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Wear mechanisms and scale effects in two-body abrasion

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Abstract

The 'particle size effect' and its manifestation in abrasion still attracts considerable debate as to its origins and the ranking of its likely causes. Experiments have been conducted to study the important contribution that the formation of wear debris can have on the progression of wear. The experiments consist of unlubricated (dry) pin-on-disc tests with silicon carbide coated paper of varying particle size, with different pin material, diameter and loads. It has been observed that the influence of debris formation on wear rate is more pronounced for fine abrasives and soft-wearing materials. Consequently, it is proposed that the particle size effect can be explained in terms of geometrical scaling and the evolution of third-body effects with diminishing particle diameter.

Keywords: Scale effect, particle size, two-body abrasion, debris

1. Introduction

Investigations of two-body abrasive wear with pin-on-disk tribometers, similar to the one shown in Fig. 1, usually find that wear rate is independent of abrasive particle size. However, below a certain particle diameter, the wear rate rapidly diminishes towards zero. Experimental

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investigations have revealed that the critical particle diameter is around 100 µm [1]. This phenomenon is often referred to in the literature as the ‘particle size effect’, and has been observed with a diversity of wearing materials ranging across metals and polymers [2], and even soft ceramics like chalk using abrasive particles ranging from 40–250 µm [3].

There remains considerable debate about the mechanisms responsible for the particle size effect. The only indisputable fact is that it arises as a result of numerous competing factors. All contributions identified are plausible, yet there is still no consensus on their rank and importance. To this end, a great deal of experimental and analytical work is still needed.

Factors that have been identified so far as likely contributions include:

1. loading of the paper with wear debris (clogging) and other third-body effects;
2. deterioration of the abrasive surface (asperity blunting, fracture and pull-out);
3. variation of abrasive shape with scale;
4. change of material properties with scale;
5. change of strain rate with scale.

These factors are all likely to play some role in the manifestation of the particle size effect. The most convincing contribution is the first (clogging), insofar as the abrasive papers’ valleys decrease in volume with decreasing particle size, thus compromising their capacity to accommodate the supposedly constant volume of wear debris. However, if clogging alone were responsible for the particle size effect, then it might be expected that the critical particle size should be quite sensitive to the contact conditions; i.e. nominal contact area, load, material hardness, etc. Surprisingly, it is not, suggesting that clogging is not to only mechanism contributing to the particle size effect.

The experimental work presented in this paper aims to observe the evolution of debris in the contact by varying the load applied to a pin, while observing the wear rate for three different grades of silicon carbide coated abrasive paper, two different pin materials and three pin sizes. A constant load pin-on-disc machine with spiral track has been used to constantly subject the pin to fresh abrasive, as shown in Fig. 1.

Direct observation with the aid of a scanning electron microscope (SEM) has been performed on both pin and abrasive surfaces. Microscopical analysis greatly assisted in identifying the propensity for abrasive deterioration and clogging, especially with the smallest particle sizes. The different debris distributions on the surfaces of coarse and fine abrasives are illustrated in Fig. 2. Visual comparison suggests that clogging is more pronounced with the finer of the two grades, i.e. the wear debris is easily contained by the depressions of the coarser grade, but seems to populate the tips of the finer abrasive. Fig. 3, on the other hand, illustrates that different modes of debris formation are possible depending on particle size, as will be elaborated upon later.

2. Theory and development

Abrasion of metals usually involves the removal of material by plastic deformation as a hard asperity is forced along a softer counter surface. The volume of material removed is related to the applied normal force, the distance traversed and the metal's resistance to plastic flow (its hardness). The simplest theory of abrasion relates wear volume per unit sliding distance Q (i.e wear rate in $mm^3 \cdot m^{-1}$), in terms of a dimensionless wear coefficient K [4],

$$Q = K.P / H \qquad (1)$$

where P is the force applied normal to the contact in Newtons and H is the hardness of the wearing material in N·mm^{-2}. The wear coefficient *K* embodies all of the complexity that characterises the contact, such as the shape of the abrasive and material response. *K* often exhibits non-linear dependency on the variables *P* and *H*.

In the theoretical formulation, *K* is dependent only on the shape of the abrasive and not on its size. This is a direct consequence of the model's assumptions, in particular, that the asperities are conical. Eq. 1 is also applied to three-body abrasion, with the notable exception that the wear coefficient is typically an order of magnitude less than comparable two-body conditions.

2.1. Clogging and third-body effects

Clogging is the most obvious contribution to the particle size effect and was identified by Avient et al. in 1960 [5]. The wear debris that is generated is momentarily trapped within the contact as the pin traverses. At the asperity level, abrasion modes other than pure cutting cause a deformation zone in front of the asperity that supports load without the generation of a well-defined chip. These modes are often termed ‘ploughing’ and ‘wedging’, and give rise to comparatively less wear than cutting-mode abrasion.

At the nominal contact level, wear debris that is generated must be accommodated in the depressions of the abrasive surface, otherwise it will interfere with the contact between the asperity and wear surface. The volume of inter-asperity depressions is directly related to the size of the abrasive particles. Simplistic arguments of geometrical similarity demonstrate that the volume of the valleys is directly proportional to particle diameter. If the volume of wear debris generated is constant, as predicted by classical theory, then it can be expected that there will be some particle size where the debris will begin to interfere with the contact. There is no sudden transition at which this occurs as the debris’ influence weighs in gradually, in a smeared manner dependent on the statistical nature of the abrasive process. This transitionary behaviour can be observed in its earliest stages in Fig. 3(c), for the P180 case, where the long continuous chips have been physically constrained within the abrasive depressions by the workpiece surface. As the chips increase in length, more energy will be expended in deforming them until fracture is likely to occur occurs. The relative length of the chip increases as particle size decreases, making its accommodation within the recesses more difficult. The chip is then more likely to rub against the workpiece or interpose itself between abrasive and workpiece. In its work hardened state, the metal chip is then capable of shielding the workpiece from the sharp cutting asperities, thus preventing further wear. The length of the chips decreases relative to the nominal contact diameter. In the extreme they are compressed and deformed within the contact until they cease to resemble their original chip form, as illustrated in Fig. 3(a) and (b).

The interactions between the asperity and the workpiece have been summarised schematically in Fig. 4. As the relative sliding distance of the asperity increases, so does the probability that debris formed by the cutting mode near the front of the nominal contact will interact with successive asperities in accordance with the coalescent mode. The coalescent mode involves large compressive deformations of the debris, sufficient to buffer the workpiece from the abrasive. The observation of this mechanism forms the basis of the argument that clogging dominates among the various other possible causes of the particle size effect.

Computer simulations indicate that, even when the debris volume is just one-hundredth of the interstitial volume, clogging can still impede abrasion [6]. This is confirmed in Fig. 5, which shows that rising load causes the number of debris islands to increase. Despite the fact that free space still exists within the contact, it is clear that the cohesive debris islands bear much of the load and are capable of mitigating wear by shielding the pin from the sharp asperities of the abrasive surface.

2.2. Deterioration of the abrasive surface

Abrasive deterioration competes with clogging in terms of its influence on wear rate. The very feature that makes abrasive asperities efficient at material removal also increases their chances of being neutralised by the existing contact forces. Consequently there is a tendency for the abrasive potential of the surface to diminish as both the engagement distance and contact load are increased, thus impacting the resulting wear rate in a fashion akin to clogging.

The presence of numerous loose particles in Fig. 3(b) (P1200) suggests that two-body abrasion may degenerate towards three-body conditions if abrasive particles become detached during contact. By comparison, relatively few loose particles are observed for P180 paper shown in Fig. 3(c). The difference may be explained by the fact that for smaller abrasives the length of contact, relative to asperity size, is much larger, thereby increasing the chance of asperity deterioration by means of particle blunting, fracture or pull-out, as noted also by Larsen-Badse [7]. With P4000 there are also relatively few loose particles evident. This is probably due to the fact that clogging is so rapid as to suppress the forces acting on the particles that would otherwise cause them to fracture or pull out.

2.3. Variation of abrasive shape

It has often been suggested that the shape of abrasive particles changes in such a way that they become less abrasive with diminishing size. Wear rate is therefore very sensitive to the slope of the abrading asperities. It has been suggested that the wear rate attributed to a single pyramidal asperity is proportional to $\tan^3\psi$, where ψ is the angle of attack at edge of contact and $0 \leq \psi < 45^{\circ}$ [8]. Unfortunately, no convincing evidence has been found yet to support the fact that decreasing particle size results in reduced angles of attack. The reason lies in the difficulty of comparing slope of surfaces over such broad scale ranges. Slope measurement is difficult per se, but another difficulty lies in applying consistent filtering to enable meaningful comparison, since slope measurement of a random surface is very sensitive to resolution and filtering conditions.

The measurement of the abrasive particles is easier but not particularly meaningful in the context of surfaces. It has been suggested that particle angularity actually increases with decreasing particle diameter [3], but generally, they exhibit subtle and insignificant shape variation with size. On the other hand the abrasive surfaces studied in this work actually do exhibit distinct morphological differences. For example, P4000 paper looks quite different to both P180 and P1200 surfaces in that it comprises an agglomerated mass of particles as opposed to a single layer, as can be seen in Fig. 3.

This may have important consequences on the structural integrity of the surface. A survivorship bias may be in effect whereby the sharpest particles are quickly removed from the surface, either engaging the workpiece as a third body, or dropping innocuously into a relatively deep valley. The remaining particles would present small angles of attack to the workpiece, resulting in the overall mitigation of the surface abrasiveness. This effect is further reinforced by the fact that smaller particles are more likely to be pulled away intact rather than fracture due to their superior fracture toughness. The particle size effect could therefore be explained by accelerated neutralisation of steep particles owing to structural differences as particle size decreases.

2.4. Change of material properties

In mainstream engineering material properties are measured under quasi-static conditions using specimens that are easily managed by hand. They are effectively tested over a scale range of two or three orders of magnitude. Given a small enough domain, material properties exhibit pseudo-linear behaviour. Extending beyond this domain often reveals significant non-linearity. This is the case with strength and stiffness material properties. It is often seen that a material’s resistance to deformation (elastic or plastic) increases substantially as the characteristic length of the deforming zone approaches micrometre proportions.

While the strain field might be geometrically identical to a larger specimen, it is argued that the distribution and density of dislocations and defects required for deformation diverge as scale decreases. It follows that strain alone inadequately determines a material's propensity to deform and that the strain gradient becomes increasingly significant.

2.5. Change of strain rate

Strain rate can have a dramatic influence on the behaviour of certain materials. Metal properties are often considered insensitive to strain rate, at least when compared to polymers for example. However, at sufficiently high strain rates, metal properties start to diverge from quasi-static values. For annealed mild steel, this transition occurs at strain rates as low as 0.1 s^{-1} at room temperature [9]. The complex strain field around an asperity makes it difficult to calculate precisely the maximum strain rate. Nonetheless, a basic approximation can be obtained by dividing speed by the characteristic dimension of the strain field. For example, a 100 µm particle might have a deformation zone 30 µm in diameter. At a traversal speed of just 1 $cm \cdot s^{-1}$ the estimated strain rate is above 300 s^{-1}. Assuming geometrical similarity of the strain field, the strain rate is inversely related to particle size. For example, 10 µm particles would generate strain rates in excess of 3000 s^{-1}. At this rate even the least strain-rate sensitive material would exhibit substantial changes to its mechanical properties. Despite the enormous variation in the response of materials to strain-rate variation, it appears incongruous that the critical particle size is relatively insensitive to the pin material used. Strain rate is therefore rejected as a major contribution to the particle size effect.

3. Experimental details

The test-rig consists of a pin-on-disk arrangement as shown previously in Fig. 1. An electric motor drives both the disk and linear actuator with suitable gearing so that the pin follows a spiral path relative to the disk's surface, thereby ensuring that the pin always traverses over fresh abrasive.

The pin diameters tested were 3, 6 and 9 mm. Different diameters were used in order to assess the influence of nominal contact size on wear rate and, indirectly, its contribution to the particle size effect. Two pin materials were chosen for their different hardness values, as summarised in Table 1. A Mitutoyo micro-Vickers instrument was used to measure the hardness. Values represent the average of three measurements of Vickers Hardness Number (VHN or $kg \cdot mm^{-2}$).

The silicon carbide paper was obtained from MetPrep, UK (Hermes brand). The grades used were FEPA (Federation of European Producers of Abrasives) P180 with average particle diameter of 82 μm; P1200 with average particle diameter of 15.2 μm; and P4000 with average particle diameter of 5 μm. The tests were conducted without lubrication (i.e. dry) in order to promote clogging [10]. Ambient conditions were approximately 20 °C with medium relative humidity (50-60 %RH).

The speed of the pin relative to the disk's surface naturally varies as it moves along the spiral path. The overall distance travelled was 8 m at an average speed of 0.13 $m \cdot s^{-1}$. The pin was securely fastened to the pin-holder, itself constrained by means of a linear bearing. The specimen was not constrained against rotation around the vertical axis. Dead weights of nominal size 1, 2, 4, 8, 16, and 24 N were used for the tests. The weight of the pin holder was added to the nominal value to obtain the net normal force pushing the pin against the abrasive surface. The pin's weight was measured before and after each test to determine its mass loss, using a balance with 0.1 mg resolution.

The worn pins and abrasive were examined using SEM. Apart from qualitative analysis of the abrasive surface, stereo-pairs of SEM images were used to generate electronic models of both fresh and used abrasive. The used abrasive was immersed in hydrochloric acid to dissolve metallic debris so that the surface geometry could be directly compared to that of unused abrasive. A customised computer program [11] was used to obtain quantitative abrasive characteristics in terms of the root-mean-squared (RMS) slope of surface profiles as a function of penetration depth into the abrasive surface. RMS slope is defined as the square root of the variance of the first derivative of the profile. Average slope is normally zero, since negative and positive slopes balance each other. Average absolute slope is usually less than RMS slope since the RMS slope gives greater weight to high and low values. This technique has been used previously to measure abrasiveness of grinding wheels for the prediction of grinding forces. A 250 μm high-frequency pass filter and a 1 μm low-frequency pass filter were applied to the surface profiles, each being 2.5 mm long. The low-frequency pass filter is very important as it has a strong influence on RMS slope and corresponds to two times the lateral point-to-point spacing of the digital model's data points, in accordance with the Nyquist criterion.

Experiments were also conducted to observe wear rate with repeated passes of the pin over the same spiral path, without disturbing the debris between passes. The decay of wear rate for the different paper grades gives valuable information on clogging and the deterioration characteristics relative to abrasive particle size.

4. Results and discussion

4.1. Wear rate versus load

Observation of wear rate versus load for different experimental conditions provided valuable insight into the particle size effect and its causes. With the P180 paper, for example, linearity between wear rate and pin load is maintained for both materials, as shown in Fig. 6(a). This confirms the validity of the classical abrasion model (Eq. 1), insofar as non-linearity attributable to clogging or abrasive deterioration is not evident. The theory is inconsistent, however, on the grounds that wear rate of aluminium is much higher than might otherwise be predicted by the hardness differential between steel and aluminium. This may be explained by more sophisticated models that take into account work-hardenability of wearing material, and the corresponding difference between surface and bulk hardness. The steel specimen is expected to work-harden more than aluminium, which is consistent with the observed trend.

The results for P1200 and P4000 paper, on the other hand, exhibit decisive non-linearity, especially with aluminium. Under given conditions of stress, aluminium will plastically deform more than a harder material like steel, resulting in the formation of larger contact junctions. The adhesion of these junctions promotes agglomeration of debris and subsequent clogging. The increased propensity of softer materials to clog probably explains how the wear rate of aluminium edges below that of steel for P4000 despite the hardness differential, as illustrated in Fig. 6(c). This mechanism is supported by SEM micrographs, insofar as long chips can be easily observed for steel under most conditions, but the same is not true for aluminium, as demonstrated by Figs. 7(a) and (b) for P4000 paper. Cutting mode for aluminium was obvious only with P180 grade paper, as shown in Fig. 3(c).

Interpretation of the micrographs suggests that wear is mitigated at high loads by both clogging and abrasive deterioration. Overall, the wear rate with P1200 paper is at least 50 % lower than P180 for otherwise identical conditions (Fig. 6). Comparative wear for P4000 paper is far less again. This outcome flies in the face classical theory, which predicts that wear rate should be independent of particle size. When clogging is factored into the model, wear rate tends towards values that might be expected for metal-on-metal conditions, where abrasion is largely suppressed and adhesion becomes increasingly important. For steel, however, abrasion is still prevalent over adhesion since dry sliding of mild steel on mild steel is only expected to produce wear rates of about 0.0001 $mm^3 \cdot m^{-1}$ [4]; i.e. three orders-of-magnitude less than for sliding of steel on P4000 paper.

The difference in wear mechanisms is confirmed by observing the abraded pin surfaces shown in Fig. 8. With large grits (P180), the worn surface exhibits classical two-body qualities with well-defined grooves. With the P1200 paper, grooves can still be observed but they are mixed with indentations and embedded grits attributable to free-rolling abrasive particles. Moreover, the surface exhibits typical three-body traits that arise because of adhesion and shearing of the metallic wear debris. The P4000 paper induces a very smooth surface devoid of the types of damage observed with either P1200 or P180 paper grades. Grooves the order of 2 μm can be observed with scattered metal debris that appears to have been rolled between the two surfaces at an oblique angle to the grooves. This phenomenon highlights effectiveness of these micro-rollers in the mitigation of wear.

There are several factors that contribute to the formation of third bodies within the contact. The first has to do with the fact that the space between abrasive grits reduces linearly with particle diameter. The debris is forced to accumulate in a smaller volume, increasing its tendency to agglomerate. A ramp of metallic debris is generated ahead of the asperity in the form of a wedge, foliated at the leading edge as debris is compressed along the wedge, as interpreted from

Fig. 3(b). Large shear stresses acting on the wedge cause the pin to wear by a combination of adhesion and abrasion, resulting in the complex surface shown in Fig. 8(b). When the load and relative debris volume are sufficiently large, these wedges coalesce, forming broad caps covering the abrasive surface.

Compared to aluminium, steel debris exhibited a reduced tendency for self-cohesion. The cohesion is found to increase with decreasing abrasive size by considering both increased surface area and cohesive energy per unit volume, as suggested in [12, 13].

4.2. Multiple pass experiments

Tests involving multiple passes were conducted to gain a better understanding of the role of debris and abrasive deterioration within the contact. The results are shown in Fig. 9. Wear rate decreases rapidly at first and then slows, suggesting that the aggressive asperities are rapidly neutralised either by particle fracture and pull-out or debris build-up. Wear rate stabilises due to equilibrium between debris formation and detachment when the junction exceeds a certain critical size. The decay of wear rate is very slow, as observed by Mulhearn and Samuels [14] and also Date and Malkin [15]. Their experiments, in contrast to the results presented in this work, consisted of thousands of passes. They concluded that pin mass loss decays exponentially towards zero with increasing number of passes. The decay rate is related to both abrasive and pin qualities.

Although it is accepted that wear rate is influenced by both clogging and abrasive deterioration, it is difficult to separate their contributions. Consequently, the RMS slope of the abrasive surface was used to determine how surface abrasiveness changed with multiple passes. RMS slope provides a measure of the equivalent angle-of-attack of the surface asperities. It is the most useful measures of surface abrasiveness, since wear rate is strongly influenced by the slope or angle-of-attack of the asperities.

In Fig. 10, the RMS slopes of unused P1200 paper and paper subjected to 32 passes (stripped of metallic debris with diluted hydrochloric acid) were calculated from digital elevation models obtained by the SEM stereoscopy technique. There is a distinct reduction of the RMS slope in the 2 to 15 μm penetration range. Micrographs of the 32-pass surface revealed that a number of particles were pulled out from the surface. These were either weakly bonded or protruded substantially from the surface, thus bearing the contact load disproportionately.

The difference in RMS slope between 1.5 and 2 corresponds to equivalent angles of attack of between 56° and 63°; hardly enough to account for the dramatic reduction of wear rate observed. This strengthens the case for clogging as the principal contribution to the particle size effect, insofar as the culling of extremely protruding asperities effectively reduces the inter-asperity volume and the capacity for debris accommodation.

More work is needed to better understand the change in structure of the surfaces during abrasive contact. This work is fundamental, not only to understanding abrasion dynamics with coated abrasives, but also in grinding. For example, it is well known that the specific grinding energy increases dramatically as wheel structure is refined, but the contribution to this phenomenon by the debris is usually overlooked. The damaging effects of grinding burn could be partly attributed to the interaction of the debris with the ground surface. The present authors recently found evidence of smeared metallic films on finely ground, rolling-element bearing raceways which exhibited thermal damage attributable to the finishing process. It is also conceivable that long arcs-of-cut relative to grinding-wheel roughness compromise coolant/lubricant efficacy, thus justifying the dry conditions studied in this work.

4.3. Effect of pin diameter

Tests were also conducted with pins of different diameter to assess the influence of nominal contact size on wear rate. Pins 3, 6 and 9 mm in diameter were used, representing a change in nominal contact area of 900 %. Theoretical arguments with pyramidal or conical abrasives indicate that wear rate should be independent of pin diameter, because despite the fact that pressure is reduced, more asperities engage the contact. In reality, the longer path of contact between each asperity and the larger pin increases the likelihood of clogging, with consequent decrease in the observed wear rate. No significant trend was observed with the P180 paper, i.e. wear rate was approximately constant. With the P1200 abrasive on the other hand, increasing the pin area did result in a small but consistently monotonic decrease in wear rate of about 15% for aluminium. The P4000 paper showed the most decisive decrease in wear rate with increasing pin diameter, as shown in Fig.11. The reduction corresponds to about 30% for steel, whereas for aluminium, the decrease was far more pronounced (up to about 70% at the highest loads). The behaviour of aluminium can be expected owing to its softness, making its debris more likely to agglomerate and stick to the abrasive. Above 10 N load the 3 mm aluminium pin tended to tear the P4000 paper, whereas the steel pin did not. Consequently there is no data for the 3 mm aluminium pin at the higher loads. These results fit in well with the theory that clogging reduces wear and that third body effects within the contact are responsible for the manifestation of the particle size effect.

5. Conclusions

From the experiments conducted, the following conclusions have been drawn:

1. Clogging by debris or third bodies is identified as the primary contribution to the particle size effect.
2. The third bodies consist of both metallic wear debris and detached or fractured abrasive grits. Only detached grits were observed for the smallest grits, P4000.

3. Fine abrasives exhibit a reduced capacity to accommodate the debris generated within the nominal contact. The debris interferes with abrasive efficiency.
4. The softer aluminium debris exhibited a more pronounced tendency to clog compared to steel.
5. The reduction of wear rate with increasing pin diameter is enhanced by reducing particle size. This supports the contribution of clogging to the particle size effect.
6. Other factors contribute to the particle size effect but these are considered secondary in view of the results obtained herein.

Acknowledgments

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Fig. 1 Experimental pin-on-disk apparatus exhibiting spiral wear track.

Fig. 2 Comparative debris accumulation in the depressions of P180 and P1200 silicon carbide paper (35×). Aluminium pin, 4 N load.

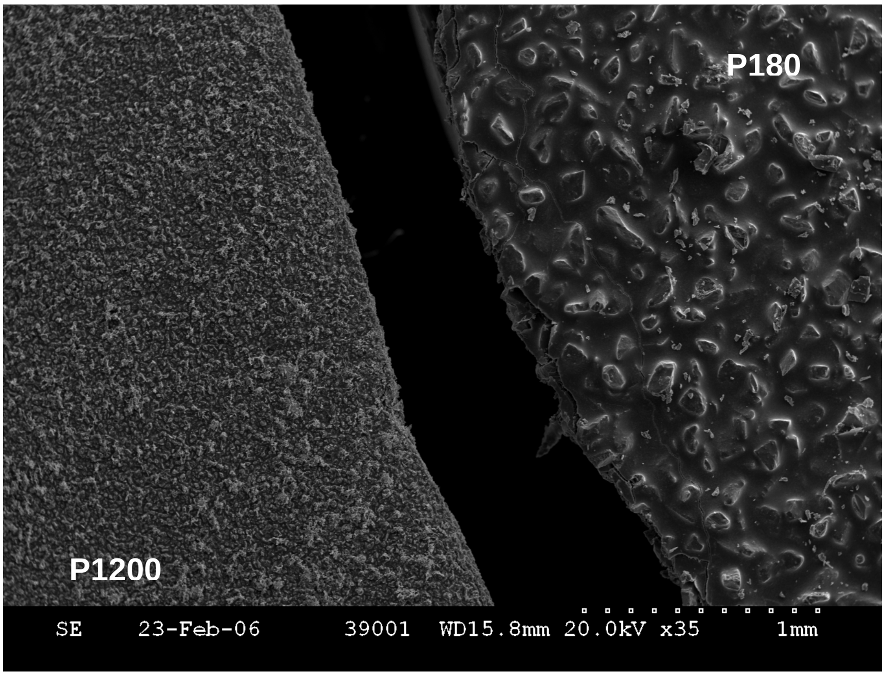
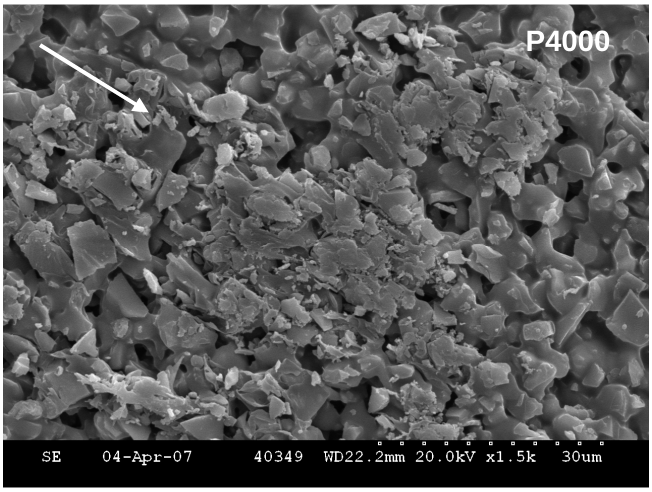
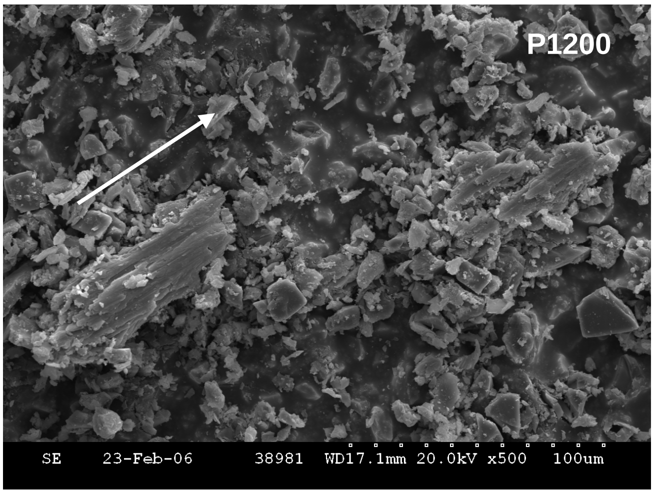


Fig. 3 Debris morphology for (a) P4000 (1500×), (b) P1200 (500×) and (c) P180 paper (90×). Aluminium pin, 24 N load. Arrow indicates the sliding direction of the pin.



(a)



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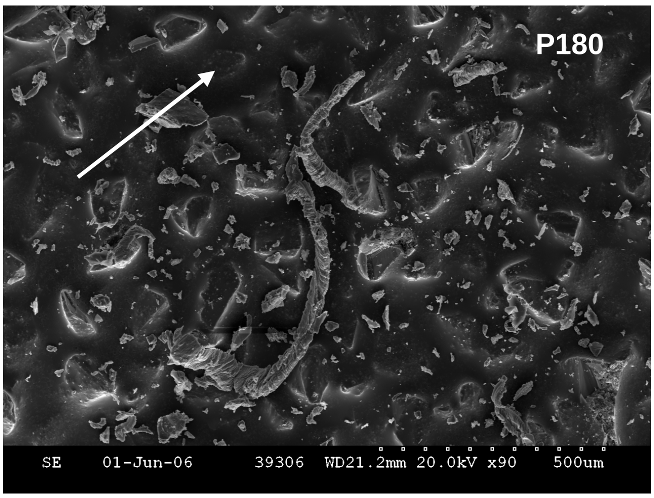


(c)

Fig. 4 Modes of debris formation and interaction with an asperity. Oblique cutting is the primary form of metal detachment. Subsequent coalescent mode occurs if debris cohesion and density are high, resulting in significant separation between abrasive and workpiece surfaces.

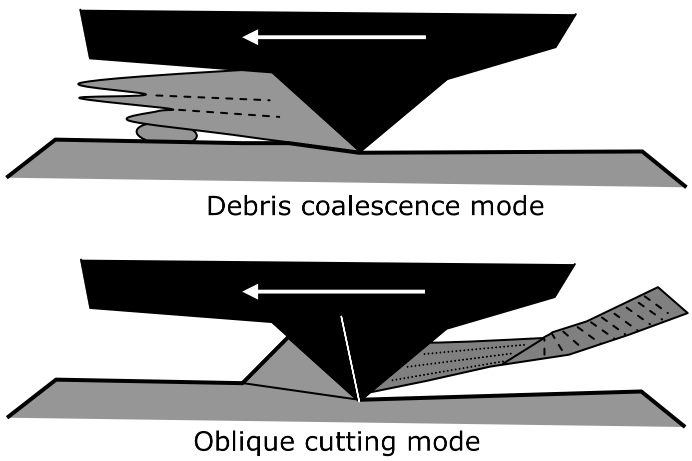
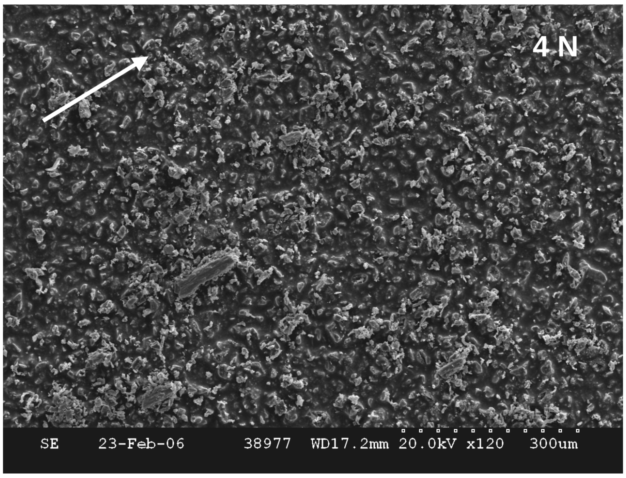
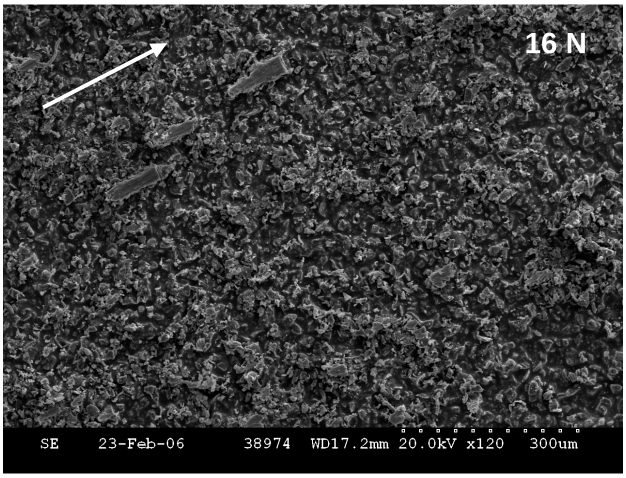


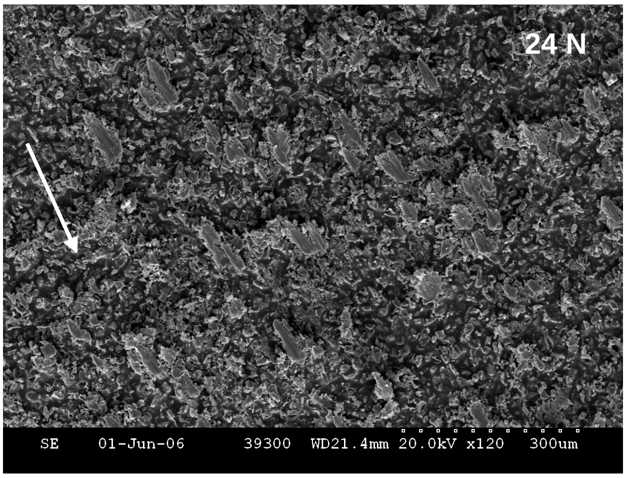
Fig. 5 Debris accumulation in the contact for a 3 mm diameter aluminium pin, P1200 grade paper (120×); (a) 4 N, (b) 16 N and (c) 24 N. Arrow indicates the sliding direction of the pin.



(a)

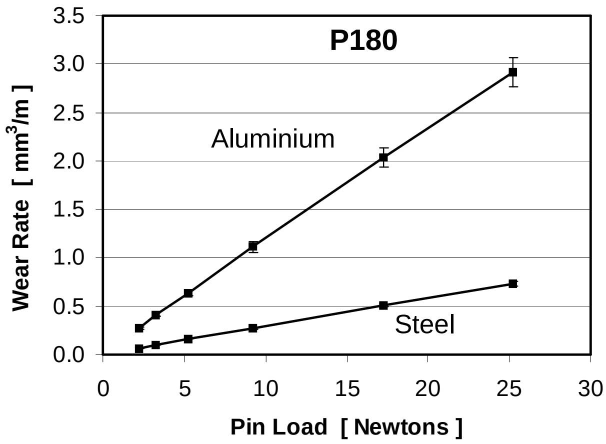


(b)

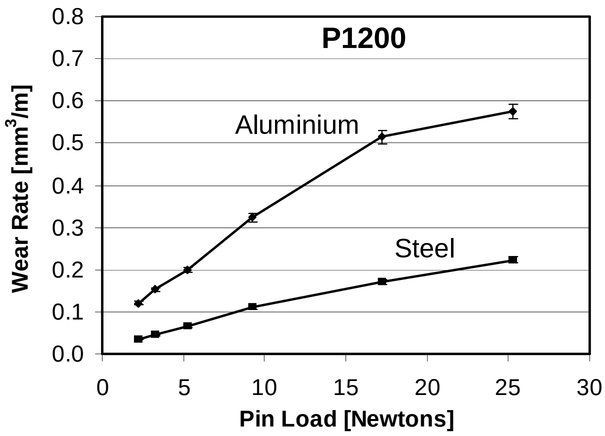


(c)

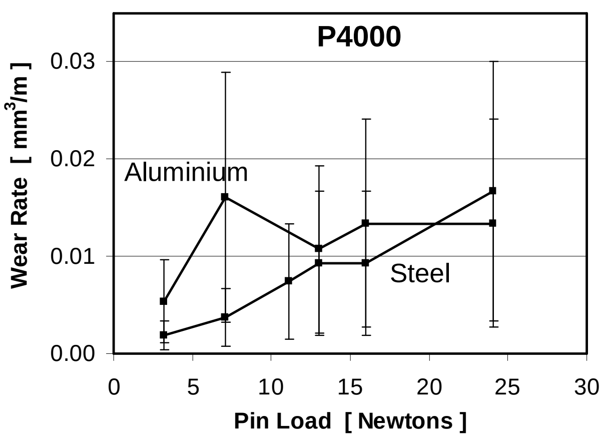
Fig. 6 Wear rates of steel and aluminium with different grades of silicon carbide paper: (a) P180, (b) P1200 and (c) P4000 grade. Pin diameter: 9 mm. Each data point is the average of two tests. Bars represent maximum percentage difference observed for a set of data pairs.



(a)

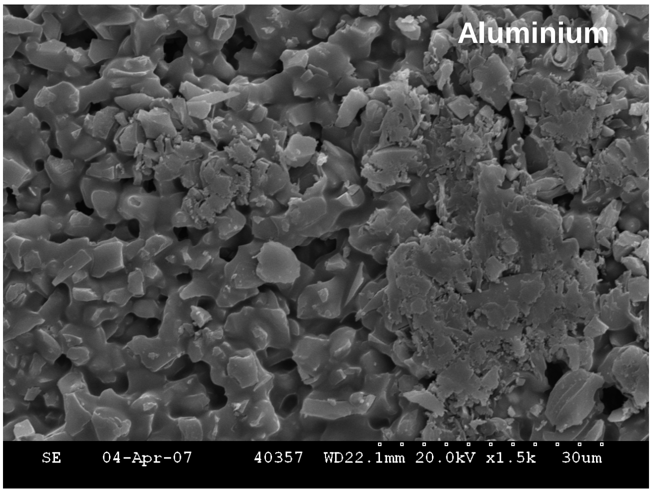


(b)

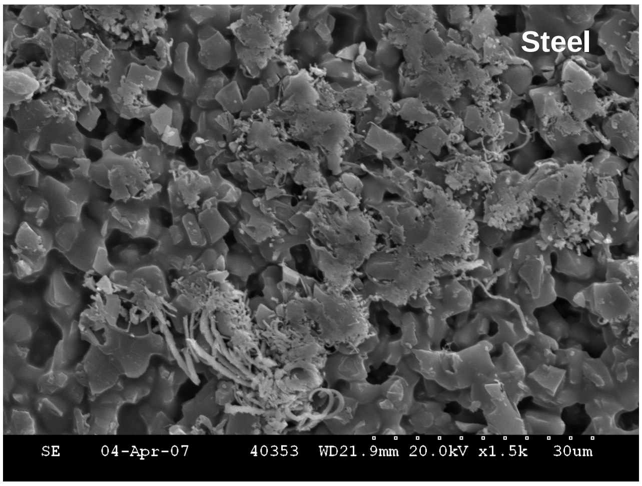


(c)

Fig. 7 Comparison of debris structure on P4000 abrasive surface (1500×); (a) aluminium and (b) steel pin. Pin load: 16 N, single pass.

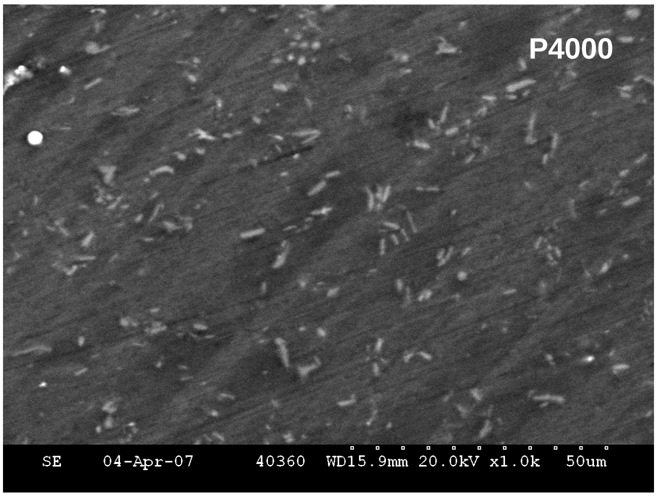


(a)

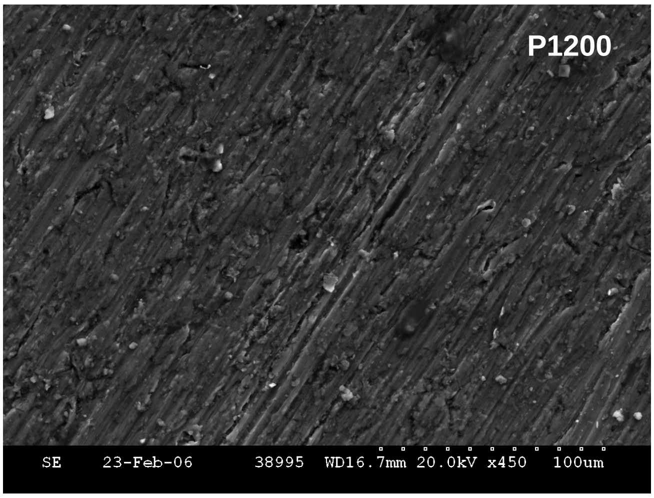


(b)

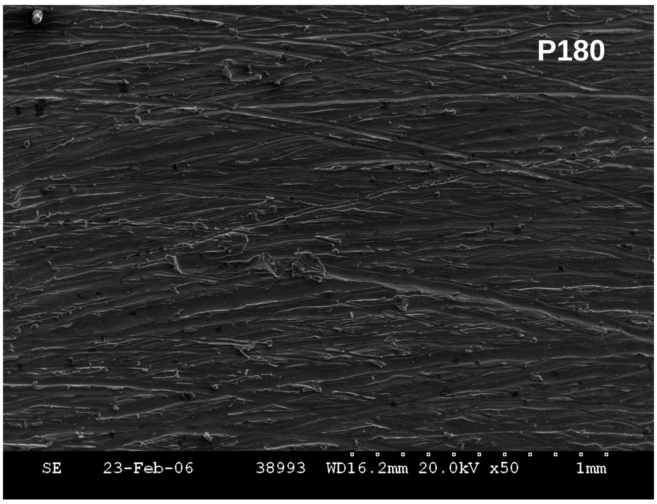
Fig. 8 Micrographs of 9mm aluminium pin surface abraded with (a) P4000 (1000×), (b) P1200 (450×) and (c) P180 (50×), single pass.



(a)



(b)



(c)

Fig. 9 Repeated traversal test on different grades of silicon carbide paper. Aluminium pin, 9 mm diameter, 16 N load.

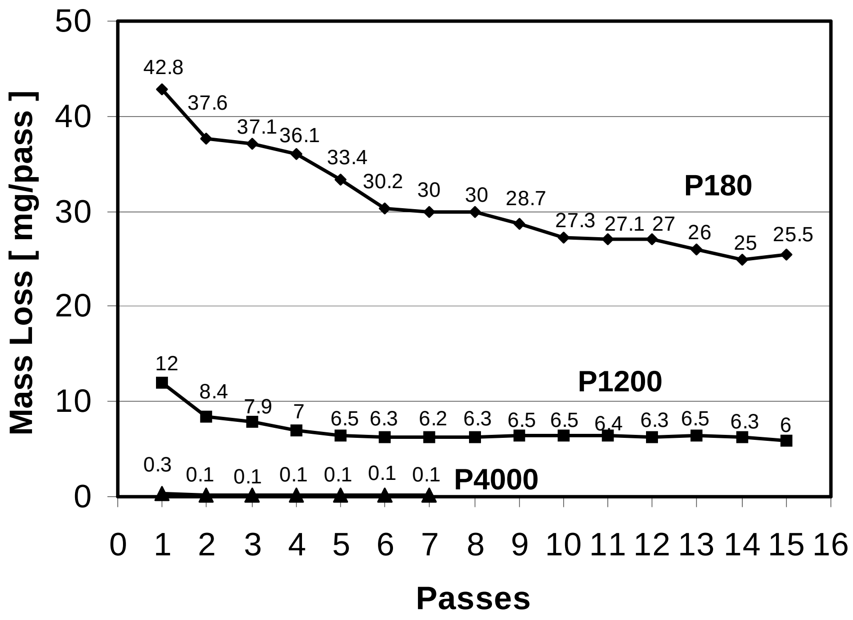


Fig. 10 Root-mean-squared slope versus penetration depth into surface of P1200 paper, calculated from SEM stereoscopy digital elevation models. Steel pin, 3 mm diameter, 3.2 N load.

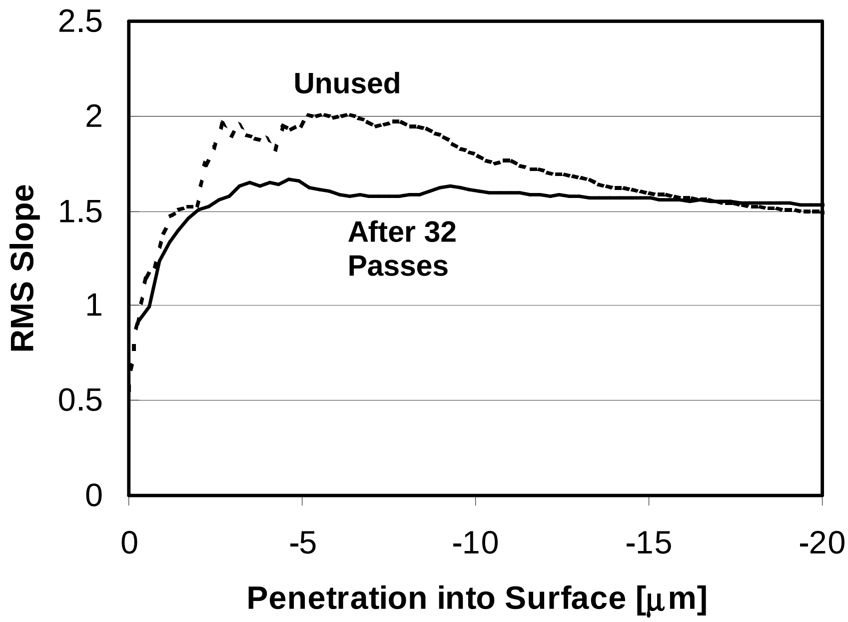


Fig. 11 Wear rates of steel and aluminium pins 3, 6 and 9 mm diameter with P4000 paper, especially for aluminium, demonstrating the importance of clogging in mitigating wear.

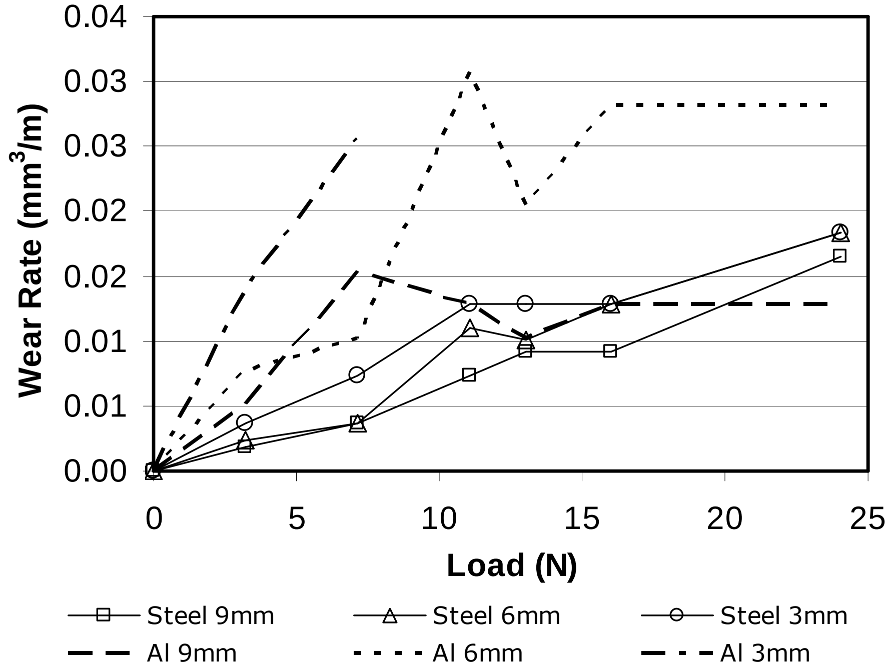


Table 1. Wear-pin alloy properties

Nominal Material	Aluminium	Mild Steel
Alloy Designation	2011-T3	EN3B
Vickers Hardness	114 HV	233 HV