of cutting zone. It was also found that titanium diffusion of tool material becomes negligible because of cryogenic cooling which otherwise was the major factor for the tool wear during the machining of titanium alloy

Literature survey on the Ultrasonic machining of titanium alloy (Ti-6Al-4V) reveals that there is a no work on cryogenic treatment of tool material was used while machining Ti-6Al-4V alloy. Most researchers have investigated the effect of various process parameters to improving the performance characteristics of USM using different tool materials. In the present investigation different tools has been prepared using a cryogenic treatment process. The optimal parametric set of combinations of process parameters is determined through experiments planned, conducted and analyzed using Taguchi method. L18 orthogonal array (35) has been selected to design the experiments and signal to noise ratio was conducted to find the optimal set of parameters for machining of titanium alloy. Machining characteristics of Ti-6Al-4V alloy have been explored using USM for their application in concerned manufacturing industry.

II. Experimental Setup

Experimental trials have been performed in an Ultrasonic drilling machine of AP-500 (Sonic Mill, USA) as shown in Figure 1. An experimental set-up having a provision for variation in process parameters have been designed and fabricated. The dimensions of the tool have been decided to keep in view the limitations of the horn shape to economize the machining operation. Titanium alloy (Ti6Al4V, composition: C=0. 1%, Fe=0. 30%, Al=6. 05%, O=0. 25%, N=0. 03%, V=4. 1%, H=0. 015% and balance Ti) with yield strength of 828 GPA, a density of 4.42 g/cm^3 and hardness of 396 HV has been used as the work material in the present investigation. Dimensions of the workpiece used for all the experiments have been kept at 90 mm x 500 mm x 10mm.

Cryogenic treated tool made of high carbon steel, high speed steel and stainless steel with straight cylindrical geometry having cross-section diameter 10 mm have been also used in this investigation. Performance of ultrasonic machining of titanium alloy is evaluated on the basis of Material Removal Rate (MRR) and Tool Wear Rate (TWR). Taguchi method has been used to determine optimal machining parameters for maximization of material removal rate and minimization of tool wear in USM.

Fig. 1: Ultrasonic Drilling Machine AP-500 (Sonic Mill, USA)

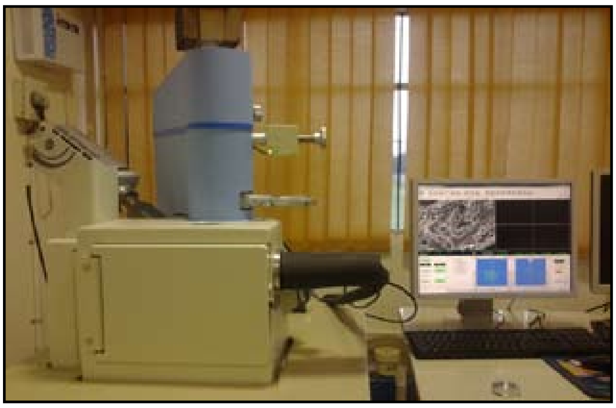

Fig. 2: Scanning Electron Microscope (Model EVO® MA 15) of ZEISS, Germany

The MRR and TWR have been calculated using equation 1 and 2 respectively.

$$MRR = \frac{(W_i - W_f)}{\rho_1 \times t} mm^3 / \min \quad (1)$$

$$TWR = \frac{(T_i - T_f)}{\rho_2 \times t} mm^3 / \min \quad (2)$$

Where;

W_i and W_f = initial and final weight of workpiece (gms);

T_i and T_f = initial and final weight of tool ;

ρ_1= Density of Ti-6Al-4V in gms/mm^3 and

ρ_2= Density of different tools in gms/mm^3 and

t = machining time (min.).

L_{18} (3^5) standard orthogonal array, which has 18 rows according to the amount of experimentation was selected for the present investigation. The process parameters like tool material, abrasives, grit size, slurry concentration and power rating have three levels each, as shown in Table 1. Fig. 2, the Scanning Electron Microscope, (model: EVO® MA 15; make: ZEISS, Germany) has been used to identify the microstructure of the machined surface under the optimal set of process parameters.

Table 1: Process Parameters and Their Values at Different Levels

	Parameters	Level 1	Level 2	Level 3
A	Tool material	HCS	HSS	SS
B	Abrasives	Al_2O_3	B_4C	Al_2O_3 + B_4C
C	Grit size	220	320	500
D	Concentration	20%	25%	30%
E	Power rating	20%	50%	80%

III. Results and Discussions

The experimental results show the effect of process variables on process performance characteristics i.e. MRR and TWR. Table 2 shows the experimental control log as per L18 orthogonal array. Each trial has replicated three times; hence total 54 experiments were performed in an entirely random manner in order to minimize the interference caused by irrelevant process parameters. In Taguchi's design approach, the deviation between the predicted value and the experimental value of performance characteristics is denoted by a loss function which further transformed into a signal to noise ratio.

Table 2: Experimental Control Log as Per L18 Orthogonal Array

Exp. No:	A	B	C	D	E
1	HCS	Al_2O_3	220	20	20
2	HCS	B_4C	320	25	50
3	HCS	Al_2O_3+B_4C	500	30	80
4	HSS	Al_2O_3	220	25	50
5	HSS	B_4C	320	30	80
6	HSS	Al_2O_3+B_4C	500	20	20
7	SS	Al_2O_3	320	20	80

8	SS	B_4C	500	25	20
9	SS	Al_2O_3+B_4C	220	30	50
10	HCS	Al_2O_3	500	30	50
11	HCS	B_4C	220	20	80
12	HCS	Al_2O_3+B_4C	320	25	20
13	HSS	Al_2O_3	320	30	20
14	HSS	B_4C	500	20	50
15	HSS	Al_2O_3+B_4C	220	25	80
16	SS	Al_2O_3	500	25	80
17	SS	B_4C	220	30	20
18	SS	Al_2O_3+B_4C	320	20	50

Here the main purpose of present investigation is the maximization of MRR and for minimization of TWR represents better machining performance; hence the "higher-the-better" type characteristics (equation 3) is selected for MRR and "lower-is-better" type characteristics (equation 4) are selected for TWR to obtain optimal machining performance.

$$\eta_{MRR} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2 \right)$$

$$i = 1,2,.........n \qquad (3)$$

$$\eta_{TWR} = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2} \right)$$

$$i = 1,2,.........n \qquad (4)$$

Where: yi is the experimental result values at the ith observation and n is the number of observations.
Table 3 and 4, the mean value of the three trials is used as response variables for performance characteristics and S/N ratio (dB) is calculated for each trial.

Table 3: Experimental Results for Material Removal Rate (MRR)

Trial	**MRR (mm^3/min)**				
	MRR_1	**MRR_2**	**MRR_3**	**Mean**	**S/N ratio (dB)**
1	0.226	0.228	0.221	0.225	-12.959
2	0.518	0.512	0.492	0.507	-5.901
3	0.411	0.424	0.429	0.421	-7.512
4	0.316	0.341	0.310	0.322	-9.856
5	0.579	0.588	0.556	0.574	-4.824
6	0.416	0.403	0.384	0.401	-7.951
7	0.444	0.414	0.422	0.427	-7.410
8	0.442	0.452	0.488	0.461	-6.756
9	0.599	0.619	0.621	0.613	-4.254
10	0.374	0.389	0.462	0.408	-7.887
11	0.689	0.671	0.708	0.689	-3.238
12	0.282	0.294	0.303	0.293	-10.674
13	0.316	0.303	0.321	0.313	-10.088
14	0.246	0.252	0.282	0.260	-11.746
15	0.559	0.583	0.573	0.572	-4.861
16	0.453	0.413	0.435	0.434	-7.276
17	0.639	0.629	0.649	0.639	-3.892
18	0.639	0.691	0.717	0.682	-3.350

Figure 3 and 4 shows the effects of the process parameters on MRR and TWR respectively. MINITAB 14 software has been used to do the analysis of experiments so that the best optimal set of parameters can be obtained. Figure 3 shows that the maximum MRR was observed when cryogenic treated stainless steel was used as a tool material perform better than other tool materials because of high hardness of stainless steel. If the hardness ratio of tool and work-piece is more, indentation in tool and work-piece increases.

Table 4: Experimental Results for Tool Wear Rate (TWR)

Trial	TWR(mm^3/min)				
	TWR_1	**TWR_2**	**TWR_3**	**Mean**	**S/N ratio (dB)**
1	0.228	0.207	0.216	0.217	13.264
2	0.198	0.203	0.212	0.204	13.790
3	0.185	0.201	0.212	0.199	13.995
4	0.226	0.253	0.231	0.237	12.507
5	0.162	0.153	0.203	0.173	15.187
6	0.221	0.203	0.218	0.214	13.386
7	0.227	0.218	0.204	0.216	13.289
8	0.178	0.186	0.191	0.185	14.653
9	0.123	0.131	0.167	0.140	16.977
10	0.235	0.255	0.223	0.238	12.467
11	0.199	0.183	0.209	0.197	14.098
12	0.215	0.227	0.221	0.221	13.110
13	0.233	0.245	0.255	0.244	12.235
14	0.205	0.189	0.192	0.195	14.179
15	0.245	0.228	0.179	0.217	13.186
16	0.172	0.181	0.193	0.182	14.789
17	0.225	0.224	0.222	0.224	13.008
18	0.219	0.202	0.194	0.205	13.754

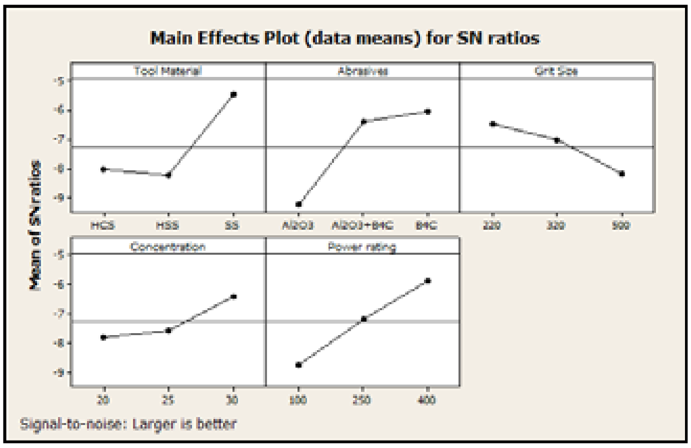

Fig. 3: Effect of Process Parameters on MRR

It can be observed that MRR increases with the increase of hardness of work-piece and cryogenic treated tool material both Indentation due to abrasive grain in the tool and work-piece is inversely proportional to the hardness ratio of tool and work-piece. Because of cryogenic treatment the force of the tool becomes harder, thereby created more impact on abrasive (rather than embedding into the tool force) to create larger penetration depth on work-piece.

It can be observed that the MRR increases with the use of boron carbide as compared to aluminium alloy and silicon carbide as abrasive because of high hardness of grains which results faster destruction of work surface. An increase in the coarseness of the abrasive grain size improves the MRR. The increase of grit size means the coarseness of the abrasive particles reduces. Hence the lower grit size of 220 promotes more efficient machining of titanium based alloy and higher slurry concentration yield higher MRR. Power rating also plays a significant role for higher MRR. Increase in power rating substantially improves the rate of machining.

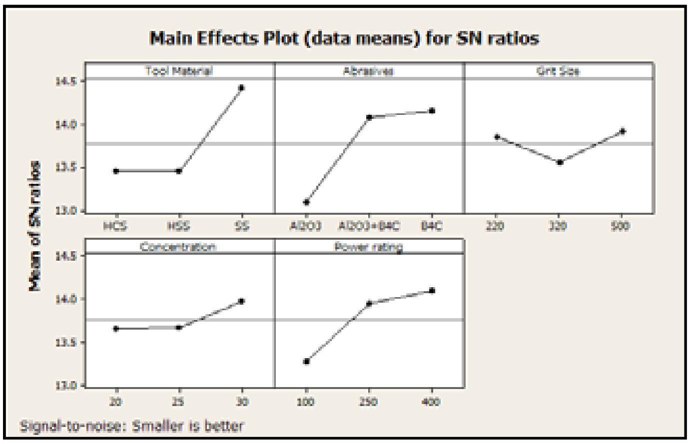

Fig. 4: Effect of Process Parameters on TWR

Fig. 4 shows the parametric effect on TWR. It can be concluded that cryogenic treated SS tool recorded higher significant effect as compared to HCS and HSS tools because of higher hardness. The abrasive (Boron carbide) used for experimentation having 500 grit size makes significant effect on TWR. Due to much finer grains the harder of the tool by cryogenic treatment does not affect tool surface, since the major mode of MRR may be due to grains kinetic energy by nitration of the tool. Thus penetration by abrasive all over the machined surface shows uniformity. The effect of power rating on TWR is similar as on MRR. Higher power rating leads to be higher TWR. With the use of cryogenic treatment of tool, dimensional error while machining has been reduced and improve machining accuracy.

A. Selection of Optimum Levels

Experimental analysis using ANOVA predicts the significant process parameters and to establish the optimal parameter set of combinations for USM of titanium alloy (Ti-6Al-4V). Pooled analysis of variance (ANOVA) for MRR as shown in Table 5, reveals that boron carbide as an abrasive is recognized a higher significant process parameter with an F-value of 19.92 and P-value of 0.00 followed by tool material, power rating and grit size . In the present investigation, higher the better value for MRR is considered for analysis. Hence from fig. 3, it can be observed that maximum MRR was achieved by using tools made up of stainless steel and abrasive is of boron carbide at 3rd level, grit size of 220 at 1st level and a power rating of 400W at 3rd level, so the optimal parameter set of combination for maximum MRR is $A_3B_3C_1E_3$.

Table 5: Pooled ANOVA Results for MRR

	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.196	0.196	0.098	13.37	0.000
B	2	0.292	0.292	0.146	19.92	0.000
C	2	0.115	0.115	0.057	7.90	0.001
E	2	0.155	0.155	0.077	10.62	0.000
Error	45	0.329	0.329	0.0073		
Total	53	1.089				

Based on ANOVA results for TWR shown in Table 6, abrasive used for machining plays a most significant role in the USM of titanium alloy with an F value of 6.76 and a P value of 0.003 followed by tool made up of stainless steel and power rating of 400W is also considered as significant parameters.

Table 6: Pooled ANOVA Results for TWR

	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.0052	0.0052	0.0026	4.94	0.011
B	2	0.0072	0.0072	0.0036	6.76	0.003
E	2	0.0038	0.0038	0.0019	3.58	0.036
Error	47	0.0251	0.0251	0.00053		
Total	53	0.0415				

Lower-the-better value for TWR is considered for analysis during the investigation. From figure 4, it can be concluded that minimum TWR was achieved by using tool material made up of stainless steel, abrasive is of boron carbide and power rating of 400W at 3rd level, so the optimal parameter set of combination for minimum TWR is $A_3B_3E_3$.

B. Estimation of Optimum Response Characteristics

In this section, the optimal values of the response characteristics e.g. MRR and TWR along with their respective confidence intervals have been predicted. Considering the influence of significant parameters, the optimal set of values of each response characteristic is predicted. The estimated mean of the material removal rate is determined utilizing the relation described by [16] and [17-18] as shown in equation (5);

$$\mu_{MRR} = \bar{A}_3 + \bar{B}_3 + \bar{C}_1 + \bar{E}_3 - 3\bar{T} \tag{5}$$

Overall mean of MRR

$$\bar{T} = \left[\sum MRR_1 + \sum MRR_2 + \sum MRR_3\right]/54$$

$$= 0.4579 mm^3/\min$$

Where, MRR_1, MRR_2, and MRR_3 values are taken from the Table 3. The predicted optimal value of MRR is calculated as: μMRR = 0.6121mm³/min. The 95 % confidence intervals of confirmation experiments (CICE) and population (CIPOP) are calculated by using the Equations (6) and (7) as rewritten below for ready reference:

$$CI_{CE} = \sqrt{f_\alpha(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{6}$$

$$CI_{POP} = \sqrt{\frac{f_\alpha(1, f_e)V_e}{n_{eff}}} \tag{7}$$

Where,

$f_\alpha(1, f_e)$ = The F ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e; n_{eff} =6; The N = Total number of experiments =54; R = Sample size for confirmation experiments = 3; V_e = Error variance for MRR = 0.0073 (Table 5); f_e = error DOF = 45 (Table 5); $f_{0.05}$ (1, 45) = 4.06 (Tabulated F value);

So $CI_{CE} = \pm 0.1220$, and $CI_{POP} = \pm 0.0704$

Therefore, the predicted confidence interval for confirmation experiments is:

$Mean\mu_{MRR} - CI_{CE} < \mu_{MRR} < Mean\mu_{MRR} + CI_{CE}$;

$0.4901 < \mu_{MRR} < 0.7341$

The 95% confidence interval of the population is:

$Mean\mu MRR - CI_{POP} < \mu_{MRR} < Mean\mu_{MRR} + CI_{POP}$;

$0.5417 < \mu_{MRR} < 0.6825$

The estimated mean of the tool wear rate is determined by using equation (8);

$$\mu_{TWR} = \bar{A}_3 + \bar{B}_3 + \bar{E}_3 - 2\bar{T} \quad (8)$$

Overall mean of TWR

$$\bar{T} = \left[\sum TWR_1 + \sum TWR_2 + \sum TWR_3\right] / 54$$

$$= 0.2060 mm^3/\min$$

The predicted optimal value of TWR is calculated as: μTWR = 0.1738 mm³/min; n_{eff} = 7.71; V_e = Error variance for TWR = 0.00053 (Table 6); f_e = error DOF = 47 (Table 6); $f_{0.05}$ (1, 47) = 4.05 (Tabulated F value);

So $CI_{CE} = \pm 0.03169$, and $CI_{POP} = \pm 0.01677$

Therefore, the predicted confidence interval for confirmation experiments is:

$Mean\mu_{TWR} - CI_{CE} < \mu_{TWR} < Mean\mu_{TWR} + CI_{CE}$; $0.1421 < \mu_{TWR} < 0.2055$

The 95% confidence interval of the population is:

$Mean\mu_{TWR} - CI_{POP} < \mu_{TWR} < Mean\mu_{TWR} + CI_{POP}$; $0.1570 < \mu_{TWR} < 0.1758$

IV. Confirmation Experiment

In order to validate the predicted response results, three confirmation experiments have been conducted for each of the response characteristics i.e. MRR and TWR at optimal levels of the process variables.

Table 7. Results of Experiments Confirmation for MRR and TWR

Response	Predicted optimal value	Experimental vales	Error
Levels	$A_3B_3C_1E_3$	$A_3B_3C_1E_3$	0.328
MRR (mm^3/min)	---	0.679, 0.695, 0.717	
Average	0.612 mm^3/min	0.697 mm^3/min	
Levels	$A_3B_3E_3$	$A_3B_3E_3$	0.061
TWR (mm^3/min)	---	0.165, 0.171, 0.163	
Average	0.174	0.166	

The average values of the characteristics have been obtained and compared with the predicted values. The results of experiments confirmation for MRR and TWR using the optimal machining parameters are shown in Table 7. The predicted value for MRR and TWR at optimal parameter setting and the experimental average value is validated by confirmation experiment using MINITAB 14 with error of 0.328 and 0.061 respectively.

V. Microstructure Analysis

The microstructure has been studied by the Scanning Electron Micrograph (SEM) at a magnification of 250-X. Fig. 5 depicts the microstructure of the machined surface at optimal parametric combination ($A_3B_3C_1E_3$). The cryogenic treatment of tool indicate much deeper penetration and less irregularity in indentations. Improvement of tool hardness by cryogenic treatment does not affect tool surface, since the major mode of MRR may be due to grain in KE by the nitration of the tool. This penetration by abrasives all over the machined surface shows uniformity and better surface finish.

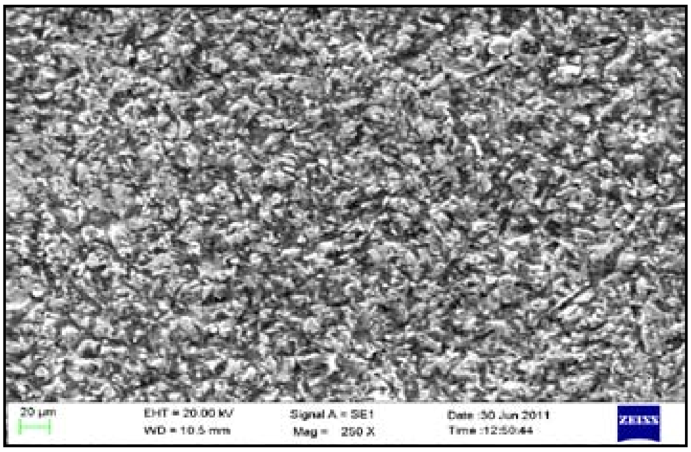

Fig. 6: SEM Micrograph of the Machined Surface

VI. Conclusion

This research work is an effort to find the optimal parametric combination of ultrasonic machining process for MRR and TWR on Ti-6Al-4V alloy with cryogenic treated tool material.

1. Abrasives play a most significant parameter for MRR. MRR increases with the use of boron carbide as compared to aluminium alloy and silicon carbide as abrasive because of high hardness of grains which results faster destruction of work surface.
2. The abrasive (Boron carbide) used for experimentation having 500 grit size makes significant effect on TWR. Due to much finer grains the harder of the tool by cryogenic treatment does not affect tool surface, since the major mode of MRR may be due to grains kinetic energy by nitration of the tool. Thus penetration by abrasive all over the machined surface shows uniformity.
3. The optimal parametric set of combinations for higher MRR is $A_3B_3C_1E_3$ and for minimum TWR is $A_3B_3E_3$.
4. The predicted value for MRR and TWR at optimal parameter setting is 0.612 mm³/min and 0.174 mm³/min respectively and the experimental average value for MRR and TWR at optimal parameter setting is 0.697 mm³/min and 0.166 mm³/min. So the above mathematical prediction for MRR and TWR using MINITAB 14 is validated by confirmation experiment with error 0.328 and 0.061 respectively.

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