Mechano-chemical wear of ceramics

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An experimental study has been carried out to ascertain the role of mechano-chemical effects in accelerated material removal from hard and brittle surfaces such as engineering ceramics. It was established that chemical effects are far more effective in material removal than the mechanical action of abrasive particles alone. Mechanical action is governed by the applied load, amount of relative slip within the contact zone, and the size of abrasive particles. Chemical effects depend mainly on the nature of additives and their ability to react with ceramic surface under contact conditions. Maximum wear rate is achieved when both mechanical action and chemical reactions take place simultaneously.

1. Introduction

Current demands on load bearing contacts in all kind of machinery are leading to developments aimed at running them at high speeds, hostile environments, increased unit loads and restricted lubrication. The design and manufacture of such contacts is at the limit of established technology. At present, the most promising designs able to cope with such extreme demands are believed to be in the area of ceramic/ceramic or ceramic/metal combinations.

Engineering ceramics have found use in many applications, such as engine parts, ball bearings, artificial bone and hip replacements, gyroscopes, mainly because of their chemical inertness, hardness, high temperature stability and very good wear resistance. These advantages of ceramics, however, are somewhat compromised by their inherent brittleness and difficulties in their processing as they are highly susceptible to damage during machining and surface finishing operations. In order to avoid damage during machining, grinding of ceramics must be carried out at a very slow rate thus making it rather an expensive operation. Typically, surface finishing of ceramic components for high contact stress applications constitutes about 50% of the total cost of manufacturing.

With a continuous increase in the demand for advanced engineering ceramics, interest in surface finishing processes has been steadily growing. Many modern surface finishing processes have been developed, such as magnetic force assisted grinding [1], creep-feed grinding [2], and ultrasonic and energy beam assisted grinding [3]. However, it seems that the dominant current industrial practice is to use diamond slurries for surface finishing of ceramics. A typical example of that is the finishing process of ceramic balls used in rolling contact bearings. Ceramic ball blanks are made by hot isostatic pressing and sintering of ceramic powders. The sintering results in shrinkage, affecting the roundness of balls, which has to be corrected by grinding during the first stage of the finishing process. The surface skin of 100–200 μm thickness is compositionally and microstructurally different from the core of the ball due to reactions with the environment during sintering. The skin has to be removed during the second stage of finishing. Finally, the surface finish required for a particular application of the ball is attained in the third finishing stage. Typically, balls of diameter in the range of 6–15 mm are required to have surface roughness of 0.005–0.01 μm [13]. All three stages of finishing are carried out by diamond abrasive lapping, each stage distinguished only by the coarseness of the abrasive particles. A typical, conventional finishing process uses two circular cast iron plates placed face to face with concentric matching grooves cut in them. Balls are fed into the grooves and are forced to roll by rotation of the plates. The contact geometry ensures that the rolling is accompanied by a spinning motion and micro-slip which is considered as responsible for the material removal; the steady motion of the balls could result in tracks developing on them. Hence, in order to secure uniform material removal the motion of a ball is interrupted by returning it to a hopper. When the ball enters the process again its orientation is randomized with respect to its previous pass. A typical batch of balls in the 6–15 mm diameter size range may be in the high hundreds, with 10% of them between the laps at any time. Total processing time may be several weeks, although any one ball may be actively processed for only 30–50 h. Typically, material removal rate is in the range of 0.1–0.2 μm/min under a load of tens of Newtons per ball, and the relative speeds of rotation of 400 mm diameter lapping plates of 50 rpm. It is obvious that the current practice in surface finish of ceramics is painfully slow and, therefore, expensive.

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The main objective of the study reported here is to explore a number of potentially useful mechano-chemical processes facilitating rapid wear of ceramic materials. Equally important is to determine what damage, if any, is inflicted on the subsurface region of a ceramic element during rapid material removal. The emphasis is on achieving an understanding of the mechanisms responsible for accelerated wear of hard and brittle materials in order to develop more effective surface finish processes of engineering ceramic.

2. Experimental

2.1. The apparatus and procedure

2.1.1. Rolling point contact

To assess the effectiveness of mechano-chemical phenomena in wear process of ceramics, experiments were carried out using an apparatus shown schematically in Fig. 1. The apparatus consists of an assembly which reasonably well simulates the currently used surface finish arrangement for ceramic balls described earlier. In this apparatus, the top specimen, usually in the form of a cone, is located in a collet carried by a vertically mounted spindle and is rotated in a loaded contact with ceramic balls placed in a specially shaped cup. The apparatus and its various testing utilizations is described in more detail elsewhere [7]. The model contact configuration used is shown schematically in Fig. 2.

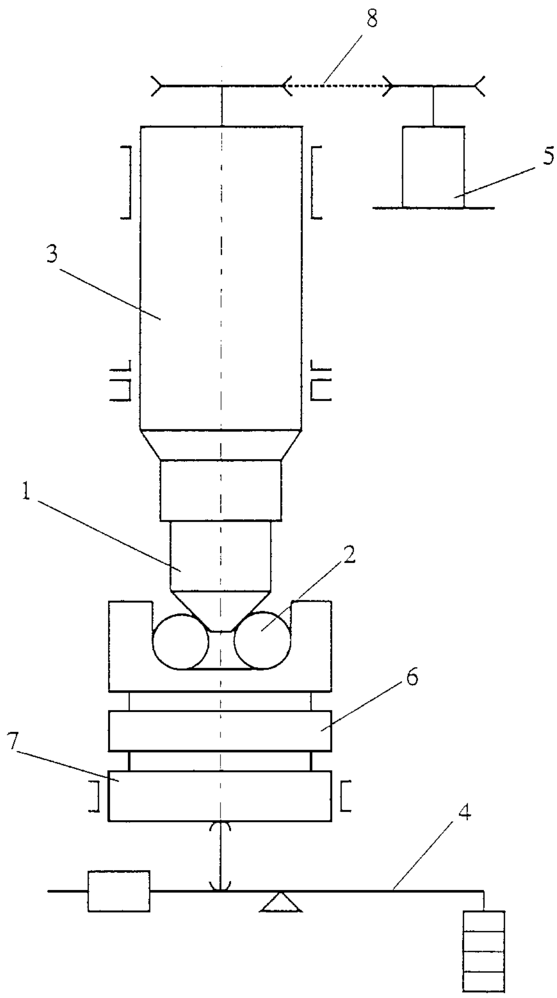


Figure 1 Schematic of the rolling contact apparatus. 1, cone and collet; 2, tested balls; 3, spindle; 4, loading lever; 5, driving motor; 6, heated plate; 7, loading piston; 8, belt drive.

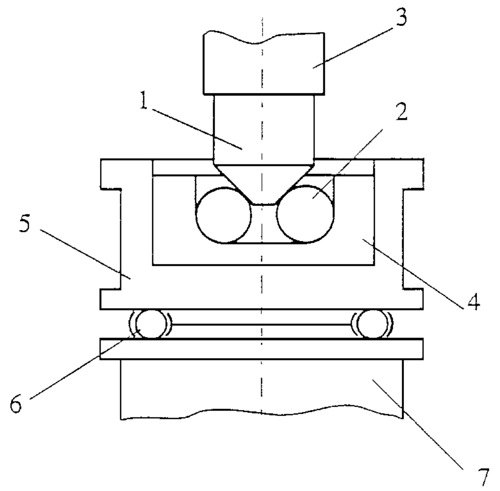


Figure 2 Schematic of contact configuration with additional cup rotation. 1, cone and collet; 2, tested balls; 3, spindle; 4, cup; 5, housing; 6, thrust rolling contact bearing; 7, loading piston.

In the study reported here, the cone and the cup were made of 304 grade stainless steel. Normally, nine ceramic balls were housed in the cup filled with specially prepared liquid to submerge the balls. The motion of the cone, driven via the spindle by an electronically controlled electric motor, produces rotation of the balls and stirs up the liquid. The motion of the balls is complex as they not only roll around the cup but also spin about their axes of symmetry. In the experiments presented here, an additional motion of the cup was introduced in order to increase the slip between the balls and the cup (with which they are in contact at two points) and between the balls and the cone (one point contact). This extra relative slip is considered to be a vital element for the increase of material removal rate [4]. A simple kinematic analysis indicates that rotation of the cup in the opposite direction to that of the spindle results in higher spin and lower orbiting velocity of the balls. The speed of the cup rotation was varied from a few revolutions per minute to up to 160 rpm. It was also possible, due to a special attachment, to circulate a gas through the cup.

A typical experiment consisted of placing balls in the cup and submerging them in about 4 ml of a special liquid containing diamond abrasive particles. Next, the required spindle speed was attained and the load carefully applied to the set of nine balls. Nominal duration of the test was 60 min. Before and after the test the balls, cup and cone were ultrasonically cleaned. The material removal rate was assessed through changes in the diameter of the balls measured with the accuracy of ± 0.1 μm. Every experiment was repeated a minimum of three times; a satisfactory reproducibility of the results was found.

2.1.2. Sliding line contact

The second apparatus used to study wear of ceramics in a line contact is shown schematically in Fig. 3. An

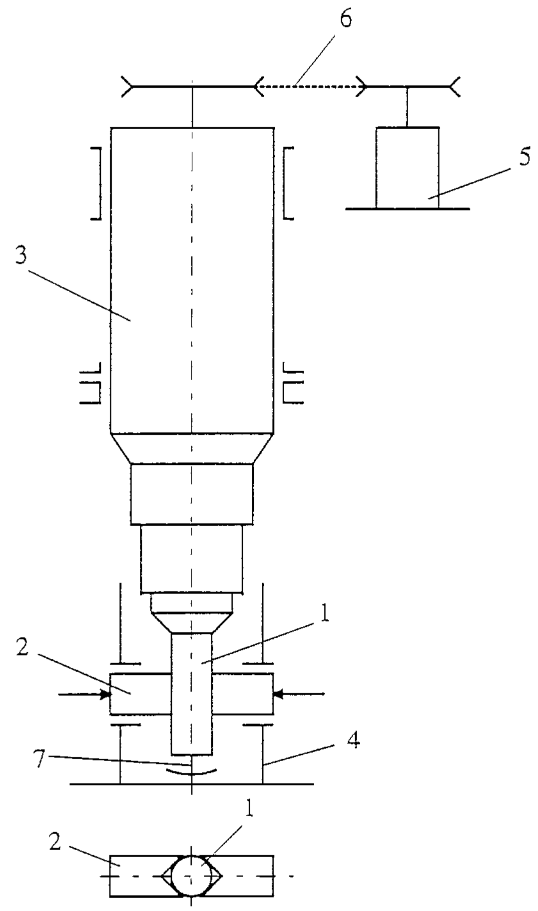


Figure 3 Schematic of the line contact apparatus. 1, ceramic rod (test sample); 2, V-shaped block (counterface); 3, spindle; 4, grinding liquid container; 5, driving motor; 6, belt drive; 7, stirer.

essential part of the apparatus consists of a ceramic sample and counterface elements. The sample is attached to the spindle driven by an electric motor. The sample was in line contact with two V-shaped blocks and the load on the contact was applied through the blocks. The length of the contact was 5 mm. Both the sample and the blocks were submerged in the grinding liquid housed in a container. Sedimentation of abrasive particles contained in the liquid was prevented by attaching a small stirrer to the specimen.

All experiments were carried out at 300 rpm and the amount of the liquid used was 20 ml.

2.2. Materials and test conditions

2.2.1. Rolling point contact

Balls were prepared by hot isostatic pressing (HIP) β-phase silicon nitride powder. An average nominal diameter of the ball at the start of testing was 6.5 mm. Blank balls had a surface roughness 100–200 μm R_a and contained many surface imperfections; to remove them each ball was subjected to a running-in process before testing.

The experiments were carried out at a rotational velocity of the cone ranging from 1500 to 7500 rpm. The normal loads on the set of nine balls ranged from 200 to 4000 N. A number of specially prepared liquids mixed with diamond abrasive particles were used. These were either an unformulated mineral oil to which one of a number of additives (with the potential to modify the ceramic surface) was added or special chemical compounds with the ability to enter into chemical reaction with the ceramic under contact conditions. Inorganic additives, namely phosphoric acid and potassium hydroxide, were also added to an unformulated mineral oil.

A typical test liquid was prepared by suspending 2% by weight 15 μm diamond particles either in the base mineral oil containing one of the additives listed in Table I or in one of the special chemical compounds specified in Table II. The concentration of abrasive particles was similar to that in commercially available grinding liquids. Reference experiments were carried out using a commercial oil-based slurry (O-type) and a water-based slurry (W-type); both of these contained either 1 or 15 μm diamond abrasive particles.

2.2.2. Sliding line contact

Specimens for sliding line contact, in the form of a rod with diameter 6.5 mm and length 10 mm, were made of commercially available sialon and alumina. Three different materials were used for the V-shaped counterfaces, namely a mild steel, brass and aluminium alloy. They were tested in "as received" conditions and did not undergo any heat treatment. Oil-based slurries (O-type) with four sizes of diamond abrasive particles, 1, 6, 15 and 25 μm, were used throughout the experiments.

TABLE I Properties of the organic additives

Additive symbol	Composition	Water solubility	Density (kg/m^3)	Flash point (°C)	Viscosity at 40 °C (cSt)	Viscosity at 100 °C (cSt)
995	Ca sulfonate	Insoluble	1220	160	1200	60
996	Na sulfonate	Partially soluble	—	160	—	200
997	Olefin sulfide	Insoluble	1045	>100	45	6
998	Olefin ester sulfide	Insoluble	960	190	300	35
HT312	Sulfide	Insoluble	1160	95	—	9.5
DBDS	Dibenzyldisulfide	—	—	—	—	—
NSE	Natural sulfurized ester	—	—	—	—	—

TABLE II Properties of chemical compounds used as base liquids

Compound symbol	Composition	Colour	Pour point (°C)	Viscosity at 40 °C (cST)	Flash point (°C)
853	Highly refined mineral oil	Amber	<18	19	190
854	Highly refined mineral oil	Amber	<9	30	200
855	Ester basestocks	Amber	<20	27–31	180
856	Poly-alphaolefin	—	—	5	135
857	Poly-alphaolefin	—	<68	31	200
858	Polyoxyalkylene glycol ether	Yellow	<25	180	180
884	Ester basestoks	Amber	<20	85	180

In a typical experiment, the required speed was set first, then the load on the contact, ranging from 135 to 900 N, was applied. The duration of a test was 60 min. Before each test, the specimen, V-blocks and the container for the grinding liquid were ultrasonically cleaned. Both the specimen and V-blocks were weighed before and after the test to obtain an estimate of the material removal rate expressed as a volume loss of material per unit time.

2.3. Surface and wear debris analyses
Reflection optical microscopy was used to examine the surface of the balls on which various tests had been carried out. Also, the metallurgical structure of the V-blocks after testing was examined under an optical microscope. Scanning electron microscopy (SEM) was used to study the surface topography resulting from wear experiments.

Wear debris were extracted from liquids used during wear tests using a rotary particle depositor. A particle quantitator was used to rank the size of wear particles. The wear debris were also examined under SEM.

3. Results
3.1. Rolling point contact
3.1.1. Material removal rate in the presence of inorganic additives
The effect of two organic additives, phosphoric acid (additive A) and potassium hydroxide (additive B), on the material removal rate was examined. They were added into a specially prepared liquid (called O-W slurry) consisting of 50% O-type slurry and 50% W-type slurry. Fig. 4 shows the results of testing silicon nitride balls in various grinding liquids containing 1 μm diamond abrasive particles. The concentration of additive A in O-W slurry was 5 mol/l and the

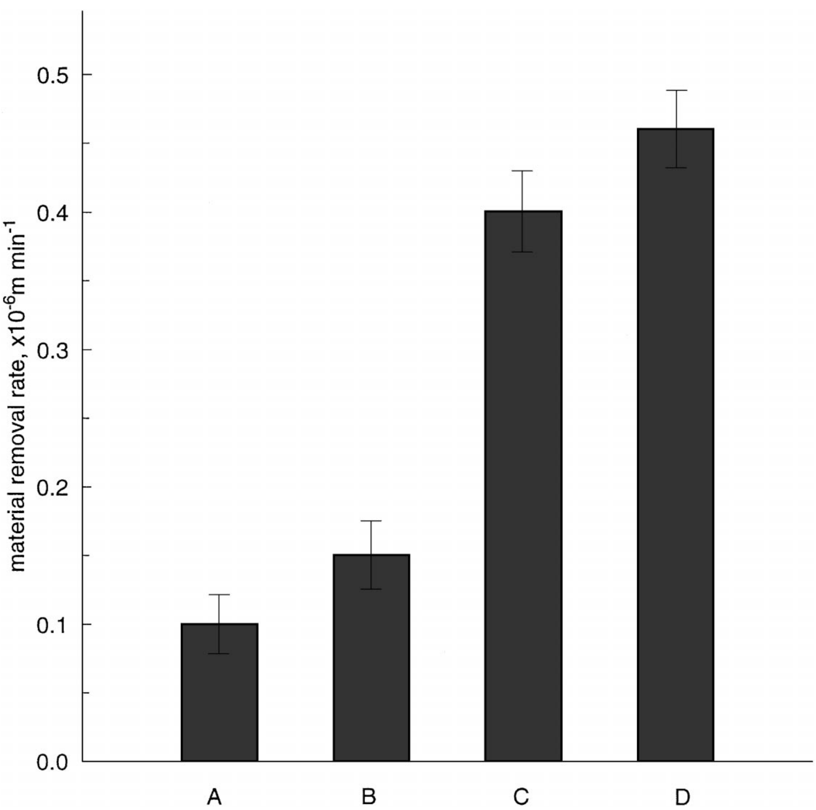


Figure 4 Effect of inorganic additives in various O-W slurries containing 1 μm diamond abrasive particles on the material removal rate of silicon nitride balls; 400 N load and 3000 rpm speed. A, oil-based slurry; B, oil-water (O-W) based slurry; C, 5 mol/l of additive B in O-W slurry; D, 5 mol/l of additive A in O-W slurry.

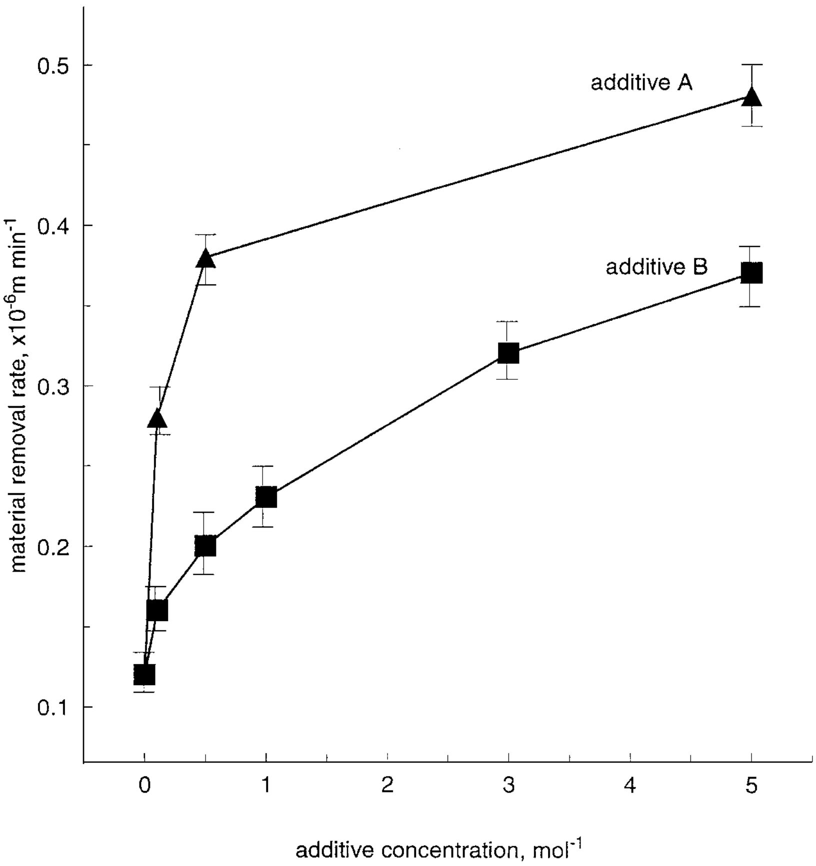


Figure 5 Variation of the material removal rate of silicon nitride balls with concentration of inorganic additives in 1 μm O-W slurry during tests at 400 N load and 3000 rpm speed.

same concentration was used for additive B in O-W slurry.

The lowest material removal rate, regarded as a reference rate, was recorded for the commercially available oil-based slurry. A slight increase in the material removal rate was noted for O-W type slurry. However, a substantial increase in the material removal rate resulted from adding additive B to O-W slurry and the highest removal rate was obtained for O-W slurry containing additive A. The effect of different concentrations of additives in O-W slurry with 1 μm abrasive particles on the material removal rate is shown in Fig. 5. An increase in concentration of either additive results in an increase in material removal rate after an initial rapid increase in the material removal stabilizes and further increases in concentration beyond 5 mol/l do not improve efficiency of the material removal process. Also, additive A is more effective than additive B throughout the whole range of concentrations used.

The influence of abrasive particle size on the material removal rate in the presence of additive A or B is shown in Fig. 6. The rate of material removal is presented as a function of additive concentration for two sizes of abrasive particles, 1 and 15 μm.

Increasing both additive concentration in O-W slurry and the size of abrasive particle leads to higher material removal rates. The O-W slurry containing 15 μm particles and either additive A or B is considerably more efficient in material removal than the slurry containing 1 μm particles. This is true for all additive concentrations used.

3.1.2. Material removal rate in the presence of chemical compounds

The effectiveness in material removal of chemical compounds listed in Table I and containing 15 μm abrasive particles in concentration 2 wt % was also studied. In this series of experiments an oil-based slurry with the same size of abrasive particles (15 μm) was used for reference purpose. Fig. 7 shows the material removal rates using the various chemical compounds and the reference slurry.

The highest material removal rate was recorded for 884 compound and the lowest for 856 compound. A relatively high material removal rate was also produced by 858 compound however, post-test examination of the balls revealed that they were not completely spherical and the deviation from sphericity was up to 10 μm. The same was found in the case of the 856 and 857 compounds but the deviation from sphericity was slightly less, namely 6 and 8 μm, respectively.

3.1.3. Material removal rate in the presence of organic additives

Seven different organic additives, listed in Table II, were used in the oil-based slurry containing 1 μm abrasive particles. The additive concentration was 1 wt %. The results are shown in Fig. 8.

The highest material removal rate was obtained using olefin ester sulfide (998) while the lowest one was recorded for olefin sulfide (997) as the aditive. The material removal rate as a function of organic additive concentration in 1 μm oil-based slurry was also examined.

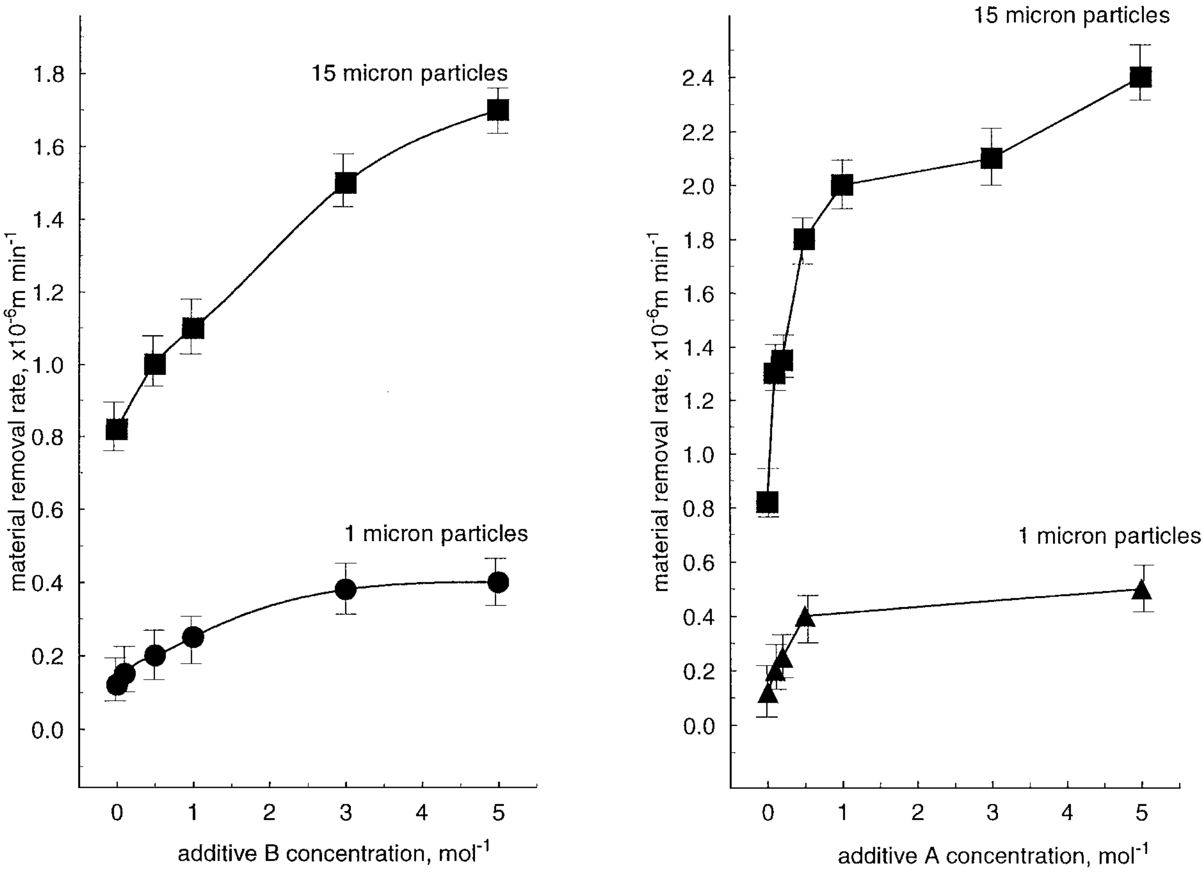


Figure 6 Variation of the material removal rate of silicon nitride balls with the concentration of inorganic additives A and B in 1 and 15 μm O-W slurries during experiment at 400 N load and 3000 rpm speed.

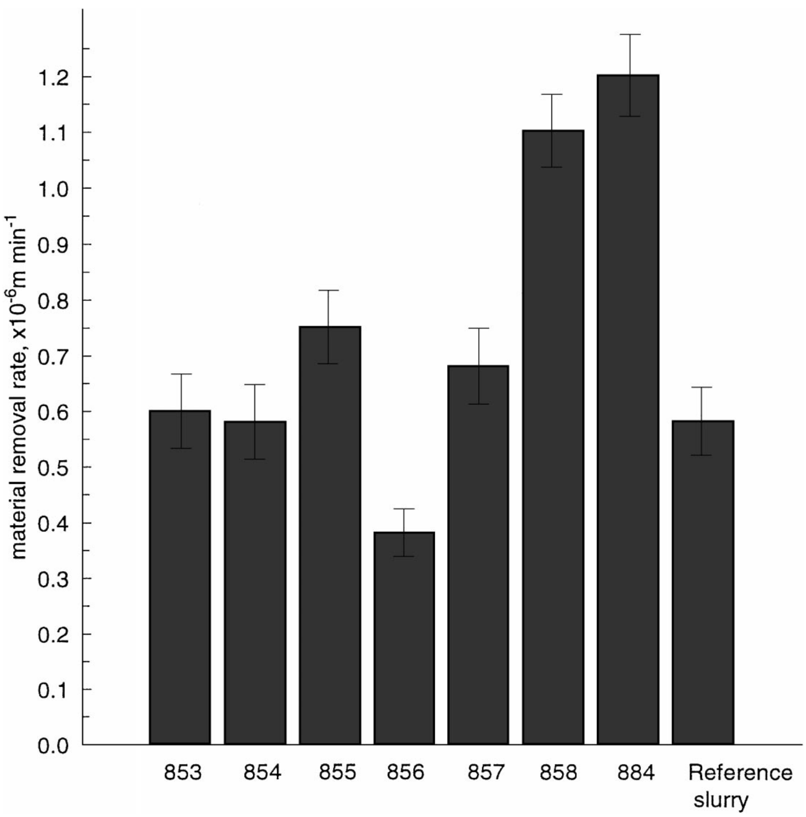


Figure 7 Material removal rate of silicon nitride balls during experiments at 400 N load and 3000 rpm speed in various chemical compounds and the reference slurry (oil-based containing 15 μm abrasive particles).

The results indicate that the material removal rate decreases with an increase in the concentration of organic additive (Fig. 9) with two exceptions, that is additive 996 (Na sulfonate) and 997 (olefin sulfide).

3.1.4. Effect of additional cup rotation

In order to examine the effect of an increased amount of relative slip within the contact area on the material removal rate, experiments were carried out using rotation

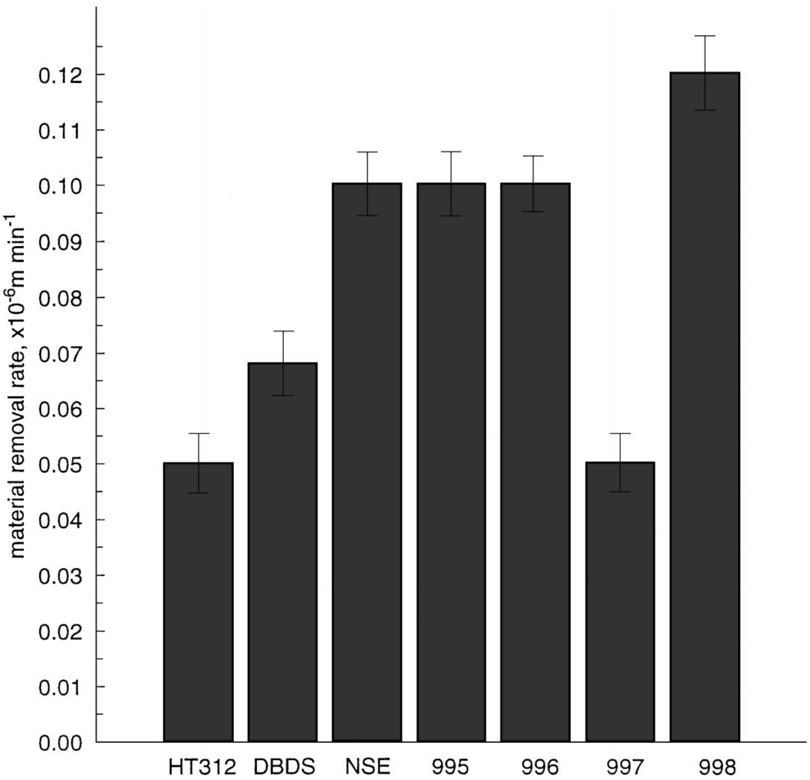


Figure 8 Effect of organic additives in an oil-based slurry containing 1 μm abrasive particles on material removal rate of silicon nitride balls during experiments at 400 N load and 3000 rpm speed.

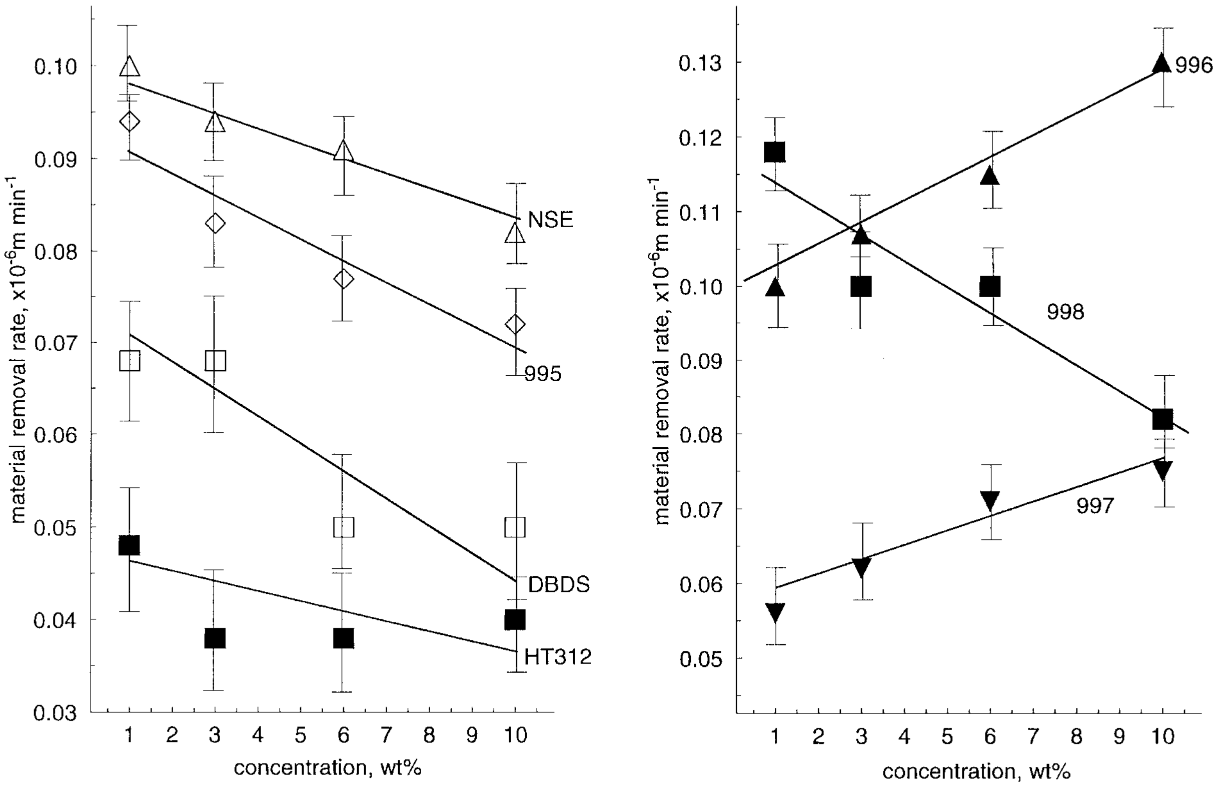


Figure 9 Variation of the material removal rate of silicon nitride balls with concentration of organic additives in 1 μm oil-based slurry during experiments at 400 N load and 3000 rpm speed.

of the cup (which is normally stationary). Standard oil-based slurry containing 15 μm abrasive particles was used. It was found that cup rotation with the velocity of 40 rpm resulted in a measurable increase in the material removal rate as shown in Fig. 10. This aspect has been discussed earlier by Jisheng *et al.* [8].

3.1.5. Effect of the flow of gas through the contact region

It has been reported by Hisakado [5] that same gaseous environments promote the wear of ceramic materials. Nitrogen and oxygen were circulated in turn through the cup filled with the oil-based slurry containing 15 μm

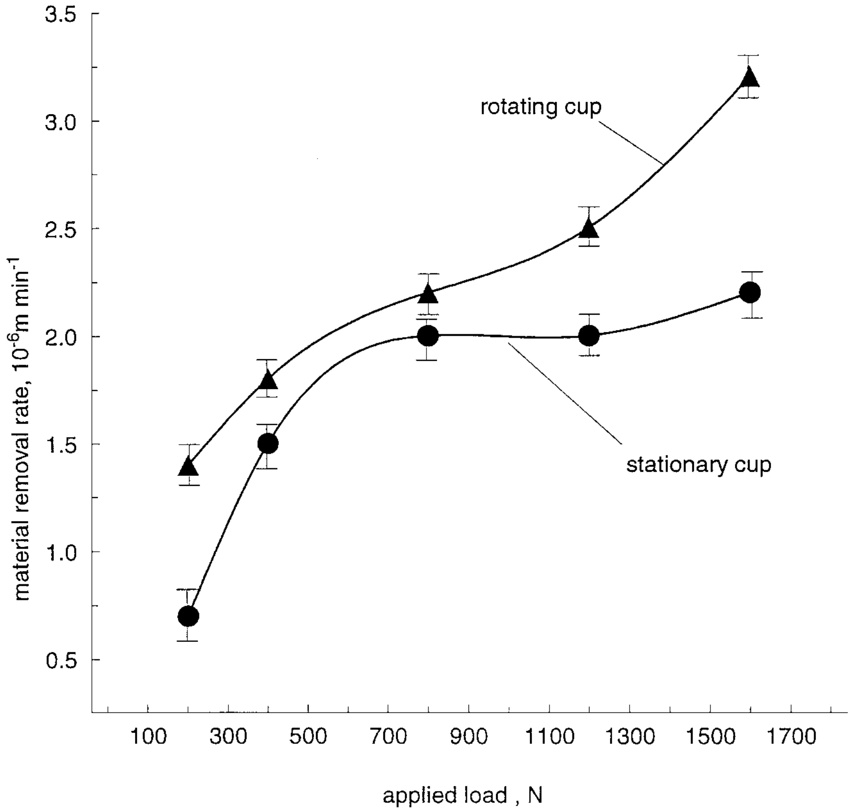


Figure 10 Effect of cup rotation on the material removal rate during experiment in 15 μm oil-based slurry at 3000 rpm cone speed and 40 rpm cup speed and different applied loads. Test duration: 60 min.

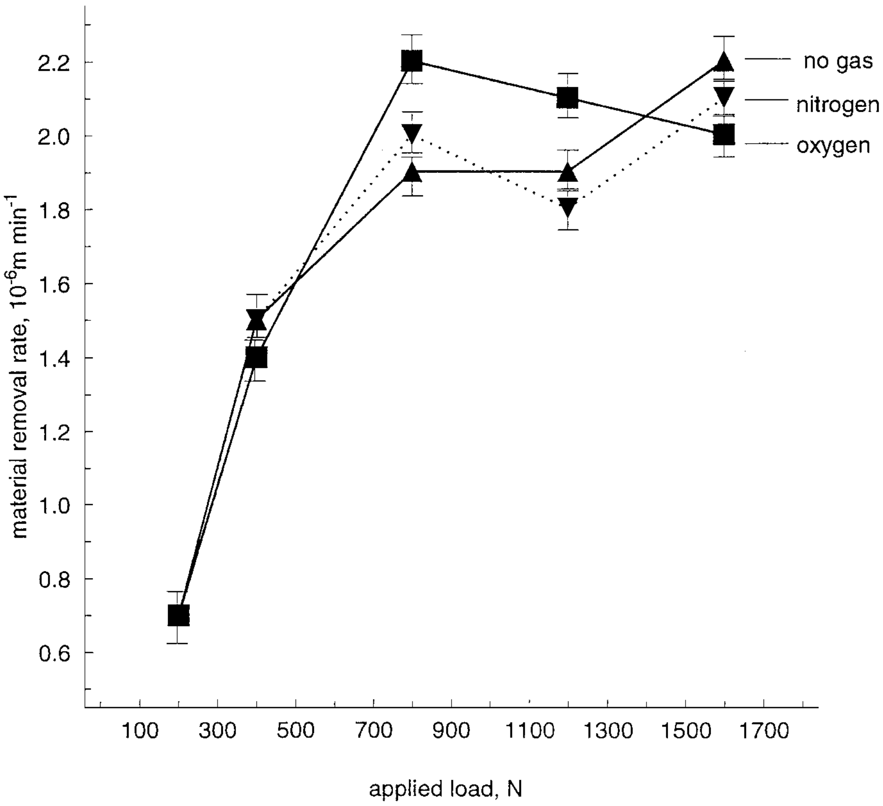


Figure 11 Variation of material removal rate with load and the presence of different gases during experiments in 15 μm oil-based slurry. Spindle speed: 3000 rpm; test duration: 60 min.

abrasive particles. Fig. 11 shows the effect of gas circulation on the material removal rate for different loads on the contact. The results are not conclusive and indicate that the presence of either nitrogen or oxygen in the contact region does not increase, in any significant way, the material removal rate.

3.2. Sliding line contact

3.2.1. Alumina experiments

Test results on alumina in contact with mild steel V-blocks are shown in Fig. 12 where the material removal rate is plotted against the load on contact for different sizes of abrasive particles added to the oil-based slurry.

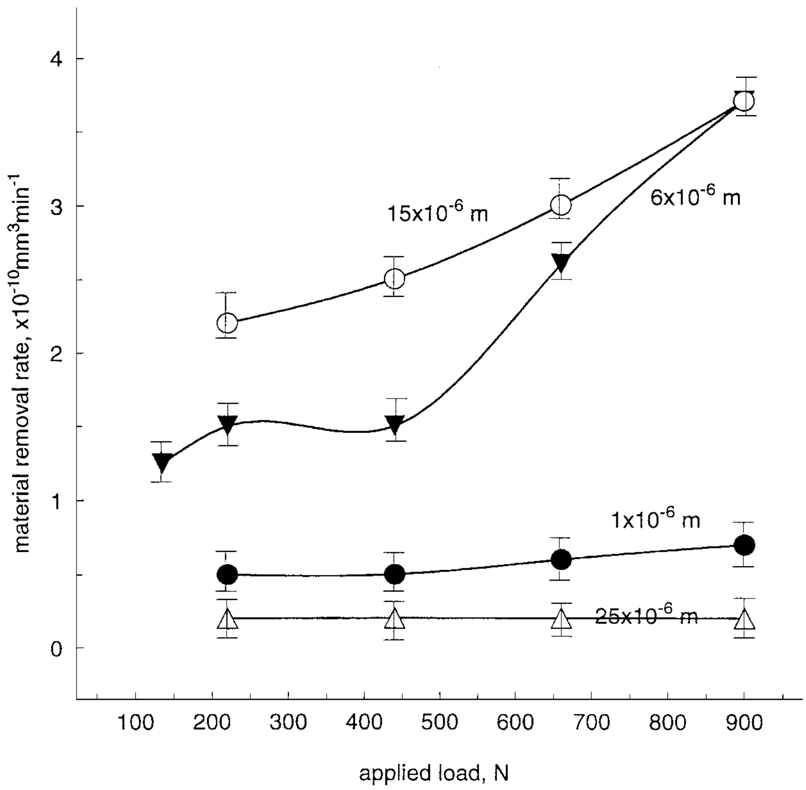


Figure 12 Material removal rate of alumina in oil-based slurry as a function of the applied load for different sizes of abrasive particles. Rotational velocity of the ceramic sample: 300 rpm; duration of the test: 60 min.

The first observation is that the material removal rate increases with applied load for all sizes of abrasive particles. For abrasive particle sizes of 1, 15 and 25 μm the change in material removal rate with load is linear. In the case of 6 μm particles, a clear transition in the material removal rate occurring at 450 N can be seen. The rate of material removal also increases with the size of abrasive particles. This is true for 1, 6 and 15 μm particles. A maximum rate of material removal occurs for 15 μm particles.

It is commonly assumed that counterface material must play an important role in wear processes. To examine the effect of counterface material on the wear rate of alumina, V-blocks were made of a mild steel, aluminium alloy and brass and tested in an oil-based slurry containing 6 μm abrasive particles. Fig. 13 shows the results obtained.

The highest material removal rate was recorded for the V-block made of aluminium alloy over the whole range of applied loads. The lowest rate was produced by the brass V-block. Removal rate somewhere between these two was obtained for the mild steel V-block. This finding points to the importance of retention of abrasive particles within the contact region. It appears that the V-block made of aluminium allowed the abrasive particles not only to embed into it but also to stay embedded. On the other hand, while the brass V-block also facilitated the embedment of abrasive particles the strength of their anchoring in the substrate was, presumably, not sufficient to retain them in the contact region.

3.2.2. *Sialon experiments*

The removal rates using sialon were investigated using two different V-block materials (mild steel and aluminium alloy) and a number of sizes of abrasive particles added to an oil-based slurry. All experiments were carried out at 900 N. The results are shown in Fig. 14.

It is interesting to note that the highest removal rate using the mild steel counterface was achieved for 6 μm abrasive particles. In the case of aluminium alloy counterface, the highest removal rate was obtained for 15 μm abrasive particles. However, both removal rates are comparable in magnitude. The relationship between removal rate and load applied is shown in Fig. 15.

The experiments were carried out in the oil-based slurry containing 15 μm abrasive particles using both aluminium alloy and mild steel V-blocks. The relationship between the load and the material removal rate is almost linear for both counterface materials, i.e. wear rate increases with increase in contact loading. The aluminium alloy counterface proved to be more effective in material removal than the mild steel counterface under nominally the same test conditions.

4. Discussion

4.1. Surface characteristics resulting from mechanical effects

4.1.1. *Abrasive particle size*

It is well known that, in general, the rate of material removal depends on the size of abrasive particles used and usually increases with the increase in their size [12, 14]. However this trend in not exactly observed in case of alumina and sialon studied in the line sliding contact experiments. As can be seen from Fig. 12, the rate of material removal is clearly lower for 25 μm particles than for 15 μm particles at which the maximum rate was observed. This trend is in agreement with findings reported by Stolarski *et al.* [10] for rolling point

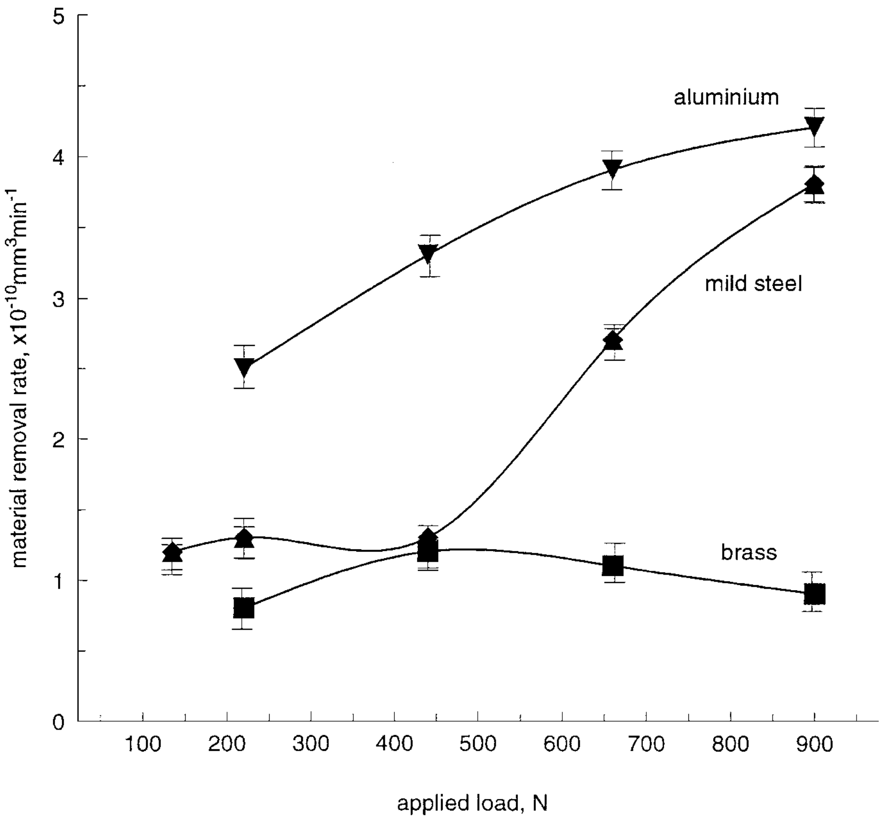


Figure 13 Variation in the alumina removal rate with applied load for different counterface materials during experiments in oil-based slurry containing 6 μm abrasive particles. Rotational velocity of the ceramic sample: 300 rpm; duration of the test: 60 min.

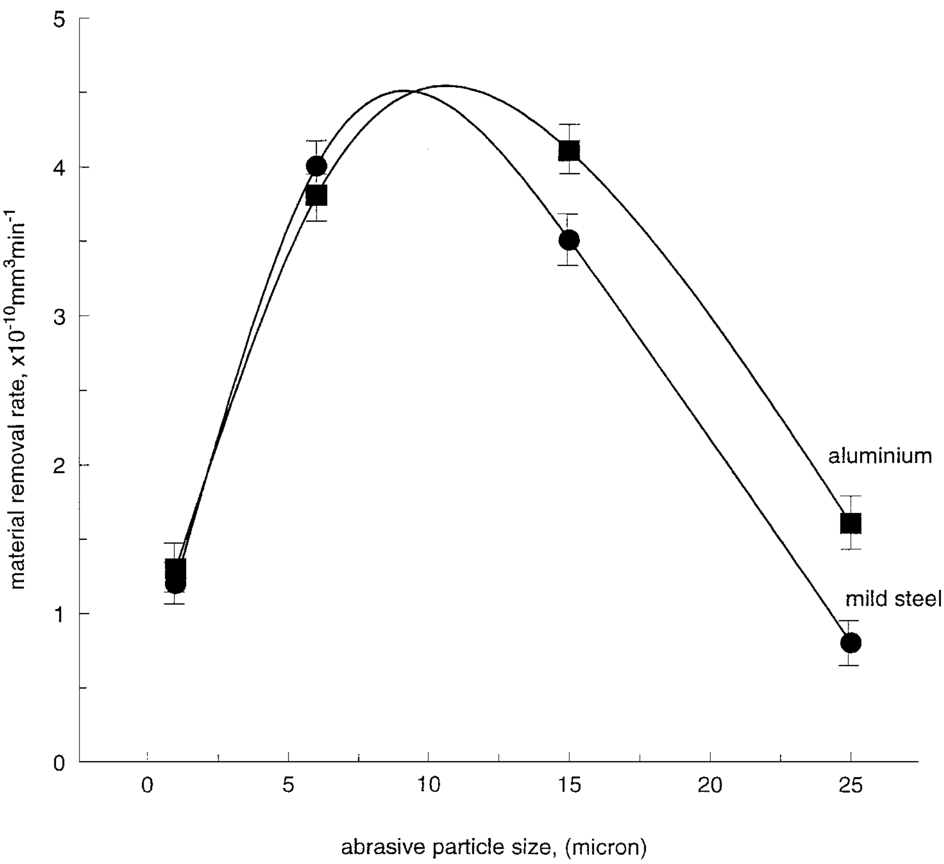


Figure 14 Sialon removal rate in oil-based slurry as a function of abrasive particles size for two counterface materials. Rotational velocity of the ceramic sample: 300 rpm; duration of the test: 60 min.

contact. The silicon nitride removal rate increases as the particle size is increased from 1 to 15 μm. Further increase in the particle size from 25 to 45 μm results in reversal of the trend. Thus, it can be concluded that there is an optimum in the size of abrasive particles giving the maximum removal rate.

The explanation for the observed trends in material removal could be based on the analysis of the number

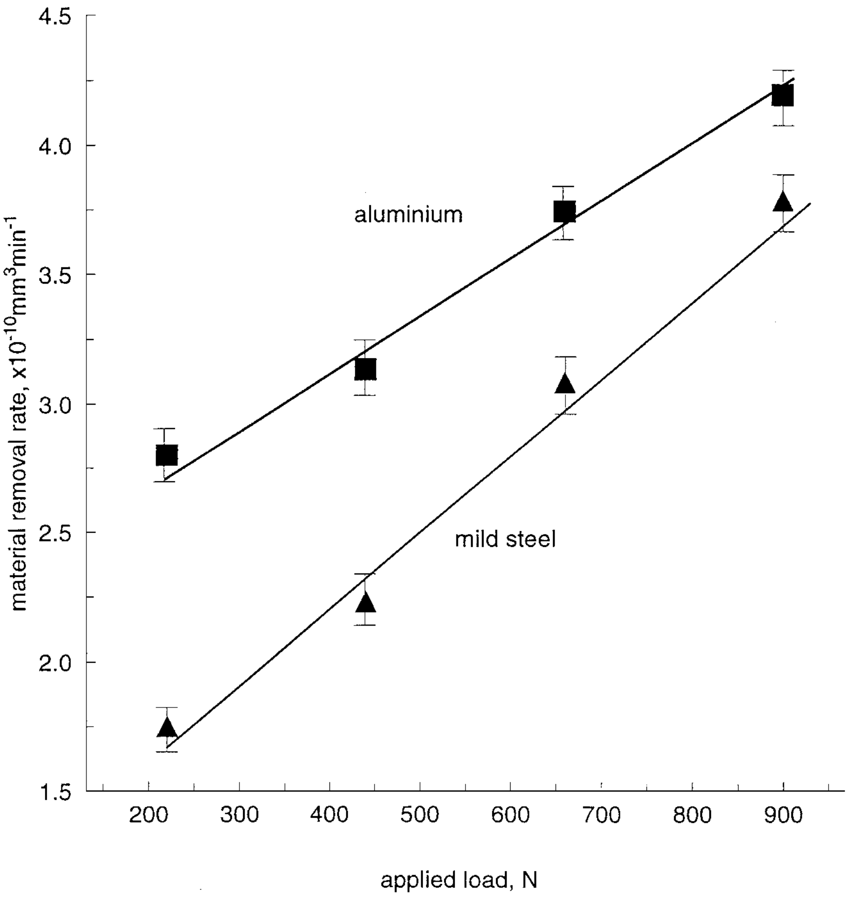


Figure 15 Sialon removal rate as a function of applied load for mild steel and aluminium alloy counterfaces. Oil-based slurry with 15 μm abrasive particles; rotational velocity of the ceramic sample: 300 rpm; duration of the test: 60 min.

of abrasive particles per unit volume of the slurry. If M denotes mass of particles per unit volume of slurry, n represents the number of particles per unit volume and m is the mass of a single particle, then

$$M = nm$$

where m is given by,

$$m = \frac{4}{3}\pi r^3 \rho$$

In the above expression ρ is the density of the abrasive particle and r its radius (assuming that the particles have a spherical shape). Thus,

$$M = n\frac{4}{3}\pi r^3 \rho$$

or

$$n = \frac{1}{r^3}\frac{3M}{4\pi\rho}$$

For fixed M and constant ρ, and for two particle sizes r_1 and r_2, the ratio of the number of particles per unit volume is,

$$\frac{n_1}{n_2} = \frac{r_2^3}{r_1^3}$$

and for $r_1 = 1$ μm and $r_2 = 45$ μm,

$$\frac{n_1}{n_2} = 91125$$

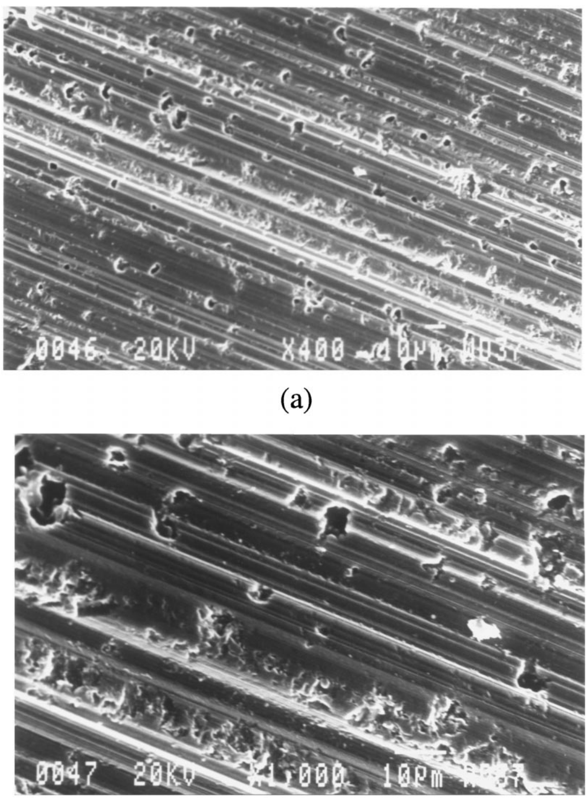
and so there are approximately 90,000 as many 1 μm abrasive particles per unit volume of a slurry as there are 45 μm particles in the same volume of a slurry. In a similar way it can be shown that, on average, there are approximately 16,000 more abrasive particles in a unit volume of 1 μm slurry than in the same unit volume of 25 μm slurry. It follows then that 1 μm slurry should give higher material removal rates due to the larger number of abrasive particle-ceramic surface contacts per unit time than in the 25 μm slurry. This conjecture depends upon the operative material removal mechanism. If it is two-body abrasion mechanism for the medium size particles, then the number of embedded particles per unit area of cup or the V-block surface will accumulate with time which will compensate for their much lower numbers per unit volume of slurry. In addition, one unit abrasive action from a medium size particle clearly removes more material than a small particle. The question why the removal rates of 25 μm particles are lower than those of 15 and 6 μm can only be answered in conjunction with possible hydrodynamic effects within the contact area. As there is no direct evidence in support of this explanation it must be regarded as tentative and hypothetical. An alternative explanation is that the load, speed, and contact configurations used probably created such conditions under which 15 μm particles were able to enter the contact and be embedded there because the fluid film created by the hydrodynamic action had an appropriate thickness. According to the test results (see

Fig. 12), these conditions apparently existed for 15 μm particles in the whole range of test parameters. This also applies, to a lesser extent, to 6 μm particles. It follows then that 25 μm particles had a restricted access to the contact region possibly because of the film thickness whilst 1 μm particles were passing through the contact zone without removing much of the material.

For a high rate of material removal to be achieved it is essential that abrasive particles gain easy access to the contact zone and stay there. The retention of particles in the contact region is only possible if they can embed themselves into the counterface. Fig. 16 shows an SEM micrograph of the mild steel V-block after wear experiments on sialon in 6 and 25 μm slurries. It appears that 6 μm particles entered the contact zone in far greater number than 25 μm particles producing substantially higher material removal rate.

4.1.2. Counterface material

Figs 13 and 14 indicate that the counterface material has a considerable effect on the removal rate. Fig. 17 shows the changes in the hardness of steel and aluminium counterfaces after wear experiments. As shown, the surface of the aluminium counterface is considerably harder than its interior. The decrease in hardness takes place over the depth of almost 200 μm, after which the hardness remains constant. This finding points to an appreciable work-hardening of the aluminium occurring during wear and is supported by the results of abrasive wear tests reported by Gahr-Zum [11]. On the other hand, the hardness of the steel counterface does not change at all (see Fig. 17).



(a)

(b)

Figure 16 SEM micrographs of the mild steel counterface after experiment at 900 N load and 300 rpm speed: (a) 6 μm abrasive particles; (b) 25 μm abrasive particles.

It could therefore be argued that abrasive particles penetrate aluminium counterface much more easily and have a better chance to be retained by the counterface due to a significant work-hardening. The steel counterface is not only harder than the aluminium counterface thus hindering the ingress of abrasive particles into the substrate but it also does not undergo any appreciable work-hardening which results in a poor retention of abrasive particles. The third counterface material used was brass characterized by a lower hardness than the other two. It also gave the lowest removal rates (see Fig. 12). SEM image of the cross-section through the brass counterface is shown in Fig. 18. A characteristic feature of the cross-section image is the presence of a well formed top layer of material. Micro-hardness measurements showed that this layer is softer than the bulk material. In the context of material removal rate it means that this relatively soft layer could have been responsible for an inadequate retention of abrasive particles in the contact zone.

4.1.3. Increased relative slip due to cup rotation

The rationale behind the experiments with additional cup rotation was an attempt to improve the material removal rate through the increase of relative slip within the contact zone. The results in Fig. 10 show that the additional cup rotation did not produce an appreciable increase in the material removal rate. However, surface roughness measurements showed that it resulted in an improved surface finish [8]. This finding can be seen as an indication that abrasive wear (either two-body or three-body) is not a predominant process responsible for material removal from hard and brittle surfaces in rolling contacts but micro-fracture taking place at discrete points of contact between ceramic surface and abrasive particles.

4.2. Surface characteristics resulting from chemical effects

4.2.1. Inorganic additives

Introduction of additive A or B to O-W slurry caused a remarkable increase in the material removal rate (see Figs 4 and 5). Typical microscope examination results of surfaces after testing in the O-W slurry containing 1 μm abrasive particles and 5 mol/l of A or B are shown in Fig. 19. Although relatively small abrasive particles were used the surface was quite rough and the material removal rate quite high. The surface looks as if it was composed of black regions on a white background. At high magnification, the black regions appeared to be very smooth whereas the white background was rough with an open surface texture (see Fig. 19). The open structure could be a form of pitting resulting from surface chemical reactions.

With decreasing concentration of the additive A in the O-W slurry, the extent of the pitted regions decreased. At the lowest concentration of A in 1 μm O-W slurry, equal to 0.05 mol/l, the pitted white

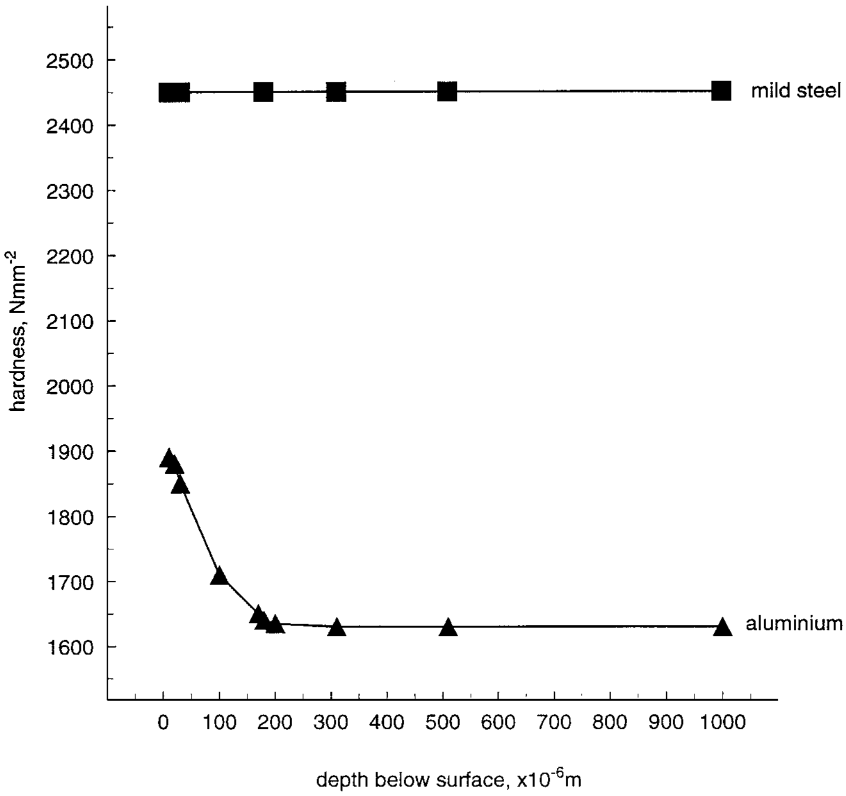


Figure 17 Hardness profile of mild steel and aluminium alloy counterfaces after experiment at 900 N load and 300 rpm speed in oil-based slurry with 6 μm diamond abrasive particles.

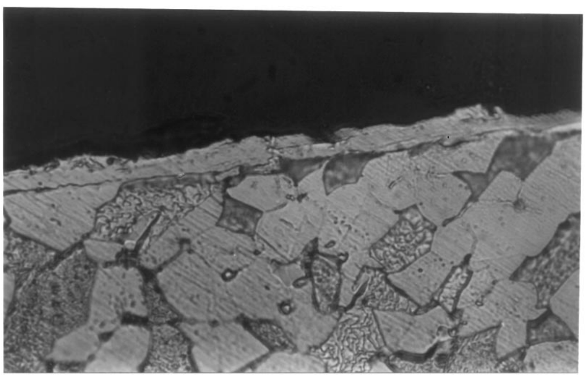


Figure 18 Optical micrograph of the cross-section through the brass counterfaces after experiment at 900 N load and 300 rpm speed in oil-based slurry with 6 μm diamond abrasive particles.

background was transformed into isolated islands on a black background.

Under the test conditions used a possible chemical reactions between the additives and the silicon nitride could be as follows:
Additive A:

$$3NH_3 + H_3PO_4 \rightarrow (NH_4)_3PO_4$$

Since additive A was in the slurry containing water, therefore,

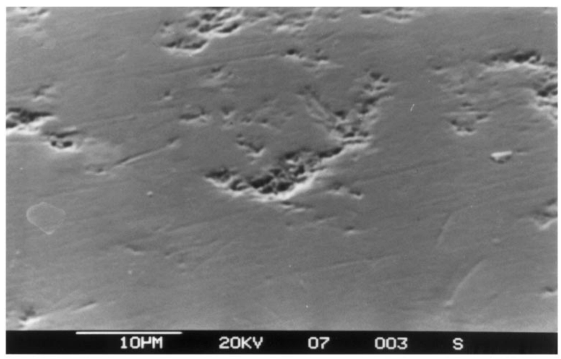
$$SiO_2 + 2H_2O \rightarrow Si(OH)_4$$

and

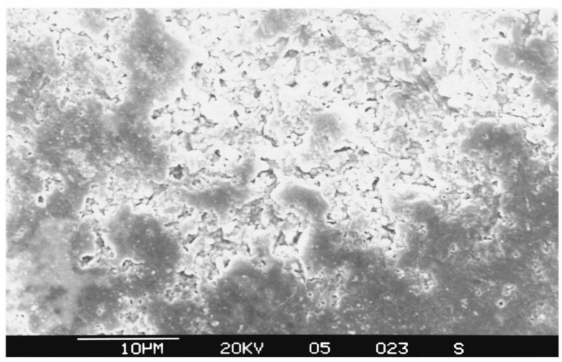
$$3Si(OH)_4 + 4H_3PO_4 \rightarrow Si_3(PO)_4 + 12H_2O$$

Similarly, since additive B was in the slurry containing water, so,

$$SiO_2 + H_2O \rightarrow H_2SiO_3$$



(a)



(b)

Figure 19 SEM micrographs of silicon nitride ball after experiment in 1 mm O-W slurry with 5 mol/l of additive A: (a) smooth black area; (b) open and rough white area.

and

$$H_2SiO_3 + 2KOH \rightarrow K_2SiO_3 + 2H_2O$$

As a result, a relatively soft layer could be formed on the surface of silicon nitride which, during wear testing, could be easily worn off thus increasing the material removal rate.

4.2.2. Organic additives

Experiments with organic additives were carried out in the sulfur containing and ester containing slurries. The slurries based on highly refined mineral oils 853 and 854, the poly-alpha-olefines 856 and 857, and polyoxyalkylene glycol ether 858 and called "blank slurries" were also used. With the exception of the 858 slurry, all blank slurries gave similar material removal rates (see Fig. 7). However, wear experiments in the 856, 857 and 858 slurries produced ovality of the balls. This probably resulted from a relatively high viscosity of the base liquid interfering with the motion of balls in the test cup.

The sulfur containing slurries included the HT312, the 997 and the DBDS. Results obtained indicate that the wear rate of silicon nitride in sulfur containing slurry decreases. However, post-test microscope examinations revealed an excellent surface finish as shown previously [9]. According to Gates *et al*. [3] the smooth surface is produced as a result of formation of a surface film during sliding in the sulfur containing liquids.

The 995 and 996 slurries were based on metal containing sulfonates. The material removal rates were slightly higher for these slurries (Fig. 8). Also, microscope examinations showed that most regions on the surface subjected to grinding had an excellent surface finish.

Ester containing slurries included the 855, the 884, the 998, and the NSE. It can be seen from Figs 7 and 8 that the ester containing slurries helped to increase the material removal rate. The presence of fine scratches and pits on the worn surfaces was found by microscope examination.

5. Conclusions

It has been demonstrated that mechano-chemical effects assist in the removal of material from hard, brittle surfaces. A fivefold increase in material removal rate, as compared to that offered by currently used methods in industry, can be achieved without a danger of damaging the surface itself.

On the basis of results produced by experiments reported here, it is justified to suppose that the main mechanism governing the material removal process consisted of creation of a surface layer due to chemical reactions initiated under the test conditions used. This layer was easily removed by the action of abrasive particles present in the grinding liquid.

Phosphoric acid and potassium hydroxide have been identified as very effective additives to a grinding liquid. The same is true of fluoride compounds but only when they are added to a grinding liquid containing traces of phosphoric acid. Surface finish of spherical surfaces can be controlled, to a certain degree, by the introduction of an additional amount of slip into the contact zone. The highest wear rates are achieved when the slip is combined with appropriate chemical additives to the grinding liquid.

The rate of wear of ceramics such as alumina and sialon depends on the size of diamond abrasive particles and the type of counterface material. The highest material removal rates were achieved for an aluminium counterface, followed by the mild steel and the brass.

An optimum size of diamond abrasive particles giving the highest material removal rates was found; the 15 μm abrasive particles were, in general, the most effective.

High material removal rate achieved solely by mechanical means is usually accompanied by the creation of a rough surface.

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