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Citation for published version (APA):
Verspui, M. A., & With, de, G. (1997). Three-body abrasion : influence of applied load on bed thickness and particle size distribution in abrasive processes. *Journal of the European Ceramic Society*, *17*(2-3), 473-477. https://doi.org/10.1016/S0955-2219(96)00148-3

DOI:
10.1016/S0955-2219(96)00148-3

Document status and date:
Published: 01/01/1997

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Download date: 16. Nov. 2023

Journal of the European Ceramic Society 17 (1997) 473–477
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0955-2219/97/$17.00
PII: S0955-2219(96)00148-3

Three-Body Abrasion: Influence of Applied Load on Bed Thickness and Particle Size Distribution in Abrasive Processes

M. A. Verspui & G. de With*

Eindhoven University of Technology, PO Box 513, 5600 MB, Eindhoven, The Netherlands

(Received 15 September 1995; accepted 22 July 1996)

Abstract

Lapping experiments at various loads showed a decreasing bed thickness with increasing applied loads. Comparison of these results with the particle size distribution, measured before and after abrasion, revealed that at higher applied loads more particles will fracture during abrasion. This also may be the cause of the slightly decreasing bed thickness in time. A quantitative interpretation of the particle size distributions was not possible, since there was a significant amount of glass present in the slurry. Nevertheless, it was clear that the actual particle size distribution under the workpiece is different from the original particle size distribution. © 1996 Elsevier Science Limited.

Introduction

Abrasive finishing processes of brittle materials are known to be relatively expensive and time-consuming. To make abrasive processes as efficient as possible, it is therefore essential to perform fundamental research on this subject. However, the discussion on abrasive processes is difficult since so many parameters play an important role.

In three-body abrasion or lapping the material-removing mechanism and the particle movement (either rolling or sliding) will depend on the particle morphology and size, applied normal load, surface hardness and the hardness ratio of the two mating surfaces.[1,2] In this regard changes in particle size and/or shape turn out to be important. Moreover, the bed thickness, defined as the distance between sample and backing plate, is dependent on particle size and applied load.[3] Buijs *et al.* estimated the bed thickness from:[4]

$$b_{\mathrm{th}}[1 + \mathrm{erf}(\frac{L_{\mathrm{m}} - b_{\mathrm{th}}}{\sqrt{2}\sigma})] = \frac{p}{f_{\mathrm{i}} N_{\mathrm{v}}} \qquad (1)$$

where

b_{th} = theoretical bed thickness [m]
L_{m} = mean particle size [m]
σ = standard deviation of particle size [m]
p = applied pressure [Pa]
f_i = load per particle [N]
N_{v} = number of particles per unit volume [m^{-3}].

Buijs *et al.* assumed that the particle size distribution is normally distributed. Values for the load per particle f_i can be obtained from surface roughness data, since:[4]

$$R_z \approx \alpha \frac{E_{\mathrm{w}}^{1/2}}{H_{\mathrm{w}}} f_i^{1/2} \qquad (2)$$

with

R_z = average peak to valley height [m]
E_{w} = Young's modulus of the workpiece [Pa]
H_{w} = Hardness of the workpiece [Pa]
α = $0{\cdot}71\ (\cot\psi)^{1/3}$ = a constant depending on the shape, where 2ψ is the included angle.

When particles fracture during lapping, the bed thickness will decrease. Previously, experiments have been described for determining the bed thickness with a Pin-On-Disk wear testing apparatus in a glass–SiC/water–copper system.[5] The various SiC powders used were examined with SEM and a particle size analyzer (Sedigraph 5000D) before and after lapping. The three-body abrasion experiments with non-replenished slurry showed a constant removal rate for large grain sizes and decreasing removal rate with time for small grain sizes. The sedigraph data suggested that the larger particles were fractured and thus remained sharp, resulting in a constant removal rate. The smaller particles did not fracture, but were assumed to blunt during grinding. In these experiments, the bed thickness was measured for a single pressure of 9·6 kPa and the results showed that 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 particle size distributions showed that the actual size distribution

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*Also affiliated with Philips Research Laboratories, Prof. Holstlaan 4, 5656 AA, Eindhoven, The Netherlands.

was different from the original particle size distribution, where the actual size distribution refers to the particle size distribution under the workpiece.

This present paper reports on three-body abrasion experiments at various loads, to investigate the influence of the applied load on bed thickness and particle size distributions.

Three-Body Abrasion Experiments

Three-body abrasive experiments were done using a Pin-On-Disk wear apparatus, as described before.[5] The backing plate was made of copper with a Vickers hardness of 940 MPa (3 N, 30 s). The samples were made of B270 glass (diameter 2 cm). The chemical composition and material properties of B270 glass are given in Table 1. The slurry consisted of SiC F280 particles in distilled water in a weight ratio of 1 : 4. The mean diameter of the original SiC F280 particles is 36·0 μm (σ = 11·9 μm). The applied pressures were, respectively, 5·92 kPa, 9·12 kPa and 12·32 kPa. The relative velocity v between sample and backing plate was 0·26 m/s. The bed thickness was determined at various loads as described before.[5] A schematic representation of the apparatus is given in Fig. 1.

The particle size distribution of the abrasive SiC F280 was measured before and after lapping. To compare the actual particle size distribution with the original one, samples of the slurry were taken near the centre of the backing plate (just outside the workpiece) and from the slurry under the workpiece (see also Fig. 1).

Results

In Fig. 2 the removal rate of the glass samples is given for various pressures. These results have been used for the determination of the bed thickness. In Table 2 the coefficients and the correlation factors are given of the power functions fitted through the measured data points of Fig. 2. Figure 3 represents the bed thicknesses measured for various pressures. Every point in this figure is the mean of three individual measurements. The mean value for the bed thickness at each applied pressure is given in Table 3. Also the estimated bed thickness on the basis of eqn (1) is given.

In Table 3 the d_{50} values of the particle size distribution of the slurry are also given. In Table 4 these values are compared with the d_{50} values of the samples taken from under the workpiece and from a place near the workpiece. In Fig. 4 four particle size distributions are given of a slurry after abrasion at a pressure p of 9·12 kPa; a. the particle size distribution of the original powder, b. particle size distribution of the unseparated slurry, c. of the slurry under the workpiece and d. of the slurry near the workpiece. See also Fig. 1 for a clarification of the differences between the various size distributions given.

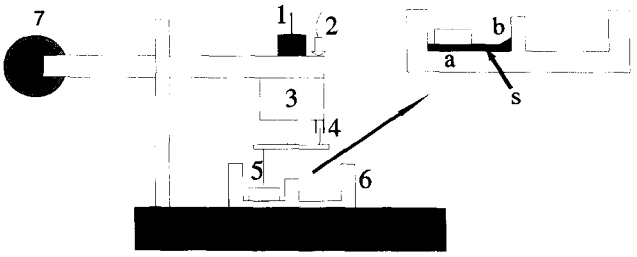

Fig. 1. Schematic representation of the Pin-On-Disk wear apparatus used for the lapping experiments; 1. applied pressure, 2. displacement transducer, 3. motor, 4. revolution counter, 5. sample holder + glass sample, 6. backing plate, 7. counterweight. In the close-up of the sample holder; s. slurry (unseparated), a. slurry under the workpiece, b. slurry near the surface.

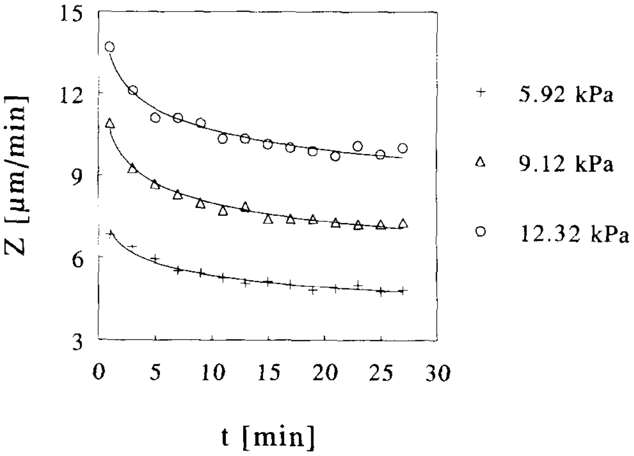

Fig. 2. Removal rate of B270 glass versus time at various pressures. Abrasive powder used is SiC F280, v = 0·26 m/s.

Table 1. Chemical composition and physical properties of B270 glass[3]

Chemical composition	*Physical properties*
65 wt% SiO_2, 12·5 wt% ZnO,	ρ = 2·51 (g/cm^3)
12 wt% Na_2O, 7·5 wt% B_2O_3,	E = 75·7 ± 1·0 (GPa)
3wt% Al_2O_3	ν = 0·223 ± 0·004 (–)
	H_v = 5·8 ± 0·2 (GPa)
	K_{Ic} = 0·89 ± 0·09 (MPa m$^{1/2}$)

Table 2. Coefficients for the power function $Z = a_0 . t^{a_1}$ describing the removal rate Z as a function of time t for SiC F280 at various pressures p

p (kPa)	a_0	a_1	R_{val}
5·92	7·03	−0·12	0·98
9·12	10·68	−0·13	0·99
12·32	13·45	−0·10	0·98

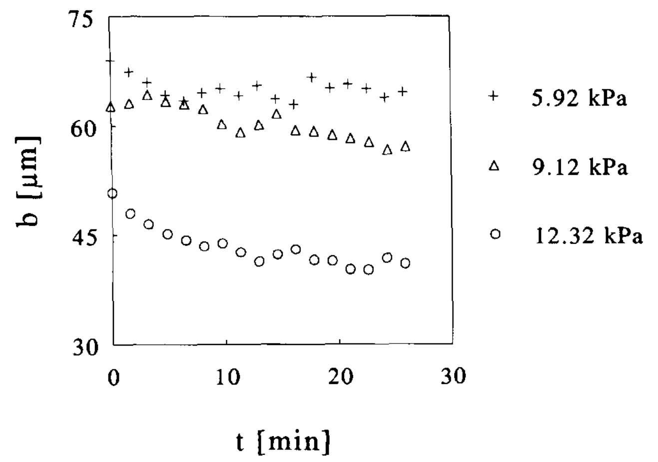

Fig. 3. Bed thickness versus time at various pressures. Abrasive powder used is SiC F280, v = 0·26 m/s. The points given in this figure are the means of three individual measurements.

Discussion

Figure 3 shows that the bed thickness decreases as the applied load increases. Moreover, there is a slight decrease of bed thickness with time. Three effects are probably involved. Firstly, at higher loads more particles fracture during abrasion and the mean particle size decreases. Secondly, at higher loads the penetration depth will increase in one of the two mating surfaces. And finally, at higher applied loads fewer particles will penetrate between the sample and backing plate. This effect is illustrated in Fig. 4. This figure shows that the actual particle size distribution (under the workpiece) is different from the original particle size distribution, as was already demonstrated in an earlier paper.[5] The d_{50} values given in Table 4 show that the median particle size under the workpiece is smaller than that near the workpiece and smaller than the median diameter for the original and unseparated abrasive powders. This means that the largest particles in a slurry will be pushed sideways by the workpiece. This effect is more important at higher loads, because the differences between the actual and original distribution are larger for higher loads. Moreover, it takes a certain time to reach a new distribution, consistent with the slight decrease in bed thickness with time.

From the observations described above it can be concluded that bed thickness is not determined by the largest particles in the original particle size distribution. This conclusion makes future calculations on the number of load-carrying particles difficult, since the number and size of load-carrying particles will be determined, apart from the the particle size distribution, by the applied pressure. In modelling abrasive processes one has to be aware of the possibility of differences between the actual particle size distribution and the original one. Figure 4 shows, consistent with earlier work,[6] that the particle sizes are not normally distributed. Assumptions about the size distributions should be therefore considered with some care. It should also be kept in mind that during abrasion particle size and shape changes occur.

Possibly, the considerations given above explain the contradiction between the theoretical and experimentally determined bed thickness as given in Table 3. Buijs *et al.* assumed that the particle size is normally distributed, which it is not. They did not take into account any particle changes during abrasion. Changes in particle size will have influence on the mean particle size L_m and on the number of particles per unit volume N_v in eqn (1). Particle shape changes will also affect the estimation for the load per particle f_i in eqn (1). A mistaken value for the included angle of the particle or a change in the included angle of 10° introduces a failure of 10–15% in the load per particle f_i. Buijs reported an angle close to the Vickers

Table 3. The calculated bed thickness b and theoretical bed thickness b_{th} at various pressures. Also the median diameter d_{50} and the standard deviation σ of the particle size distribution are given

p [kPa]	*b (μm)*	*b_{th} (μm)*	*d_{50} (μm)*	*σ (μm)*	*Vol% glass in SiC*
5·92	65·2	93·0	36·7	17·3	5·2
9·12	60·6	90·5	34·7	19·1	7·3
12·32	43·3	90·0	33·7	18·7	9·6

Table 4. Comparison of particle size distributions of the slurry under and near the workpiece

	Slurry unseparated		*Slurry under workpiece*		*Slurry near workpiece*	
p (kPa)	*d_{50} (μm)*	*σ (μm)*	*d_{50} (μm)*	*σ (μm)*	*d_{50} (μm)*	*σ (μm)*
5·92	36·7	17·3	34·0	17·9	38·1	16·8
9·12	34·7	19·1	32·2	17·8	37·4	18·1
12·32	33·7	18·7	31·0	18·2	36·3	16·4

indenter (140°). For SiC F280 an angle of 104·0° ($\sigma = 28{\cdot}7°$) was determined by manual angle measurements on 23 particles. In the calculations of the theoretical bed thickness as given in Table 3 an included angle of 105° was assumed and the d_{50} value of the original size distribution was used.

Quantitative analyses of the relation between bed thickness and particle size are not possible with the results presented in Fig. 4 and Table 4. The amount of glass in the slurry after abrasion is about 5–10 vol%. The glass chips having a diameter assumed to be smaller than the mean diameter of SiC, will influence the lower part of the size distribution significantly. The Sedigraph results can only be used for qualitative analyses. For a more accurate measurement of the particles size after abrasion it is necessary to remove the glass from the slurry. So far no separation technique has been found to accomplish this. The moment this problem is solved, it probably will be more realistic to use in an appropriately modified eqn (1) the mean particle size of the actual particle size distribution, thus of the powder under the workpiece without glass.

The same experiments described above for SiC F280 have been performed for SiC F400 with a mean diameter of 16·2 μm. At an applied pressure of 5·92 kPa the bed thickness is almost constant with a value between 10 and 20 μm. For the other applied pressures the bed thickness is mainly decreasing in time, from ± 20 μm to ± 5 μm after abrasion. The decrease in the bed thickness may point to significant changes in particle size, although we assumed before that this is not likely to happen for the smaller particle sizes. To resolve this matter, the degradation behaviour of particles in abrasive processes will have to be studied.

Conclusions and Recommendations

In a three-body abrasive system with non-replenished slurry, the removal rate will decrease with time and can be described by a power function. The removal rate increases with increasing load.

The bed thickness depends on the particle size and on particle degradation behaviour, but it also depends on the applied load. With increasing load, the bed thickness decreases. Probably other factors, e.g. penetration depth, play an important role. There is a significant discrepancy between the experimentally determined bed thickness and the theoretical bed thickness. It should be investigated whether this difference is mainly caused by incorrect assumptions on particle size and shape, by particle size changes during abrasion or by both.

The particle size distribution measurements of the slurry are disturbed by the presence of glass pieces and therefore the distributions can only be analyzed in a qualitative manner. Nevertheless, the results show that there is a difference in particle size between the original slurry and the slurry under and near the workpiece. These differences become larger if the load increases. But, in all cases the median particle diameter is smaller for the slurry under the workpiece than for the slurry near the workpiece or the original slurry. This can only mean that the workpiece pushes the larger

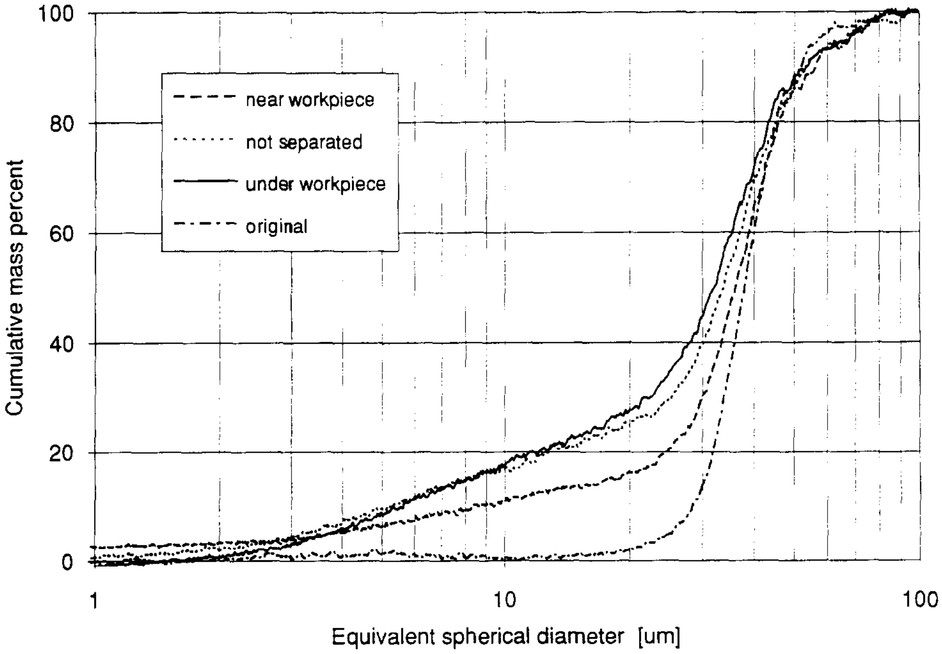

Fig. 4. Particle size distribution of the SiC F280 powder after three-body abrasion determined with a Sedigraph 5000D; a. original abrasive powder; b. slurry not separated; c. slurry under the workpiece (track) and d. slurry near the workpiece. The applied pressure was 9·12 kPa.

particles sideways. So, the large particles do not contribute to the bed thickness.

More experiments on the accurate measurement of bed thickness in relation to particle size distributions are necessary. It is necessary to remove the glass completely from the slurry. Also more attention should be paid to particle degradation and penetration depths in three-body abrasion, before the behaviour can be fully understood.

Acknowledgements

The authors wish to thank P. J. Slikkerveer and H. in't Veld for useful discussions on the interpretation of the sedigraph data.

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