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Carbon Fibre-reinforced (YMAS) Glass-ceramic Matrix Composites: Dry Friction Behaviour

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Abstract

Unidirectional continuous carbon fibre-reinforced (YMAS) glass–ceramic matrix composites have been fabricated for dry friction applications. Pitch-based fibres (P55) and PAN-based fibres (T400H and M40) were used. Friction and wear tests were carried out using a disc-on-disc tribometer. The tribological behaviour of carbon fibre-reinforced (YMAS) glass–ceramic matrix composites is mainly linked to the fragility of the matrix and to the microcracking induced during preparation of these composites. The fibre graphitization rate does not seem to influence the tribological behaviour of carbon-fibre M40-reinforced glass–ceramic matrix composites. The mechanisms of formation of the third body are associated with the fragmentation of the matrix and fibres. A velocity accommodation mechanism occurs by shearing of the pressed powder bed in zones of lift. This study has shown the potential of carbon fibre-reinforced (YMAS) glass–ceramic matrix composites in dry friction, notably with regard to the low wear rate. © 1999 Elsevier Science Limited. All rights reserved

Keywords: composites, carbon, fibres, glass ceramics, wear resistance.

1 Introduction

The use of monolithic ceramics for thermostructural applications is always limited by their brittleness and their low toughness. Consequently particular attention has been given to fibre-reinforced ceramic matrix composites mainly for the aerospace industries. Much works are devoted to ceramic matrix composites and specially glass and glass–ceramic composites because they present the advantage of fabrication at low temperature.[1,2]

For wear applications, carbon fibre-reinforced matrix composites can be expected to present a low friction coefficient due to the possible solid lubricant properties of carbon fibres in some conditions.[3] Unidirectional continuous carbon fibre-reinforced (YMAS) glass–ceramic matrix composites have been fabricated for dry friction applications.[4]

The tribological behaviour of materials in dry friction depends on the mechanical strength of the rubbing bodies, on mechanical aspects and physico-chemical reactions at the interface between both the first bodies. However the difference in velocity between the two first bodies is accommodated through the third body in agreement with the velocity accommodation mechanism (VAM) concept.[5]

The purpose of this work is to study the formation mechanisms of third body and the velocity accommodation mechanisms in the contact, and to understand these phenomena with respect to the tribological behaviour of carbon-fibre-reinforced (YMAS) glass–ceramic matrix composites.

2 Experimental

2.1 Materials

Preparation of samples for the experiments has been previously described.[6] Three grades of fibres which differ according to the precursors and their final properties were used. They are pitch-based fibres (P55) and PAN-based fibres (T400H and M40). Pre-forms were prepared by using a slurry

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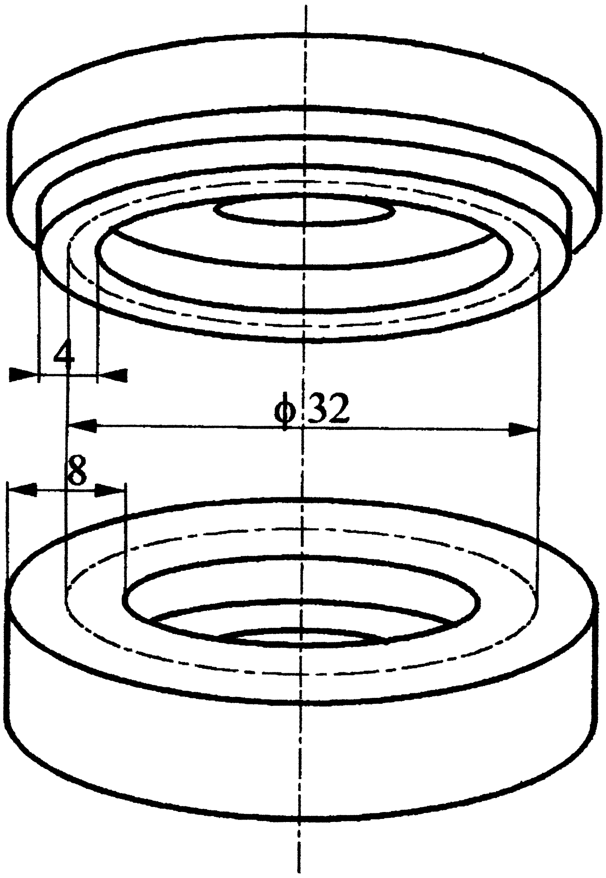

Fig. 1. Shape of test discs.

infiltration process of fibre tows. The impregnated fibres were wound on a cylindrical mandrel using multilayers. Each pre-form was cut into discs. Then the samples were densified in argon by hot-pressing. Sintering affects the microstructural changes of the YMAS (Y_2O_3, MgO, SiO_2) matrix. Thermal treatments were optimised to lead to an improvement of mechanical properties. After sintering, the surface samples were machined by grinding.

2.2 Apparatus

Friction and wear tests were carried out using a disc-on-disc tribometer[7] where a lower rotating disc slides against an upper stationary disc fixed to a torque cell. The friction torque is continuously monitored. The shapes of the test discs are shown in Fig. 1.

The test discs were set in a chamber surrounded by a furnace which allows the tests to be performed between room temperature and 1000°C. Sliding velocities, measured for the average diameter (32 mm) can be regulated from 0·01 to $10\,\mathrm{m}^{-1}$. The normal load (10 daN < N < 1000 daN) is applied on the upper disc. The wear track is a ring with a width of 4 mm and an average diameter of 32 mm. The surface of contact is $400\,\mathrm{mm}^2$. Before tests the samples are prepared as mentioned in the VAMAS research program.[8] The wear rate K (Pa^{-1}) of the first body is determined from detached particle volume, by the following relationship:

$$K = \frac{v}{N.V.t}$$

where v is the volume of detached particles (m^3), N is the normal load (N), V is the sliding velocity ($\mathrm{m\,s}^{-1}$) and t is the duration of the test. The volume v is calculated by the relationship:

$$v = \pi.D_m.S_m$$

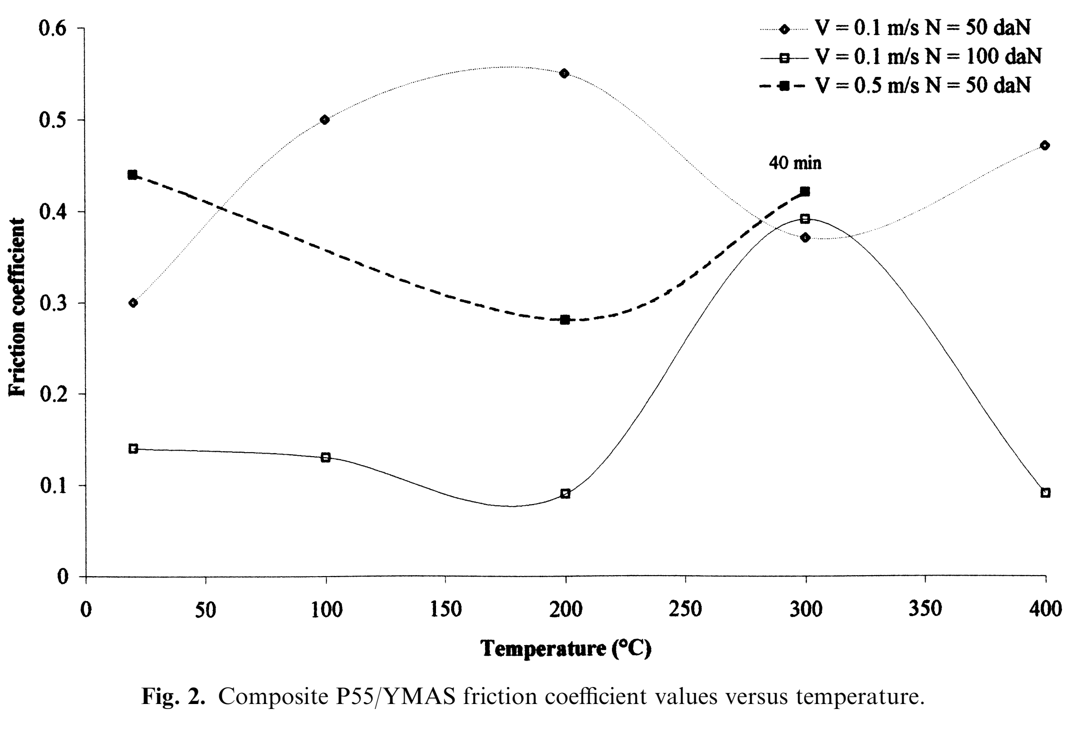

Fig. 2. Composite P55/YMAS friction coefficient values versus temperature.

where D_m is the average diameter and S_m is the average surface of cleaned wear track profile of the lower sample, obtained by measuring four cross-sectional areas of the profile with a profilometer Perthen C5D.

3 Results

All friction curves recorded during tests show very strong instantaneous fluctuations of the friction coefficient value. Indicated values correspond to average values. Values are those measured after 1 h of test. When the test was stopped in less than 1 h, the time is indicated.

3.1 Pitch-based (P55) composite fibres

The friction coefficient of composite P55/YMAS varies with the applied normal load, the environmental temperature and the sliding velocity (Fig. 2). For given experimental conditions, the value of the friction coefficient evolves with time (Figs 3 and 4).

The strong fluctuations of the value of the friction coefficient suggest that several velocity accommodation mechanisms act simultaneously or in relay. The amplitude of these fluctuations decreases when the sliding velocity and the normal load increase. They are to be associated with stick–slip phenomena, but can also be the consequence of a deviation from surface parallelism of samples.

During a test, the value of the friction coefficient can reach a maximum. The time when this maximum appears decreases with temperature (Fig. 5). The phase before the maximum corresponds to the formation of the third body. The second phase characterises the life of the third body. In all tests the wear rate of the upper disc is approximately equal to that of the lower disc. The two first bodies participate in the formation of the third body. Whatever the experimental conditions, values of wear rate are low and have similar magnitude (Fig. 6).

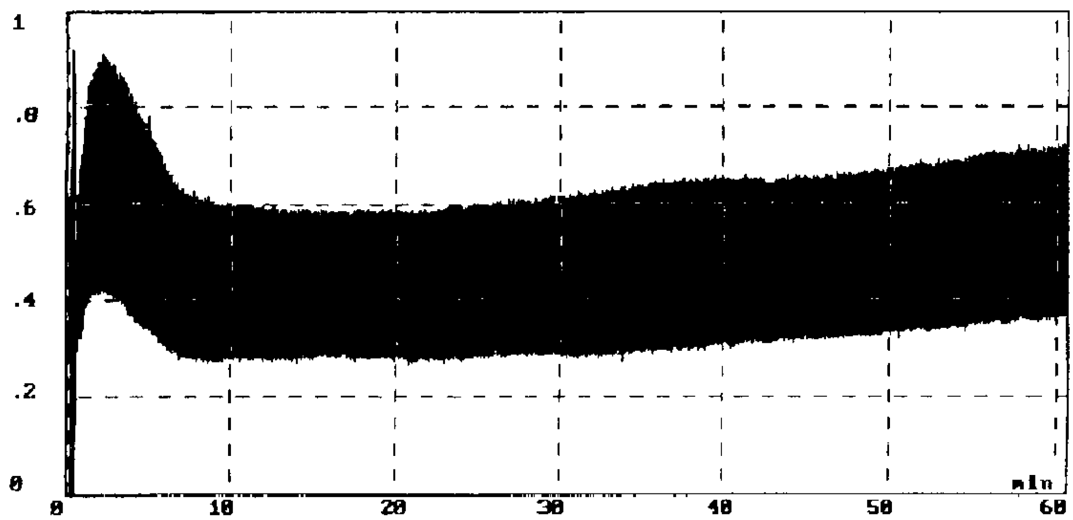

Fig. 3. Composite P55/YMAS friction coefficient values versus time $V = 0{\cdot}1$ m s^{-1}; $N = 50$ daN; $T = 200$°C.

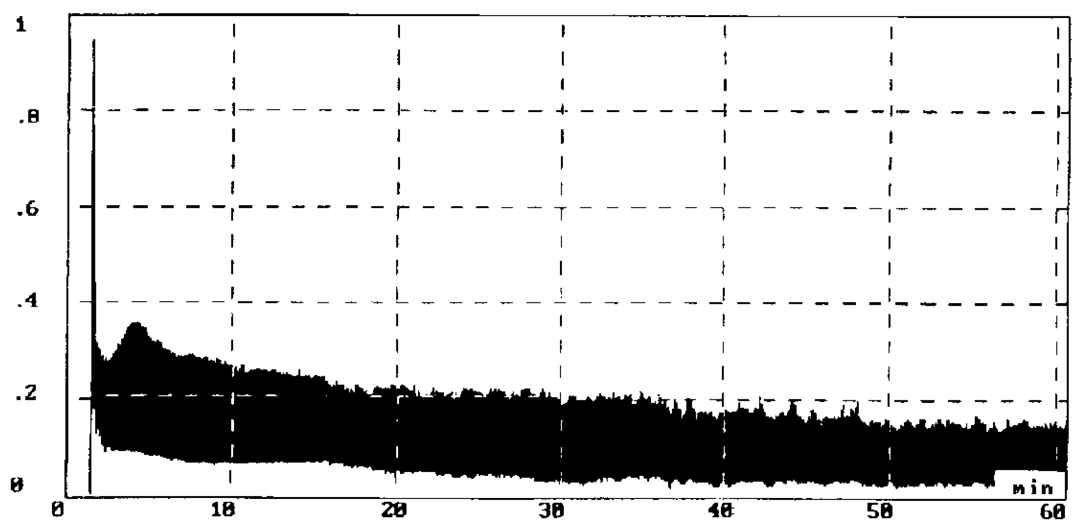

Fig. 4. Composite P55/YMAS friction coefficient values versus time $V = 0{\cdot}1$ m s^{-1}; $N = 100$ daN; $T = 200$°C.

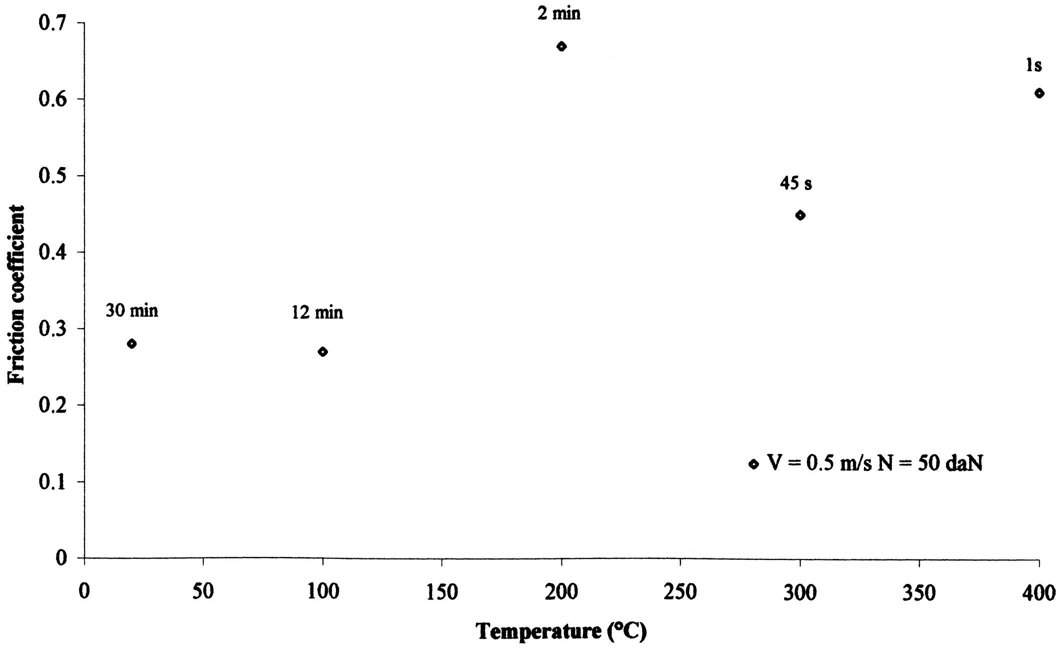

Fig. 5. Composite P55/YMAS maxima friction coefficient values versus temperature.

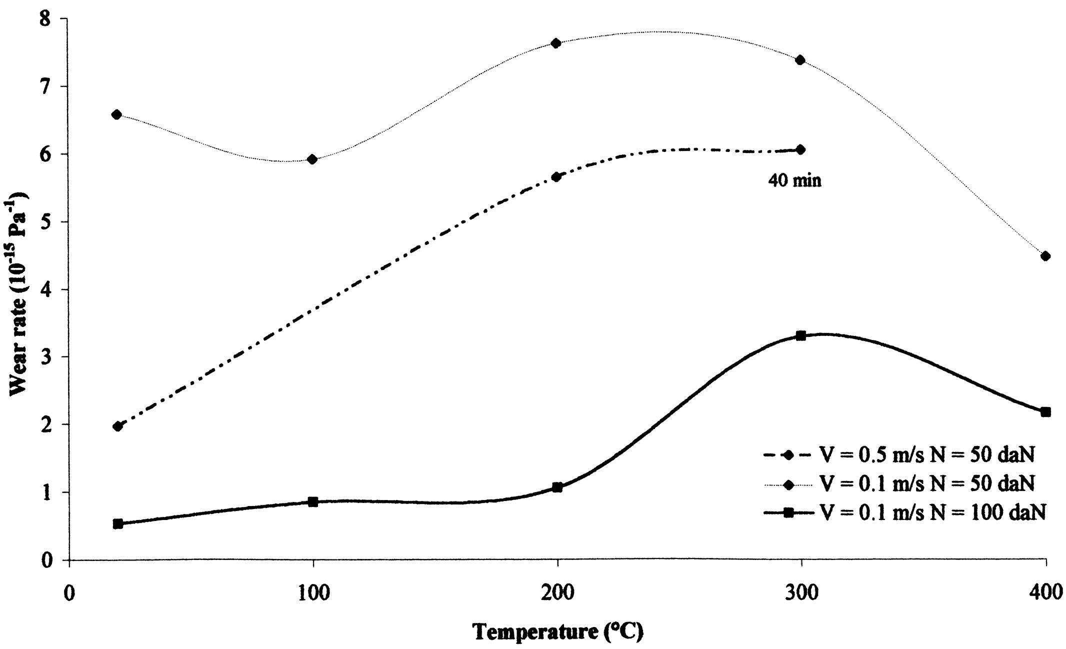

Fig. 6. Composite P55/YMAS wear rate values versus temperature.

For the velocity $V = 0{\cdot}1\ \mathrm{m\,s^{-1}}$ and for all test temperatures, the wear rate is higher for the normal load $N = 50\,\mathrm{daN}$ than for $N = 100\,\mathrm{daN}$. Some authors have observed, for other material couples, the diminution of the wear rate with the increase in the load.[9] The compaction of the powdery third body leads to a better lift and a better trapping in the contact. In the two cases the wear rate is maximal at $T = 300°\mathrm{C}$. The rheology of the third body, but also mechanical properties of the first bodies, are modified by the temperature. The increase in velocity from 0·1 to 0·5 $\mathrm{m\,s^{-1}}$ decreases the wear rate only at room temperature. In fact it is very difficult to compare tests because although the environmental test temperature is known, the temperature in the contact cannot be measured. At a constant friction coefficient, energy dissipated in the contact by friction is five times greater at 0·5 $\mathrm{m\,s^{-1}}$ than at 0·1 $\mathrm{m\,s^{-1}}$. The average temperature of the contact increases sharply preventing the comparison of tribological behaviour for different test conditions.

Observation of the wear track of the lower disc (Fig. 7), after the opening of the contact, shows that the disc surface has been polished during the test. Microcracks of great length are observed. Due to the thermal expansion mismatch between the fibres and the matrix, a network of microcracks appears in the composites on cooling after hot-pressing.[10]

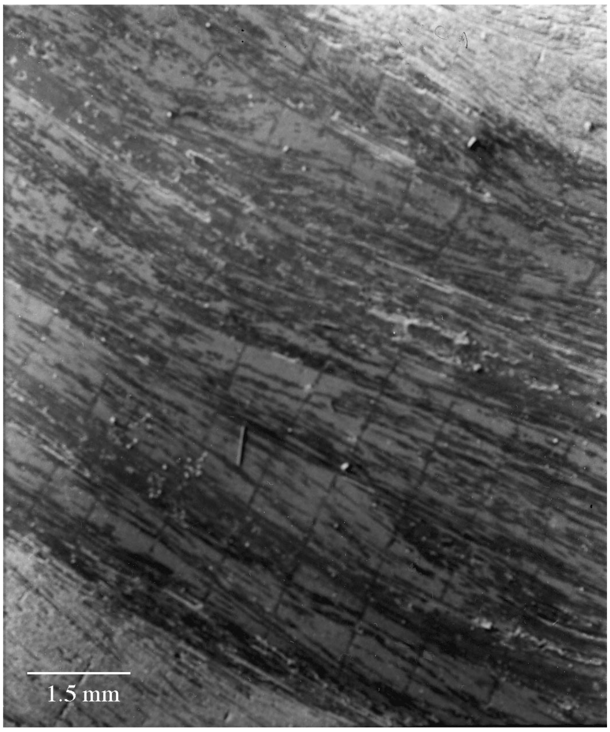

Fig. 7. Composite P55/YMAS—$V=0{\cdot}1$ m s^{-1}; $N=100$ daN; $T=20$°C.

Tests carried out with a linear alternative motion tribometer[11] of the Laboratoire de Mécanique des Contacts (INSA Lyon) have allowed mechanisms for the formation of the third body to be visualised. In these tests the composite C-YMAS rubs on a plate of glass. Through the glass observations are made with the help a microscope coupled to a video-recorder. From these observations, we can conclude:

- the matrix is microcracked in zones of lift (Fig. 8), the fibres stop their propagation;
- the matrix detaches and is ground under the mechanical stress field (Fig. 9);
- the matrix and fibres, for raised loads, can be pulled in blocks (Fig. 10).

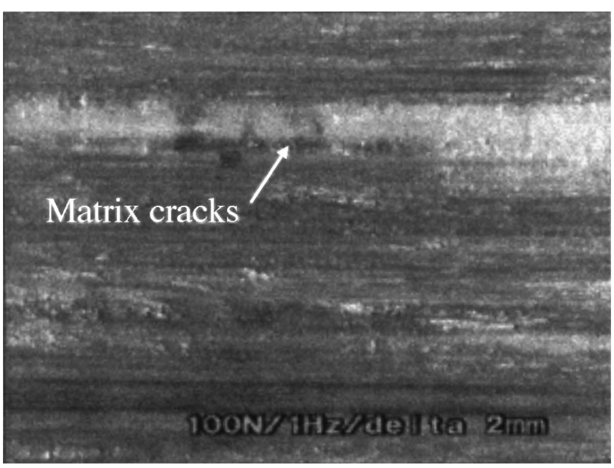

Fig. 8. Cracking of matrix—composite P55/YMAS sliding against glass ($N=10$ daN/1 Hz/ ± 2 mm).

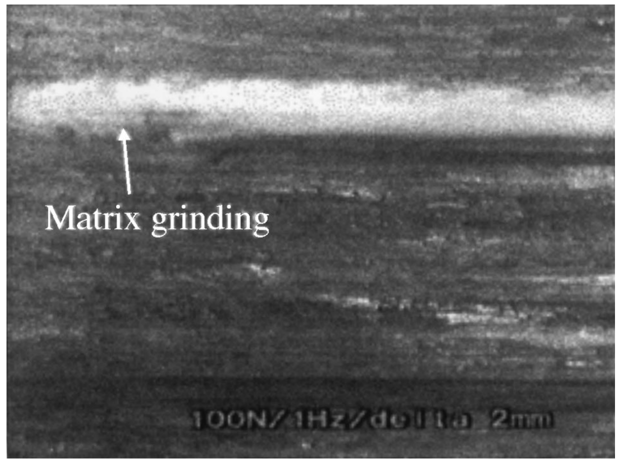

Fig. 9. Grinding of matrix—composite P55/YMAS sliding against glass ($N=10$ daN/1 Hz/ ± 2 mm).

Thus, under low solicitations, the third body is mainly composed of particles of finely ground matrix, while under high solicitations it is composed of matrix particles and fragments of ground fibres. An increase in the temperature favours the detachment of fibres and matrix blocks, because mechanical properties of the glass matrix decrease very rapidly above 400°C. The lamellar graphite, in the periphery of the fibres, does not allow transfer films to be formed as we have observed with carbon fibre-reinforced (SiC) ceramic matrix composites.

At room temperature ($N=50$ daN, $V=0{\cdot}1$ m s^{-1}), observations of the open contact, show wide graphite layers (Fig. 11) which are weakly adherent to the first bodies surface. The rapid elimination of third body out of the contact, necessitates its regeneration. For these experimental conditions the wear rate is therefore important ($K=6{\cdot}5$ 10^{-15} Pa^{-1}). Velocity accommodation occurs mainly by shearing in the thickness of the third body (VAM S_3M_3).

After a test at $T=200$°C ($N=50$ daN, $V=0{\cdot}1$ m s^{-1}), the SEM observation showed that outside the pressed debris zone, the third body is composed

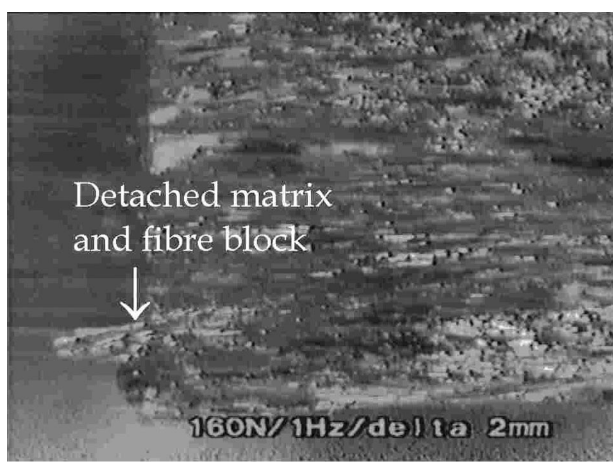

Fig. 10. Pull of a matrix and fibres block—composite P55/YMAS sliding against glass ($N=16$ daN/1 Hz/ ± 2 mm).

Fig. 11. Composite P55/YMAS—$V=0{\cdot}1$ m s^{-1}; $N=50$ daN; $T=20$°C.

of a mix of ground matrix particles and fragments of carbon fibres (Fig. 12).

After a test at $T=400$°C ($N=50$ daN, $V=0{\cdot}1$ m s^{-1}), the SEM observations did not reveal fragments of fibres. The EDS analysis of third body particles did not reveal carbon. We can assume that the real temperature of the contact leads to the thermal decomposition of fibre fragments.

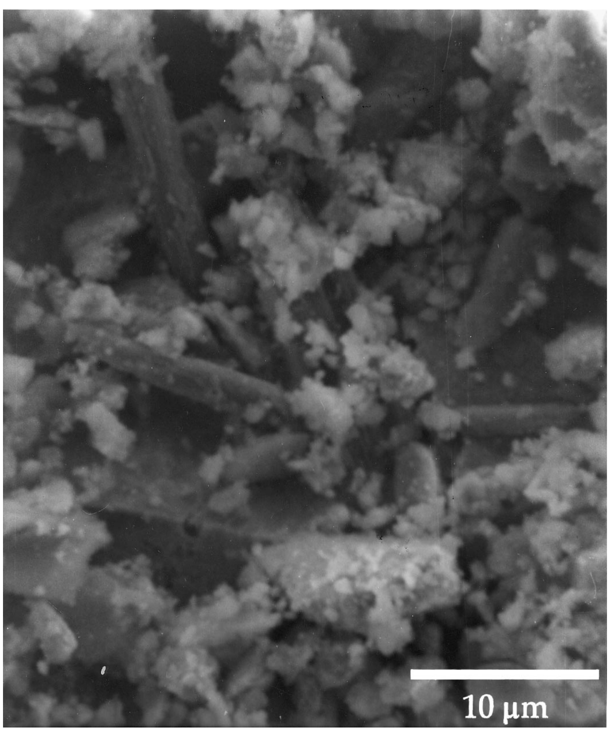

Fig. 12. Composite P55/YMAS—$V=0{\cdot}1$ m s^{-1}; $N=50$ daN; $T=200$°C.

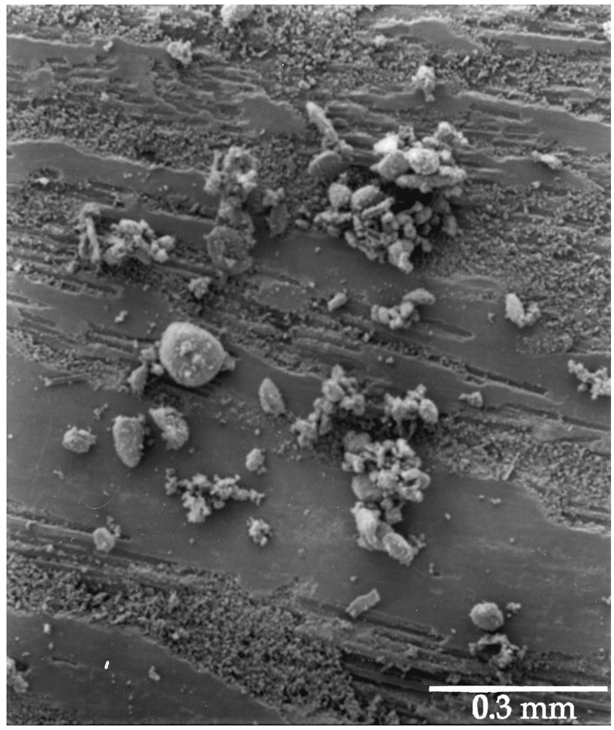

Fig. 13. Composite P55/YMAS—$V=0{\cdot}5$ m s^{-1}; $N=50$ daN; $T=300$°C.

For a sliding velocity $V=0{\cdot}5$ m s^{-1} and for the temperature $T=300$°C, the wear track is totally covered with third body plates of pressed matrix particles (Fig. 13). These plates evolve during the test under the effect of mechanical stresses. They are microcracked (Fig. 14) permitting the internal flow of third body inside the contact to be maintained.

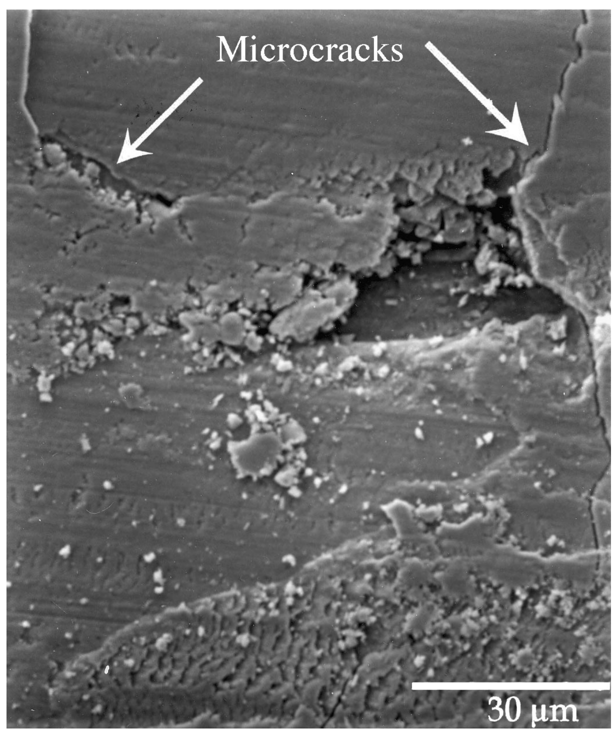

Fig. 14. Composite P55/YMAS—$V=0{\cdot}5$ m s^{-1}; $N=50$ daN; $T=300$°C.

3.2 PAN-based composite fibres

Two types of composites developed with fibres T400H and M40 have been tested. Tests were carried out under the same experimental conditions as those used for pitch-based (P55) fibre composites.

3.2.1 Composites T400H/YMAS

Tests at low velocity ($V = 0{\cdot}1\ \mathrm{m\,s^{-1}}$) indicate an instability of the tribological behaviour, associated with stick-slip phenomena. The results obtained, indicate that values of the friction coefficient (Fig. 15) are higher for $N = 50\,\mathrm{daN}$ than for $N = 100\,\mathrm{daN}$, except for $T = 20$ and 300°C. The wear rate (Fig. 16) is lower for tests with normal load $N = 100\,\mathrm{daN}$, except for $T = 400$°C.

At high velocity ($V = 0{\cdot}5$ and $1\ \mathrm{m\,s^{-1}}$), a change of tribological behaviour (sharp increase in friction coefficient values) occurs before the end of the test.

This change of friction regime appears after $t = 20$ min for $V = 0{\cdot}5\ \mathrm{m\,s^{-1}}$, and $t = 5$ min for $V = 1\ \mathrm{m\,s^{-1}}$. For these tests we have observed a red glow of the contact that shows a very strong elevation of the temperature. The tribological behaviour of the composite is linked to the friction energy and to the capacity of the material to dissipate it. Thereby comparisons of results for the different

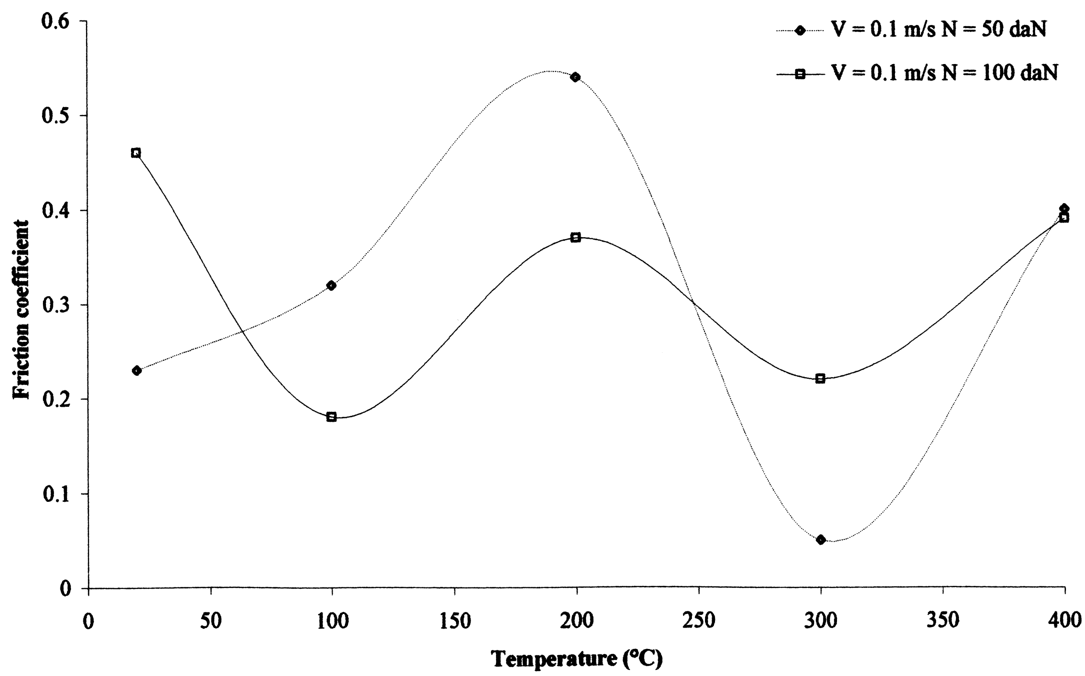

Fig. 15. Composite T400H/YMAS Friction coefficient values versus temperature.

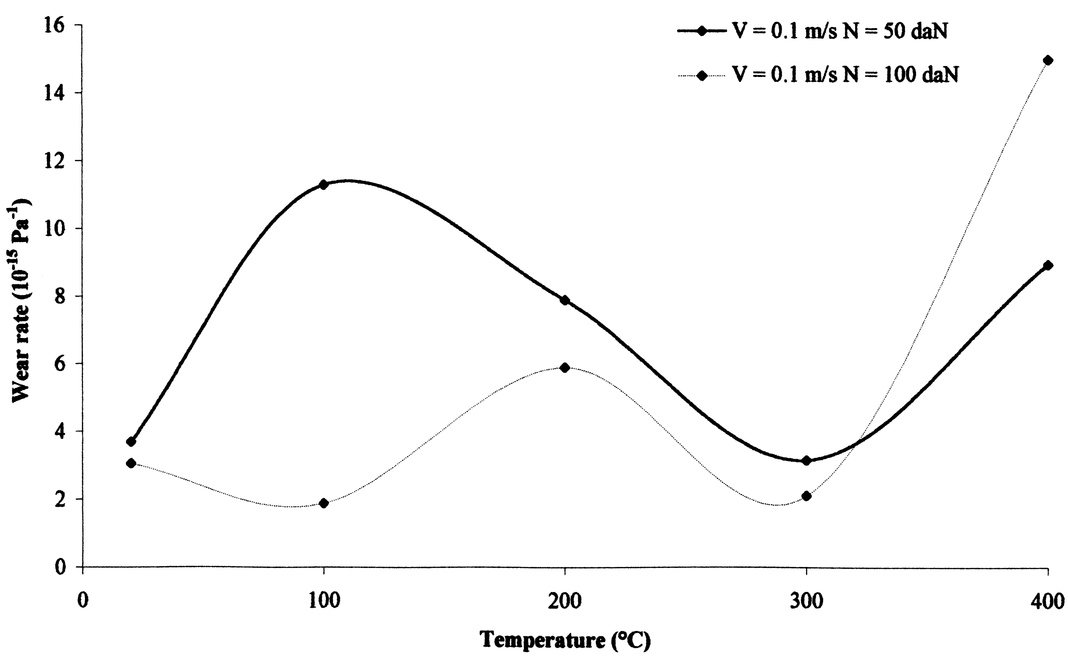

Fig. 16. Composite T400H/YMAS wear rate values versus temperature.

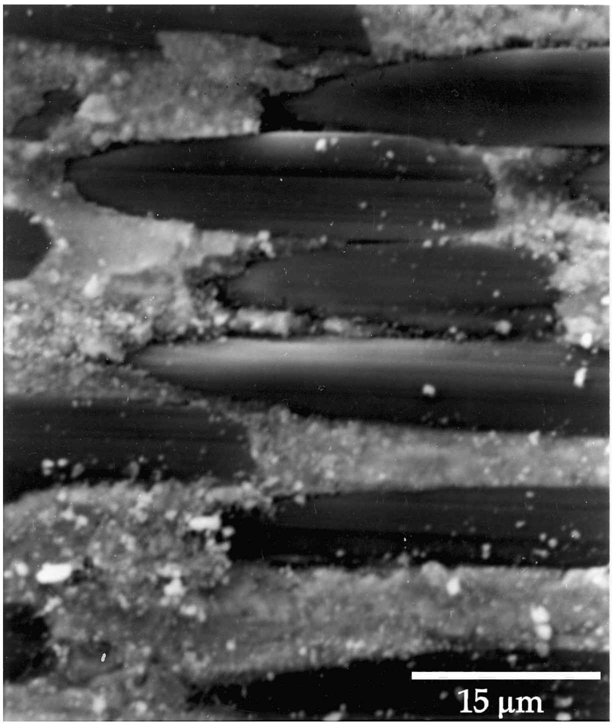

Fig. 17. Composite T400H/YMAS—$V=0{\cdot}1$ m s^{-1}; $N=50$ daN; $T=20°$C.

test conditions are very difficult. It would be preferable to compare results at identical contact temperatures, but this last parameter is not measurable.

The SEM observations lead to the same conclusions as P55 composite fibres. The third body is formed from fragmentation of matrix and fibres. When the wear rate is low, emergent fibres participate in the lift of the first bodies (Fig. 17), and their degradation is progressive. The velocity accommodation occurs by shearing of the pressed powder bed in zones of lift (VAM S_3M_3). These third body plates (Fig. 18) are fractured and reconstituted during the test permitting the internal flow of third body inside the contact to be maintained.

Fig. 18. Composite T400H/YMAS—$V=0{\cdot}1$ m s^{-1}; $N=50$ daN; $T=20°$C.

3.2.2 Composites M40/YMAS

Tests at $V=0{\cdot}1$ and $0{\cdot}5$ m s^{-1}, for $N=50$ daN and $T=20°$C, were carried out to identify the influence of the graphitization rate on the tribological behaviour of carbon-fibre M40-reinforced glass–ceramic matrix composites. The graphitization rate of M40 fibres is higher than that of T400H fibres.

At low velocity ($V=0{\cdot}1$ m s^{-1}) the behaviour is similar for the two composites. Friction is stable during the entire duration of the test ($\mu=0{\cdot}25$), and the wear rate is very low ($K=4\ 10^{-15}$ Pa^{-1}).

At high velocity ($V=0{\cdot}5$ m s^{-1}), friction coefficient values are stable ($\mu=0{\cdot}17$) during 40 min, then increase sharply ($\mu=0{\cdot}4$) at the same time as the contact becomes red hot.

The graphitization rate does not seem to influence the tribological behaviour of carbon-fibre M40-reinforced glass–ceramic matrix composites. In comparison, the friction coefficient value of SiC-fibre-reinforced (YMAS) glass–ceramic matrix composites tested in the same experimental conditions ($V=0{\cdot}1$ m s^{-1}, $N=50$ daN and $T=20°$C) is very high ($\mu=0{\cdot}8$). This comparison demonstrates the advantage of carbon fibre. One other study carried out with carbon-fibre M40-reinforced (SiC) ceramic matrix composites[12] has shown that fibres with a high graphitization rate (fibres PAN-based M40) permit the formation of transferred graphite layers which are strongly adherent to the first bodies. The velocity accommodation mechanism occurs by shearing thin sheets of graphite (VAM S_3M_3). This third body protects the first body from matrix degradation. The wear rate in this case is low ($K=2{\cdot}1\ 10^{-15}$ Pa^{-1}) but higher than that of carbon-fibre M40-reinforced glass–ceramic matrix composites.

4 Conclusion

The tribological behaviour of carbon-fibre-reinforced (YMAS) glass–ceramic matrix composites is mainly linked to the fragility of the matrix and to the microcracking induced during preparation of these composites.

The mechanisms of formation of the third body are associated with the fragmentation of the matrix and fibres. The intense grinding of matrix fragments leads to a bed of amorphous glass powder. The compaction of the powdery third body permits a velocity accommodation mechanism to occurs by shearing through its thickness (VAM S_3M_3).

The rheology of the powdery third body changes depending on the temperature. The wear rate is low when the physicochemical properties of the third body improve the adhesion between the particles of the third body and with the first bodies.

The tribological behaviour of carbon-fibre-reinforced (YMAS) glass–ceramic matrix composites does not depend on the fibre graphitization rate but it is mainly governed by the properties of the matrix.

Static SEM observations and dynamic observations with a linear alternative motion tribometer, have been very useful to understand formation mechanisms of the third body and velocity accommodation mechanisms in the contact. This study has shown the potential of carbon-fibre-reinforced (YMAS) glass–ceramic matrix composites in dry friction, notably with regard to the low wear rate.

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