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Application of Nano-Laminar Solid Lubricants in Silicon Nitride Ceramics Grinding

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Abstract

This work discusses the use of nano-laminar solid lubricants in minimum quantity lubrication (MQL) during grinding of silicon nitride by diamond wheel. Nanoparticles of MoS_2 and graphite were mixed in the carrier media (Deionized water) using probe sonicator. Face-centered cubic (FCC) design of experiment has been used to study the grinding characteristics at varying wheel speed, feed rate and depth of cut . The results of the nano MQL conditions were compared with the dry condition and it has been found that laminar solid lubricants significantly reduced the grinding forces, and enhanced the surface quality. The ground surfaces have been also analyzed using scanning electron microscope (SEM). Regression model has been developed to predict the forces. ANOVA has been performed to check the efficacy of the model and the model has been found to be adequate.

Keywords: Grinding, Silicon nitride, nanofluid, ANOVA

1. INTRODUCTION

Silicon nitride ceramics have high strength, good wear resistance, high thermal shock resistance and chemical inertness, etc. Due to these attractive properties, silicon nitride has been widely used in aerospace, automotive, chemical industries and other fields [1-6]. Grinding with super-hard abrasives is the conventional material removal process for machining of silicon nitride and other ceramics to achieve the desired tolerances and surface integrity. However, the penetration of cutting tool in ceramics is difficult due to the high degree of hardness and brittleness which leads to increase in tool wear, deteriorates the surface quality and reduces the strength of the machined component[2, 7-9]. During ceramic grinding, the friction between the wheel and the workpiece generate heat in the contact zone and therefore lead to wheel abrasive dulling. Many researchers have made efforts to enhance the machinability and grindability of ceramics by high-speed grinding [8], optimizing machining parameters [9, 10], developing new machining coolants and lubricants [11]. Hwang et al. [8] investigated the grinding performance of ceramics at high speed and found that the grinding performance can be enhanced by reducing the depth of cut and increasing wheel speed. Agarwal [9] optimized the grinding parameters for silicon carbide and indicated that feed rate, depth of cut, grit density and grit size were the major influencing factors for better surface integrity in the ground products. From the literature, it can be concluded that development of new machining coolants and lubricants are required to overcome the adverse effect of heat and friction in the grinding zone. The application of nano-sized laminar solid lubricants in minimum quantity lubrication (MQL) mode helps in reduction of friction and heat between the wheel and workpiece [12, 13]. Emami et al. [11] studied the effect of different types of lubricants on cutting forces, surface roughness and specific energy during near dry (MQL) grinding of Al_2O_3 ceramic. The study revealed that the lubrication technique has more influence on surface roughness as compared to grinding forces and specific energy. Alberts et al. [12] studied the effect of graphite nanoplatelets during surface grinding of hardened D-2 tool steel and concluded that the smaller size nanoplatelets were more effective in reducing grinding forces, roughness and specific energy. Zhang et al. [13] evaluated the effect of hybrid nanoparticles of MoS_2 and CNT during grinding of difficult to cutting materials (Ni-alloy). The analysis showed that the hybrid nanoparticles achieved better lubrication in terms of grinding forces, surface finish and coefficient of friction than single nanoparticles. The above-mentioned studies indicate that the nanosize solid lubricants have great potential to reduce the grinding forces, friction and the heat between the mating surfaces. The present study hence focuses on investigating the effect of nanosize solid lubricants during the surface grinding of silicon nitride using resin bonded diamond wheel. The effect of process parameters and the nanosize solid lubricants in MQL mode on grinding forces and surface quality were investigated. The experimental study was conducted using FCC design and the efficacy of the model was checked using analysis of variance (ANOVA)

2. EXPERIMENTAL SETUP

Silicon nitride (Si_3N_4) ceramic of dimension 20 × 20 × 4 mm was used as workpiece material in the grinding experimentation. The mechanical properties of the workpiece are given in Table 1.

Table 1. Mechanical properties of silicon nitride workpiece

Density	Hardness	Bending strength	Thermal conductivity	Young's modulus	Fracture toughness
3.23 Mg/m^3	1500 HV (500g)	1000 MPa	20 W/mK	308 GPa	7.2 MPa $m^{1/2}$

The experimental study was conducted to investigate the effect of nano graphite and MoS_2 of particle size 400 nm and 500 nm respectively during grinding of silicon nitride on grinding forces and surface finish. The nanopowders were mixed and dispersed in deionized water (carrying media) using ultrasonic probe sonicator. To avoid the quick sedimentation of powders, SDBS (Sodium dodecyl benzene sulfonate) was added in deionized water. The average contact angle (CA°) of graphite nano-fluid and MoS_2 nano-fluid was measured using Goniometer and found to be 62.3° and 52.4° respectively. The resulting solution was supplied to the grinding zone immediately to avoid the precipitation or the agglomeration of the nanoparticles. The truing of grinding wheel was done with the help of alumina wheel (AA60K5V8) using Brake controlled truing device. The wheel was dressed before each experimentation using alumina stick (WA320E9V18N) to maintain the sharpness of the grits. The experimental parameters used for the experiments are given in Table 2.

Table 2. Grinding parameters

Workpiece material	Silicon nitride ceramic (20 × 20 × 4 mm)
Grinding Wheel	ASD54R125B2 (Resin bonded)
Grinding mode	Surface grinding, up cut
Environmental coddditions	Dry, MQL (Nano graphite nano MoS_2)
Experimental	Wheel speed 10m/s, 15 m/s and 20m/s Table speed 3 m/min, 6 m/min and 9 m/min Depth of cut 10 μm, 20 μm and 30 μm
MQL conditions	Flow rate 150 ml/h Nozzle distance 30mm (from wheel) Nozzle height 15 mm (from workpiece) Nozzle angle (α) = 15°

The onsite measurement of grinding forces have been done using Kistler dynamometer (Type 9257B) attached with charge amplifier and the date have been captured by dyno ware software. The surface roughness of ground samples was measured using Talysurf surface profilometer. For each experimental condition (dry, graphite and MoS_2) ANOVA was performed using design expert software for forces and surface roughness.

3. Result and discussion

The experimental parameters and respective output responses are given in Table 3. The variation of grinding forces with wheel speed at depth of cut 20 micron and table speed 3 m/min is shown in Fig. 1. Both tangential force and normal force decreases with increase in wheel speed. The variation of grinding forces with table speed at wheel speed of 15 m/s and depth of cut 10 μm is shown in Fig. 2. It can be clearly seen from Fig. 1, Fig. 2, and Table 3 that the application of nanofluids significantly reduced the grinding forces by converting nanoparticles into thin physical film in the grinding zone. At wheel speed 10 m/s, table speed 9 m/min and depth of cut 30 μm, the tangential force is reduced by approximately 30 % and 35 % in case of nano graphite and nano MoS_2 respectively as compared to dry condition. The normal force decreases by approximately 14 % and 35 % in case of nano MoS_2 as compared to dry condition at i) wheel speed 15 m/s, table speed 9 m/min and depth of cut 30 μm and ii) wheel speed 15 m/s, table speed 6 m/min and depth of cut 20 micron respectively. It can be seen from Fig. 3, Fig. 4, and Table 3, the surface roughness of the ground surface is lower in case of MoS_2 nanofluid as compared to dry and graphite nanofluid. The MoS_2 nanofluid reduced the surface roughness by approximately 41 % and 44% as compared to dry condition at i) wheel speed 15 m/s, table speed 3 m/min and depth of cut 20 μm and ii) wheel speed 15 m/s, table speed 6 m/min and depth of cut 10 μm respectively.

Table 3. The experimental parameters and respective output responses

Run	Wheel Speed	Depth of Cut	Table Speed	Dry			Graphite			MoS_2		
	m/s	μm	m/min	F_T(N)	F_N(N)	Ra(μm)	F_T(N)	F_N(N)	Ra(μm)	F_T(N)	F_N(N)	Ra(μm)
1	20	30	9	71.27	271.98	0.56	54.6	287.15	0.49	41.4	209.41	0.34
2	10	20	6	67.84	217.19	0.51	47.44	232.64	0.45	33.37	164.86	0.37
3	15	20	6	36.84	128.62	0.49	26.18	124.24	0.43	19.39	88.98	0.35
4	10	30	3	83.48	279.28	0.51	76.37	367.53	0.46	50.92	246.05	0.30
5	15	20	3	18.73	63.76	0.51	17.57	82.04	0.45	16.6	73.93	0.28
6	20	20	6	24.36	87.67	0.54	17.51	91.06	0.54	16.28	83.22	0.37
7	15	20	6	36.85	128.3	0.57	26.79	126.68	0.49	19.06	83.35	0.32
8	15	20	9	37.23	130.92	0.53	28.57	141.55	0.48	28.73	134.93	0.33
9	15	10	6	23.45	79.49	0.53	14.27	52.65	0.46	8.7	39.11	0.30
10	15	20	6	36.75	128.38	0.57	27.53	130.84	0.48	19.71	88.61	0.32
11	15	30	6	67.09	243.72	0.58	56.7	276.41	0.53	30.14	139.51	0.39
12	20	30	3	14.94	52.69	0.53	13.69	67.89	0.48	12.54	63.87	0.33
13	15	20	6	37.39	130.41	0.53	26.09	123.86	0.48	20.59	94.49	0.32
14	10	10	3	23.55	74.61	0.53	19.84	81.7	0.49	13.35	66.22	0.33
15	10	10	9	33.63	106.4	0.51	23.97	122.12	0.44	17.12	86.71	0.30
16	20	10	3	9.69	35.64	0.58	5.52	29.85	0.50	5.42	28.05	0.38
17	15	20	6	37.12	129.48	0.66	26.79	127.13	0.53	18.75	81.99	0.40
18	15	20	6	36.43	127.18	0.54	27.12	128.24	0.51	19.67	88.43	0.36
19	10	30	9	106.18	410.17	0.57	74.32	398.2	0.49	68.99	352.22	0.37
20	20	10	9	12.2	45.05	0.54	10.79	57	0.47	8.39	43.62	0.32

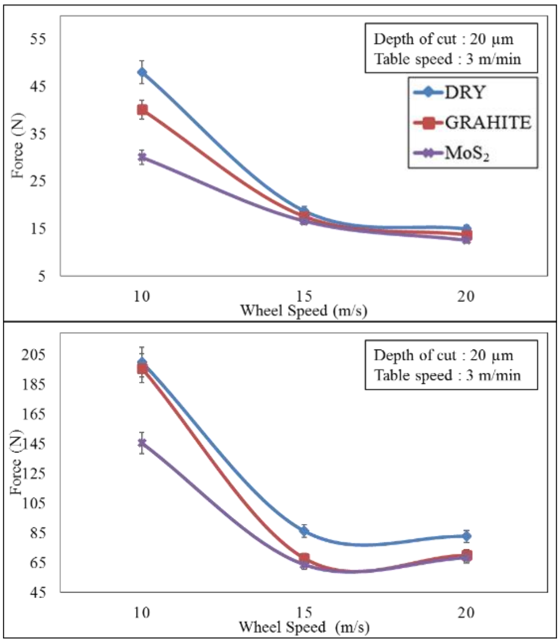

Fig. 1. Variation of tangential force and normal force with wheel speed at table speed 3 m/min and depth of cut 20 µm

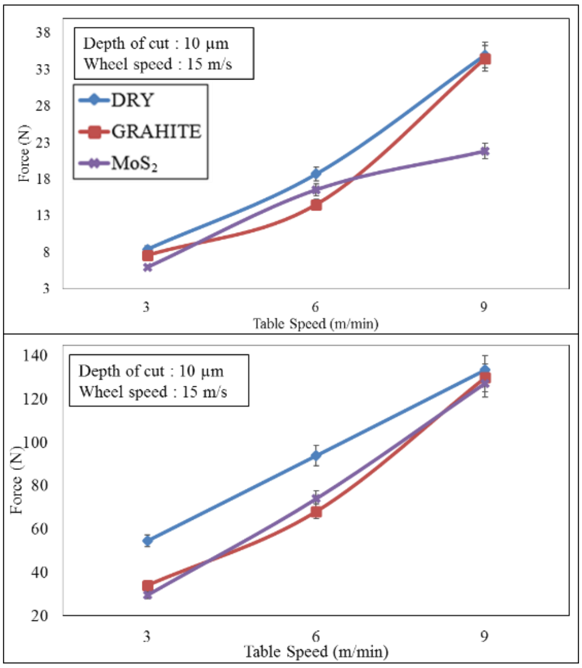

Fig. 2. Variation of tangential force and normal force with Table speed at wheel speed 15 m/s and depth of cut 10 µm

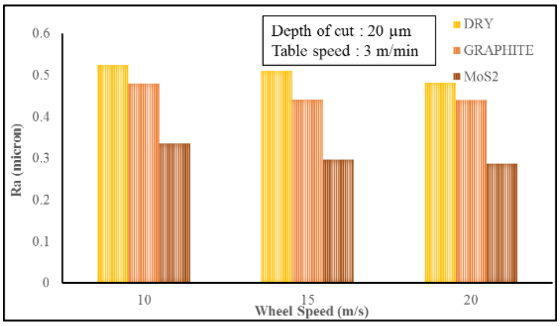

Fig. 3. Variation of surface roughness (Ra) with wheel speed at table speed 3 m/min and depth of cut 20 µm

The ground surface morphology under MoS2 is shown in Fig.5.

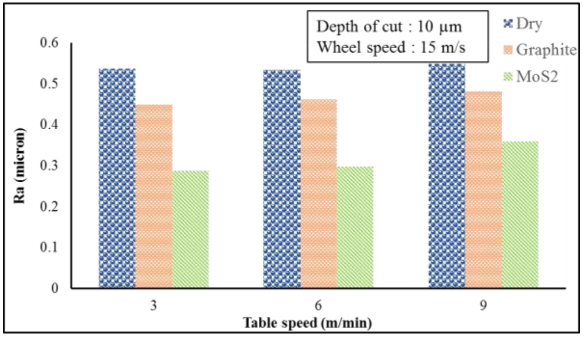

Fig. 4. Variation of surface roughness (Ra) with Table speed at wheel speed 15 m/s and depth of cut 10 µm

The smooth surface with low irregularities height under nano MoS_2 is due to lubrication effect caused by nanoparticles [3, 13]. In order to check the efficacy of the selected model for the experimental data, analysis of variance for grinding forces and roughness in case of nano MoS_2 is given in Table 4. This analysis showed the influence of input parameters on the grinding forces and surface roughness. The depth of cut is found to be the most influencing factor on grinding forces and surface roughness in dry and nanofluid conditions [14].

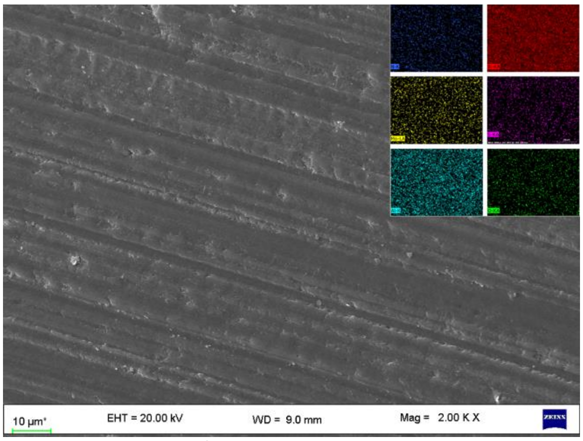

Fig. 5. Ground surface morphology under nano MoS_2 condition

4. CONCLUSIONS

Grinding of silicon nitride using resin bonded diamond wheel has been conducted under dry and nano MQL conditions. The following conclusions may be drawn from the experiments:

- The application of nano-laminar solid lubricants during grinding of silicon nitride reduced the grinding forces and enhanced the surface finish. The improvement in grinding performance is possibly due to the conversion of nanoparticles into thin physical film on the ground surface.
- The reduction in tangential force, normal force and surface roughness was approximately 35%, 14% and 36% respectively as compared to dry condition at wheel speed 10 m/s, table speed 9 m/min and depth of cut 30 micron.

- The significance of model parameters was determined using ANOVA analysis and the analysis showed that for the adopted range of process parameters, the depth of cut has significant effect on the grinding forces and surface roughness.

Table 4. ANOVA analysis of normal force, tangential force and surface roughness in MoS_2 condition

Normal Force (Fn)					
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	105208.0	6	17534.7	18.9	< 0.0001 significant
A-Wheel Speed	23804.1	1	23804.1	25.7	0.0002
B-Depth of Cut	55853.2	1	55853.2	60.3	< 0.0001
C-Table Speed	12163.7	1	12163.7	13.1	0.0031
AB	7425.0	1	7425.0	8.0	0.0142
AC	148.4	1	148.4	0.2	0.6955
BC	5813.7	1	5813.7	6.3	0.0263
Residual	12043.6	13	926.4		
Lack of Fit	11943.1	8	1492.9	74.3	< 0.0001 significant
Tangential force (Ft)					
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	4226.1	6	704.3	28.7	< 0.0001 *significant*
A-Wheel Speed	994.4	1	994.4	40.5	< 0.0001
B-Depth of Cut	2280.4	1	2280.4	93.0	< 0.0001
C-Table Speed	433.0	1	433.0	17.7	0.0010
AB	303.9	1	303.9	12.4	0.0038
AC	12.5	1	12.5	0.5	0.4883
BC	201.9	1	201.9	8.2	0.0132
Residual	318.8	13	24.5		
Lack of Fit	316.8	8	39.6	97.8	< 0.0001 *significant*
Surface Roughness (Ra)					
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	0.0150	6	0.0025	6.8	0.002 *significant*
A-Wheel Speed	0.0035	1	0.0035	9.6	0.0085
B-Depth of Cut	0.0024	1	0.0024	6.6	0.0233
C-Table Speed	0.0075	1	0.0075	20.6	0.0006
AB	0.0006	1	0.0006	1.8	0.2067
AC	0.0002	1	0.0002	0.6	0.4591
BC	0.0005	1	0.0005	1.4	0.265
Residual	0.0047	13	0.0004		
Lack of Fit	0.0046	8	0.0006	25.9	0.0012 *significant*

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