Paper:

Effect of Nanoparticle Lubrication in Diamond Turning of Reaction-Bonded SiC

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Lubrication is a key issue in diamond turning of hard materials. This paper explores the feasibility of nanoparticle lubrication in diamond turning of reaction-bonded SiC. Four types of nanoparticles were dispersed in lubricating grease and applied to a workpiece surface. Results showed that the type and concentration of dispersed nanoparticles significantly affected lubricating performance. Grease containing 10% Cu nanoparticles produced the highest surface quality and the lowest tool wear. Lubrication is discussed in terms of nanoparticle-induced solid lubricating film formation at the tool-workpiece interface.

Keywords: precision machining, diamond turning, silicon carbide, nanoparticle, solid lubrication

1. Introduction

Reaction-bonded silicon carbide (RB-SiC) has become an important ceramic for fabricating precision molding dies for high-temperature glass molding presses (GMP) [1]. Machining RB-SiC molding dies is most often done in diamond grinding followed by diamond lapping/polishing. Although these produce a fine surface finish, machining efficiency is low and production cost is high [2, 3]. Compared to polishing, diamond turning has a higher material removal rate and can be used for fabricating complex shapes and microstructures. Machining RB-SiC by diamond turning remains a challenge due to extremely rapid tool wear [4]. Such wear involves serious flank wear due to the abrasion of SiC grains [5], making it vital to reduce wear.

Conventionally, oil – mostly kerosene – mist is widely used in diamond turning to reduce tool wear, but such mist does not effectively reduce wear in RB-SiC diamond turning because the film formed at the tool-workpiece interface is easily destroyed by high contact pressure. A potential alternative is solid lubrication using nanoparticles, and many successful applications of solid particle lubrication under high pressure and high temperature have been reported [6, 7]. Interface conditions in these studies resemble friction at the tool-workpiece interface in diamond turning. The effectiveness of solid particle lubrication has also been verified in machining processes. Rao et al. [8], for example, studied solid lubricant application in rough turning of steel, and their results showed the effectiveness of 50-μm boric acid particles as a feasible alternative to dry and wet machining. Reddy et al. [9] verified the improvement in cutting forces, surface quality, and specific energy in the use of graphite and MoS_2 with 2-μm particles as lubricants in machining AISI 1045 steel by end milling. Deng et al. [10] studied the lubricating effects of CaF_2 in dry cutting of hardened steel and cast iron. CaF_2 with particles smaller than 1 μm were added to Al_2O_3/TiC ceramic in tool fabrication, but all of the above work focused on particle lubricating effects at the micron level in rough metal machining. To date, no report has, to our knowledge, been made on lubrication using nano-level particles in ultraprecision cutting of ceramics.

Our objective is to determine nanoparticle lubrication feasibility in RB-SiC diamond turning. The effects of particle size, type, and concentration on lubrication performance is thus studied in the sections that follow. Nanoparticle lubrication is expected to effectively lubricate the ultraprecision cutting of hard materials.

2. Experimental Details

2.1. Nanoparticle Lubricants

Four types of commercially available nanoparticles – molybdenum disulfide (MoS_2), graphite fiber (GF), copper (Cu), and copper oxide (CuO) – were used for lubricating RB-SiC diamond turning and their effects were compared. Particles ranged from a few tens to hundreds of nanometers. **Fig. 1** shows scanning electron microscope (SEM) photographs of the four types of particles. Detailed specifications are given in **Table 1**.

2.2. Delivery of Nanoparticles

During machining, nanoparticles maybe delivered to the cutting zone by directly spraying particles thereon or by spraying a type of lubricating fluid in which the nanoparticles are dispersed. Fluid spraying induces nanoparticle suspension in air, which may pollute the environment and harm operators. The new lubrication we propose applies nanoparticles to the workpiece as a thin film dispersing nanoparticles into a type of lubricating grease. The grease used was soft and calcium-based

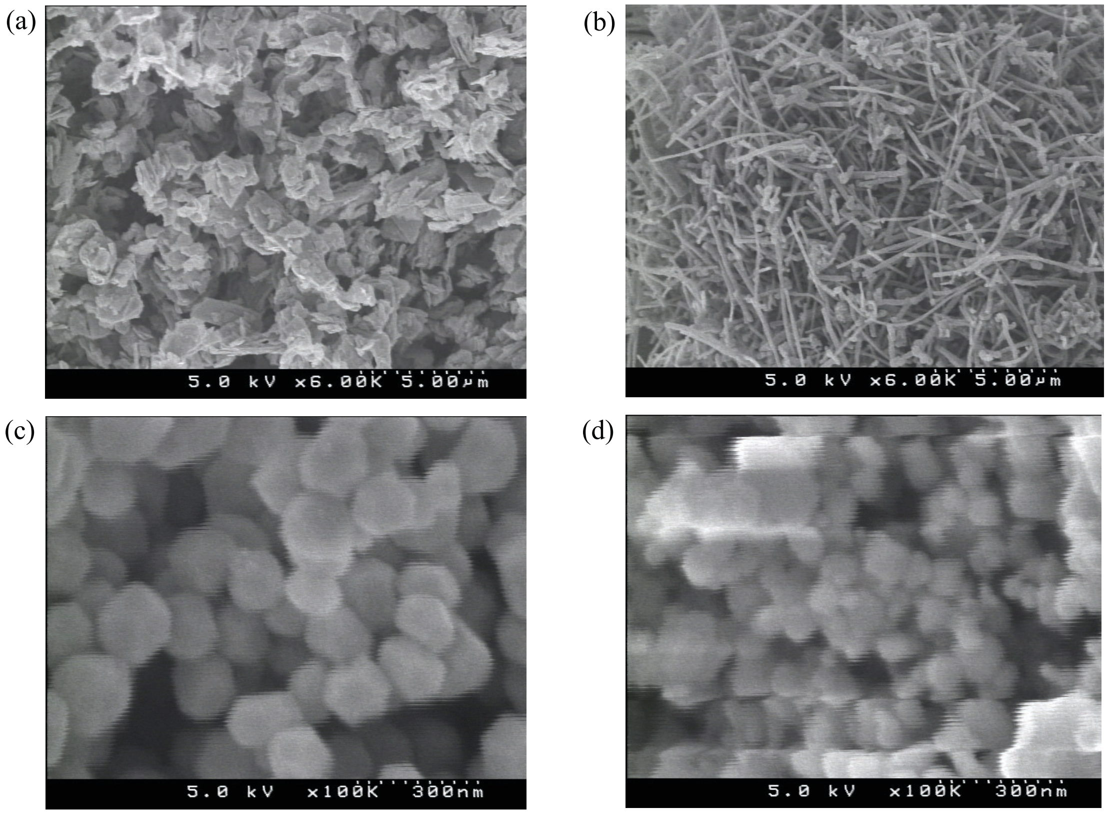

Fig. 1. SEM photographs of nanoparticles: (a) MoS_2, (b) GF, (c) Cu, and (d) CuO.

Table 1. Nanoparticle specifications.

Particle material	Size (nm)	Shape	Bulk hardness (Mohs)
MoS_2	1000	Multilayer	1–1.5
GF	150	Multilayer	1
Cu	200	Spherical	3
CuO	48	Polyhedron	4

grease, with a consistency of 310-340 (No.1). Grease containing nanoparticles was then stirred using a Keyence HM-500 hybrid mixer. After 15 min of stirring, grease showed a uniform color, indicating that nanoparticles had been dispersed homogeneously. Before diamond turning, grease containing nanoparticles was then smeared on the workpiece as film 100 μm thick.

Grease is more viscous than lubricating oil, making it critical to deliver grease onto the tool-workpiece interface for effective lubrication. To do so, we used tool-swinging cutting proposed elsewhere [11]. As shown in **Fig. 2(a)**, swinging is applied to a round-nosed cutting tool during tool feeding, where the swinging center agrees with the tool edge curvature center. **Fig. 2(b)** shows nanoparticle lubricating in tool swinging. In swinging, the cutting point changes along the tool edge and temperature increase at one cutting point can be greatly reduced. Lubricating grease containing nanoparticles easily enters the tool-workpiece interface thanks to tool swinging, so combining tool swinging and the use of grease containing nanoparticles as a lubricant is expected to yield very high lubrication in hard material diamond turning.

2.3. Experimental Apparatus

Diamond turning experiments were conducted on a numerically controlled three-axis ultraprecision lathe, Nachi-ASP15, as shown in **Fig. 3**. The machine tool has an air-bearing spindle and two perpendicular hydrostatic sliding tables on the X and Z axes. A B-axis rotary table is built into the X-axis table. A three-dimensionally adjustable tool holder is set on the rotary B-axis table. A three-component piezoelectric dynamometer, Kistler 9256C2, on the tool holder measures cutting force. Diamond cutting tools are moved in the X direction while being swung around the B-axis center. Round-nosed single-crystal diamond cutting tools used in experiments have 10 mm nose radii, a $-40°$ rake angle, and a 10° relief angle. Using a highly negative rake angle avoids microchipping of the cutting edge [11].

2.4. Machining Conditions

Cylindrical samples were 30 mm in diameter and 10 mm thick. **Table 2** details machining conditions. The spindle rotated at 1,000 rpm, the depth of cut was 2 μm, and tool feed was 20 μm/min. Tool swinging speed was set to 60°/min. Generally, the higher the swinging speed, the better the lubrication [11]. The tool-swinging angle was set at 5°. Lubricants in different concentrations were

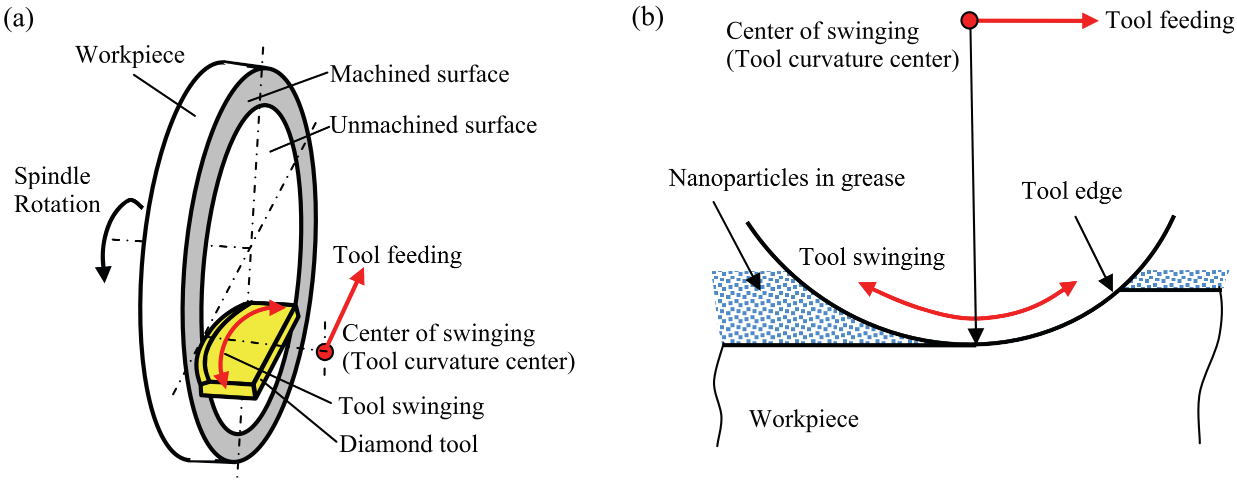

Fig. 2. (a) Tool-swinging cutting and (b) nanoparticle lubricating the cutting zone induced by tool swinging.

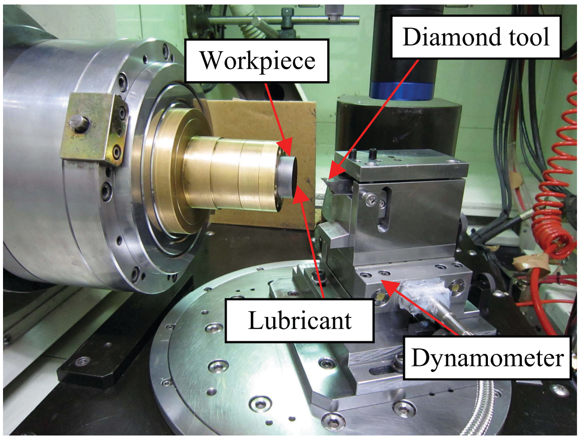

Fig. 3. Experimental setup.

Table 2. Machining conditions.

Spindle rotation speed (rpm)	1000
Depth of cut (μm)	2
Feed rate (mm/min)	20
Maximum undeformed chip thickness (nm)	400
Tool-swinging speed (°/min)	60
Tool-swinging angle (°)	5
Concentrations of MoS_2, CuO, Cu (%)	1, 3, 5, 10, 20
Concentrations of GF (%)	0.2, 0.5, 1, 3, 5

prepared by changing particle weight percentages. MoS_2, CuO, and Cu concentrations were 1%, 3%, 5%, 10%, and 20%, while those for GF were lower at 0.2%, 0.5%, 1%, 3%, and 5% because GF has very low volume density. Effects of particle concentration and particle type were studied by analyzing cutting force, surface roughness, and tool wear patterns.

3. Results and Discussion

3.1. Particle Concentration

Figure 4 shows variations in cutting force with changes in concentration of nanoparticle type. A concentration of 0% means no nanoparticles were dispersed and only base grease was used. Both thrust and principal force were reduced using grease containing nanoparticles. Because force is closely related to the tribological properties of the cutting tool and workpiece, reduced force indicates that nanoparticles acting as a lubricant have reduced friction at the tool-workpiece interface. Both thrust and principal force decrease when MoS_2 particle concentration increases from 0% to 10%. Thereafter, cutting force is not substantially reduced even if concentration is increased from 10% to 20% (**Fig. 4(a)**). Similar trends are seen for other types of particles in **Figs. 4(b)–(d)**, except that curve slopes differ. **Fig. 4** shows that optimal MoS_2 particle concentration is 10%, for GF 3%, for Cu 10%, and for CuO 10%.

3.2. Particle Type

We studied optimal nanoparticles concentration and evaluated the lubricating performance of kerosene mist and base grease for comparison. **Figs. 5(a)** and **(b)** show variations in thrust and principal force, with machined surface area. For all lubricants, force increased with machined surface area, although thrust and principal force clearly were lowest with grease containing 10% Cu particles.

Figures 6(a) and **(b)** show surface roughness variations with machined surface area. When the machined surface exceeded 400 mm^2, surface roughness for both Ra and Rz increased markedly. The lowest surface roughness was, as stated, obtained with grease containing 10% Cu particles.

Figure 7 shows SEM micrographs of tool wear patterns after an area of 565 mm^2 was machined. With grease containing MoS_2 (**Fig. 7(a)**) and GF (**Fig. 7(b)**) particles, abrasive wear patterns on the flank dominate. The wear

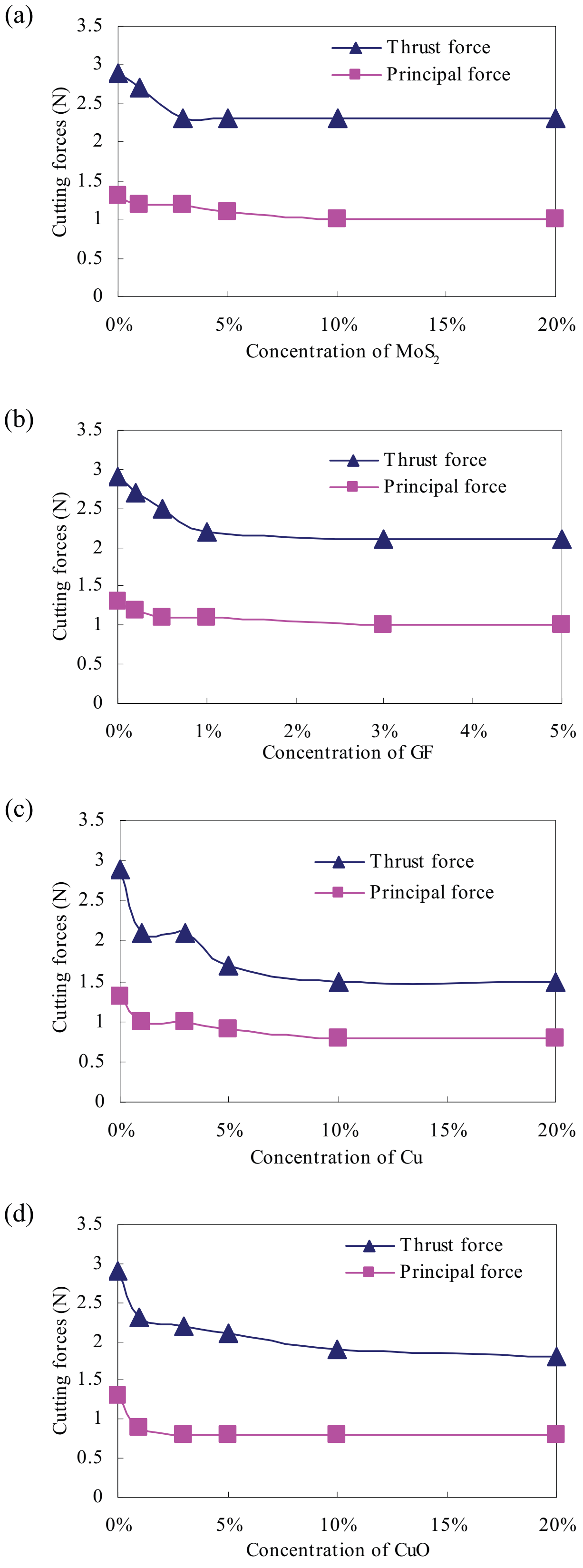

Fig. 4. Variations in thrust and principal force with the concentration of nanoparticles: (a) MoS_2, (b) GF, (c) Cu, and (d) CuO.

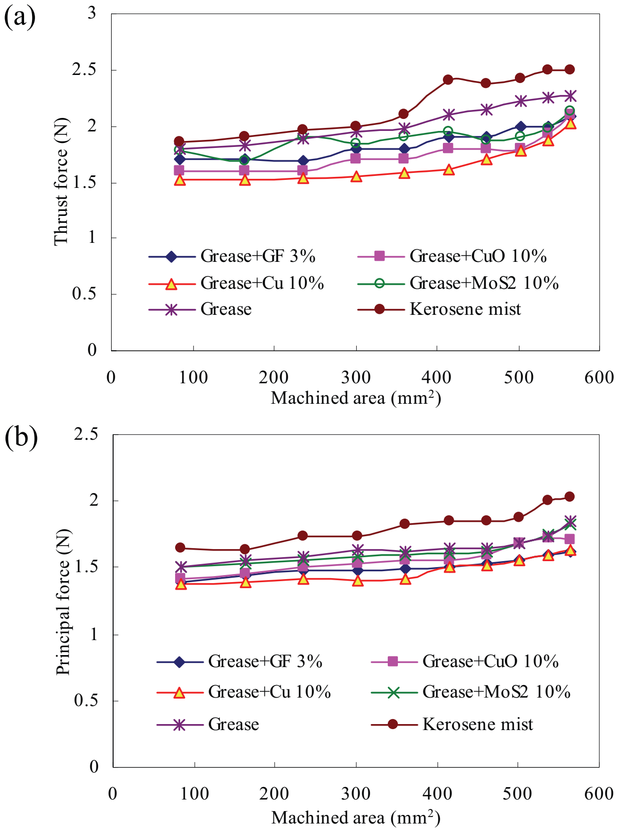

Fig. 5. Variations in (a) thrust force and (b) principal force with machined surface area.

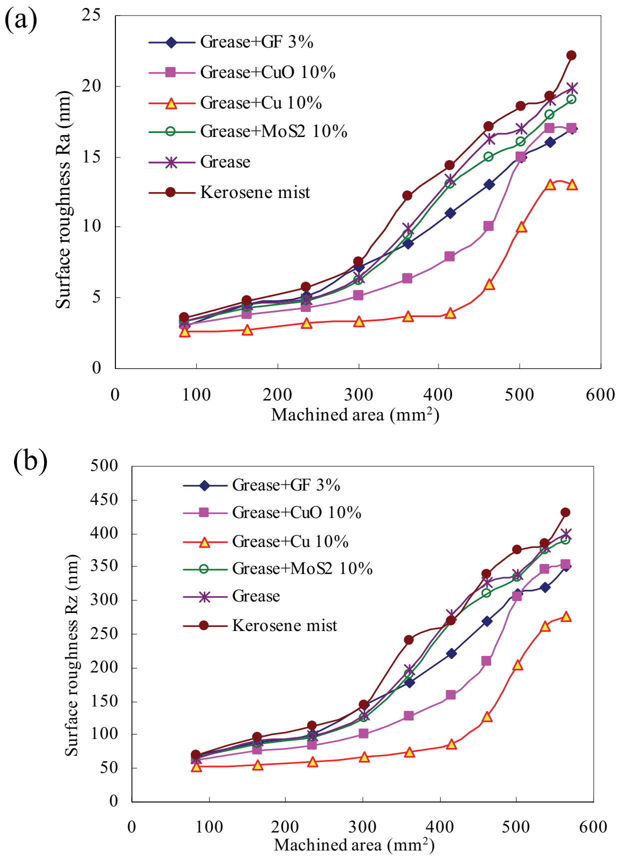

Fig. 6. Variations in surface roughness (a) Ra and (b) Rz with machined surface area.

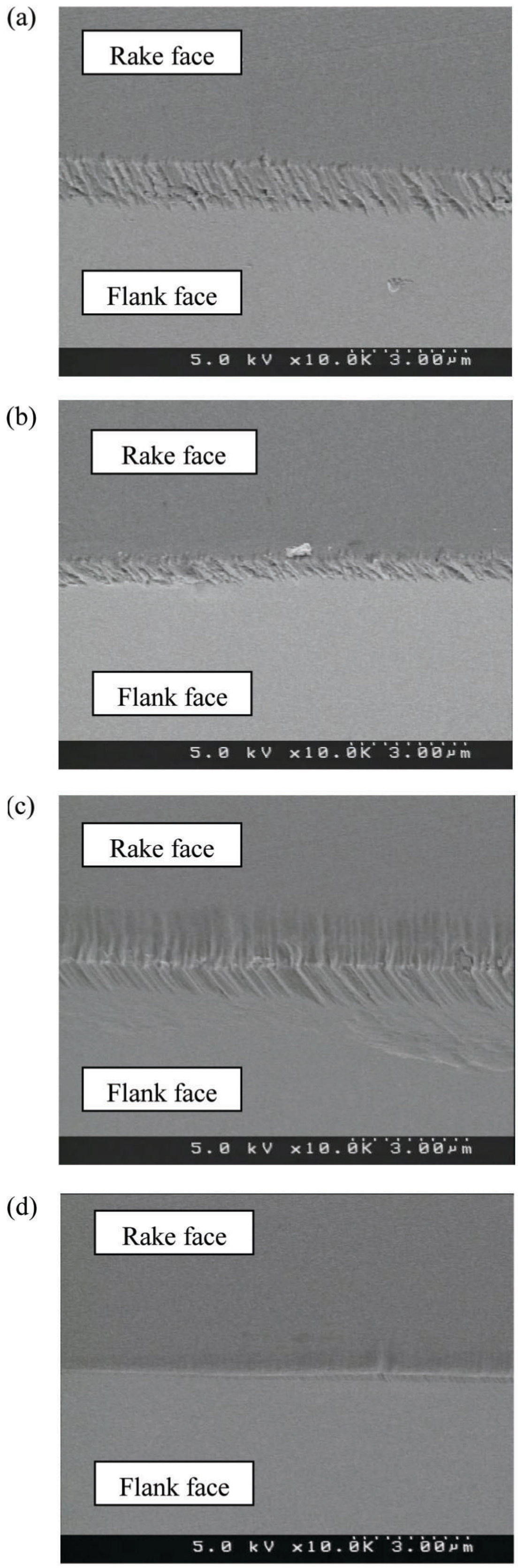

Fig. 7. SEM micrographs of wear patterns on a machined surface of 565 mm^2 using different nanoparticles: (a) MoS_2, (b) GF, (c) CuO and (d) Cu.

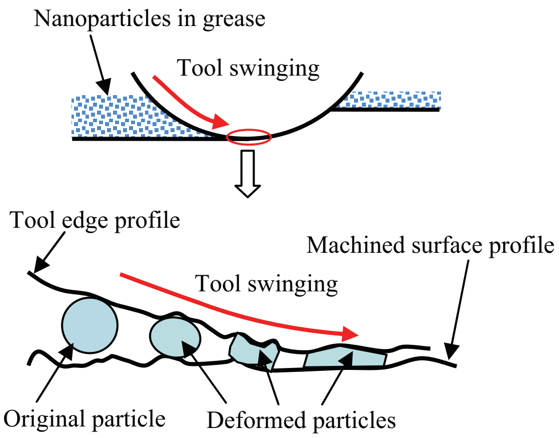

Fig. 8. Schematic models for nanoparticle-induced lubricating film formation in tool swinging cutting.

land width with GF is less than that with MoS_2 particles, indicating that GF lubricates better than MoS_2 under present machining conditions. This may be because GF particles are smaller, facilitating cutting zone accessibility. For CuO particles (**Fig. 7(c)**), both rake and flank wore, with fine scratches visible on wear lands. Scratches may have been caused by SiC grain abrasion or by the thermal-chemical reaction between CuO and diamond. When using grease containing Cu particles (**Fig.7 (d)**), however, only very shallow crater wear was found on the rake, and flank wear was too small to clearly identify. This indicates that Cu particles perform in protecting the flank from abrasive wear during diamond turning. Results in **Fig. 7** agree with cutting force results in **Fig. 5** and surface roughness results in **Fig. 6**.

3.3. Discussion

Nanoparticle lubrication performance may depend on microparticle fracture/deformation, which may generate an extremely thin solid lubricant film, significantly reducing direct asperity between the cutting tool and workpiece as shown in **Fig. 8**. Excellent lubrication by Cu particles may be due to Cu's significantly higher microplasticity than other particles'.

Another factor affecting lubrication performance is particle size. Smaller particles are generally preferable to larger ones because smaller particles can enter the tool-workpiece interface more easily. Using small particles is especially important in early cutting, where the tool edge and machined surface are smooth. In later cutting, however, even large particles may enter the tool-workpiece interface during tool swinging thanks to microasperities generated on the tool face and workpiece surface. Under high contact pressure, big particles may fracture into smaller ones or be squeezed into thin films, maintaining lubrication in durable machining.

4. Conclusions

The feasibility of introducing nanoparticle lubrication into diamond turning of RB-SiC has been experimentally demonstrated, with results showing that lubrication performance of grease is significantly improved by nanoparticle dispersion. Four types of particles – MoS_2, GF, CuO, and Cu – were used and their concentration effects were studied. Grease containing Cu particles at a concentration of 10% by weight were found to produce the highest surface quality and the lowest tool wear. Particle lubrication depends on particle size and microfracture/deformation.

Acknowledgements

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