Carbon-fibre reinforced glass matrix composites: self-lubricating materials for wear applications in vacuum

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The self-lubricating wear behaviour of a C-fibre reinforced borosilicate glass matrix composite in vacuum was investigated by using a rotating pump experimental facility. The vanes were made of the composite material and the stator of the pump was of cast iron. Glass composite wear was accompanied by material transfer onto the stator surface. The formation of isle-type and continuous graphitic films on the counter-body surface was observed. The continuous film provided adequate lubrication during friction, leading to a relatively low wear rate of the composite for the conditions investigated.

Glasmatrix-Verbundwerkstoffe mit Kohlenstoffaser-Verstärkung: selbstschmierende Werkstoffe für Reibungsanwendungen im Vakuum

Das selbstschmierende Verschleißverhalten von C-Faser-verstärkten Borosilicatglasmatrix-Verbundwerkstoffen im Vakuum wurde mittels einer Rotations-Vakuumpumpe untersucht. Die Schaufeln waren aus dem Verbundwerkstoff und der Stator aus Gußeisen hergestellt. Der Verschleiß des Glasmatrix-Verbundwerkstoffes wurde von einem Materialtransport auf die Statoroberfläche begleitet. Es wurde die Bildung einer graphitischen Schicht auf der Statoroberfläche beobachtet. Diese bleibende und kontinuierliche Schicht sorgte für eine ausreichende Schmierung während der Reibungsbelastung, wodurch eine relativ niedrige Verschleißrate des Verbundwerkstoffes unter den untersuchten Bedingungen bewirkt wurde.

1. Introduction

Glass and glass-ceramic matrix composites containing fibres and particles as reinforcement are being increasingly considered for self-lubricating wear applications under conditions involving relative high temperatures and in oxidative environments, including applications in the automotive and aerospace sector [1 to 9].

Carbon-fibre reinforced glass and glass-ceramic matrix composites present a low coefficient of friction and exhibit relatively low wear rates due to the solid lubricant properties of carbon fibres. It has been shown, for example, that the coefficient of friction of C-fibre reinforced borosilicate glass matrix composite against cast iron in pin-on-disc experiments (under pressures of 1 MPa and velocity of 1 m/s) is about 0.1, while the unreinforced glass matrix exhibited a friction coefficient of 0.5 [1]. It has also been found that the friction coefficient of unreinforced borosilicate (Pyrex®) glass is about ten times higher than that of the carbon reinforced material when tested against steel [2].

Despite these encouraging results, the authors are not aware of previous research conducted to assess the suitability of glass matrix composites as wear-resistant material in the vacuum technique, although glass, especially of borosilicate composition, is a common material used in this application area [10]. Other materials, notably polymer-based composites, have been more frequently considered for applications in vacuum pumps [11]. Thus, the primary purpose of the present work was the investigation of the tribological behaviour of a carbon-fibre reinforced borosilicate glass matrix composite as self-lubricating material for possible applications in rotary vacuum pumps.

2. Experimental details

The material investigated was a bidirectional C-fiber (Toray T800) reinforced borosilicate (DURAN®) glass

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Table 1. Mechanical properties of the C-fibre reinforced glass matrix composite investigated [13]

property	
bending strength in MPa	445
Young's modulus in GPa	71
work of fracture in kJ/m^2	21.9

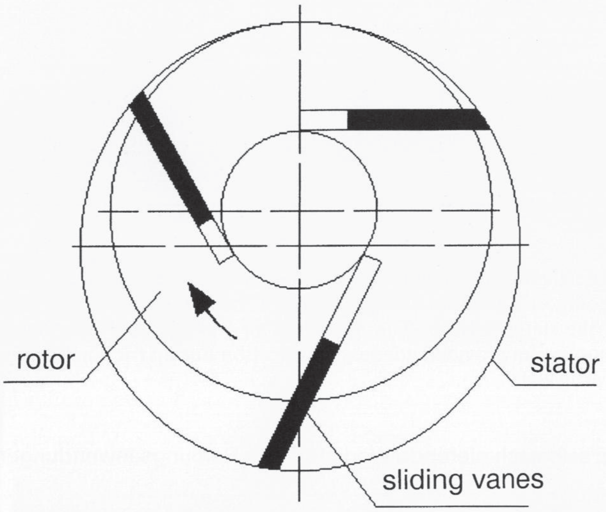


Figure 1. Schematic diagram showing the vane-stator vacuum pump configuration used for the tribological tests.

matrix composite fabricated by Schott Glas, Mainz (Germany). The composites were prepared by the sol-gel-slurry method, as reported in the literature [12]. The fibres were arranged in 0/90 ply layers. Nominal properties of the composite are given in table 1 [13]. The fibre volume fraction was ≈0.4. The composite exhibited a fairly homogeneous distribution of the fibres and absence of porosity in the glass matrix. The samples were received in the form of rectangular tiles of nominal dimensions ((2.87 × 25 × 100) mm^3), from which the vanes for the tribological experiments were cut.

The experiments were carried out on a vacuum pump stand, which is schematically depicted in figure 1. The eccentrically located rotor rotates in the cylindrical chamber of the pump. The vanes are located in the cuttings inside the rotor. During the rotation, the vanes slide out of the rotor, pushed by centrifugal forces, until they make contact with the stator and begin to slide along it [14].

The vanes were made of the C-fibre reinforced glass matrix composite. The size of the specimens was (2.87 × 24 × 25) mm^3. The contacting surfaces of the vanes were cut at angles of about 65°. The pump stator, serving as the counter-body, was made of cast iron GG25 (hardness: HB210, surface roughness parameter: Ra = 0.87 µm). It had a diameter of 70 mm and a length of 24 mm.

The experiments were carried out at room temperature. The pressure in the chamber was measured to be 700 mbar. The temperature was measured by means of a thermocouple, connected to the stator at a distance of 0.5 mm from the surface of contact. The results were registered in a PC. After each experiment, the mass of the vane was determined through analytical weight. The experimental error in the determination of the mass was 0.01 g. The surface of the stator was examined visually and the vane surfaces were observed by scanning electron microscopy (SEM).

Taking into consideration the tangential force on the vane, the load between the vane and the stator was calculated to be in the range 3.8 to 5.8 N. The rotation velocity used was 1800 rpm, which resulted in a sliding velocity of 5.5 to 7.8 m/s, depending on the exact position of the vane during the rotation cycle.

3. Results and discussion

The tribological properties of C-fibre reinforced glass matrix composites have been investigated by several authors [1 to 9], but this is the first report dealing with wear behaviour in vacuum atmosphere. Dry sliding and abrasive wear behaviour, including the determination of wear rates and friction coefficients against different metals (e.g. steel, cast iron, aluminium alloys, etc.), ceramics (e.g. Al_2O_3, SiC), glass and abrasive counterparts (e.g. SiC paper) have been studied [1 to 9]. Generally, block-on-ring, ring-on-ring or pin-on-disc testing configurations have been employed. The present work involves a more realistic testing condition relevant for applications in rotary vacuum pumps. A rotary vane pump experimental simulation was used here, where the vanes were made of the C-fibre reinforced composite and the cast-iron stator of the pump served as the counter-body.

The dependence of the iron stator surface temperature upon duration of sliding indicated that a significant increase of the stator temperature occurred. The temperature stabilized however after a given time period. Continuous temperature measurements indicated a temperature of 50 °C after 10 h test run. This value closely agrees with those measured by McKitrick et al. [3] during pin-on-disk wear tests of C-fibre reinforced glass matrix composites against cast iron.

Figure 2 shows the time dependence of worn mass loss of the C-fibre reinforced glass matrix composite vanes. After a 30 h run, which corresponds to 1182 km of sliding distance, the absolute wear mass loss of the vanes was measured to be 0.10 g. This value of mass loss, which is a measure of the wear resistance of the composite, is relatively low, if one relates it to the total volume of the vanes. This is a preliminary indication that

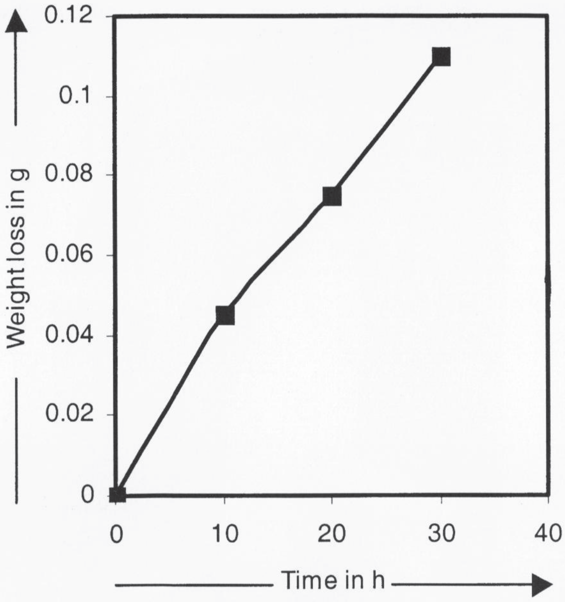


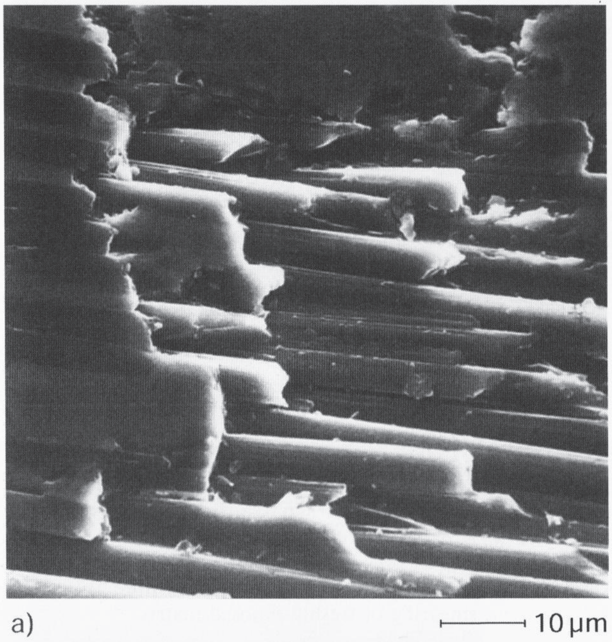
Figure 2. Time dependence of worn mass loss of C-fibre reinforced glass matrix composite vanes during wear test in the vacuum pump configuration of figure 1.

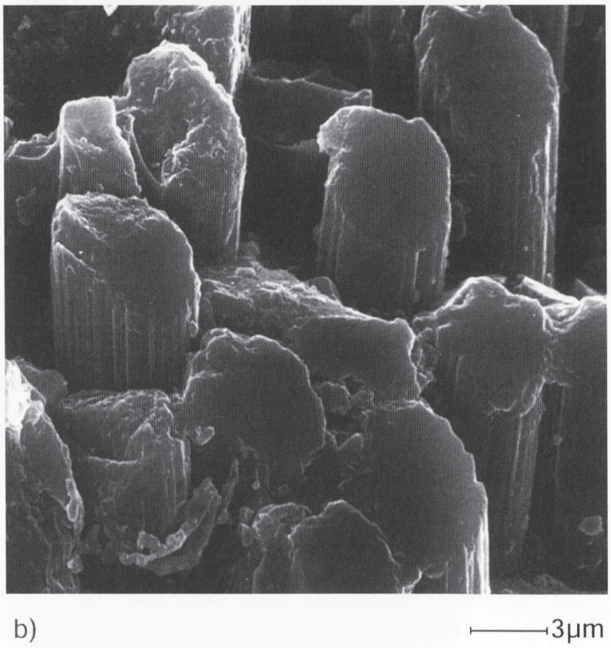
self-lubricating C-fibre reinforced glass matrix composites are candidate materials for wear-resistant applications in vacuum pumps.

The material microstructure plays an important role in determining the active wear mechanism in fibre reinforced composites, as pointed out in the literature [1 to 9]. In the present composites, on areas with high volume fraction of fibres, a low rate of wear was detected and the surface was smooth. On the contrary, in areas with lower fibre concentration severe deterioration of both fibre and matrix surface occurred.

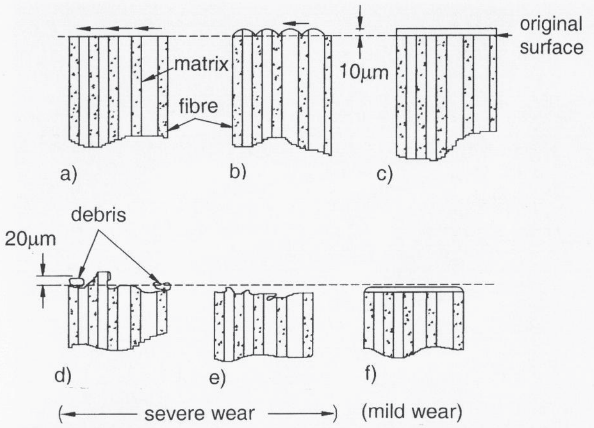
A preliminary understanding of the wear mechanisms' operating was obtained by SEM observation of the worn surfaces of the vanes (figures 3a and b). Damaged areas were clearly visible, which were the result of fibre and matrix fractures caused by the abrasive wear mechanisms. Figures 3a and b show typical worn surfaces of glass matrix composite vanes after 30 h wear test duration. The typical feature is the accumulation of wear debris in the form of a layer in some areas of the worn surface due to the effect of protrusion of fibres oriented perpendicularly to the stator surface, which impede the removal of matrix particles. This effect has also been observed by Lu et al. in their study of the wear behaviour of fibre reinforced glass matrix composites against steel [8]. The observed inclined fractured edges of the fibres, as seen for example in figure 3b, are caused by the fact that the vanes when sliding along the stator make contact at a certain angle which depends upon the contact site geometry.

The bending response of fibres oriented perpendicularly to the wear surface is critical for the wear behaviour of these composites. This is because considerable shear loads are applied to the end of the fibres as a result of the acting friction forces. Thus, fibre fracture must occur for wear to proceed. As pointed out by McKittrick et al. [3] fibre fracture occurs where there is an unsupported length. Loss of support can result from the chipping of the matrix around the fibre or by softening of the matrix, leaving the fibre as a cantilevered beam [3]. This fracture mechanism in fibres oriented perpendicularly to


a)


b)

Figures 3a and b. SEM micrographs showing typical worn surfaces of vanes made from C-fibre reinforced glass matrix composite after 30 h run (1182 km friction distance). The fibres were parallel (figure a) and perpendicular (figure b) to the stator surface.



Figures 4a to f. Schematic illustration of the wear of graphite-fibre reinforced glass matrix composites, according to the model of McKittrick et al. [3]; a) original surface, b) softening and flowing of glass, c) mild wear of smooth smeared film, d) chipping and breaking of smeared glass on fibres and interfilament regions, e) breakage of unsupported critical fibre length, f) softening and smearing of freshly exposed matrix.

the stator surface was clearly visible on the worn vane surfaces (figure 3b). It is however absent in fibres lying parallel to the stator surface (figure 3a).

The softening of the glass matrix, which leads to smearing, affects the wear behaviour. At high sliding velocities, higher interfacial temperatures are reached and greater volume of glass can smear. The wear mechanisms of material removal, as suggested by McKittrick et al. [3], are illustrated schematically in figures 4a to f. After the initial development of a smooth surface (figure 4a), frictional heating causes softening and thermal expansion of the glass, which extends beyond the fibres as these remain unexpanded (figure 4b). Eventually the glass is smeared over the surface of the composite (figure 4c). During this stage, small amount of glass is transferred to the counter-surface, resulting in mild wear. For longer sliding duration, the glass layer may begin to break up in some areas (figure 4d) leading to the formation of debris and severe wear damage. Glass fracture can occur not only at the original composite surface but also below it, leaving many graphite fibres not surrounded by matrix material. This is the stage documented in our own experiments by figures 3a and b. Eventually these unsupported lengths of fibres are broken off, leaving the surface relatively clean (figure 4e) and the process can start again (figure 4f).

Thus, the wear of the glass matrix composite was accompanied by material transfer onto the stator surface. This effect, which has been referred to as "third body formation" [9], has also been observed by other authors in previous studies on the dry-wear behaviour of C-fibre reinforced glass matrix composites [3, 8 and 9]. Indeed the presence of a wear film of composition in the system Si$-$C$-$O on the counterface is beneficial for a low wear rate and coefficient of friction.

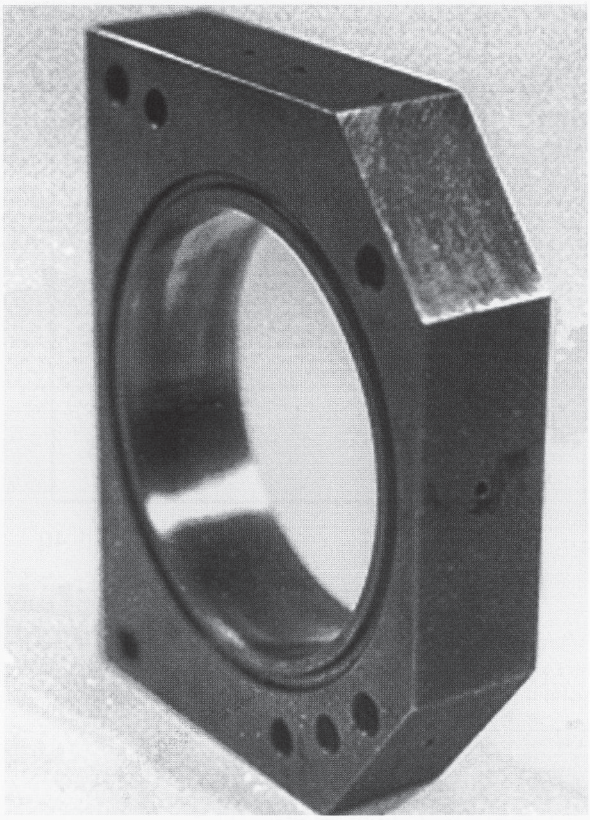


Figure 5. The counter-body (stator) after the wear experiment showing the continuous shiny friction transfer film on the cast iron surface.

In our experiments, an isle-shaped discontinuous film was usually formed on the metal surface, which became continuous in some areas. The character of this material transfer (i.e. isle or continuous film formation) generally depends upon the load$-$velocity ($p-\upsilon$) range at the contact. In the present composites, film formation should be mainly associated with the extent of fragmentation of glass matrix and fibres. Moreover, a thermal effect due to viscous deformation and smearing of the detached glass particles should also be taken into account [3]. A significant feature determining the material transfer mechanism is the extent of adhesion of wear particles to the metallic surface of the counter-body. The extent of adhesion depends on the $p-\upsilon$ range, which is different at different points of the stator in the eccentric rotor configuration employed (see figure 1). When the adhesion is poor, isle-type film formation occurs. On the other hand, for strong adhesion, the transfer film becomes continuous. As figure 5 shows, the continuous friction film formed on the stator surface was shiny and thin. Visual inspection of the film led to the conclusion that this is a graphite-rich film. Thus, during the continuous friction process, an elastic friction contact was provided, which led to self-lubricating conditions and to the relatively low wear of the composite vanes. Moreover, the formation of a continuous film is desired because the wear particles are kept in the wear zone and the vacuum chamber remains free of wear debris. It must also be pointed out that the environment plays an important role in the process of film transfer formation. It is known that vacuum favours the adhesion of wear particles to the counter-body [15].

4. Conclusions

Wear tests of C-fibre reinforced borosilicate glass matrix composites were carried out in a vacuum pump configuration. Fibre fracture and glass matrix particle detachment were observed as wear mechanisms, and the wear behaviour of the composites could be described qualitatively by the model of McKittrick et al. Composite wear is accompanied by material transfer onto the stator surface. A graphitic film is formed on the counter-body surface, which provided adequate lubrication during the experiment leading to relatively low wear rates. These preliminary experiments show that the self-lubricating glass matrix composite material investigated may be an adequate candidate for dry wear applications in vacuum pumps. However, final conclusions can be drawn only after a thorough examination of the wear processes taking place under various loads, velocities and levels of vacuum has been undertaken. This is the focus of current research.

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