



A Study of Creep-Feed Grinding of Metallic and Ceramic Materials

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Industrial Summary: The application of modern materials in severe working environment requires that the surface integrity of ground elements should reach a high level to obtain satisfactory resistance to various external stimuli. In response, extensive attention has been paid to study this key factor such that the working reliability of ground components could be improved to the full extent.

The technique of creep-feed grinding (CFG) has been found to be most suitable for geometrical shaping, and hence been expected to improve effectively the productivity and surface quality of components with complex profiles. In the last few decades, however, many problems have been encountered in the application of CFG processes, which attracts numerous researchers to study the grinding mechanisms for different materials and explore correspondingly the optimal grinding conditions.

The present paper investigates experimentally the effects of grinding conditions on the surface integrity of some metallic and ceramic materials in the CFG regime. Some important factors, such as grinding forces, specific energy, material removal rate, coolant supply method, surface roughness and residual stresses are discussed in detail. In the experiment, different types of grinding wheels and workpiece materials were used to generate representative results for particular comparisons. The X-ray diffraction method was applied to measure the distribution of surface residual stresses. It is found that the coolant supply method has a significant effect on the distribution of surface residual stresses but its contributions to the grinding forces and specific energy are negligible. The SEM examination of ground surfaces indicates that the technique of ductile-regime creep-feed grinding for ceramic materials may be developed for practical application.

1. INTRODUCTION

With the increasing application of advanced materials in industry, such as the manufacturing of ceramic engines, semiconductors and ultra-precision measuring equipment, an immediate problem is the accomplishment of the satisfactory surface integrity of machined components[1].

The technique of creep-feed grinding has been found to be a promising machining process because it combines the advantage of a high shaping accuracy, which is the character of conventional grinding, and the merit of a high material removal rate, which is the quality of tool cuttings. It is therefore expected that the CFG process would offer a high productivity and surface finish for components with complex profiles[2]. Unfortunately, many other factors such as the

surface micro-damage and local stress concentration become more significant. A direct undesirable effect is the degradation of the strength of ground components and their resistance to diverse working environment[3]. Consequently, an in-depth investigation into the dependence of CFG products upon various grinding conditions is essential.

The present paper studies experimentally the effects of grinding conditions on the surface integrity of metallic and ceramic materials in the CFG regime. Some important factors, such as the grinding forces, specific energy, material removal rate, coolant supply method, surface roughness and the residual stresses are discussed in detail. The paper generates useful results for the further investigation of the CFG technique.

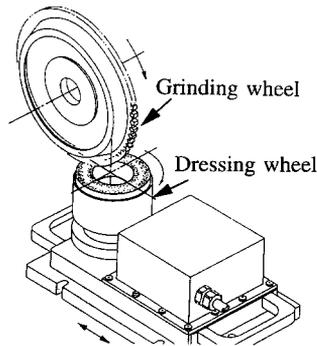
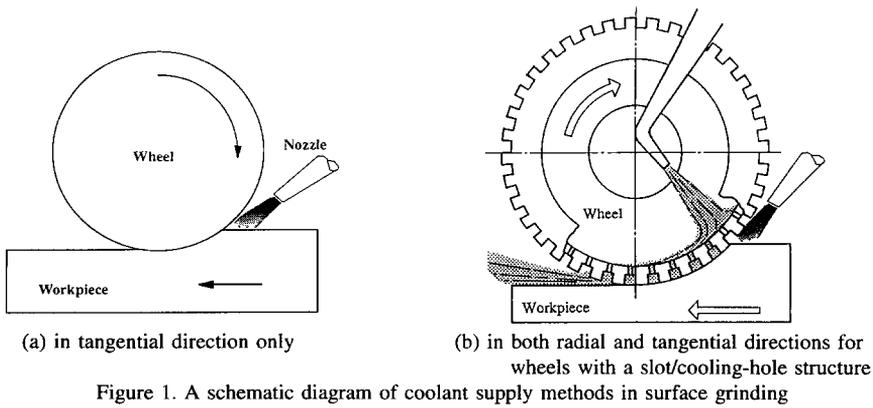


Table 1. Description of the grinding wheels

Wheel	Grain	Bond	Diameter (mm)	Width (mm)
HA60F12VA-2	Al ₂ O ₃ (99.5%)	Vitrified	205	19
CBN170Q5SV5	CBN	Vitrified	205	5
MDY170Q5SV5	Diamond	Vitrified	205	5
GC80HV (cup)	SiC	Vitrified	Inner 50, Outer 90	20
HA150GV (cup)	Al ₂ O ₃ (99.5%)	Vitrified	Inner 50, Outer 90	20

Table 2. Properties of the grinding coolant NET909

Properties	Tested value	Testing condition
specific weight	1.011	15/4 °C
PH	8.9	× 30 water
surface tension	32.1 dyne/cm	× 30 water
kindling temperature	140 °C	C. O. C
viscosity	146 c.p.	40 °C

Table 3a. Dressing conditions for CBN and MDY wheels

Dressing parameters	Dressing procedures	
	Step 1	Step 2
Dresser	GC80HV	HA150GV
Peripheral velocity of the grinding wheel (m/s)	10	10
Peripheral velocity of the dresser (m/s)	2.5	2.5
Table speed (mm/min)	500	500
Depth of feed (mm × pass)	0.01× 100	0.03 × 10

Table 3b. Dressing conditions for HA wheels

Dresser	Single point diamond dresser
Depth of feed (mm × pass)	0.01× 10
Cross feed rate (mm/revolution)	0.1

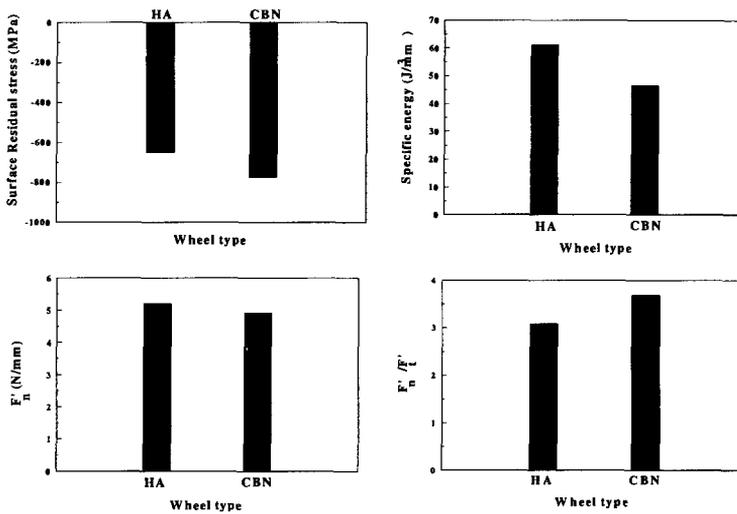


Figure 3. Effect of types of grinding wheels

2. EXPERIMENTAL SETUP

Surface CFG operations were performed in the down-grinding mode, see Fig.1, where HA (Al_2O_3 grains with vitrified bond) and CBN wheels (cubic boron nitride grains with vitrified bond) were used for grinding the metallic material (SUS304) and MDY wheels (man-made diamond grains with vitrified

bond) were for ceramic materials (SiC and Si_3N_4). The HA wheels were of smooth peripheral surfaces but the CBN and MDY wheels have a "slot/radial cooling hole" structure, as shown in Fig.1. Detailed descriptions of the wheels are listed in Table 1. Two different coolant supply methods were used: (1) coolant applied in tangential direction only(Fig.1a); and (2) coolant supplied in both the

tangential and radial directions at the same time (Fig. 1b). For HA wheels, only the first method could be used. The coolant was the NET909 attenuant with water of 20 times. Its properties are presented in Table 2.

Wheel dressing was controlled with the parameters shown in Table 3. The dressing device is illustrated in Fig. 2. For CBN and MDY wheels, a standard calibration procedure was designed to identify a wheel surface condition after dressing: A newly dressed wheel was applied to grind a specified material under a standard condition (in this study, the depth of wheel cut $t = 1.0$ mm and the table speed $v = 1.0$ mm/s were set). The wheel surface was thought to be identified when the resultants of the calibrating operation, such as grinding forces, surface roughness and grinding power, were approximately coincident with those of a pre-selected sample. The calibration procedure in conjunction with the well-controlled dressing conditions would produce comparable surface topography of wheels in the sense of macroscopic reliability.

The measurement of grinding forces was conducted with a dynamometer of KISTLER 5007 in three directions and plotted against grinding time with a YEW 3056 pen recorder. The spindle power of the grinding machine was digitised by a YEW digital AC power meter of type 2503. The surface roughness of ground workpieces and wheel surfaces were traced by TALYSURF 6 and the data were treated by TALYDATA 2010, a program for surface texture analysis. The length of the shaped specimens along the grinding direction was 100 mm. Surface residual stresses were measured by X-ray diffraction method (machine model: Rigaku-Type MSF-1M(PSPC)). All measurements of surface texture were conducted in the neighbourhood of the mid-point of the length, where most stable grinding conditions were achieved and maintained in a grinding pass.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Grinding Wheels

For a given workpiece material, the types of grinding wheels have a significant effect on the grinding processes. Fig. 3 presents the detailed comparisons for the CBN and HA wheels when the

bearing steel, SUJ2, was used as the specimen material. The comparison clearly shows that the CBN wheel offers more desirable results: a greater compressive surface residual stress, a smaller specific energy, a lower normal grinding force and a larger grinding force ratio, where F'_n and F'_t are respectively the normal and tangential grinding forces per unit grinding width.

The value of force ratio indicates that the CBN wheel was "sharper" than the HA in cutting the material, thus the CBN wheel was more efficient. In addition, the CBN wheel needed a smaller normal force to keep the specified wheel depth of cut.

It is the fact that there are three sources for surface residual stresses in a ground component: the mechanical traction, the thermal flux and the material phase transformation[3], as illustrated by the schematic diagram Fig. 4. The strength of the grinding heat plays an important role here. In the case of a high grinding heat input, the surface residual stress would usually be tensile. Under a fine cooling condition, however, the resultant residual stress may become compressive. The slotted surface of the CBN wheel makes it more efficient to bring coolant into the grinding zone so that it could lower the residual stress level to a large extent.

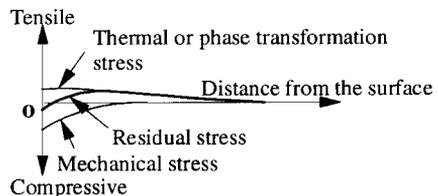


Figure 4. Variation of residual stresses

3.2 Effect of Coolant Supply Method and Material Removal Rate

The coolant supply method has almost no effect on the specific energy and grinding forces. However, it seems that method (2) will slightly lower the sharpness of the wheel because it decreases the force ratio, see Fig. 5. Residual stresses were influenced greatly by the coolant supply method. As has been stated before, it was caused by the high cooling rate inside the grinding zone when the coolant was applied in both the radial and tangential directions at the same time.

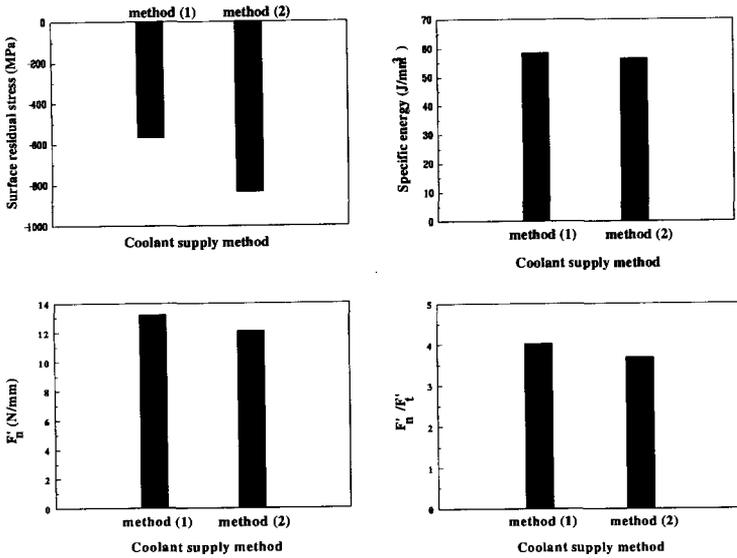


Figure 5. Effect of coolant supply methods

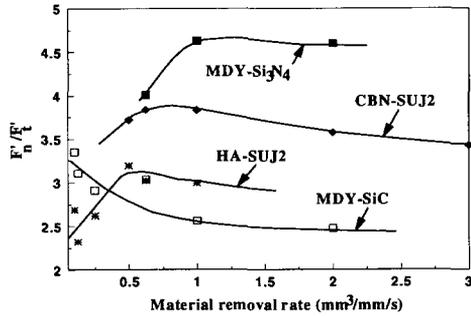


Figure 6. Effect of the material removal rate

In the CFG regime, except that of grinding SiC, the grinding force ratios always increase first and then decrease when the material removal rate increases, see Fig.6. Hence, for an individual material, there exists an optimal range in which

grinding operations could be performed most efficiently. The big difference between the curves of Si₃N₄ and SiC presents that MDY wheels are more appropriate for grinding Si₃N₄.

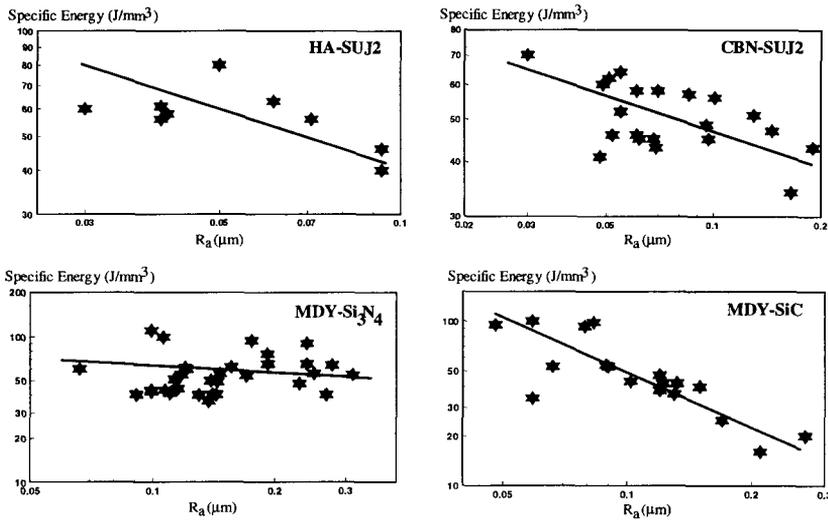


Figure 7. The specific energy and surface roughness

Table 4. Some Properties of Si₃N₄ and SiC

Materials	Si ₃ N ₄	SiC
Fracture Toughness KIC (MPa m ^{1/2})	6.0	4.0
Hardness (HV)	1600	2000
Young's Modulus	280	410
Yield Point (GPa)	3.8	7.8-10.8

3.3 Specific Energy and Surface Roughness

For both the metallic and ceramic materials, the specific energy decreases with the increase of surface roughness, as shown in Fig.7. For the brittle materials studied, SiC and Si₃N₄, it is thought that the surface roughness increases when the fracture mechanism prevails in material removal. On the other hand, the brittle fracture mechanism of material removal needs less energy so that a larger surface roughness may correspond to a smaller specific energy. However, it is not clear why the ductile material behaves in a similar way. In addition, the variation of specific energy

with the roughness in grinding Si₃N₄ is even weaker than that in grinding the ductile material, which also leaves much room for further investigation.

3.4 Wheel Surface Loading

Chips loaded on a wheel surface affect considerably the efficiency and quality of a grinding operation. No loaded ceramic chips were found on the MDY wheel surface after any grinding pass, see Fig.8a. It could be explained by the chip formation mechanisms in grinding brittle materials. The formed ceramic chips would first be

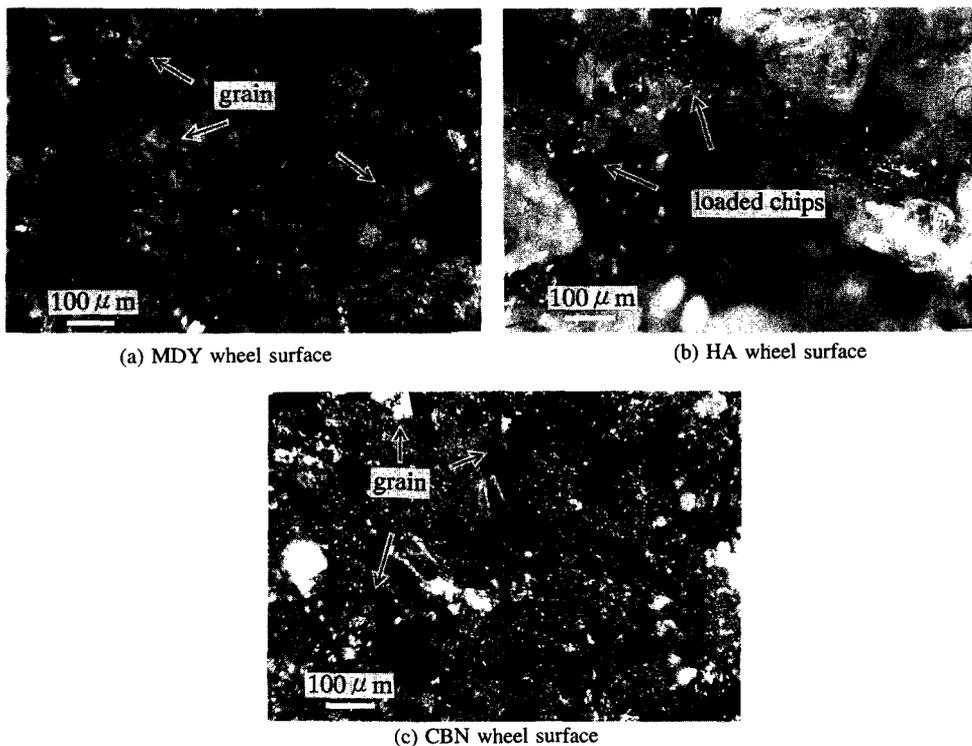


Figure 8. Optical microscopic examination of wheel surface loading

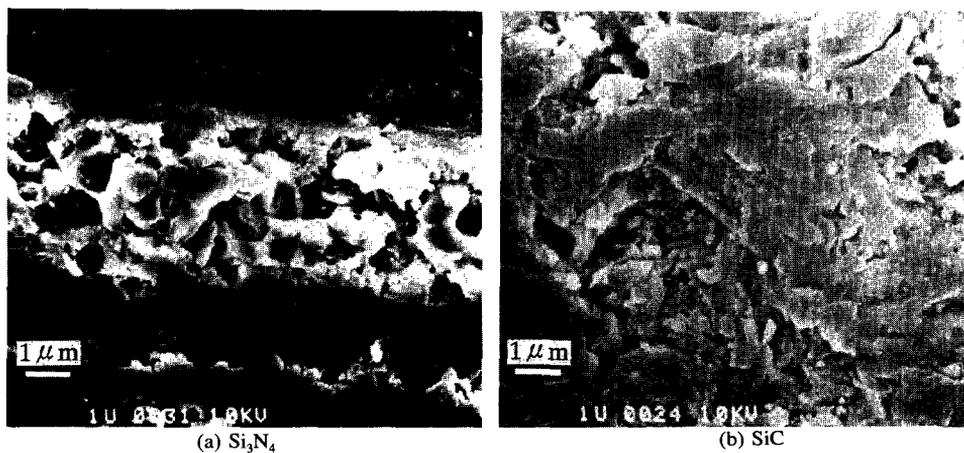


Figure 9. SEM pictures of ground surfaces

fragmented into smaller pieces in the grinding zone and then washed away easily by the coolant.

An interesting phenomenon was observed in grinding the bearing steel, when HA and CBN wheels were used individually. Severely loaded chips were found on the HA wheel surface around the active grains (Fig.8b). On the contrary, the CBN wheel surface was very clean (Fig.8c). It could be considered as one of the reasons that CBN wheels were sharper. Furthermore, it may argue that although the chip formation mechanism is plastic flow for both HA and CBN wheels in grinding SUJ2, the wheel structure, wheel porosity and the grain size all affect chip loading. Firstly, the slot/cooling-hole structure of the CBN wheel offers much space for chips. Secondly, the CBN wheel is of smaller grain size and lower porosity such that the chip thickness is smaller. Another possible factor is the difference between the chemical properties of the CBN and Al_2O_3 grains, which influences the micro-interaction between the chips and grain surfaces.

3.5 A New Material Removal Mechanism for Ceramics in CFG Regimes

It has been commonly accepted that ceramic materials are ground by the brittle fracture mechanism in CFG regimes. However, a careful examination of the present ground surfaces by scanning electron micrographs (SEM) shows that chip formation mechanisms of SiC and Si_3N_4 were rather different. For Si_3N_4 (Fig.9a), plastic flanges emerged clearly on the sides of the grinding grooves formed by active grains. The bottom and side walls of the grooves were very smooth and no cracks were detected. The deformation pattern was like that of a ground metallic surface. However, the surfaces of SiC specimens presented a different mechanism where chip formation was dominated by brittle fracture, see Fig.9b. Micro-cracks and fractured fragments could be observed clearly. Evidently, the mechanical properties of the workpiece materials had governed the grinding mechanisms here. Compared with SiC, see Table 4 [4], Si_3N_4 has a lower yield point, hardness and Young's modulus but a larger fracture toughness. Hence, it is easier to be deformed plastically.

It should be pointed out especially that the ground surface of Si_3N_4 shown in Fig.9a was associated with a large wheel depth of cut $t = 2.0$

mm and a table speed $v = 1.0$ mm/s. For the SiC, however, the ground surfaces always show the same pattern as presented by Fig.9b whose conditions were $t = 0.1$ mm and $v = 1.0$ mm/s. It therefore remains to be seen quantitatively how the mechanism of material removal varies with the properties of materials.

The above results state that a ductile-regime grinding is not only associated with a very small wheel depth of cut, but also possible to be achieved in the CFG regimes. The inherent reasons to alter the material removal mechanisms are: (1) the material properties of the individual ceramics; and (2) the considerable difference between the wheel depth of cut and the grain depth of cut; the latter is much smaller than the former.

4. CONCLUSIONS

(1) The coolant supply method has a significant effect on the distribution of surface residual stresses but almost has no contribution to the specific energy and grinding forces.

(2) The CBN wheel with a slot/cooling-hole structure possesses advantages in grinding metallic materials. It can avoid wheel loading and is more efficient and flexible for the application of different coolant supply methods.

(3) The specific energy decreases with the increase of surface roughness. For brittle materials, it indicates that the material removal mechanism of brittle fracture needs less grinding energy.

(4) The technique of ductile-regime creep-feed grinding may be developed for ceramic materials whose properties are close to the Si_3N_4 studied.

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