

# INVESTIGATION INTO MACHINING CHARACTERISTICS OF TRI-ALUMANE ZIRCONIUM PARTICLE REINFORCEMENT IN METAL MATRIX COMPOSITE USING ULTRASONIC MACHINING PROCESS

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## Abstract

Particle reinforced metal matrix composites (PRMMCs) are the materials that are extremely difficult to machine using conventional manufacturing method due to high tool wear caused by presence of the hard ceramic reinforcement. This paper presents details of an investigation into the machinability of **Tri- Alumane zirconium ( $Al_3Zr$ ), Zirconia ( $ZrO_2$ ) and Silicon carbide ( $SiC$ )** particulate reinforced aluminium alloy matrix using non- conventional machining process such as Ultrasonic Machining (USM). The effect of different input parameters namely power rating, type of abrasive slurry, concentration of abrasive slurry, abrasive grit size and tool material were investigated on response parameters i.e. material removal rate (MRR) and Surface roughness ( $R_a$ ) and significance of input parameters on variation in output responses have been analyzed by using techniques such as ANOVA. Optimization and verification of the process parameters and modelling of results has been done by applying regression analysis. Main effect plot for significant factors and S/N ratio have been used to determine the optimal design for output response. Through various experiments and comparisons with conventional results, the superiority of our novel method is verified. The paper also depicts the type of fracture that might have taken place during machining process with the help of scanning electron microscopy of machined area.

**Keywords:** Aluminium composite, ultrasonic machining, MRR, surface roughness, ANOVA.

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## 1. INTRODUCTION

Particle reinforced metal matrix composites (PRMMCs) represent a group of materials where properties of matrix material like ductility and toughness are combined with hardness, strength and resistance of the reinforcement. Aluminium is most frequently used matrix material due to its low density [2]. Because of their extreme hardness and temperature resistant properties: Tri- Alumane zirconium ( $Al_3Zr$ ), Zirconia ( $ZrO_2$ ) and Silicon carbide ( $SiC$ ) ceramic particles are often used as reinforcement within the Al-matrix. These types of materials are more frequently used in automotive industries, particularly in various engine components as well as brakes. Zirconia ( $ZrO_2$ ) finds its application in dental and surgical operations as well as used in artificial ornaments. However full potential of these materials is hindered by the high manufacturing cost involved mainly because of difficulties in machining these materials. The machining of these materials with conventional methods such as turning, drilling, sawing etc., results in excessive tool wear due to very abrasive nature of these materials. As a consequence non- conventional machining processes such as Ultrasonic machining (USM), Electro discharge machining (EDM) and other techniques

are increasingly being applied for the machining of PRMMCs [2].

## 2. MECHANISM OF ULTRASONIC MACHINING

Ultrasonic machining (USM) is of particular used for the machining of non-conductive, brittle work piece materials such as engineering ceramics. Because the process is non-chemical and non-thermal, materials are not altered either chemically or metallurgically (Thoe, T.B *et al*, 1988). The process is able to effectively machine all materials harder than HRC 40, whether or not the material is an electrical conductor or an insulator (Benedict, G, *et al* 1987). 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. This causes the tool to vibrate along its longitudinal axis at high frequency; usually >20 kHz with an amplitude of 12–50  $\mu m$  (Kennedy and Grieve, 1975; Kremer, 1991). The power ratings range from 50 to 3000 W and a controlled static load is applied to the tool. Abrasive slurry, which is a mixture of abrasive

material; for example, 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 micro-chipping (Moreland, 1984). Fig. 1 shows basic set up for ultrasonic machining.

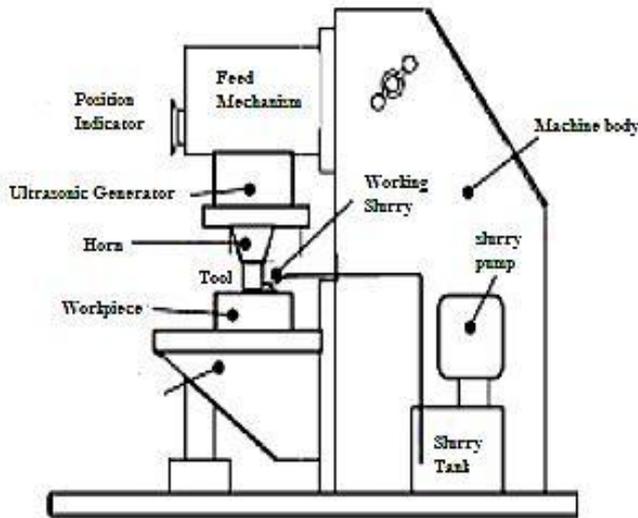


Fig1 Schematic diagram of Ultrasonic machine tool [3]

3. MATERIAL AND METHOD

The metal matrix composite used for investigation were A356/SiC/17p, A356/Al<sub>3</sub>Zr/15p and Al356/ZrO<sub>2</sub>/10p. The first composite consist of Aluminium A356 (0.9% Mg, 0.25 % Cu, 0.25% Fe, 0.2% Zn, 0.05% Mn and remaining Al) reinforced by 17 % Silicon Carbide particles of approximately 11-15 μm in size. The material (A356/SiC/17p) was produced by spray deposition. The second composite was made using A356 and reinforced by 15% Al<sub>3</sub>Zr particle (approximately 14 μm in size). This material (A356/Al<sub>3</sub>Zr/15p) was produced by powder metallurgy involving hot-isostatic pressing [2]. The third composite consisted of A356 and reinforce by 10% ZrO<sub>2</sub> particles (approximately 13 μm in size). The material (Al356/ZrO<sub>2</sub>/10p) was produced through spray deposition method. Flexure strength for three materials is depicted in Table 1.

Table 1 Flexure strength of work pieces

S.NO	Material	Flexural Strength(MPa)
1	Al356/SiC/17p	406
2	Al356/Al <sub>3</sub> Zr/15p	420
3	Al356/ZrO <sub>2</sub> /10p	390

Three types of abrasive materials have been used: Silicon Carbide, Aluminium oxide and Mix (Silicon carbide + Aluminium Oxide). Three different grit sizes have been selected for each abrasive material: 280 (44 micron), 400 (23.6 micron) and 600 (16 microns). Slurry concentrations

30%, 40%, 50% have been used. Power rating was selected another process parameter for investigation. Two levels of power rating were finalized from the pilot experimentation: 40% of 500 W i.e. 200 W and 60% of 500 W that comes out to be 300 W. All the above parameters were selected on the basis of pilot experiments carried out before the start of actual experimentation. The process parameters and their levels selected for final experimentation has been depicted in Table 2.

Table 2 Process parameters and their levels

Factors	Level 1	Level 2	Level 3
Power rating (A)	200	300	-----
Work piece (B)	Al356/Al <sub>3</sub> Zr /15p	Al356/ZrO <sub>2</sub> /10p	Al356/SiC /17p
Slurry type (C)	Al <sub>2</sub> O <sub>3</sub>	SiC	50% (Al <sub>2</sub> O <sub>3</sub> ) + 50% (SiC)
Slurry concen. (D)	30	40	50
Grit size (E)	320	400	600

The orthogonal array (OA) which has been used for this experimentation is L<sub>18</sub>, which has 17 DOF assigned to its various columns.

The experiments were conducted on an ‘AP-500 model Sonic-Mill’ ultrasonic machine (manufacture by SONIC MILLS, Albuquerque, NM). The complete setup is divided into the four sub systems: power supply, Mill module system, slurry re-circulating system and work piece. During experimentation some of the input parameters were kept constant. Table 3 depicts the constant parameters.

Table 3 Fixed Input parameters

Frequency of vibration	21 KHz
Static load	1.63 Kg
Amplitude of vibration	25.6 μm
Depth of cut	2 mm
Thickness of work piece	10 mm
Tool geometry:	Straight cylindrical with dia 8 mm
Slurry temperature:	28°C(ambient room temperature)
Slurry media	Water

The tool used for the experimentation was High Chromium High Carbon Steel (DENSITY: 7.8 gm/cc), a versatile high-carbon, high-chromium, and air-hardened tool steel, with composition: C-2%, Cr-12%, Mo-0.75%, V-0.90%, Si-0.30%, Mn-0.30%.



Fig 2 Tool for Ultrasonic Machine

4. EXPERIMENTATION

The experimental design was according to L<sub>18</sub> array based on Taguchi Design of Experiment approach. Before finalizing a particular orthogonal array for the purpose of designing experiments, the following two things must be established:

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

In the present study, five different process parameters have been selected as already discussed. The power rating factor has two levels whereas all other parameters such as abrasive type, grit size, slurry concentration and work piece have three levels. Hence L<sub>18</sub> (in modified form) has been selected for present investigation. The array L<sub>18</sub> is used because of the reason that it has 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 main effect of the various parameters is minimized.

Each trial was carried out twice. The slurry was maintained at fixed flow rate. To avoid dullness of the edges of abrasive grains, a large volume of slurry was prepared before start of experimentation. Table 4 shows the total number of trials to be carried out along with arrangement of various parameters and their levels according to L<sub>18</sub> orthogonal array.

Table 4 L<sub>18</sub> orthogonal array for experimentation

Trial No	Power Rating (W)	Work piece	Type of slurry	Slurry concentration (%)	Grit size
1	200	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub>	30	320
2	200	Al-Al <sub>3</sub> Zr	SiC	40	400
3	200	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub> +SiC	50	600
4	200	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	30	400
5	200	Al-ZrO <sub>2</sub>	SiC	40	600
6	200	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> +SiC	50	320
7	200	Al-SiC	Al <sub>2</sub> O <sub>3</sub>	40	320
8	200	Al-SiC	SiC	50	400
9	200	Al-SiC	Al <sub>2</sub> O <sub>3</sub> +SiC	30	600
10	300	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub>	50	600
11	300	Al-Al <sub>3</sub> Zr	SiC	30	320
12	300	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub> +SiC	40	400
13	300	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	40	600
14	300	Al-ZrO <sub>2</sub>	SiC	50	320
15	300	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> +SiC	30	400
16	300	Al-SiC	Al <sub>2</sub> O <sub>3</sub>	50	400
17	300	Al-SiC	SiC	30	600
18	300	Al-SiC	Al <sub>2</sub> O <sub>3</sub> +SiC	40	320

4.2 Analysis of Variance (Anova)

The percent contribution of various process parameters on the selected performance characteristic can be calculated using ANOVA. Hence it depicts the information about the

significance of the effect of each controlled parameter on the quality characteristic of interest for given experiment.

### 4.2 Main Effect due to Parameter

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 data and/or S/N ratio data at each level of each parameter and plotting the values in graphical form. The level average response from the raw data helps in analyzing the trend of the performance characteristic with respect to variation of the factor under study. The level average response plots based on the S/N ratio data help in optimizing the objective function under consideration. The peak points of these plots correspond to the optimum condition.

### 4.3 Evaluation of S/N Ratio

The S/N ratio stand for signal to noise ratio obtained using Taguchi 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.

## 5. RESULTS AND DISCUSSION

The 18 experimental runs were completely randomized to minimize the effect noise factor and error. The result obtained for Material Removal Rate and Surface Roughness has been indicated in Table 5. All the values indicated are average of three samples for each run as each experiment was replicated twice

**Table 5** Result for MRR and SR

Trial No	Power Rating (W)	Work piece	Type of slurry	Slurry concentration (%)	Grit size	MRR (mg/min)	SR (microns)
1	200	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub>	30	320	10.4850	0.89
2	200	Al-Al <sub>3</sub> Zr	SiC	40	400	10.6362	0.68
3	200	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub> +SiC	50	600	10.6654	0.75
4	200	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	30	400	10.6127	0.81
5	200	Al-ZrO <sub>2</sub>	SiC	40	600	10.6749	0.56
6	200	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> +SiC	50	320	11.2964	0.86
7	200	Al-SiC	Al <sub>2</sub> O <sub>3</sub>	40	320	10.3183	0.75
8	200	Al-SiC	SiC	50	400	10.9993	0.52
9	200	Al-SiC	Al <sub>2</sub> O <sub>3</sub> +SiC	30	600	10.4233	0.71
10	300	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub>	50	600	10.2611	1.16
11	300	Al-Al <sub>3</sub> Zr	SiC	30	320	11.2612	1.06
12	300	Al-Al <sub>3</sub> Zr	Al <sub>2</sub> O <sub>3</sub> +SiC	40	400	11.4554	1.25
13	300	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	40	600	10.5564	1.13
14	300	Al-ZrO <sub>2</sub>	SiC	50	320	11.6192	0.91
15	300	Al-ZrO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub> +SiC	30	400	11.2565	1.91
16	300	Al-SiC	Al <sub>2</sub> O <sub>3</sub>	50	400	10.2914	0.91
17	300	Al-SiC	SiC	30	600	10.9265	0.88
18	300	Al-SiC	Al <sub>2</sub> O <sub>3</sub> +SiC	40	320	11.5842	1.18

### 5.1 Material Removal Rate (MRR)

The effect of parameters i.e. power rating, work piece, type of abrasive, slurry concentration, grit size can be evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each 18 runs was completed to measure the Signal to Noise Ratio (S/N ratio). MRR is calculated from the loss of weight of work piece during performance trial.

$$MRR = \frac{(w_i - w_f)}{\rho \times t} \times 1000 \text{ mm}^3/\text{min}$$

Where,

w<sub>i</sub> = initial weight of work piece material (grams)

w<sub>f</sub> = final weight of work piece material (grams)

t = time period of trials in minutes

ρ = density of work-piece (gm/cc)

The variance data for each factor and their interaction were F-test to find significance of each factor. ANOVA table shows that the Power rating (F value 17.39), type of abrasive (F value 27.69), grit size (F value 12.77) are the factors that were found significant and affects MRR. The interactions within factors were not considered in the study. It is observed that type of slurry used in the experiment was most significant factor which contributed to MRR, followed by Grit size of abrasive and power rating. Work piece used and slurry concentration had negligible effect.

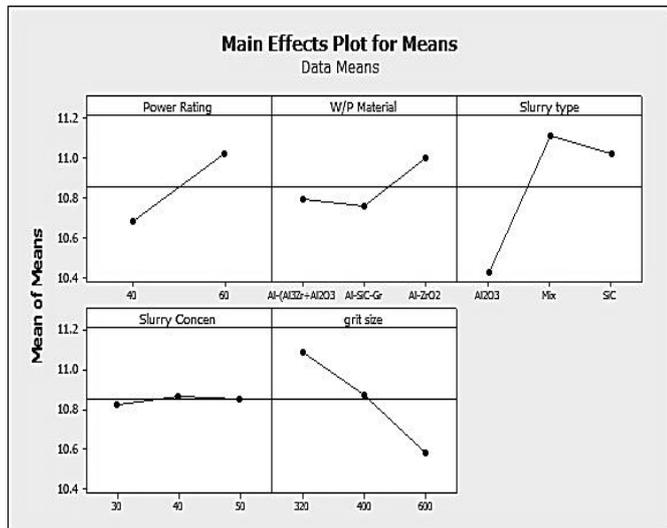


Fig3 Main effect of MRR for means

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the MRR. MRR is Higher is better type response which is given by:

$$(S/N)_{HB} = -10 \log_{10} (MSD_{HB})$$

Where, MSD is Mean Square Deviation for Higher the better response

$$MSD_{HB} = \frac{1}{r} \sum_{i=1}^r \left( \frac{1}{y_i^2} \right)$$

ANOVA S/N ration for MRR at 95% confidence interval shows that Type of abrasive slurry (F value 9.70) is most significant factor in affecting MR according to F-test. It is observed that type of slurry used in the experiment was most significant factor which contributed to MRR, followed by Grit size of abrasive and power rating. Work piece used and slurry concentration had negligible effect.

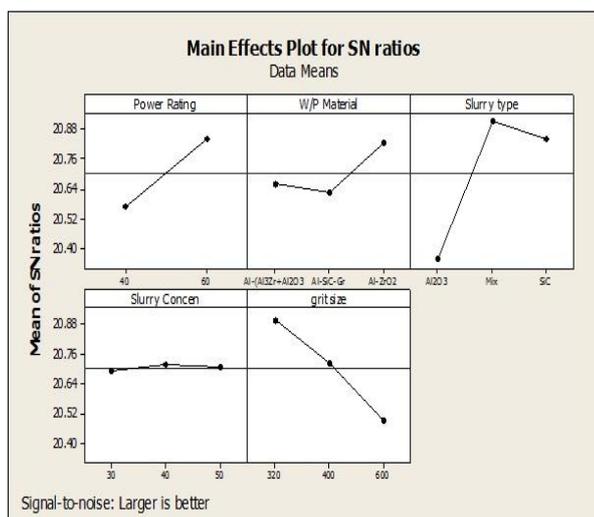


Fig4. Main effect of MRR for S/N ratio

The confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence. The estimate of mean  $\mu$  is only a point based on the average of result obtained from the experiment. Confidence interval around the estimated Mean

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}}$$

Where,  $F_{\alpha, v_1, v_2} = F$  - ratio

$\alpha =$  risk (0.05)

confidence =  $1 - \alpha$

$v_1 =$  DOF for mean which is always = 1

$v_2 =$  DOF for error =  $v_e$

CI around the MRR comes out to be  $11.528 \pm 0.345$  mm<sup>3</sup>/min

Surface Roughness (SR)

The effect of parameters i.e. power rating, work piece, type of abrasive, slurry concentration, grit size can be evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each 18 runs was completed to measure the Signal to Noise Ratio (S/N ratio). Surface Roughness (Ra) is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement. It is a 'Lower is Better' phenomena. Surface Roughness was measured using the Perthometer.

The variance data for each factor and their interaction were F-test to find significance of each factor. ANOVA table shows that the power rating (F value 571.1), type of abrasive (F value 84.59), work piece used (F value 26.51), grit size (F value 8.91) and concentration of slurry (F value 8.32) are significant factor that affect Surface Roughness. The interactions within the factors were not considered for the study.

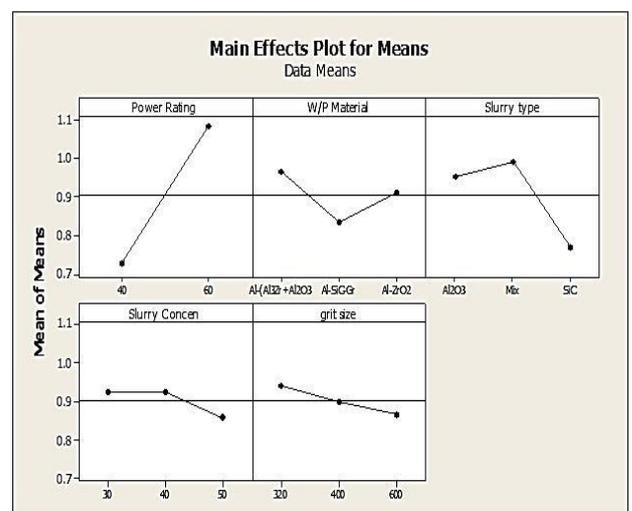


Fig5. Main effect of SR for means

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in

the SR. SR is Lower is better type response which is given by:

$$(S/N)_{LB} = -10 \log (MSD_{LB})$$

Where, MSD is Mean Square Deviation for Lower the better response

$$MSD_{LB} = \frac{1}{r} \sum_{i=1}^r (y_i^2)$$

ANOVA S/N ration for SR at 95% confidence interval shows that power rating (F value 1025.5), is most significant factor in affecting SR according to F-test. Type of abrasive (F value 171.113), work piece used (F value 50.339), Grit size (F value 25.527), concentration of slurry (F value 15.783). Interactions within the factors were not considered for the study. Figure 5 shows the graphical representation of effect of various parameters in surface roughness

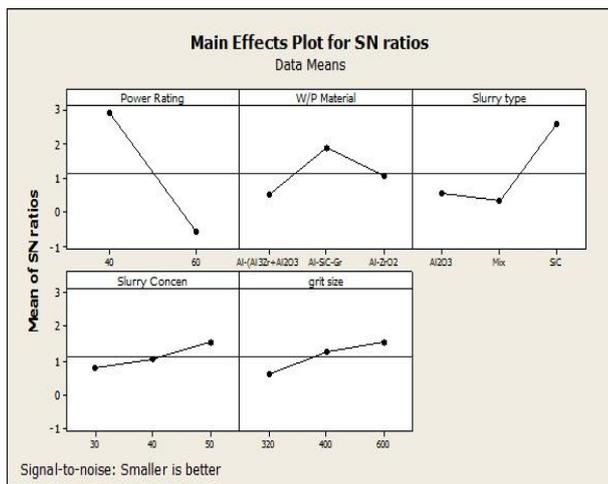


Fig-6 Main effect of SR for S/N

It is observed that type of Power rating was most significant factor which contributed to SR, followed by Slurry type and Work piece, grit size and slurry concentration.

Interactions within the factors were not considered for the study. Figure 5 shows the graphical representation of effect of various parameters in surface roughness

The confidence interval is a maximum and minimum value between which the true average should fall at some stated percentage of confidence. The estimate of mean  $\mu$  is only a point based on the average of result obtained from the experiment. Confidence interval around the estimated Mean

$$CI_1 = \sqrt{\frac{F_{\alpha, v_1, v_2} V_e}{n_{eff}}}$$

Where,  $F_{\alpha, v_1, v_2}$  = F – ratio

$\alpha$  = risk (0.05) confidence = 1- $\alpha$

$v_1$  = DOF for mean which is always =1

$v_2$  = DOF for error =  $v_e$

CI around the MRR is given by  $0.28556 \pm 0.0895 \mu\text{m}$

## 6. MICRO STRUCTURE ANALYSIS

The microstructure of the machined surface was obtained for randomly selected 3 trial machined sample by using scanning electron microscope at a magnification level 1000x. The microstructure of each machined sample at other magnifications was also obtained in order to perform a detailed study of the machined surface.

The samples were prepared for SEM analysis:

Firstly, Samples were cut to round shape with 9 mm diameter and 4 mm thickness with flat base. After that machine surface was cleaned with wire brush, clean them with acetone and ultrasonic gel in order to remove dust particle.

Figure 6 depicts the microstructure of work piece Al-Al<sub>3</sub>Zr after machining with USM under the experimental conditions corresponding to experiment no. 1.

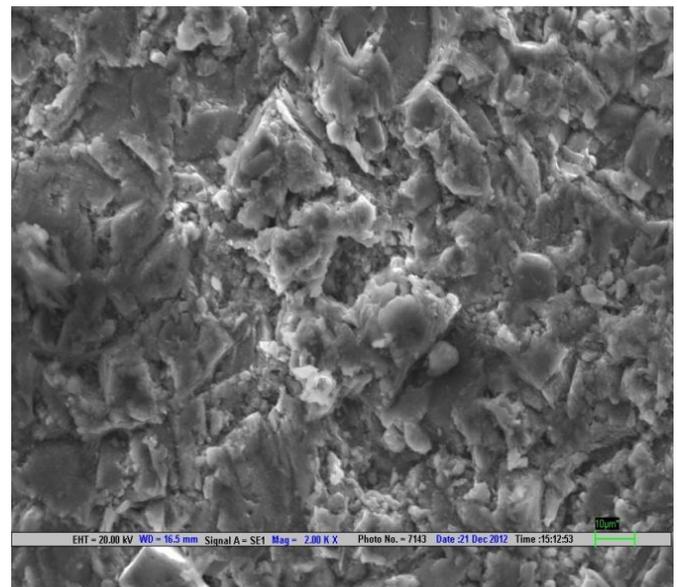
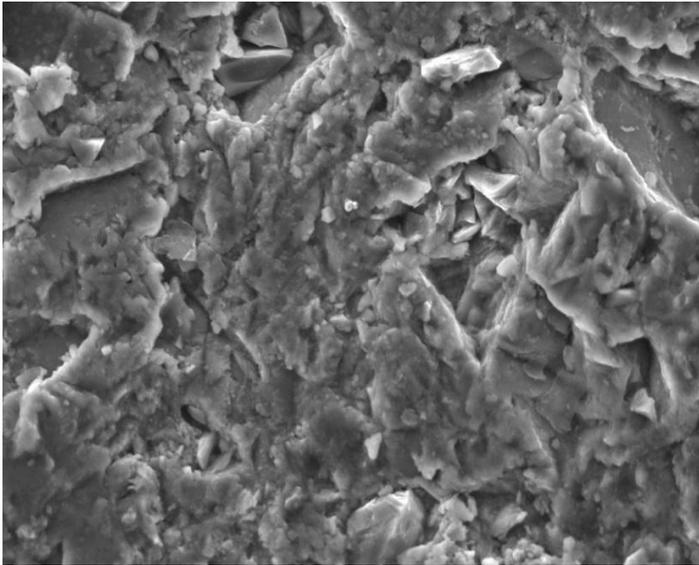


Fig7. Microstructure for trial 1

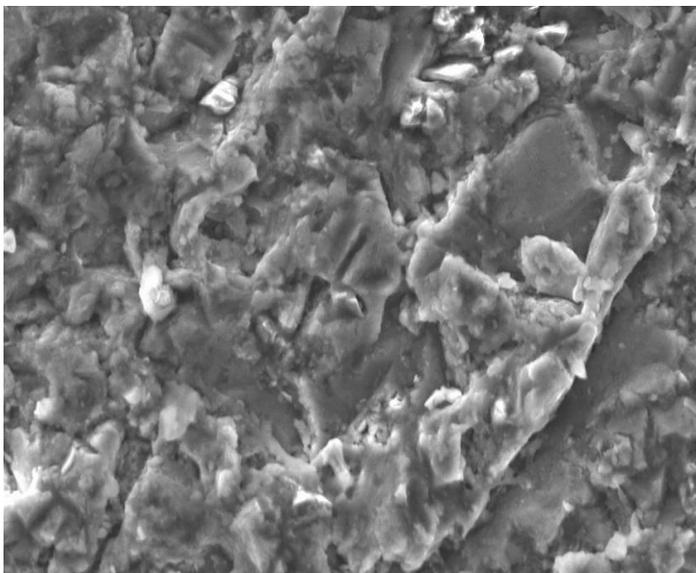
Material faced significant amount of plastic deformation before failure and there is no evidence of brittle fracture. Hence, the material was machined by ductile failure of the work material. This could be attributed to the extremely low energy input into the abrasive as the experimental conditions involved use of a softer abrasive (Al<sub>2</sub>O<sub>3</sub>) with low power rating (40%) with concentration 30% and grit size 320. The work piece material used Al-Al<sub>3</sub>Zr. Also, the high fracture toughness associated with the work material has contributed towards the increment in the hardness of the work surface due to work hardening.



**Fig8.** Microstructure of Trial 8

The microstructure of Al-SiC after machining with USM under the experimental conditions corresponding to experiment no. 8 at magnification levels of 2000 X. The process settings include silicon carbide slurry with grit size 400 with 50% concentration and power rating 40%. It can be observed from figure 7 that the cleavage type of fracture took place. The increase in the surface hardness is moderately high because of a longer machining time required as the machining rate observed was quite low.

Figure 8 shows the microstructure of Al-ZrO<sub>2</sub> after machining with USM under the conditions corresponding to experiment no. 13 at magnification levels of 2000 X. Purely brittle fracture is observed as the parameter settings indicate a moderate to high level of energy input into the work. The input parameters settings for this trail include Al<sub>2</sub>O<sub>3</sub> as abrasive slurry with a medium grit size (600) and concentration 40%. Power rating used was (60%).



**Fig9.** Microstructure for trial 13

## 7. CONCLUSIONS

1. The rate of material removal depends on the type of abrasive slurry, power rating and grit size.
2. The surface roughness depends on the power rating, slurry type, slurry concentration grit size and work-piece.
3. The observation depicts that power rating, type of slurry and grit size greatly affects the material removal rate and surface roughness.
4. It is also observed that metal removal takes place through cleavage fracture and brittle fracture in case of abrasive type SiC and ductile fracture in case of Al<sub>2</sub>O<sub>3</sub> as abrasive type..

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