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Attrition of silicon nitride as a function of counterface material and contact zone kinematics

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Engineering ceramics have found use in many practical applications. This growing demand for engineering ceramic components triggered interest in effective and safe methods of surface finishing. The paper presents the results of experimental studies into the influence of different counterface materials, contact zone kinematics and abrasive particle concentrations on the wear rate of silicon nitride. Three different counterface materials were used, i.e. grey cast iron, bronze and aluminium. Silicon nitride balls produced by hot isostatic pressing were used as specimens. Abrasive particle concentration in grinding fluid varied from 1 to 10 per cent by weight. Also, an additional motion of the specimen was introduced and combined with the main motion of the counterface. It was found that all three parameters studied have a significant influence on the rate of material removal. The material of the counterface and the additional motion of the specimen were especially important in this respect.

1. Introduction

Engineering ceramics have found use in many applications, for instance as engine parts, ball bearings, artificial bone and hip replacements and high-speed air lubricated bearings. In the case of rolling contact bearings, the use of ceramic materials achieves clear practical advantages over traditional bearing steels. This is because of such properties of ceramics as low density, high stiffness, high hardness, dimensional stability at elevated temperatures and also, in some cases, very good wear resistance. However, the manufacture of rolling contact elements to a specified surface finish is quite difficult and expensive mainly because of the very small rate of material removal during grinding and polishing operations. It is justifiable to say that a significant fraction of the total cost of ceramic rolling element manufacture is attributed to surface finishing processes.

Due to the growing demand for engineering ceramic components, the interest in effective and safe methods of surface finishing of ceramics is also rapidly increasing. Although a number of surface finishing processes have recently been developed [1–4], the dominant industrial method of grinding, however, is still based on using diamond slurries, even though it is rather slow and, therefore, expensive. Undoubtedly, the traditional method of surface finishing of ceramics needs to be improved and the way to accomplish that is through a better understanding of the grinding process itself and identification of the factors controlling the material removal rate.

The main objective of the study presented in this paper was to investigate the influence of different counterface materials, the contact zone kinematics and abrasive particle concentration on the material removal rate. Silicon nitride balls, produced by Norton Advanced Ceramics using hot isostatic pressing (HIP), were used as specimens and grey cast iron, bronze and aluminium were utilized as counterface materials.

2. Experimental procedure

2.1. Test setup

All experiments were carried out with the contact configuration schematically shown in Fig. 1. In this testing device, designed and bulit in the authors' laboratory, the specimen in the form of a ceramic ball 12.5 mm in diameter is loaded against the periphery of rotating disc which constitutes the counterface and has a diameter of 120 mm. The rotational speed of the disc (typically 270 rpm which corresponds to 1.7 m/s linear sliding velocity) could be continuously varied. The contact was lubricated with an additive-free base mineral oil (Shell Talpa 20, SAE30) containing a known concentration of abrasive particles (silicon carbide #1200). The amount of grinding fluid entering the contact was controlled by a micro-pump.

In Fig. 1b, contact between stationary ball and rotating disc is depicted. The load on the ball was applied through a loading arm by dead weights. In another version of this testing configuration, the ball was enabled to rotate, independently of the rotation of the disc, about its load axis (Fig. 1c). The angular velocity of the ball, ranging from 0.16 to 2 radians/s (i.e. 1.6 to 20 rpm), was adjusted by means of an electronically controlled electric motor.

When the ball is stationary, the sliding velocity is the same for all points within the contact zone and velocity

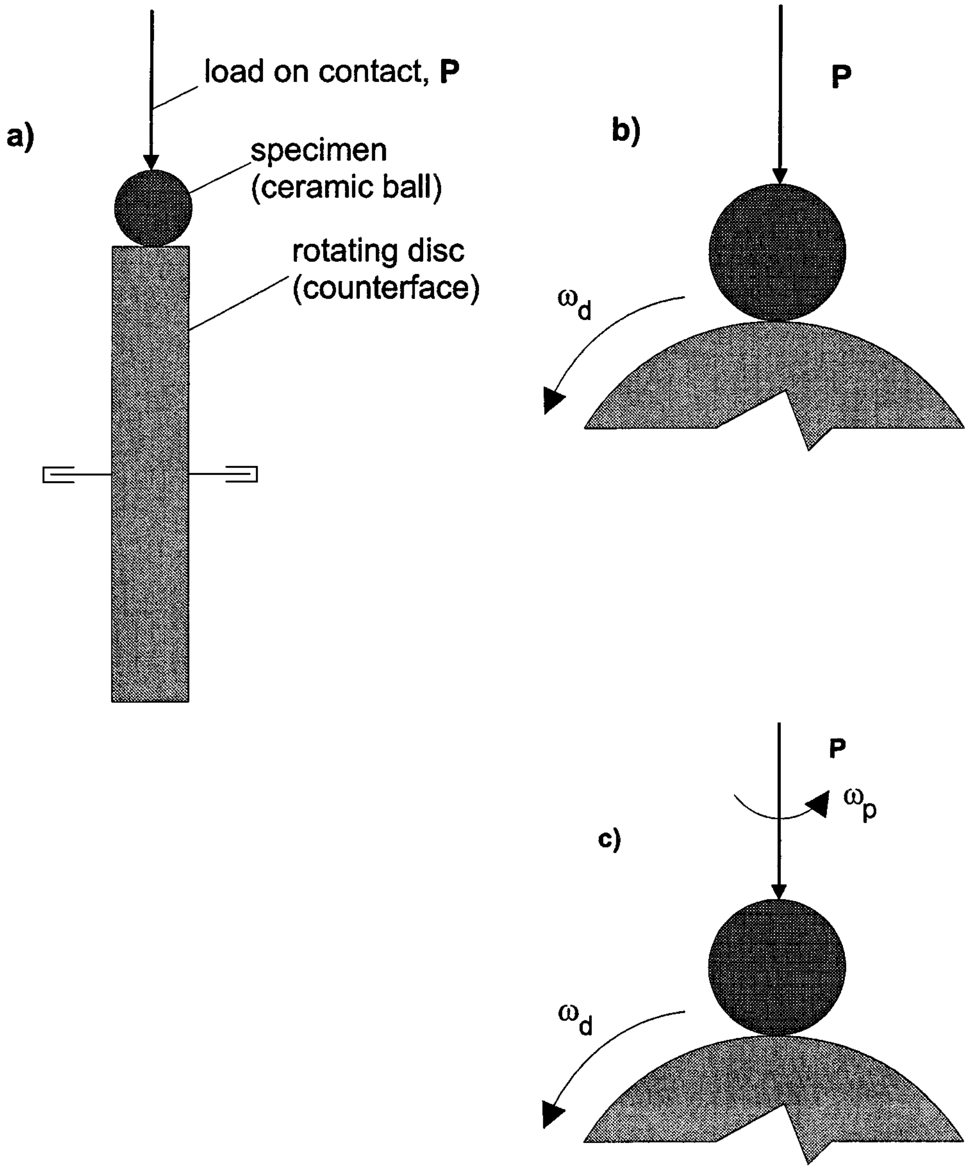

Figure 1 Schematic of testing machine configuration (a) general situation; (b) contact between stationary specimen and rotating disc; (c) contact between specimen rotating about its load axis and rotating disc.

trajectories are all straight lines. The same trajectory can be produced by sliding a ball along the straight line on the surface of a flat plate. The additional rotation of the ball considerably changes the kinematics of the contact and has some important consequences for the material removal rate.

2.2. Test parameters and procedure

Wear experiments were carried out for a number of different test conditions. Seven different concentrations of silicon carbide particles in the oil were used: 0.05%, 0.1%, 0.25% (low concentration) and 1%, 2.5%, 5% and 10% (high concentration). The following rotational velocities of the ball were used: 1.6, 4 and 20 rpm. As the ball was rotating about its own axis, the linear sliding velocity was varying with the distance from the centre of rotation where it was zero to a maximum value defined by the size of the contact area created by wear process. The effect of additional motion of the ball was tested at one concentration of abrasive particles, that is 0.1% by weight. Normally, tests were carried out at a load of 15 N acting on the contact between the ball and the counterface. Because of the cooling effect of the grinding fluid the temperature of the test piece was close to the room temperature.

After running-in, the ball was ultrasonically cleaned and weighed on a precision balance. This was supplemented by micrometer measurements of the diameter. After the required velocity of the disc and the load on the contact were set, a typical experiment was run for 15 or 60 minutes depending on the concentration of abrasive particles in the grinding fluid. At the end of the experiment, the ball was removed from the holder and after cleaning the loss of material was measured using a precision balance. Surface of the counterface (disc) was usually containing embedded abrasive particles, therefore, an attempt to measure the wear of the disc was thought to be impractical.

An additive-free base mineral oil was used as the carrier of abrasive particles to the contact zone. With a stationary ball, the initial point contact was gradually changing, due to wear, into an elliptical contact.

All tests were repeated at least three times and if the scatter of results was greater than 5% further tests were carried out in order to generate more results and decrease the scatter.

3. Results and their discussion

3.1. The effect of abrasive particle concentration

3.1.1. High particle concentrations

Fig. 2 shows the amount of material removed from the ball as a function of test time for different abrasive particle concentrations and with the aluminium counterface. The load applied was 15 N and the linear sliding velocity of the counterface was 1.7 m/s. The amount of material removed is given as a difference, in grammes, between the initial weight of the ball and its weight after the completion of the test. As expected, the material removal increases, in general, with the increase in concentration of abrasive particles although there is an anomaly; 5% concentration produced slightly lower removal of material than 2.5% concentration.

Fig. 3 contains the results of ceramic ball wear when the bronze was used as the counterface. Tests were carried out under the same normal load on the contact to the case of aluminium counterface. However, the difference in elastic modulus values between the

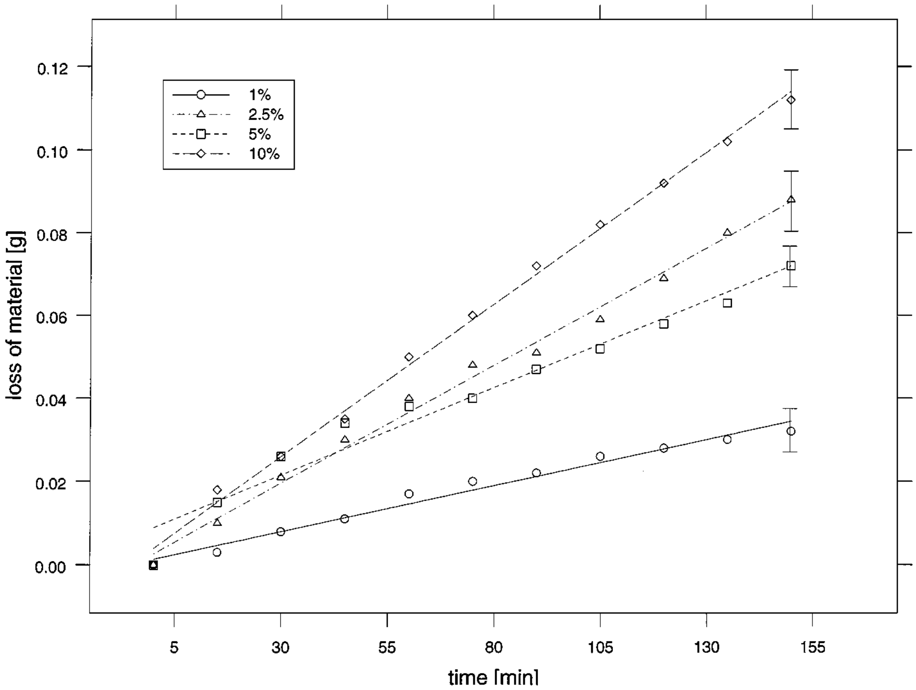

Figure 2 Loss of material from the ball versus test duration with the aluminium disc and different abrasive particle concentrations. Load on contact—15 N. Disc velocity—1.7 m/s.

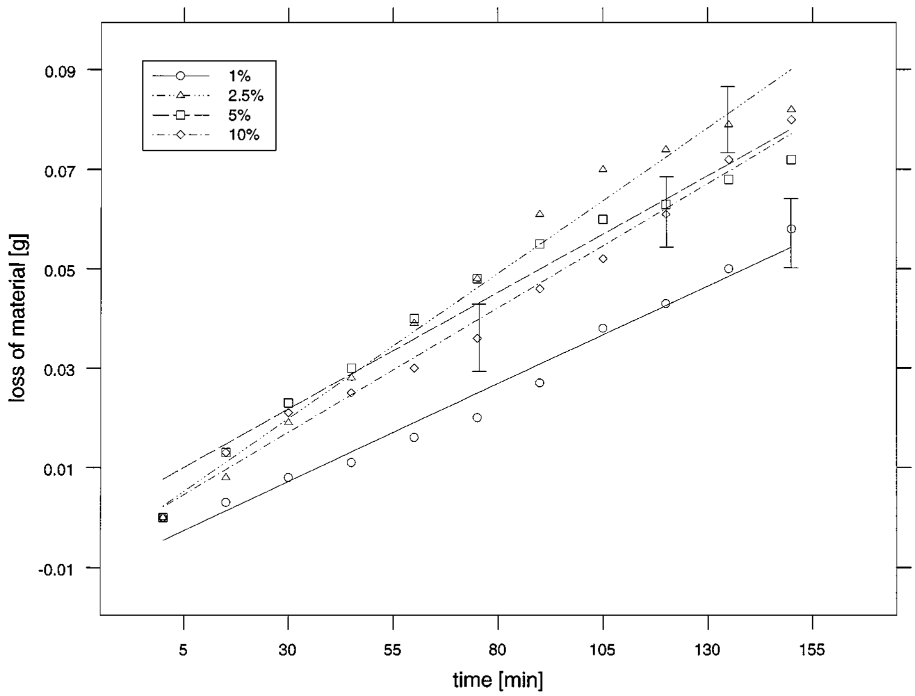

Figure 3 Loss of material from the ball versus test duration with the bronze disc and different abrasive particle concentrations. Load on contact—15 N. Disc velocity—1.7 m/s.

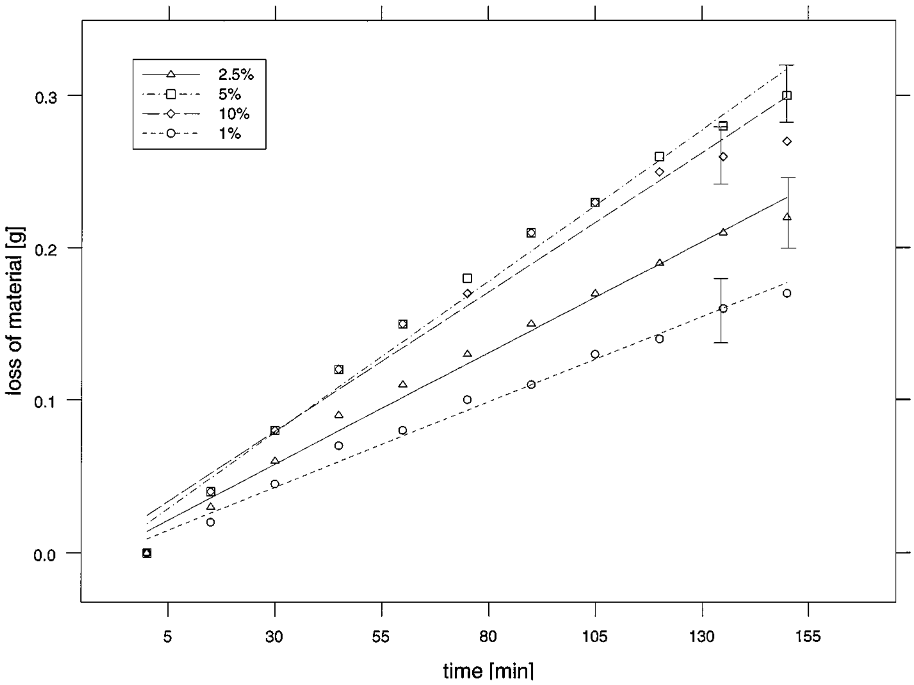

Figure 4 Loss of material from the ball versus test duration with the cast iron disc and different abrasive particle concentrations. Load on contact—15 N. Disc velocity—1.7 m/s.

aluminium and bronze undoubtedly resulted in different contact stresses and the size of the nominal contact area. The lowest removal of material was achieved for 1% concentration—a result similar to that for aluminium counterface. Rather surprisingly, the highest removal occurred at 2.5% concentration with the concentrations 5% and 10% somewhere between the two extreme limits.

Results of wear tests with the grey cast iron counterface were obtained from tests carried out under nominally the same test conditions to the other two counterface materials and are shown in Fig. 4. This time the highest material removal was observed for 5% concentration. The lowest material removal, as with other counterface materials, occurred at 1% concentration.

For abrasive particle concentration in the range of 2.5% to 10%, the highest rate of material removal from ceramic ball was recorded with the grey cast iron as counterface. However, for a concentration of 1%, the highest removal of material was recorded for the bronze counterface. The relation between removal of material and the concentration of abrasive particles is not straightforward and defies the expected trend that the higher the concentration the higher the removal of material. It can be seen from Fig. 5 that the grey cast iron counterface consistently produces the highest removal of material from ceramic ball for abrasive particle concentrations in the region of 2.5% to 10%. The differences between the aluminium counterface and the bronze counterface are not very substantial and can be regarded as inconclusive. It can also be observed from Fig. 5 that the best performance of grey cast iron counterface takes place at 5% concentration of abrasive particles in the base mineral oil.

Two conditions need to be met to secure rapid removal of material during the wear test. Firstly, the abrasive particles have to be able to enter the contact zone. Secondly, the abrasive particles, when within the contact zone, must be able to stay there in order to facilitate the removal of material. The first condition is closely linked to the film thickness formed by the grinding fluid and the physical space available within the contact zone for the abrasive particles. It is well known that the film thickness is controlled, among other things, by the applied load, velocity of relative motion of the contacting surfaces, lubricant viscosity under the contact conditions, geometry of the contact, and the elastic properties of the contacting materials. In view of different elastic moduli of the three materials used for the counterface (cast iron—E = 180 GPa; aluminium—E = 65 GPa; bronze—115 GPa), it has to be accepted that the sizes of the nominal contact area for each material were also different. Simple Hertzian contact stress analysis shows that in the case of aluminium and bronze the size of the contact area is larger than that produced when the ball is in contact with the cast iron counterface. The fact that the highest removal of material for grey cast iron was achieved at 5% concentration simply means that the physical space within the contact zone created by test conditions matched the space required by the number of abrasive particles entering the contact at this particular concentration. In other words, optimal conditions for efficient material removal were created at this concentration as the contact zone space was fully saturated by the abrasive particles. Appreciably lower removal of material at 2.5% concentration was probably caused by insufficient number of abrasive particle in the grinding fluid to fill in the available contact zone space completely. Hence, the conditions for removal of material were far from optimal. The slightly lower removal of material at 10% concentration could result not from insufficient number of abrasive particles in the grinding fluid but from too many of them. As a result of that, the entry to the contact zone could be obstructed

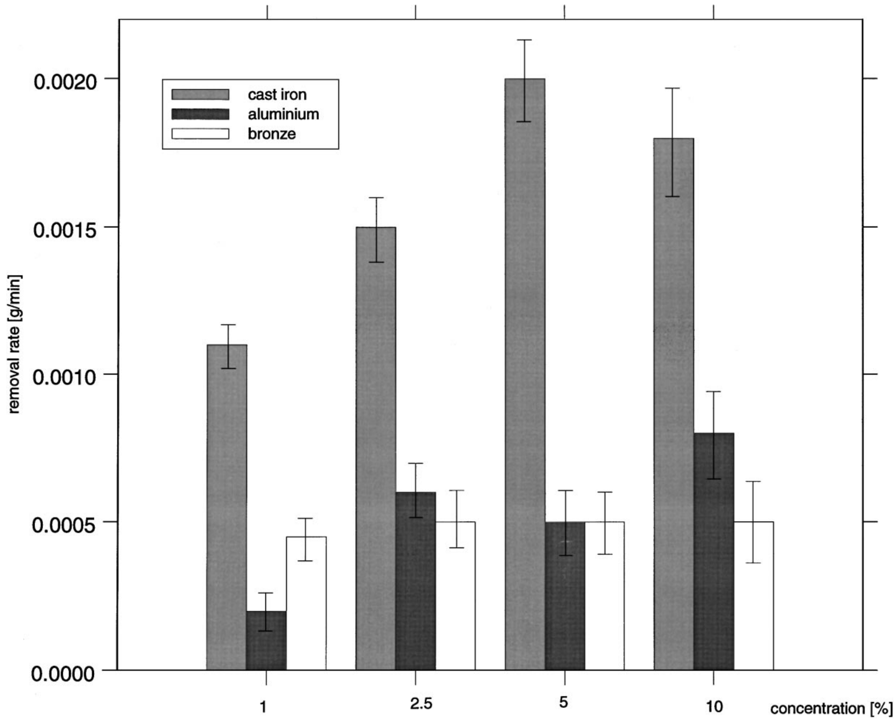

Figure 5 Abrasive particle concentration versus the rate of material removal from the ball for the three disc materials. Test conditions: load—15 N, disc velocity—1.7 m/s.

and the available contact zone space not completely filled.

The second condition for effective removal of material is the retention of abrasive particles within the contact zone. Clearly, the grey cast iron counterface was the best in this respect. It is well known fact that the structure of grey cast iron facilitates the retention of abrasive particles through their embedment in the surface layers of material. This process leads to a so called two-body abrasion wear and a considerable enhancement of material removal from the mating surface. It seems that in the case of the bronze and aluminium counterfaces the above mechanism did not operate equally effectively although the number of particles potentially able to enter the contact zone space was nominally the same in both cases due to the use of grinding fuilds with identical particle concentrations. The abrasive particles were not retained there as effectively as in the case of grey cast iron counterface.

3.1.2. Low particle concentration

The effect of low concentration of abrasive particles on the rate of material removal was also studied. Concentrations of 0.05%, 0.1% and 0.25% by weight were used. As in the high concentration experiments, silicon carbide particles (#1200) were used. Other test parameters, i.e. load on contact and rotational velocity of the counterface, were as for experiments described earlier.

The results for the aluminium counterface are shown in Fig. 6. It can be seen that concentrations 0.1% and 0.25% produced almost identical removal of material from the ceramic ball. Removal of material at 0.05% concentration was found to be considerably lower.

Fig. 7 shows the results for the bronze counterface. They are similar to the results obtained for the aluminium counterface in terms of material removed from the ball versus concentration of abrasive particles. As in the case of the aluminium counterface, the lowest removal of material was recorded for 0.05% concentration whilst 0.1% and 0.25% gave almost identical removal rates. The only difference is the amount of material removed; the bronze counterface produced higher removal of material than the aluminium counterface.

Fig. 8 contains the results for the grey cast iron counterface. In this case the differences in removal of material from the ball obtained for the three concentrations used are almost indistinguishable. In terms of the amount of material removed at low concentrations the grey cast iron counterface did not perform as well as at high concentrations. In fact, it gave the lowest amount of material removed.

Summary of the results at low concentrations is shown in Fig. 9. The bronze counterface is the best in terms of the material removal rate at all three concentrations used. It is important to note that in terms of material removal rate, measured as loss of weight per unit time, the low concentration rates are an order of magnitude smaller than high concentration rates. Also, the ranking of counterface materials is completely different in case of low concentrations and high concentrations. It is rather surprising to find that at low concentrations the grey cast iron counterface is one of the two worst in terms of material removal rate from the ball. Moreover, the bronze counterface, which was one of the two worst at high concentrations is now the best. This means that the explanation of the relationship between material removal and concentration of abrasive particles advanced for high concentrations is not applicable for low concentrations. Undoubtedly, the contact zone space was the same for both high and low concentrations as the basic test parameters were the same.

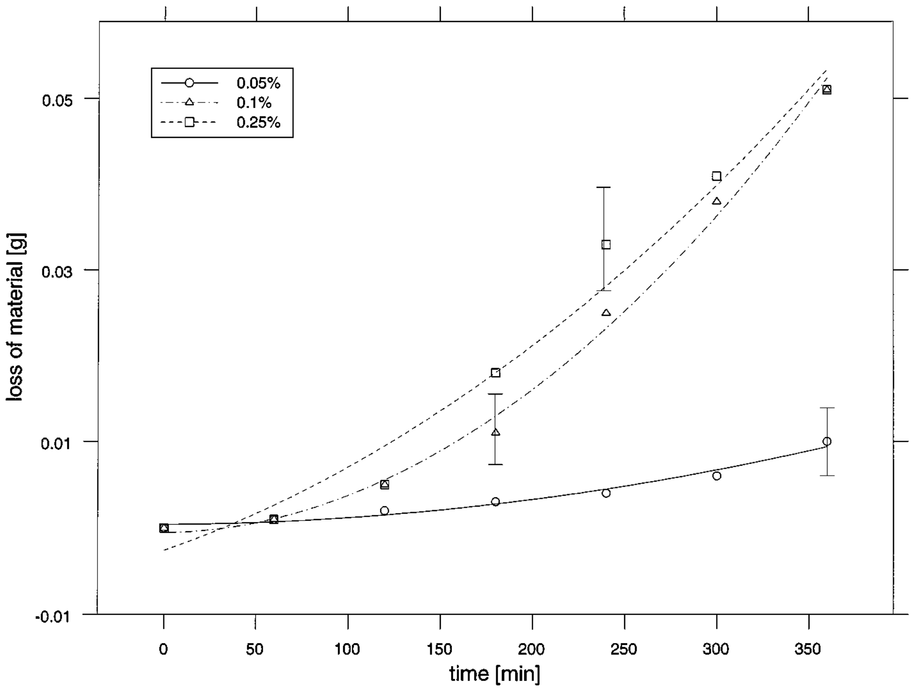

Figure 6 Loss of material from the ball versus test duration with the aluminium disc and different abrasive particle concentrations. Load on contact—15 N. Disc velocity—1.7 m/s.

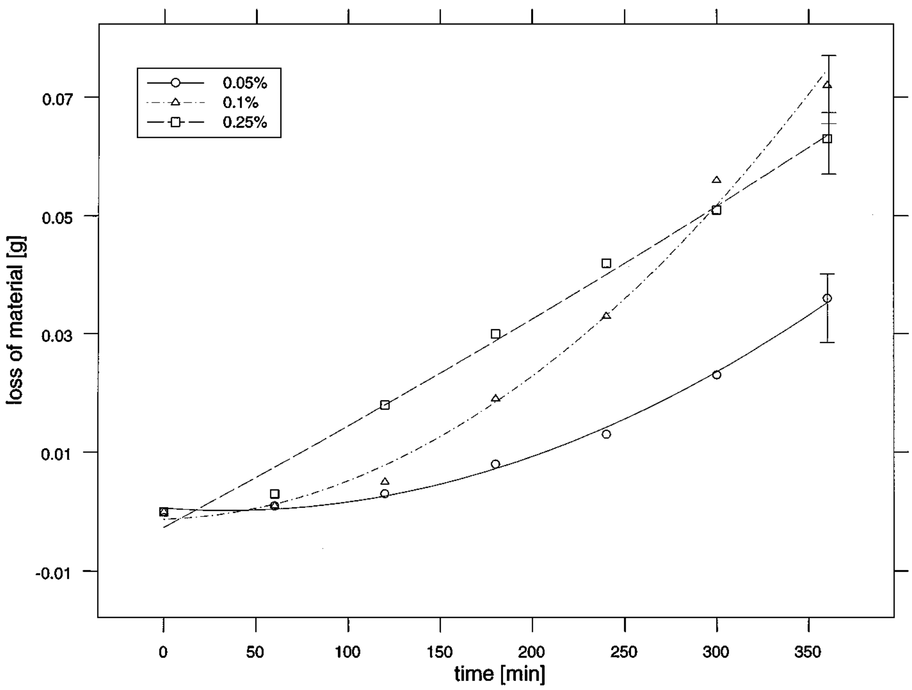

Figure 7 Loss of material from the ball versus test duration with the bronze disc and different abrasive particle concentrations. Load on contact—15 N. Disc velocity—1.7 m/s.

However, the number of abrasive particles able to enter the contact zone was definitely much smaller at low concentrations. Therefore, the conditions at the interface for effective removal of material were far from optimal. This fact could explain the order of magnitude smaller material removal rates observed at low concentrations. The reason why at low concentrations, the bronze counterface turned out to be the best and the grey cast iron one of the two worst is rather difficult to explain. At high concentrations, the grey cast iron removal rate is three to four times greater than the bronze removal rate while at low concentrations the bronze removal rate is up to nearly three times greater than the grey cast iron removal rate. Certainly, this low concentration figure is significant. In the light of the experimental results is must be assumed that at low concentrations the retention of abrasive particles by the grey cast iron deteriorated for some reason and resulted in a reduction of the removal of material from the ball. If that argument is accepted then a possible rationale is that with a much smaller number of abrasive particles embedded in the surface layer of material the work

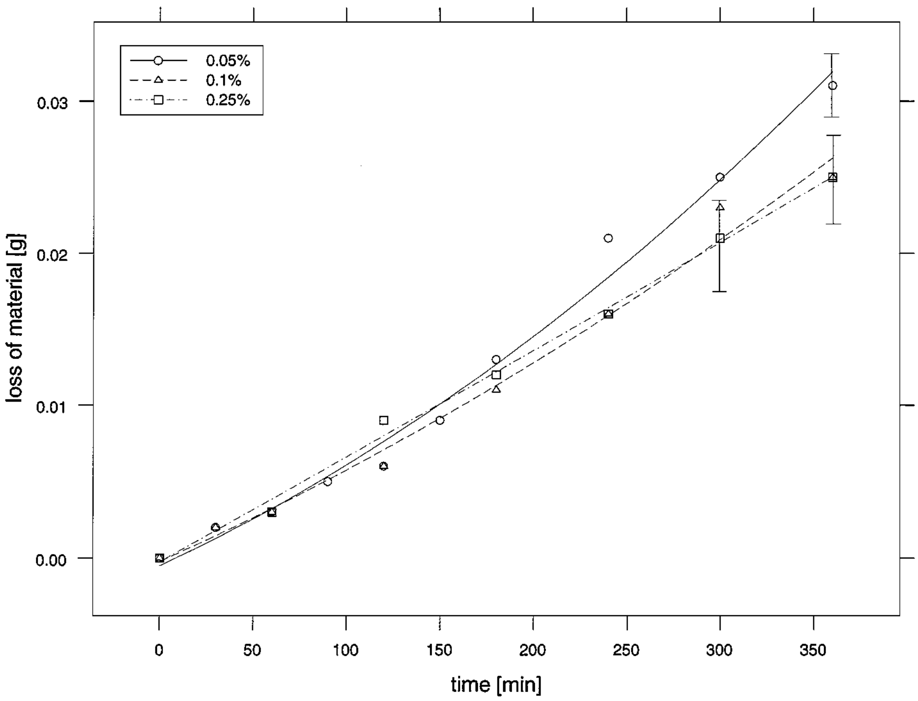

Figure 8 Loss of material from the ball versus test duration with the cast iron disc and different abrasive particle concentrations. Load on the contact—15 N. Disc velocity—1.7 m/s.

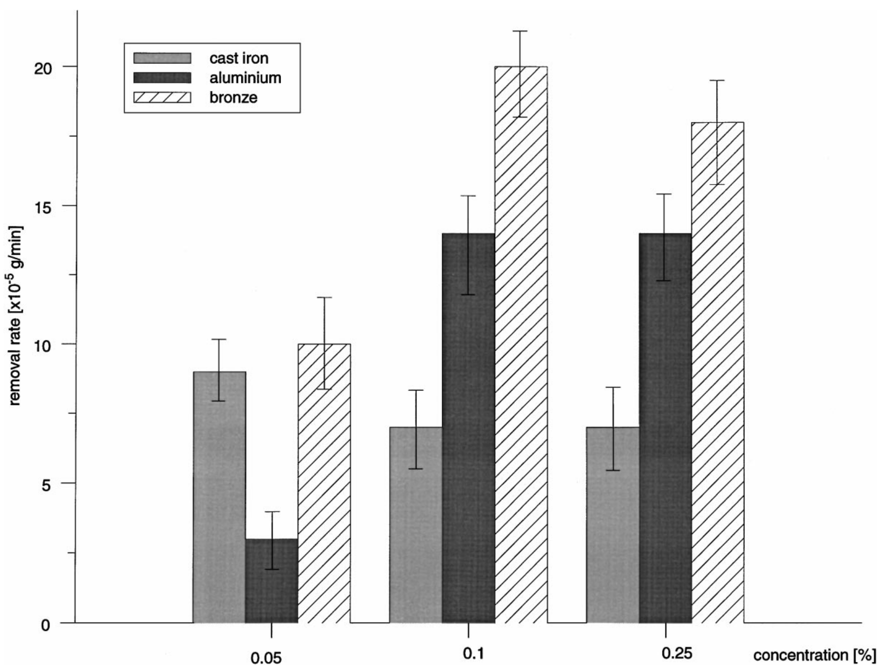

Figure 9 Rate of material removal from the ball versus abrasive particle concentration for the three disc materials. Test conditions: load—15 N, disc velocity—1.7 m/s.

hardening effects are very much reduced, resulting in an appreciably weaker anchoring of them. The consequence of that could be much easier removal of abrasive particles from the contact zone and diminished material removal rate.

3.2. The effect of additional rotation of the specimen

The essential feature of this type of experiment consisted in introducing an additional, and independent of counterface motion, rotation of the specimen about its load axis. Experiments were carried out at 0.1% concentration of abrasive particles for grey cast iron and aluminium counterfaces. It was found that this experimental variable affects the removal of material in a clear, unambiguous way.

Fig. 10 shows the influence of ball rotation on the removal of material from the ball when the aluminium counterface is used. It is apparent that the best results were obtained at the specimen angular velocity of 0.16 s^{-1}. The removal of material at the other two angular velocities used, i.e. 0.4 s^{-1} and 2 s^{-1}, is considerably lower. Fig. 11 shows the results of the same test but for

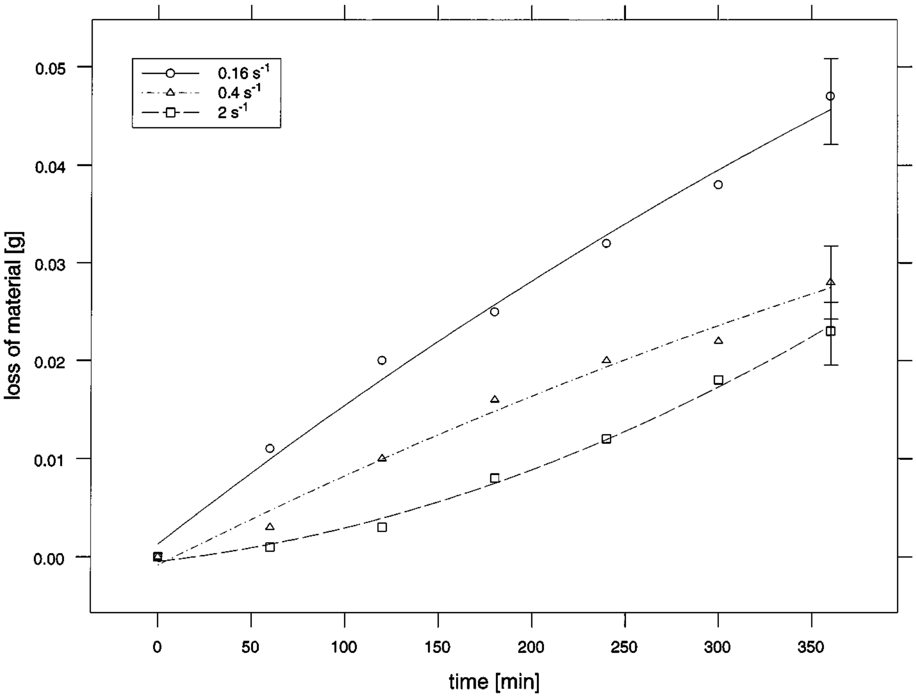

Figure 10 Loss of material from the ball versus test duration with the aluminium disc and additional ball rotation. Load on the contact—15 N. Disc velocity—1.7 m/s.

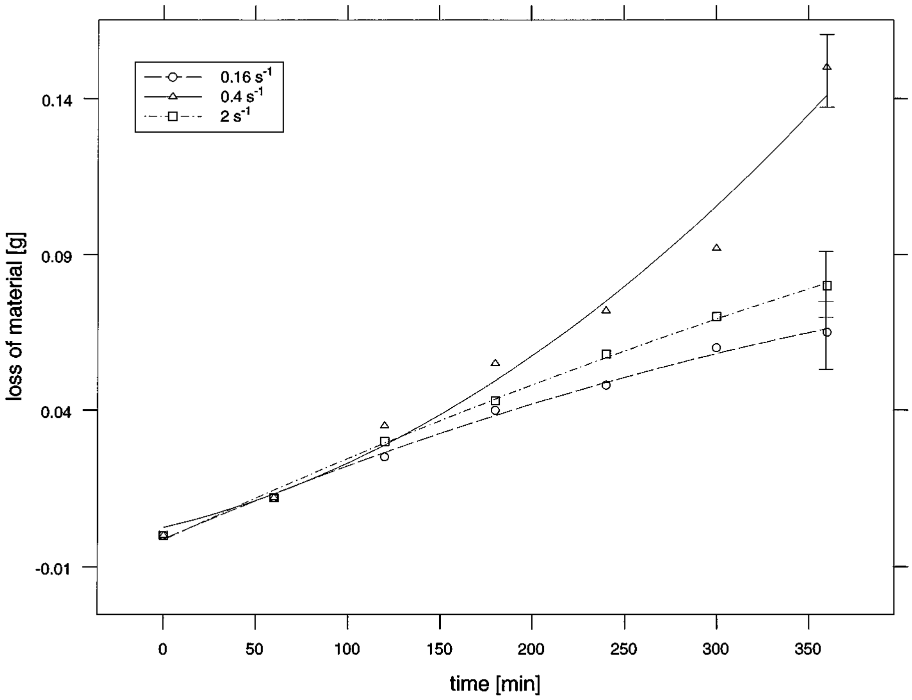

Figure 11 Loss of material from the ball versus test duration with the cast iron disc and additional ball rotation. Load on the contact—15 N. Disc velocity—1.7 m/s.

the grey cast iron counterface. Unlike in the case of aluminium counterface, the best results were recorded for specimen angular velocity of 0.4 s^{-1} and the worst for specimen rotating at 0.16 s^{-1}—a complete reversal for the latter angular velocity. Fig. 12 summarizes the results of the effect of additional specimen rotation on the removal of material. It is quite apparent that the grey cast iron counterface consistently outperformed the aluminium counterface at all rotational speeds of the specimen other than zero. At 0.4 s^{-1}, for example, the grey cast iron counterface produced four times greater material removal than the aluminium counterface.

It ought to be recalled that at low concentrations of abrasive particles and with a stationary specimen, the grey cast iron couterface was among the last in the material removal ranking. It was then argued that at low concentrations only few abrasive particles enter the contact zone and are not able to fill in the available space to a saturation point. This insufficient saturation of the contact zone space did not fully initiate the work hardening effect and, in consequence, the abrasive particles were not effectively retained within the contact zone. Now, at the same low level of abrasive particle concentrations but with additional rotation of the specimen, the grey

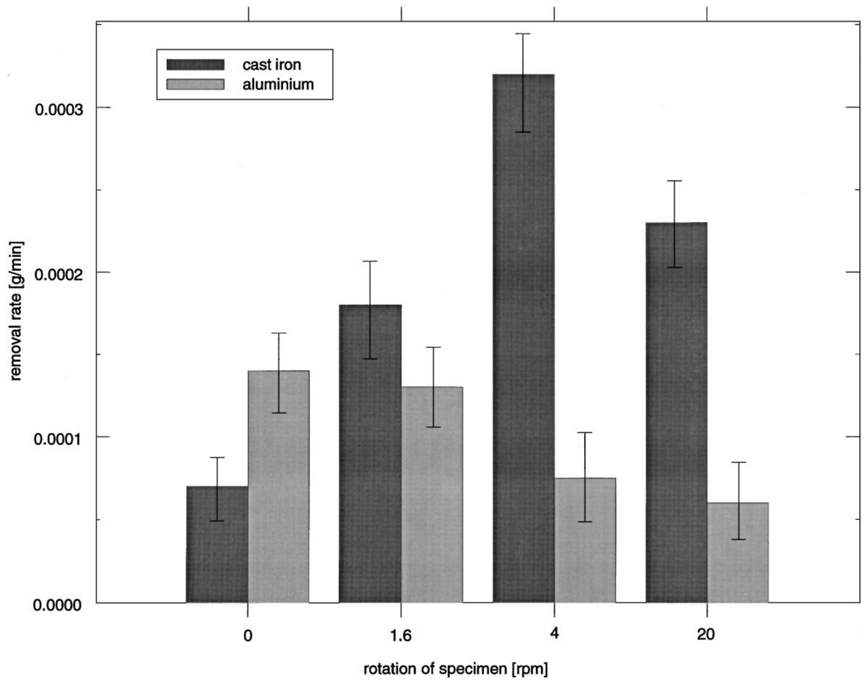

Figure 12 Material removal rate from the ball versus additional ball rotation for two disc materials. Test conditions: load—15 N, disc velocity—1.7 m/s, abrasive particle concentration—0.1%.

cast iron was found to be the best counterface material from the material removal point of view. Clearly, the additional specimen rotation helped to introduce or retain more abrasive particles within the contact zone. Also, the complex kinematics created by the additional specimen rotation may have increased the effectiveness of the abrasive particles in material removal.

4. Conclusions

The main conclusions resulting from the studies presented in this paper are:

(i) at high abrasive particle concentrations (up to 10% by weight) and a stationary ball the best material removal rates were achieved with grey cast iron counterface,

(ii) at low abrasive particle concentrations (up to 0.25% by weight) and a stationary ball the bronze counterface produced the highest material removal rates,

(iii) tests at a low abrasive particle concentration of 0.1% by weight and with additional rotation of the ball about its load axis proved that the extra motion within the contact zone has a significant effect on the material removal rate,

(iv) the highest material removal rate was obtained with an angular velocity of the ball of 0.4 s^{-1} and grey cast iron as counterface.

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