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On the Precision Grinding of Advanced Ceramics

A. G. Mamalis[1], J. Kundrak[2], K. Gyani[2] and M. Horvath[3]

[1]Manufacturing Technology Division, Department of Mechanical Engineering, National Technical University of Athens, Greece; [2]Department of Production Engineering, University of Miskolc, Hungary; and [3]Department of Manufacturing Engineering, Technical University of Budapest, Hungary

The use of advanced ceramics in manufacturing is spreading, and, therefore, the elaboration of suitable grinding technologies is important. Grinding is problematic because crack-free ceramics are difficult to process owing to their particular microstructure. In this paper we report on the application of an advanced precision grinding process, elaborating continuous wheel dressing based on electrochemical principles, namely the ECDM process. The material removal rate can be increased significantly and the surface roughness is improved. Problems encountered in grinding of ceramics are also discussed.

Keywords: Ceramics; Continuous dressing; Crack formation; Grinding; Surface integrity

1. Introduction

The number of parts made of ceramic materials has gradually been increasing in the field of mechanical engineering. The materials of the parts are the so-called advanced ceramics, as opposed to the well-known traditional ceramics. Mechanical engineering ceramics have spread because of three very favourable characteristic features of their application, namely, heat, wear, and corrosion resistance. Today's advanced engines and gas-turbines contain several parts which must work durably and reliably at 2000°C. The extraordinary wear resistance is very beneficial for bearings, packing (sealing) elements and ball-end operation. To illustrate the rate of their spreading their production in the Japanese market is valued at about $30 billion per year (1986 prices), and an estimated 6% increase per year is forecast [1]. However, the very favourable features are accompanied by difficulties associated with machining and mainly with grinding because of the high values of hardness and stiffness of the ceramics and the demand for the required accuracy and surface quality of the ground components.

Correspondence and offprint requests to: Professor A. G. Mamalis, Manufacturing Technology Division, National Technical University of Athens, 42 28th October Avenue, 106 82 Athens, Greece. E-mail: mamalis@central.ntua.gr

The present paper reports experimental results pertaining to the precision grinding of advanced ceramics by continuous wheel dressing based on the electrochemical principle. Problems encountered when grinding ceramics are described and theoretical considerations are outlined and compared with the experimental findings.

2. Fundamentals of Material Removal Processing for Advanced Ceramics

From the grinding point of view, ceramics belong to the hard and brittle type of materials, therefore, they can be machined by diamond grinding, or by polishing with free abrasive grains. The main difficulties of material removal are associated with the characteristic crystal structure of the ceramics which is covalent or ion-bonded consisting of atomic bonds, which differs from a metal structure which possesses free electrons. Aluminium oxide (Al_2O_3) for example, is an oxide ceramic, possessing covalent and ion bonding in a 4:6 ratio, while silicon carbide (SiC) is a non-oxide ceramic, covalent and ion bonded in a 9:1 ratio. The common feature of these bondings is that the outer electron shield is completely closed, and, therefore, because of the lack of free electrons, the ceramics are resistant to chemical influence, and are electrical insulators.

The physical and mechanical features of the most common oxide and non-oxide ceramics are shown in Table 1. Note that, the density of the ceramics is much smaller than that of steels, therefore, the interatomic distance is large, and the density of the electrons is small. Covalent bondings possess a large bonding energy (1.1×10^{-17} J atom^{-1}), which is nearly 1000 times larger than that of metallic bonding (1.5×10^{-20} J atom^{-1}). In such structures, the density of dislocations is small and their mobility is poor, leading to high values of hardness (*HV*) and extreme rigidity. The rigidity is also indicated from the high values of the Young's modulus, *E*, but is even more striking if the *E*/*HV* quotient is compared in ceramics and steels: in the case of high ductile materials the value *E*/*HV* is high, about 250, whereas in the case of the highly brittle ceramics it is only 20. The fracture toughness K_{Ic} or the stress intensity factors are also directly associated with rigidity, brittleness and/or cracking, and its values can be found in Table 1.

Table 1. Physical and mechanical characteristics of advanced ceramics.

	Density g cm^{-3}	Vickers hardness (HV)	Elasticity modulus E (GPa)	Fracture toughness K_{1c}, (MP $\sqrt{m}$)	Bending strength (MPa)	Thermal conductivity (W mK^{-1})	Stiffness (N mm^{-1})
Al_2O_3	3,8. . .4,2	16,5	344	4	304	25	360
ZrO_2	5,9	13	206	5	980	28	420
SiC	3,1. . .3,2	25	392	3,6	490	59	700
B_4C	2,5	26	300	7,5	700	29	400
Si_3N_4 HPSN	3,2	15	294	6	588	30	690
Si_3N_4 RBSN	2,5	17	345	6	750	17	215
C45	7,8	–	210	120		50	600

HPSN: hot-pressed Si_3N_4
RBSN: reaction-bonded Si_3N_4

Because of the large interatomic distance, the ceramics' surface energy is small (10–50 J m^{-2}), which indicates high brittleness.

From the characteristic material features, outlined above, it is evident that the material removal mechanism in the case of grinding of ceramics differs considerably from classical grinding theory. In the latter case, in so-called ductile-type grinding, the chip removal is accomplished by elasto-plastic change. In the brittle-type grinding of ceramics, the material removal from ceramics is carried out by crack formation, separation, and spalling of the material. The crack formation mechanism is shown in Fig. 1, see also [2], based on the point indentation of the material by a ball indenter with a small diameter; the characteristic Bousinesque stress distribution, which is produced by a sharp loading element with a small ball-shaped tool producing a compressive stress profile and a tensile stress field extending into deeper layers, develops under the surface, see Fig. 1. The six characteristic phases of the crack formation can be seen in the same figure. Initially, a plastic zone of small diameter is developed near the surface, see Fig. 1(a), whereas subsequently, owing to the developed tensile stress field, a small longitudinal crack initiates, see Fig. 1(b) and propagates as the indentation proceeds and increases in size, see Fig. 1(c). A decrease of the load results in reducing the size and/or closing the longitudinal crack owing to the compressive stresses prevailing, see Fig. 1(d). Subsequent decrease of the load results in the formation of transverse cracks owing to the lateral tensions (Fig. 1(e)). After unloading, because of the tensile residual stress field developed, the size of the lateral cracks increases leading to possible separation and/or spalling of the materials in the form of chips, see Fig. 1(f).

This metal removal mechanism with spall formation may be the governing chip formation mechanism in the precision grinding of ceramics; the particular effect on a precision ground ceramic is indicated in Fig. 2, see also [3]. Note, also, that, when grinding ceramics, it must be taken into account that the real depth of cut is larger than the assumed depth because the

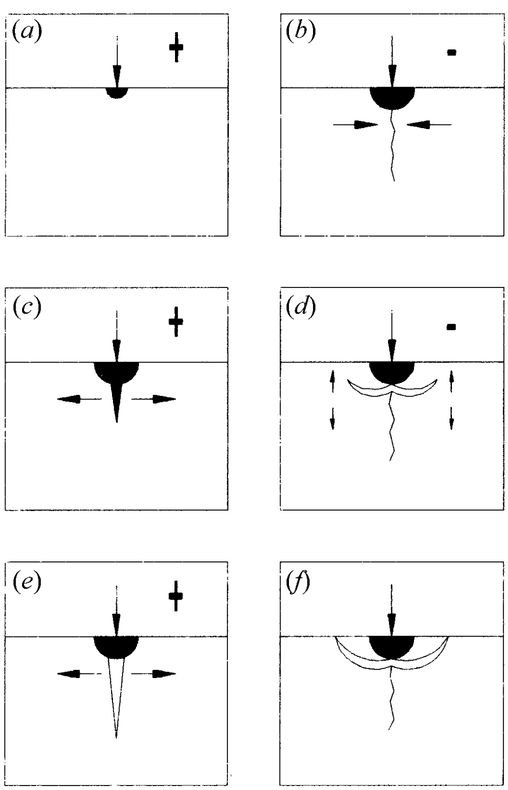

Fig. 1. Stages of crack formation under point indentation [2]. Permission to reproduce figures 1 & 2 from 'Grinding Mechanism for Ceramics' by S Malking and T W Hwang, Annals CIRP 1996 granted by CIRP.

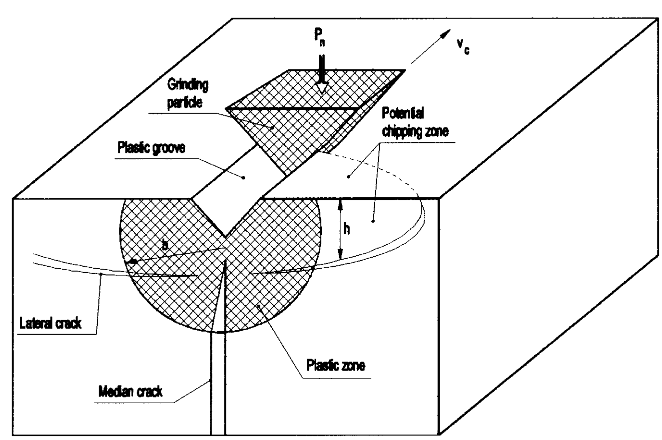

Fig. 2. Plastic zone and crack formation due to scratching by an abrasive grain [2]. Permission to reproduce figures 1 & 2 from 'Grinding Mechanism for Ceramics' by S Malking and T W Hwang, Annals CIRP 1996 granted by CIRP.

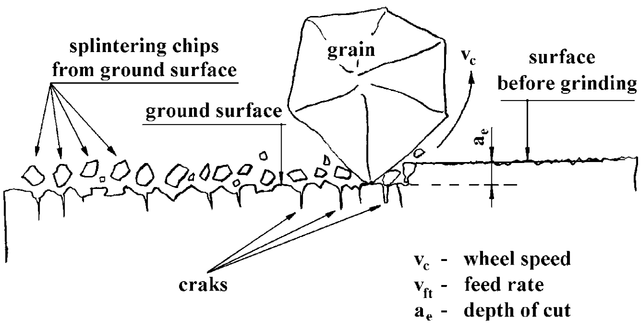

Fig. 3. Model of chip formation in grinding of advanced ceramics.

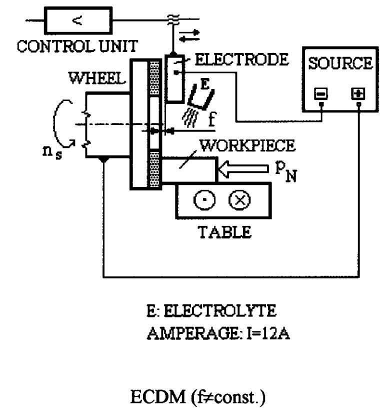

Fig. 5. A schematic diagram of the continuous electrolyte dressing equipment.

movement of the grains causes additional splintering leading to a larger depth of cut, see Fig. 3.

The main task in grinding ceramics is to define the conditions under which they can be ground economically with minimal crack formation. Economical considerations are provided by the grinding results shown in Fig. 4. In that respect, the precision grinding ratio for different materials with continuous dressing of the grinding wheel [4], was measured.

3. Experimental Results

The test material used was Al_2O_3 plates of size $30 \times 20 \times 10$ mm^3. The precision grinding machine was a WENDT WHE 90/2, operating with a constant force of 14 N. The cutting parameters employed were $v_c = 18$ m s^{-1} (wheel speed); $n_w = 46$ (double stroke min^{-1}); and $L = 50$ mm (stroke length). The grinding wheel was Wheel: 6A2ϕ200 × 20 × 1 × 50-SD-160/125-B-100. The continuous dressing of the wheel was performed electrolytically with additional equipment mounted on the grinding machine.

Our method, the ECDM process (electro-chemical-dressing-Miskolc), is related to a continuously operating wheel dressing, whose principle of operation can be traced back to Faraday's law, see Fig. 5 and [6]. The apparatus can be mounted on grinding machines on which the working surface is flat and the main spindle is insulated. The continuous dressing (conditioning) is carried out by an electrochemical process using a copper electrode, fitted to the wheel with an appropriate gap. Thus the metal-bonding material of the wheel is removed continuously and so the unchanged protrusion of the grains is ensured. Note, that the basis of the ECD process is the continuous dissolution of the metallic boundary of the grinding wheel. The electric current that flows between the copper electrode and the grinding wheel, through the electrolyte, breaks down the metallic boundary into ions and converts them into oxides and hydroxides. Thus, the protrusion of the grains increases considerably, which can be even larger than the grain size itself. The large chip dimension and the protruding grains ensure and maintain a very good grinding ability for the grinding wheel.

In order to establish the operating direct current for electrolytic continuous dressing, because it has an effect on the material removal rate, and the roughness and the grinding ratio, experiments were performed with a current range of 5–20 A, and the electrolyte rate was 8 l min^{-1}; the measurements obtained are shown in Fig. 6. From the measured characteristics, an average surface roughness, parallel and perpendicular to the field direction, was obtained, see Fig. 7.

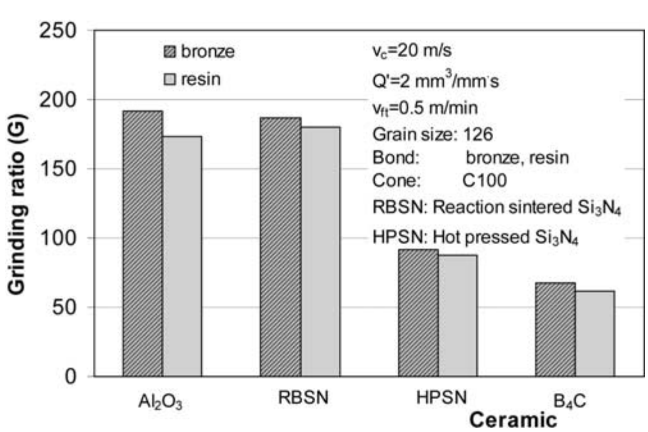

Fig. 4. Grinding ratio vs. grain size and concentration.

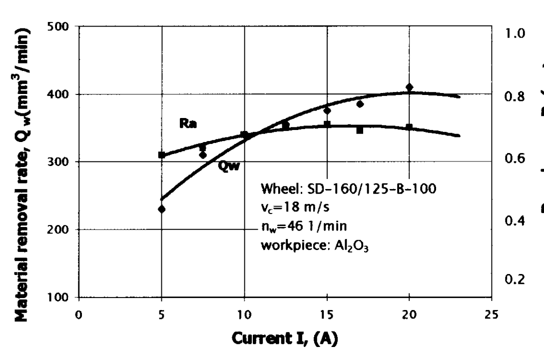

Fig. 6. Variation of material removal rate and surface roughness with dressing current when precision grinding Al_2O_3 ceramic using an ECDM dressed wheel.

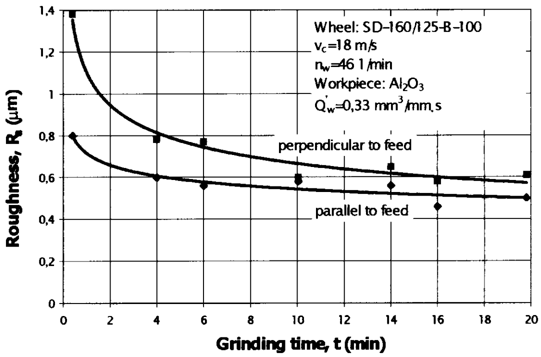

Fig. 7. Variation of surface roughness with grinding time when precision grinding Al_2O_3 ceramic using an ECDM dressed wheel.

4. Discussion

Grinding with diamond grains performed with continuous conditioning can be applied effectively for grinding ceramics. In Fig. 5, the variation of material removal rate and the variation of surface roughness with current are presented; from these measurements, a current larger than 12 A may be recommended, because the roughness of the material removal stabilises and the grinding ratio is also highest. Note that the productivity (material removal rate) is 2–3 times higher than in traditional grinding, whilst the application of a constant normal force may be also proved to be advantageous, because the output parameters of the grinding operation remained constant. Note, also that the material removal does not occur because of elasto-plastic deformation, but the governing mechanism is due to splintering and flaking, which is characteristic for hard and brittle materials, see the cracking mechanism shown in Figs 1–3. The plastic zone, shown in "b" of Fig. 2, may be considered to be very small in relation to the depth of cut and, therefore, its effect is almost negligible. Existing formulae for calculating the thickness of the damaged subsurface layer can be found in [7]. Note that, the performance of the Al_2O_3 cutting tool inserts used was good, and did not extend the existing meridional cracks in the material.

According to both experimental and industrial experience, ceramics can be ground well with a diamond wheel. The G ratio of oxide ceramics can reach 200, that of nitride ceramics is about 100, and that of B_4C is a maximum 50, see Fig. 4, for precision grinding, 150 (mesh) grain size is recommended [8]. The wheel's circumferential speed is optimal in the range 18–25 $m\,s^{-1}$ [4]; it is advantageous to grind with a constant force, because the possibility of crack formation is then smaller.

The characteristics of surface integrity involve surface roughness, contact temperature, and the specific energy. From Figs 6 and 7, it may be concluded that, although reduction of the grain size is an effective method for improving the roughness, because of splintering, which is due to brittleness, the roughness is always slightly greater than in the case of ductile materials. Note that, after the initial mechanical dressing of the wheel, which was carried out with a SiC wheel, the roughness slightly decreased, however, after 15–20 min of grinding no significant changes occurred.

5. Conclusions

Summarising the main features of the results reported, pertaining to the precision grinding of brittle ceramic materials using an electrochemically dressed wheel, it may be concluded that the continuous wheel dressing, employing the ECDM process, can be effectively applied in precision grinding of ceramics. The material removal can increase significantly and an improved surface integrity is obtained. However, additional experimental work is underway to defining the threshold force and the critical depth of cut, under which ceramic surfaces may be ground without crack formation.

Acknowledgement

With kind thanks to CIRP Annals 1996 for granting permission to reproduce Figure 2. 'Plastic zone and crack formation due to scratching by an abrasive grain' in this journal.

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Notation

b	plastic zone radius
E	Young's modulus
G	grinding ratio
h	depth of cut
HV	hardness
I	dressing current
K_{Ic}	fracture toughness
l	length
n_w	double stroke
P_n	force
Q_w	material removal rate
R_a	roughness
t	grinding time
v_c	wheel speed
v_f	feed speed