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Performance Evaluation of Diamond Grits during Precision Surface Grinding of Silicon Carbide

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ABSTRACT
The excellent material properties of silicon carbide (SiC), such as extreme hardness, high durability, high wear resistance and light weight, have caused a wide range of industrial applications of this material. Among the engineering applications of this material, it is an excellent candidate for optic mirrors used in an Airbone Laser (ABL) device. However, the brittleness and low fracture toughness characteristics of the SiC are predominant factors for its poor machinability. This paper presents surface grinding of SiC using resin bonded diamond abrasive cup wheels to assess the cutting performance of diamond grits on the roughness and morphology of the ground work-pieces. The wheel grits of grit 46 μm, 76 μm and 107 μm were used. The parameters employed during the machining investigation are depth of cut between 10 - 30 μm and feed rate between 2 - 22 mm/min. It is observed that the 76 μm grit performs better in terms of low surface roughness value and minimal fractured surface morphology.

Keywords: Silicon carbide, surface grinding, cup wheel, diamond grits, surface roughness and morphology.

1 INTRODUCTION

Silicon carbide (SiC) material had long been introduced in into the precision manufacturing industries in the mid-1990s due to its potential industrial applications although the material has been around since 1891. The material is well known for its material properties like extreme hardness, high durability, high wear resistance and light weight. According to Ravindra, et al. [1], SiC being one of the advanced engineered ceramics, was designed to operate in extreme environments. Also, it had been revealed by [2, 3] that SiC had been employed as a coating and structural material due to its unique properties which are not limited to the larger energy bandgap and breakdown field allowing of the material to be used in high temperature, high-power and radiation-hard environments, its mechanical stiffness expressed by high Young's modulus and the material's tribology properties such as wear resistance and self-lubricating. Silicon carbide is an excellent candidate for optic mirrors used in an Airbone Laser (ABL) device. Despite the salient properties of this SiC material, it is nevertheless noted for its low fracture toughness and extreme brittleness which result into its poor machinability.

Based on the author's [4, 5] machining research experience, it has been observed that hard and brittle like semiconductors, ceramics and glasses are problematic especially when it comes to machining. However, the authors' [4, 5] research works have demonstrated that when attempting to machine ceramic like SiC to improve the surface finish, a 'damage free' machining operation often through ductile mode machining (DMM) is possible. Ductile mode machining is a process of machining a nominally hard and brittle material such that the materials as if it is ductile material. Such a material removal process can be considered in terms of fracture dominated mechanisms or localized plastic deformation. A fracture (brittle fracture) dominant mechanism for ceramics can result in poor surface quality and also deteriorates the material properties and performance [6].

Grinding research conducted on brittle materials by Bifano et al. [7] revealed that two types of material removal mechanisms are associated with the machining processes, ductile machining in which plastic flow of material in the form of severely sheared machining chips occurs and brittle machining where material removal is through crack propagation. Several physical parameters that influence the ductile to brittle transition in grinding of brittle materials are discussed machining literature. Some successes have been reported on ductile mode grinding of

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brittle materials but neither a machining model was not proposed nor a suitable explanation for the origin of ductile regime machining was confirmed until Bifano showed up. Bifano et al. [7] proposed a model defining the ductile to brittle transition of a nominally brittle material based on the material's brittle fracture properties and characteristics. They introduced a critical depth of cut model based on Griffith fracture propagation criteria, hence the expression for the critical depth of cut (d_c) which follows:

$$d_c = (E \,.\, R) / H^2 \quad (1)$$

where E is the elastic modulus, H the hardness and R the fracture energy. The value of the fracture energy (R) can be evaluated using the relation:

$$R \sim Kc^2 / H \quad (2)$$

where K_c is the fracture toughness of the material. The combination of equations (1) and (2) represents the critical depth (d_c) which is a measure of the brittle to ductile transition depth of cut:

$$d_c \sim (E / H) \,.\, (K_c / H)^2 \quad (3)$$

The researchers successfully determined a correlation between the calculated critical depth of cut and the measured depth generally considered as the grinding infeed rate. The constant of proportionality was estimated as to be 0.15. This constant when introduced in equation (3) resulted into more accurate empirical equation (4):

$$d_c \sim 0.15 \, (E / H) \, (K_c / H)^2 \quad (4)$$

Equation 4 gives an insight into how a depth of cut is critical in machining brittle materials, considering the material properties and characteristics. This paper presents surface grinding of silicon carbide using diamond cup wheels to assess the performance of diamond grits with respect to the surface roughness generated on the machined surface and also the morphology ground work-piece.

2 EXPERIMENTAL DETAILS

2.1 Work and Tool Materials

The dimensions of the Silicon Carbide (SiC) workpiece used in this research work are samples of 20 mm x 20 mm x 10 mm. There were glued in specially fabricated fixtures made of aluminum as shown in Figure 1. The cutting tools chosen for this study are resin bonded diamond cup wheels (Figure 2) of different grain sizes. The experimental conditions are shown in Table 1.

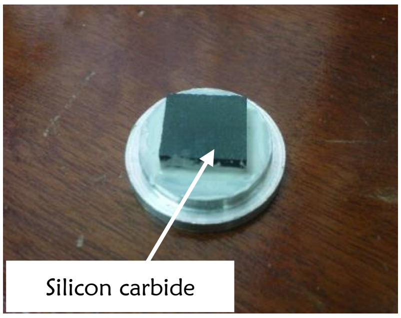

Figure 1: Silicon Carbide work-piece glued on an aluminum fixture.

Figure 2: Diamond cup wheel 75 x 10 x 3 x 16mm bore

Table 1: Experimental condition and variables

Workpiece	Silicon Carbide (SiC) (20mm x 20mm x 10mm)
Tool material	Diamond cup wheel 75 x 10 x 3 x 16mm Bore
Grain size, *A*, (µm)	46, 76, 107
Depth of cut, *B*, (µm)	10, 20, 30
Feed rate, *C*, (mm/min)	2.0, 12.0, 22.0

2.2 Experimental Setup and Procedure

The setup for the machining experiments on a 3-axis vertical NC Deckel Maho (DMU) machine, which maximum rotational speed of 6300 rpm, is depicted in Figure 3. A total of 17 trial runs (Table 2) were carried out based on Box-Behnken design of experiments. Surface roughness measurements were done on a Mitutoyo Surftest SV-500 surface tester, Figure 4. A 0.8 mm cut-off length was used and average roughness readings were noted. Scanning electron microscopy technique was used to examine the surface morphology of the ground silicon surfaces.

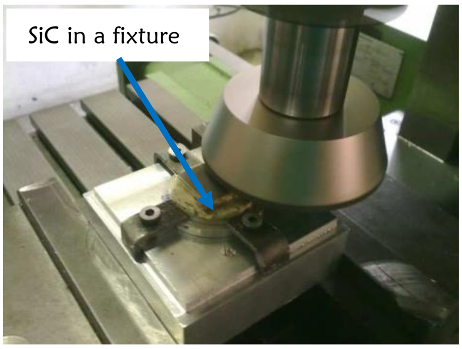

Figure 3: Experimental setup of the work-piece on DMU 35M Deckel Maho milling Machine.

Figure 4: Mitutoyo Surftest SV-500 machine on which, surface roughness was measured.

3 RESULTS AND DISCUSSION

3.1 Discussion of Surface Roughness Results

Box-Behnken experiment design was used to study the relationship between grinding parameters and the response roughness variable (R_a). Table 2 shows the surface roughness (R_a) results obtained based on Box-Behnken experimental design with three center points. Analysis of variance (ANOVA), Table 3, was done to verify the adequacy of the developed models. The main and interaction effects of the grinding parameters on the response parameters have been established. From Table 3, it is observed that interaction AB between parameters A (grit size) and B (depth of cut) virtually has no effect on the response variable, hence model reduction was necessary. The reduced ANOVA is shown in Table 4.

From the reduced ANOVA Table 4, it can be seen that the Model F-value of 10.94 implies the model is significant. On statistical basis, there is only a 0.14% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant and values greater than 0.1000 indicate the model terms are not significant. In this case A, B, A^2, B^2, C^2, AC, BC are significant model terms. The "Lack of Fit F-value" of 1.88 implies the Lack of Fit is not significant relative to the pure error and there is a 27.88% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is desired as we want the model to fit. The normal plot of residuals (Figure 5) and the oulier plot (Figure 6) reveal no problem with the trial runs.

Table 2: Box-Behnken designs showing trial runs and response variable R_a.

Std	Run	Factor A: Grit size (μm)	Factor B: depth of cut (μm)	Factor C: Feed rate (mm/min)	Response surface roughness (μm)
13	1	76.50	20.00	12.00	0.17
16	2	76.50	20.00	12.00	0.17
02	3	107.00	10.00	12.00	0.13
01	4	46.00	10.00	12.00	0.16
14	5	76.50	20.00	12.00	0.16
13	6	46.00	30.00	12.00	0.15
04	7	107.00	30.00	12.00	0.12
07	8	46.00	20.00	22.00	0.12
11	9	76.50	10.00	22.00	0.16
10	10	76.50	30.00	2.00	0.13
8	11	107.00	20.00	22.00	0.14
15	12	76.50	20.00	12.00	0.18
17	13	76.50	20.00	12.00	0.18
09	14	76.50	10.00	2.00	0.13
05	15	46.00	20.00	2.00	0.14
12	16	76.50	30.00	22.00	0.10
06	17	107.00	20.00	2.00	0.11

Table 3: ANOVA for Response R_a

ANOVA for Response Surface Quadratic Model [Partial sum of squares]							
Source		Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model		8.807E-003	9	9.78SE-004	8.51	0.0050	Significant
	A	6.125E-004	1	6.725E-004	5.33	0 0544	
	B	8.000E-004	1	8.000E-004	6.96	0.0335	
	C	1.250E-005	1	1.250E-005	0.11	0.7513	
	A^2	1 253E-003	1	1.253E-003	10.89	0.0131	
	B^2	9.161E-004	1	9.161E-004	7.97	0.0257	
	C^2	3.127E-003	1	3.127E-003	27.19	0 0012	
	AB	0 000	1	0 000	0 000	1.0000	
	AC	6.250E-004	1	6.250E-004	5.43	0 0525	
	BC	9 000E-004	1	9.000E-004	7.83	0 0266	
Residual		8.050E-004	7	1.1506-004			
	Lack of fit	5 250E-004	3	1.750E-004	2.50	0 985	Not significant
	Pure error	2.800E-004	4	7.000E-005			
Cor Total		9.612E-003	16				

Table 4: Reduced ANOVA for Response R_a

ANOVA for Response Surface Reduced Quadratic Model [Partial sum of squares]							
Source		Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model		8.807E-003	8	1.101E-004	10.94	0.0014	Significant
	A	6.125E-004	1	6.125E-004	6.09	0 0389	
	B	8.000E-004	1	8.000E-004	7.95	0.0225	
	C	1.250E-005	1	1.250E-005	0.12	0.7336	
	A^2	1 253E-003	1	1.253E-003	12.45	0.0077	
	B^2	9.161E-004	1	9.161E-004	9.10	0.0166	
	C^2	3.127E-003	1	3.127E-003	31.07	0 0005	
	AC	6.250E-004	1	6.250E-004	6.21	0 0374	
	BC	9 000E-004	1	9.000E-004	8.94	0 0173	
Residual		8.050E-004	8	1.006-004			
	Lack of fit	5 250E-004	4	1.313E-004	1.88	0 2788	Not significant
	Pure error	2.800E-004	4	7.000E-005			
Cor Total		9.612E-003	16				

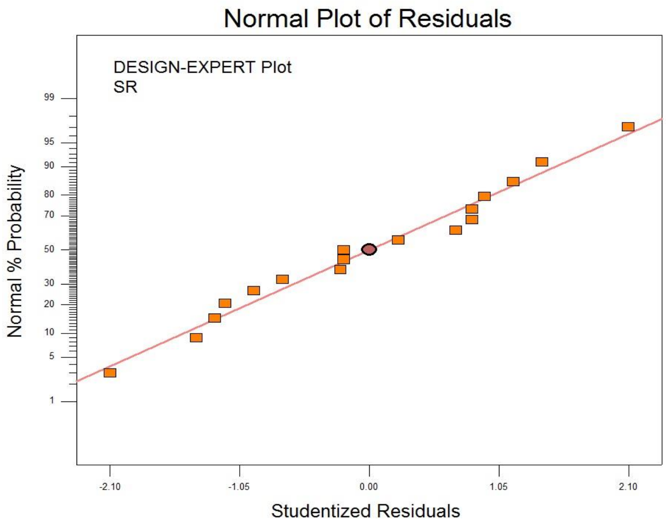

Figure 5: The normal plot of residuals

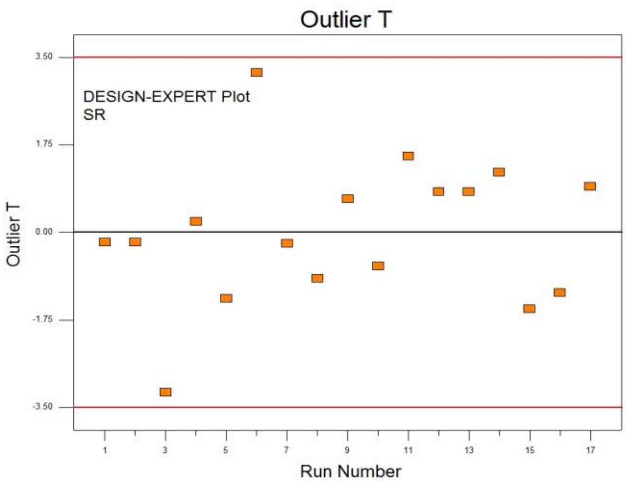

Figure 6: The outlier plot indicating the trial runs are within range.

A mathematical model represented by equation (5), was proposed to relate the response variable (R_a) and the grinding parameters. Thus,

$$R_a = \phi(A, B, C) \quad (5)$$

where R_a is the surface roughness; ϕ the response function, A, the diamond grit size, B, the depth of cut and, **C**, the feed rate. Second order model (equation (5)) was observed the most suitable to relate surface roughness and the grinding parameters. The procedure for establishing a second order model is well detailed out in Alao's [8] work. The model equation 6 has been developed based on the results obtained in this study.

$$R_a = +0.17 - 0.008750A - 0.010B + 0.001250C - 0.017A^2 - 0.015B^2 - 0.027C^2 + 0.012AC - 0.015BC \quad (6)$$

Verification of the adequacy of the model is shown in the ANOVA Table 4 where the Model F-value of 10.94 implying the model is significant. The Model Graphs Figure 7 shows the individual effects of the process grinding paprameters. From this plots, it can be seen that to get better (lower) surface roughness, it better to incresae the depth of cut (B) and use higher grit size (A). Figures 8 and 10 illustrate the 2D interaction effects of the process variables, the corresponding 3D interaction effects are depicted in Figure 9 and 11 respectively.

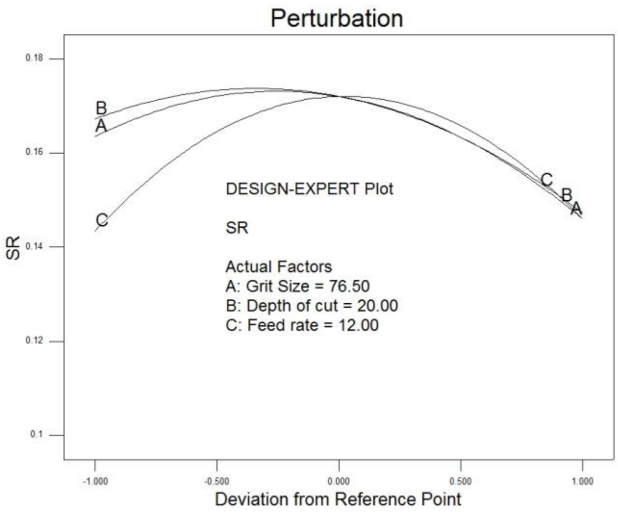

Figure 7: Individual effects of the process variables.

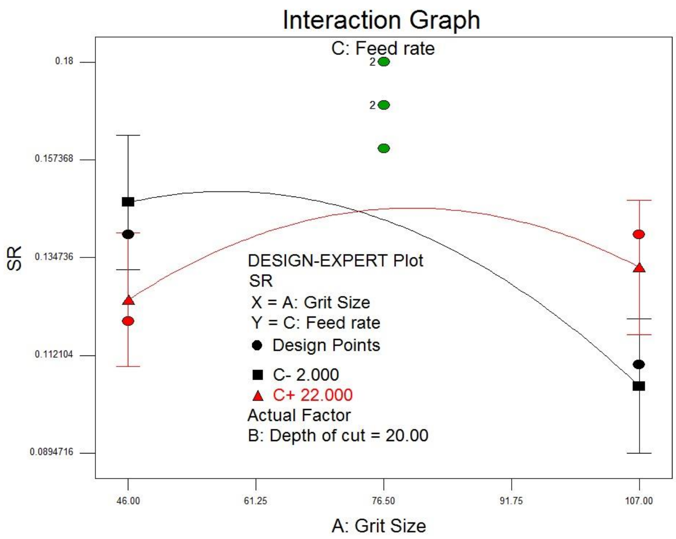

Figure 8: The interaction effect of feed rate and grit size.

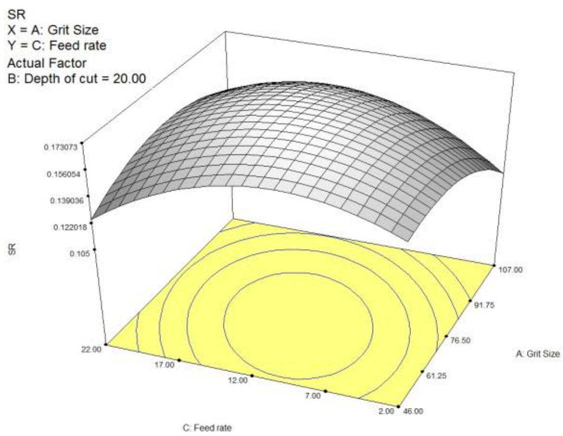

Figure 9: The 3D plot of the interaction effect of feed rate and grit size.

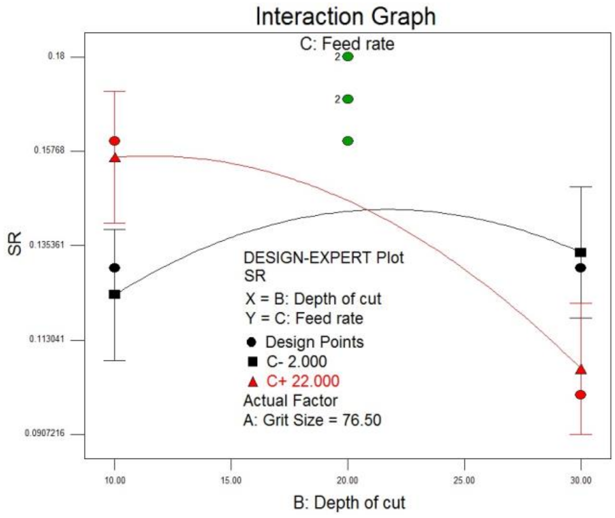

Figure 10: The interaction effect of feed rate and depth of cut.

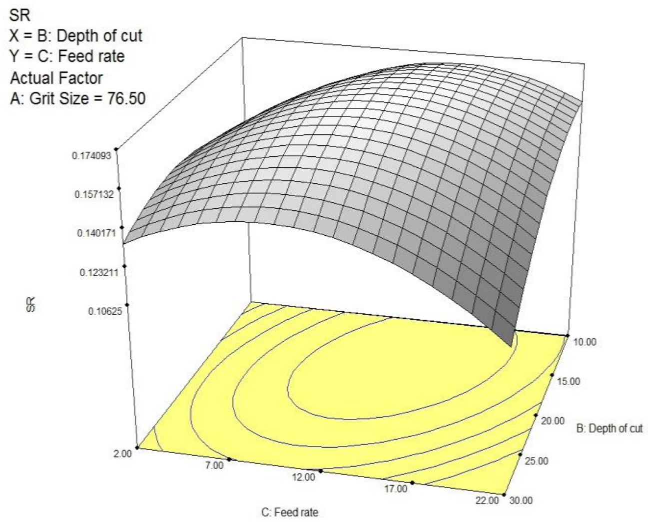

Figure 11: The 3D plot of the interaction effect of feed rate and depth of cut.

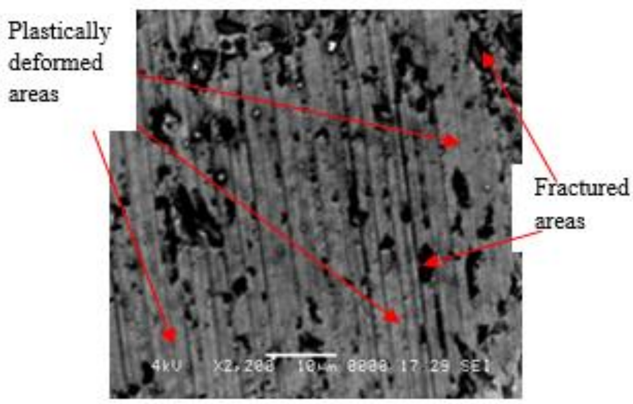

Figure 12: Scanning Electron Microscopic image for trial run 16 in Table 2: grit size = 76 μm, depth of cut = 30 μm an 22 mm/min showing large areas of plastically deformed surface.

3.2 Discussion of Surface Morphology Results

Scanning Electron Microscopy examination of the surface corresponding to a trial condition 16 in Table 2: grit size = 76 μm, depth of cut = 30 μm an 22 mm/min, shows considerably large areas of the surface that have been plastically deformed, Figure 12. Macro-fractures are also evident at the ground surface.

4 CONCLUSION

For the surface grinding experimental investigations conducted using resin bonded diamond cup wheels of three grits 46 μm, 76 μm and 107 μm; depth of cut of 10 μm, 20 μm and 30 μm; and feed rate of 2 mm/min, 12 mm/min and 22 mm/min, the following can be concluded.

- It has been observed that the 76 grit performs better in terms of low surface roughness value and this is evident in Table 2, run 16 where the roughness value R_a = 0.10 μm.
- A mathematical model has been developed for predicting surface roughness values within the limits of the machining parameters that has been tested.
- It has also been observed that the ground surfaces consist of large plastically deformed areas and small areas of fractured surfaces.

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