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Bed thickness and particle size distribution in three-body abrasion

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Abstract

Three-body abrasion is an important abrasive process in the surface finishing of ceramics and glasses. Generally it is assumed that material removal is achieved by rolling (indenting) particles. In this study, the removal rate of glass has been determined using SiC slurry as the abrasive and Cu as counter material. For large abrasive particle sizes the removal rate remains constant with time, while for small abrasive grain sizes it decreases. This is attributed to fracture and blunting of the abrasive particles. Displacement measurements revealed a decreasing ratio of bed thickness and mean abrasive particle size with particle size. The results are related to the particle size distributions of the abrasive powders used. On the basis of the particle size distributions, it can be concluded that the actual particle size distribution between workpiece and backing plate is different from the distribution of the slurry not lodged between both plates.

Keywords: Three-body abrasion; Bed thickness; Particle size; Brittle materials; Glass

1. Introduction

Three-body abrasion is an important method for surface finishing of ceramics and glasses. It is used in the manufacturing of optical glasses (e.g. lenses, prisms and mirrors) and cathode ray tubes. Ceramics and glasses are hard and difficult to shape and therefore abrasive machining contributes significantly to the production costs of brittle components. For this reason, it is important to have more fundamental knowledge of the three-body abrasion process.

Two different material-removing mechanisms are accepted [1,2]: (a) cutting: abrasives, embedded in the backing plate, scratch the substrate, thereby removing material; (b) rolling: abrasives leave a trace of indentations on the workpiece and each indentation may lead to chipping.

Fang et al. [1] studied the movement patterns of abrasive particles in three-body abrasion. They concluded that the morphology of the particle determines whether the particle will roll or slide. In either case, the removal rate might be dominated by plastic deformation or by fracture.

Plastic deformation is favoured in the following cases [3]: (a) the load on the abrasive particle is small, i.e. for small abrasive particles or low loads applied, (b) the abrasive is blunt or blunts during grinding, (c) the ratio of fracture toughness to hardness of the material is high.

In the fracture regime, the removal process is often seen as a sequence of indentations [4–7]. Lawn and Wilshaw [8] described how crack formation will proceed under point indentation. Indentation fracture is favoured when [3]: (a) the load on the abrasive particle is high, i.e. for large particle sizes or high loads applied; (b) the abrasive is sharp or remains sharp, because it fractures during contact with the workpiece; (c) the ratio of fracture toughness to hardness of the material is low.

Three-body abrasion of glass with e.g. SiC is assumed to be fracture controlled. The material is removed by rolling, indenting particles. The removal rate Z was found to depend linearly on the applied pressure p , to increase non-linearly with increasing particle sizes [4,7,9] and to increase linearly with the relative velocity v between workpiece and backing plate [4,10]. The following equation for the removal rate was derived [4]

$$Z = \alpha n \frac{f_i^{3/4} E_w^{5/4}}{L_{m,c} K_{lc,w} H_w^2 p v} \quad (1)$$

A list of all symbols used in this manuscript is given in Appendix A.

Because the load per particle f_i is inversely proportional to the total number of abrasives between workpiece and lapping plate, and this number is proportional to $L_{m,c}^{1/2}$, it follows from Eq. (1) that the removal rate is in fact proportional to $L_{m,c}^{1/2}$.

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The first measurements on bed thickness were probably performed by Phillips et al. [7]. They determined the bed thickness b for three abrasive systems (glass/water, silica/water and silica/decanol) and concluded that the bed thickness is roughly twice the mean particle size. This implies that only particles twice the mean size are load carrying. According to their rotation model, these particles are forced to rotate between both the workpiece and the backing plate. They defined a parameter b as

$$b = L \cos \theta_a \quad (2)$$

Since it is not possible to measure the angle of attack directly, θ_a was estimated on the basis of the drag coefficient [7]. Other investigators [2,4] derived equations for the bed thickness by making an assumption for the distribution of the particle size L . The mean particle size L_m of this distribution can be used in Eq. (1). For example, Buijs [4] assumed $\phi(L)$ to be Gaussian.

This paper describes measurements of the bed thickness under various conditions for a glass–SiC/water–copper abrasive system. To gain information about the size of the load carrying particles and the amount of load carrying particles, the bed thickness was determined and related to the particle size distributions of the abrasive powders.

2. Materials and methods

2.1. Equipment

Three-body abrasion tests have been done under various conditions using a modified pin-on-disk wear testing apparatus [11]. The pin was replaced by a holder for the glass sample and the disc by a Cu cup (Fig. 1). Unloaded, the counterweight is in balance with the motor and the sample holder (including the sample). The cup filled with SiC/water slurry and an applied load on top of the motor driving the sample holder then constitutes a three-body abrasive system. The bottom of the cup act as backing plate. The distance between sample and backing plate is called the bed thickness.

Fig. 1. Schematic representation of the equipment used. (A) Side view; (B) top view; (C) backing plate; (1) backing plate; (2) motor; (3) total load applied; (4) sample holder and sample; (5) displacement transducer; (6) counterweight; (7) furnace; (8) revolution counter; (9) strain gauges.

To avoid sedimentation of the abrasive particles in the middle of the cup, a cylinder was placed in the centre of the cup. The copper cup will further be referred to as the backing plate. A displacement transducer registered, as function of time, the displacement of the bridge and therefore of the sample holder attached to it. The slurry was not replenished during an experiment.

2.2. Materials

The backing plate was made of copper with a Vickers hardness of 940 MPa (3 N, 30 s). The samples with a diameter of 2 cm were made of B270 glass (Table 1). The slurry consisted of SiC particles in distilled water in a weight ratio of 1:4. Four different SiC powders were used. The mean diameters of the powders (Table 2) were determined with a particle size analyzer (Sedigraph 5000D). Because of the incapability of the Sedigraph 5000D for measuring sizes above 100 μm , the particle size distribution of SiC F150 was determined with a different apparatus (Shimadzu SA-CP4). However the accuracy for large sizes is limited.

2.3. Type of experiments and data analyses

Experiments were made with a relative velocity v between sample and backing plate of 0.26 m s^{-1} . The total load applied p was varied in the range 1–4 N.

The displacement registered by the displacement transducer is caused by (a) material removal, (b) fracture of the abrasives and/or (c) wear of the backing plate. Using interchangeable Cu plates the wear of copper was measured by weighing the plates before and after lapping for 1 h. It was

Table 1
Chemical composition and physical properties [4] of B270 glass

Chemical composition	Physical properties
65 wt% SiO_2	$\rho = 2.51 \text{ (g cm}^{-3}\text{)}$
12.5 wt% ZnO	$E = 75.7 \pm 1.0 \text{ (GPa)}$
12 wt% Na_2O	$\nu = 0.223 \pm 0.004$
7.5 wt% B_2O_3	$H_v = 5.8 \pm 0.2 \text{ (GPa)}$
3 wt% Al_2O_3	$K_{Ic} = 0.89 \pm 0.09 \text{ (MPa m}^{1/2}\text{)}$

Table 2
Mean diameters and standard deviations of SiC powders used ($\rho = 3.2 \text{ g cm}^{-3}$)

SiC ^a	Mean diameter (μm)	Sample standard deviation (μm)
SiC F150 ^b	113.7	40.1
SiC F280	36.0	11.9
SiC F400	16.2	4.5
SiC F600	8.3	0.4

^a The designation for the SiC powders is given according to the FEPA-standard: $L_m \approx 440869.67 \text{ (FEPA-no)}^{-1.67}$.

^b The particle size distribution of SiC F150 was determined with a centrifugal particle size analyzer (Shimadzu SA-CP4) with an UV-light source.

Fig. 2. SEM photo of the surface of a copper plate after abrasion ($p = 3$ N, $v = 0.26$ m s⁻¹) with SiC F150.

Fig. 3. Schematic representation of the abrasive process: d , thickness of glass sample; b , bed thickness; h_0 , reference height; $H(t)$, height at time t ; $d - \int Z dt$, removed height of glass sample.

found that the wear rate was about 1 or 2 $\mu\text{m h}^{-1}$ at $v = 0.26$ m s⁻¹ and $p = 9.6$ kPa for SiC F150. Wear of the backing plate is therefore negligible with respect to the removal rate of glass. Because of this very low wear rate, it is assumed that the mechanism of copper wear is dominated by plastic deformation. Fig. 2 shows an SEM photo of the surface of the copper plate after abrasion. Almost no embedded particles were found.

The bed thickness is given by (Fig. 3)

$$b(t) = H(t) - H_0 + \int_0^t Z dt \quad (3)$$

During the experiment, $H(t) - H_0$ was measured as was the thickness change $\int Z dt$ of the glass sample.

The various SiC powders were examined with SEM and a particle size analyzer (Sedigraph 5000D) before and after lapping.

3. Results

Fig. 4 shows the particle size distribution before and after lapping for 30 min for two different grit sizes.

The results of the three-body abrasion experiments show that the removal rate Z decreases in time, except for SiC F150

(Fig. 5). Fig. 6 shows the experimentally determined values for the bed thickness as a function of time for the four different particle size distributions. Note that the experiments were repeated several times.

Fig. 7 shows a SEM photo of an abraded glass surface. The mechanism of material removal of glass is assumed to be fracture controlled.

Fig. 4. (A) Particle size distribution of SiC F150: (a) before three-body abrasion, (b) after three-body abrasion for 30 min. (B) Particle size distribution of SiC F280: (a) before three-body abrasion, (b) after three-body abrasion for 30 min.

Fig. 5. The removal rate as a function of time for various SiC powders ($p = 9.6$ kPa, $v = 0.26$ m s⁻¹): The experimental data points are due to three independent experiments and the line drawn represents the fit $Z = at^{-b}$.

(a)

(b)

Fig. 6. (a) Bed thickness b_{exp} as a function of time for F150 and F280 ($p = 9.6 \text{ kPa}$, $v = 0.26 \text{ m s}^{-1}$). Different markers for the same particle size indicate independent experiments. (b) Bed thickness b_{exp} as a function of time for F400 and F600 ($p = 9.6 \text{ kPa}$, $v = 0.26 \text{ m s}^{-1}$). Different markers for the same particle size indicate independent experiments.

4. Discussion

The discussion on the transition between ‘ductile’ and ‘brittle’ behaviour of materials is rather complicated. Atkins [12] argues that at a small enough scale any material can behave in a ductile fashion. The transition takes place at a critical depth of cut, depending on material properties. On

Fig. 7. SEM photo of glass surface after abrasion ($p = 2 \text{ N}$, $v = 0.29 \text{ m s}^{-1}$) with SiC F280.

the basis of Atkins’ theory the critical depth of cut h can be estimated by

$$h \sim \left(\frac{K_{\text{Ic}}}{H/3} \right) \approx 0.15 \text{ } \mu\text{m} \quad (4)$$

Sedigraph measurements showed that the range of debris sizes is $0.5\text{--}10 \text{ } \mu\text{m}$. This indicates that the mechanism of glass wear is indeed mainly fracture controlled.

For calculation of the bed thickness b with Eq. (3), the removal rate Z has to be known. The removal rate for SiC F150, with the largest mean particle size, was almost constant in time (Fig. 5). The average removal rate was calculated from all the data points measured and this value has been used in Eq. (3). The removal rates for the other particle sizes decrease with time (Fig. 5). They can be approximated by power functions ($Z = at^{-b}$). These functions are used for determining the bed thickness as a function of time (Figs. 6(a) and (b)). The same tendencies have been found for the other loads applied in the range $1\text{--}4 \text{ N}$.

In contrast with what is described above, other investigations showed a constant removal rate in time [4,13]. The slurry in the experiments described above was not replenished and this could be an explanation for the difference observed. Since it is known that smaller particles have higher strengths than larger particles [14,15], it is assumed that SiC F150 particles fracture during grinding and therefore remain sharp, while the finer abrasives become blunt during three-body abrasion. The particle size distributions of the slurries both before and after lapping are given in Fig. 4. Fig. 4(a) shows that the particle size distribution of SiC F150 shifts to smaller particle sizes during three-body abrasion, which is consistent with the assumption that SiC F150 particles fail during grinding. For the other abrasives, the average particle size remains approximately constant during three-body abrasion, as shown for SiC F280 in Fig. 4(b).

From Fig. 6, it is seen that the bed thickness is almost constant in time for SiC F280, SiC F400 and SiC F600,

Table 3
Bed thickness and mass percentage load carrying particles for various abrasives

SiC	L_m (μm)	b_{exp} (μm) ($t=0$)	b_{th} (μm)	b/L_m	Mass percentage load carrying particles
F150	113.7	170.0	302	1.5	1.0–3.5
F280	36.0	75.1	94	2.1	1.5
F400	16.2	21.0	39	1.3	10.0
F600	8.3	9.5	10	1.2	25.0

L_m is the mean particle size, b_{exp} the initial bed thickness measured at $t=0$ and b_{th} the theoretical bed thickness calculated on the basis of Eq. (5).

Fig. 8. Particle size distribution for SiC F400 after 30 min lapping: (a) from slurry between sample and backing plate, (b) from slurry not lodged between sample and backing plate.

whereas for SiC F150, a decreasing bed thickness was found. The mass percentage load carrying particles is estimated by the amount of material larger than the bed thickness. Table 3 shows an increase in the mass percentage of load carrying particles with decreasing (average) particle sizes. This behaviour gave rise to the idea that the actual particle size distribution between workpiece and backing plate is probably different than the original particle size distribution even at the start of the experiment. This was confirmed by measurements with SiC F400. Samples of the slurry were taken near the centre of the backing plate just outside the workpiece and from the slurry under the workpiece. Indeed the average diameter of the abrasives between sample and backing plate is smaller than the average particle size of the original distribution. It is also smaller than the average particle size of the slurry which was not lodged between workpiece and backing plate (Fig. 8).

The value for the average particle size under the sample $L_{m,s}$ is smaller than the L_m of the original distribution. This results in a larger value for $b/L_{m,s}$ than for b/L_m which is given in Table 3. The ratio of the bed thickness and mean particle size is not necessarily 2, as described by Philips et al. [7], but depends on the size of the grains. Dwyer-Joyce et al. [16] and Williams et al. [17] discuss that, besides the effect of particle morphology [1], for a given bed thickness and range of abrasive sizes, some particles will roll and some will slide. They suggest that rolling occurs when the ratio of the size of the load carrying particles and the bed thickness

is less than about 2. In the experiments described in this manuscript, the bed thickness was not prescribed, but determined by the process and measured. It showed a range of ratios of the mean size of the particles and bed thickness between 0.5 and 0.9, depending on the particle size.

Buijs et al. [4] described a model to predict the bed thickness for a given particle size distribution ($L_{m,\sigma}$), applied pressure p , number of SiC particles per unit volume of slurry N_v and load per particle f_i . Assuming the particle size distribution to be Gaussian, the equation Buijs et al. [4] derived was

$$b_{\text{th}} \left[1 + \operatorname{erf} \left(\frac{L_m - b_{\text{th}}}{\sqrt{2}\sigma} \right) \right] = \frac{p}{f_i N_v} \quad (5)$$

The load per particle can be calculated on the basis of the surface roughness of the workpiece [4]. The bed thicknesses calculated are given in Table 3. The experimental bed thicknesses compare favourably with those of the theoretical model. The similarity however is probably fortuitous since the particle size distribution is more probably log-normal instead of normal [10].

On the basis of the surface roughness [4], the load per particle f_i can be estimated. This load f_i can also be estimated from the slope of the removal rate Z vs. the velocity v or pressure applied p using Eq. (1). An useful approximation of the number of load carrying particles N_c is the ratio of the pressure applied p and the pressure per particle p_i [2,4]

$$N_c = \frac{p}{p_i} \quad (6)$$

The values for the load per particle p_i and the number of load carrying particles calculated from the R_z data, from Z vs. v or from Z vs. p , are given in Table 4. The three estimations correspond very well with each other. It would be interesting

Table 4

The load per particle p_i and the number of load carrying particles N_c for the surface roughness R_z and removal rate Z for $p = 3 \text{ N}$

SiC	From R_z data		From Z vs. p		From Z vs. v	
	p_i	N_c	p_i	N_c	p_i	N_c
F150	0.44	7	0.21	14	0.30	10
F280	0.11	27	0.072	42	0.10	30
F400	0.030	100	0.014	214	0.019	158
F600	0.0062	500	0.0046	652	0.0064	469

to compare the load per particle with load necessary to fracture the particle. This will be one of the subjects in a more detailed investigation on three-body abrasion of glass.

5. Conclusions and recommendations

The bed thickness of a three-body abrasive system can be determined in a relatively simple way under various conditions. Three-body abrasive experiments with non-replenished slurry showed a constant removal rate for large abrasive grain sizes and decreasing removal rate with time for small grain sizes. From sedigraph analyses it became clear that the larger particles fracture and thus remain sharp, resulting in a constant removal rate. The smaller particles do not fracture, but become blunt, resulting in a decreasing removal rate.

The ratio of bed thickness and mean particle size is dependent on the particle size; smaller ratios are found for smaller abrasive grain sizes. The actual particle size distribution between workpiece and backing plate is not identical to the original size distribution. In future modelling this effect has to be taken into account. Also the influence of various parameters on the number of load carrying particles and on the load per particle has to be studied further. Combining these studies with measurements on the bed thickness under various conditions, with the possibility to replenish the slurry or not, it should be possible to improve the modelling of three-body abrasive processes.

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Appendix A. Nomenclature

b	bed thickness (μm)
b_{exp}	experimental bed thickness (μm)
b_{th}	theoretical bed thickness (μm)
d	thickness of sample (μm)
f	load (N)
f_i	load per particle (N)
h	depth of cut (μm)
n	number of indenting points per particle
p	pressure applied (N m^{-2})
p_i	pressure per particle (N m^{-2})
t	time (min)
v	velocity between workpiece and backing plate (m s^{-1})
E_w	Young's modulus workpiece (GPa)
H	height (μm)
H_0	reference height (μm)

H_v	Vickers hardness (MPa)
H_w	hardness workpiece (GPa)
$K_{\text{Ic,w}}$	fracture toughness of workpiece ($\text{MPa m}^{1/2}$)
L	particle size (μm)
L_m	mean particle size (μm)
$L_{m,c}$	mean particle size of load carrying particles (μm)
$L_{m,s}$	mean particle size under sample (μm)
N_c	number of load carrying particles
N_v	number of particles per unit volume
R_z	surface roughness (μm)
Z	removal rate ($\mu\text{m min}^{-1}$)
α	shape factor
θ	angle of attack (deg)
ν	Poisson's ratio
ρ	density (g cm^{-3})
σ	standard deviation (μm)

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