Mode of Loading and Contact Configuration Effects in the Wear of Polymers

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SYNOPSIS

Results of an experimental study into the relationship between the wear of PMMA and the mode of loading and contact configuration are presented. It was found that the wear of PMMA under cyclic loading is significantly lower than is the wear under static loading of a magnitude equal to the mean load of the cycle. Different contact configurations, represented by the angle between the axis of the PMMA sample and the axis of the steel disc (counterface), proved to have only a minor effect on the wear of PMMA. The lowest wear rate for both static and cyclic loading was obtained for smaller angles. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

Many studies have been carried out on polymer wear. Various models, such as adhesion, abrasion, fatigue, and crazing, have been suggested to explain the nature of the wear process. It was found that factors such as hardness, toughness, and resistance to crack propagation influence the rate of wear. Much effort has been put into understanding the wear mechanisms operating in polymer sliding contacts. This also applies to poly(methyl methacrylate) (PMMA) for which the microwear process involves three distinct stages.[1] First, there is a plateaulike upheaval during which no wear takes place. This is followed by distortion of the surface to produce projections, again involving no wear. Finally, the surface is subjected to wear and wear particles are produced. A special feature of PMMA is that the deformation rapidly proceeds to destruction.

Wear of polymers has been analyzed by considering such factors as primary energy dissipation zones, conditions of contact, surface damage, and debris formation.[2] The role of crack propagation in the wear of polymers has also received attention.[3] There is a clear relationship between fatigue crack growth and the rate of wear for PMMA. Additionally, it is usually affected by the fluid environment in which testing takes place. A theoretical relationship between the wear rate and certain parameters in the Paris equation for fatigue crack growth was devised.[3] Wear and fatigue crack growth are very sensitive to organic fluids. This could be related to the absorption of the liquid into the polymer, which, in turn, could result in surface plasticization or reduction of the minimum stress for the onset of crazing or cracking. Quite often, the main contributory factor to polymer wear is the cyclic nature of loading and subsequent surface fatigue.[4] Another possible cause of polymer wear is fretting fatigue.[5]

The studies described in this article were devoted to the wear of PMMA using a configuration in which a polymer rod was in contact with the periphery of a steel disc, thus forming initially a point contact (two crossed cylinders configuration). The load applied to the contact was fluctuating between certain minimum and maximum values. The effect of the position of the axis of the rod relative to the axis of the steel disc on PMMA wear was also studied.

EXPERIMENTAL

A diagrammatic representation of the apparatus is shown in Figure 1. The testing in this apparatus involves applying a load (static or fluctuating) to a loading arm which transmits it to a polymer sample

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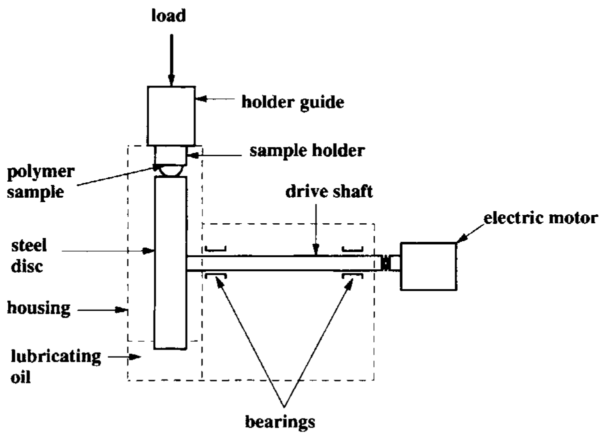

Figure 1 Schematic representation of the layout of experimental apparatus.

pressed against a lubricated rotating steel disc with a diameter of 120 mm. The samples were cut from an 8 mm diameter PMMA rod to a length of 8 mm. The static load was applied using weights attached directly to the loading arm. The fluctuating load was delivered to the loading arm via a pneumatic cylinder connected to an air line of around 6 bar. The pressure admitted to the pneumatic cylinder was controlled by a computer interfaced with an electromagnetic valve.

The loading system is shown, schematically, in Figure 2. In this system, a compressed air line is connected to a filter and pressure regulator (1) and from there to a proportional pressure regulator (2) which controls the pressure of the air leaving it. The proportional pressure regulator is linked to the computer where the voltage could be set in order to obtain the required pressure of the air leaving the regulator (2). The air from the regulator (2) is directed to the air cylinder (3) which applies load to the loading arm via a strain gauge (4) and a set of coil springs. The resistance of the gauge is measured by a bridge whose output is sent to the controller and then to the computer where it can be read. A computer code was written to generate a cyclic load in a controlled way.

A special specimen holder was made enabling stepwise adjustment to the angle between the specimen axis and the disc axis. Lubrication of the contact was achieved by the disc dipping into a bath of lubricant. A base hydrocarbon oil containing no additives was used.

Before each test, the PMMA sample was cleaned and weighed. The sample was then placed in the holder and the contact with the disc was made. The motor driving the disc was then switched on, and after adjusting to the required velocity (usually 240 rpm) which translates to 1.5 m/s sliding velocity), the load was applied to the contact. The test was left to run for a specified period. At the end of the test, the sample was removed from the holder, cleaned of wear debris, and weighed again. The amplitude of cyclic loading was 15% of the mean load, and the frequency of load fluctuations was 75 cycles per minute.

Tests were initially carried out with the axis of the sample being perpendicular to the axis of the disc (0° angle) and then at different angles (30°, 60°, and 90°). The amount of wear was determined by measuring the weight of the sample before and after testing. The initial contact pressure for each angle was the same and equal to 26 MPa.

RESULTS

Overview

In general, it appears that, under the conditions used in this study, the cyclic load reduced the wear of PMMA compared to a static load whose magnitude was equal to the mean of the cyclic load. The different angles between the axis of the sample and the axis of the disc gave varying wear rates for nominally the same initial contact pressure. The overall wear rates seemed to be fairly constant against time despite an inevitable increase in contact area and subsequent decrease in contact stress. Some of the samples showed signs of melting resulting from overheating. Also, the relatively constant wear rates indicate that the wear may be fairly independent of the contact area.

Details

Figure 3 shows the results obtained for the 0° angle between the axis of the sample and the axis of the

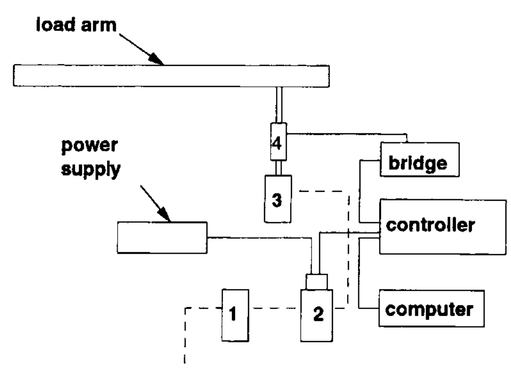

Figure 2 Diagram of the control system of the apparatus.

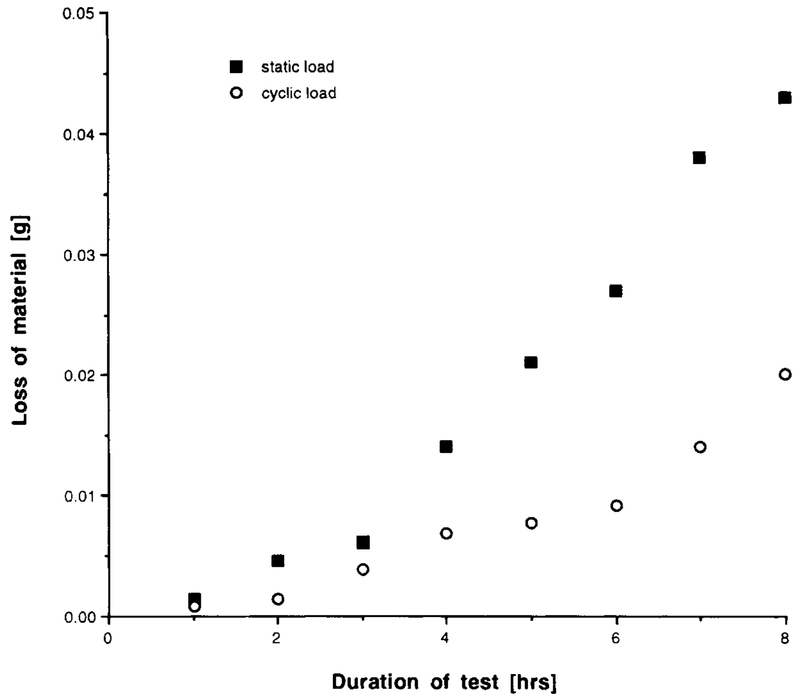

Figure 3 Loss of material as a function of test duration for 0° contact configuration.

disc (crossed cylinders configuration). It can be seen that the wear for the static load is significantly greater than for the cyclic load. In the case of the 30° angle (Fig. 4), the amount of wear for static loading is only slightly greater than for the cyclic loading. The amount of wear obtained for both static and cyclic loading became very much similar for the 60° angle (Fig. 5). For the 90° angle (Fig. 6), the wear for static loading was much greater than for cyclic loading. For both static and cyclic loading,

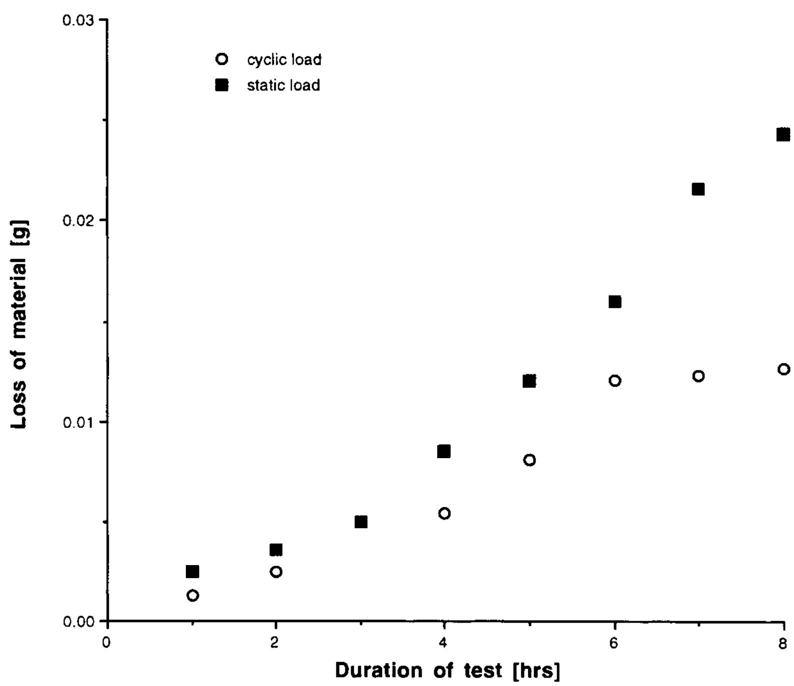

Figure 4 Loss of material as a function of test duration for 30° contact configuration.

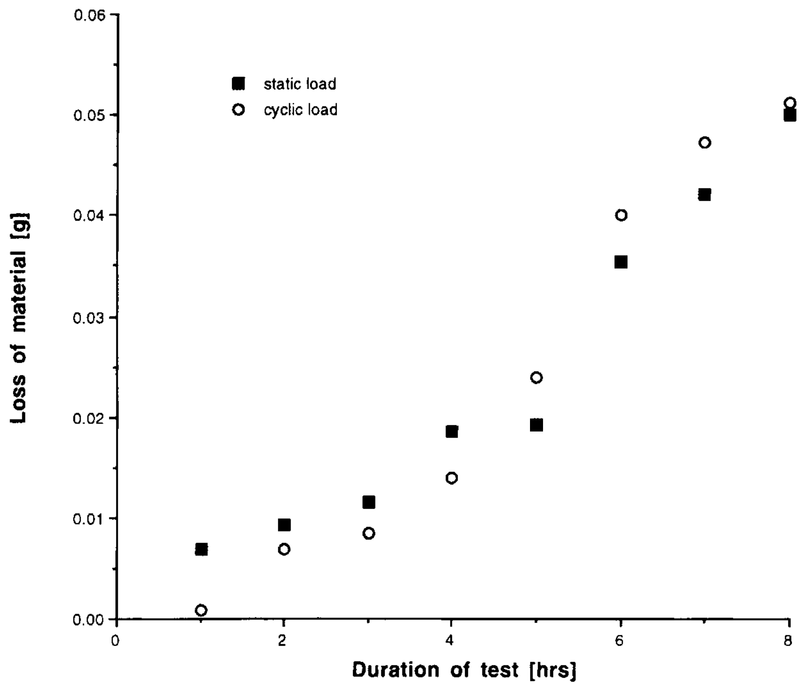

Figure 5 Loss of material as a function of test duration for 60° contact configuration.

the 30° angle configuration gave the lowest wear. For static loading (Fig. 7), the 0° and 60° angle tests produced very similar overall wear rates. For the majority of tests, however, the wear rates obtained for the 60° angle were higher than that for 0°; the wear rate at the 90° angle was double of that for other angles. In the case of cyclic loading (Fig. 8), the differences between wear rates produced for different angles are rather insignificant.

DISCUSSION

The first interesting feature of the results obtained is that there are no large changes in the wear rate although the contact area increased with time. With the contact configuration used, it was impossible to prevent this increase from occurring. Although the initial contact stress was nominally the same for all the contacts used, the load on the contact was different for different contact configurations and was kept constant throughout the test. Consequently, the contact stress was decreasing as a result of contact area increase due to wear. A sort of balance between contact conditions and the severity of wear must have been established to give a fairly constant wear rate.

Changing the angle between the axis of the sample and the axis of the disc could have changed the size and shape of the initial contact area. A point contact area was initially created when the axis of the sample was perpendicular to the axis of the disc (0° angle). The contact area became progressively elongated as the angle was increased and eventually assumed a rectangular shape at 90° (the case when the axis of the sample is parallel to the axis of the disc).

Although the wear testing was carried out under conditions which should secure boundary lubrication, nevertheless, the thickness of the film might have been affected by the different contact configurations. This, in turn, could have influenced the wear rate. The usual parameter used to define the lubrication regime is the specific film thickness. It is accepted that, if the value of specific film thickness is less than 1, then the contact operates within the boundary lubrication. Taking into account initial contact conditions and nominally the same contact pressure for all contact configurations, the film thickness was calculated with the help of known equations.[6] It was found that the film thickness was 19.1×10^{-8} m for a 90° angle, 5.05×10^{-8} m for a 60° angle, 5.32×10^{-8} m for a 30° angle, and 5.37×10^{-8} m for a 0° angle. The surface roughness of the steel disc was 40×10^{-8} m; therefore, the specific film thickness is less than 1, which clearly indicates boundary lubrication conditions.

Apart from the 90° angle with static loading, the differences between wear rates for different contact

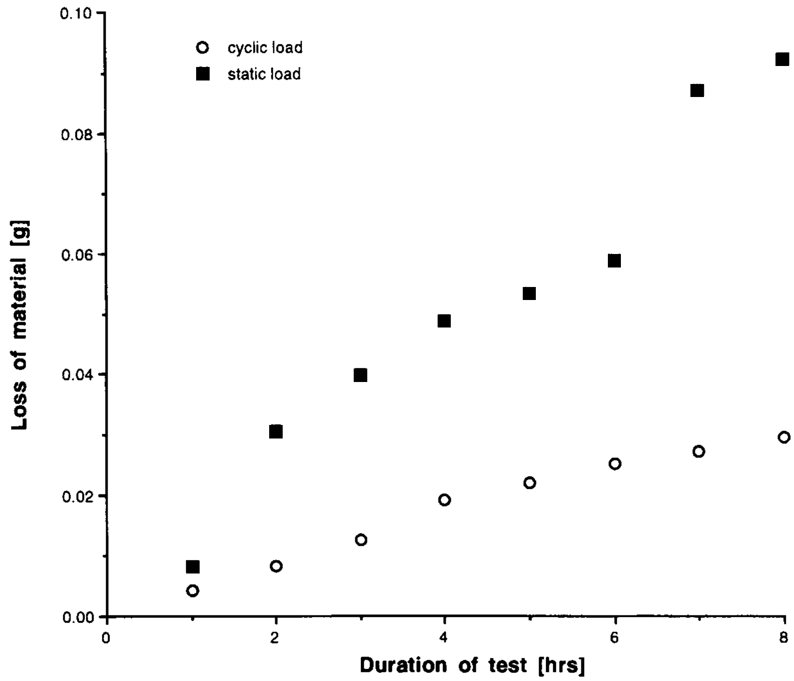

Figure 6 Loss of material as a function of test duration for 90° contact configuration.

angles are not very significant. As the PMMA is a material with a glassy structure, therefore, it is not surprising that no orientation effects were found as in the case of some other polymers.[7] The reason why the cyclic load resulted in a reduction of the wear is more difficult to explain. One thing is quite obvious: Cyclic loading somehow interfered with the wear process normally occurring under static loading. This could be a periodic reduction in interfacial shear stresses, thus affecting overall heat generation, or, simply, regular easing in the severity of the contact conditions helped to slow down the rate of ma-

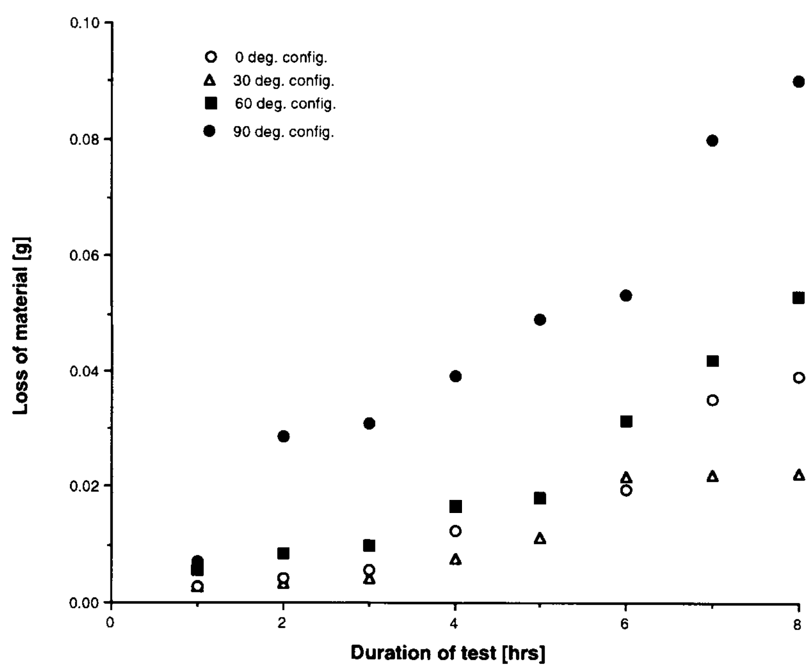

Figure 7 Loss of material as a function of time for static loading.

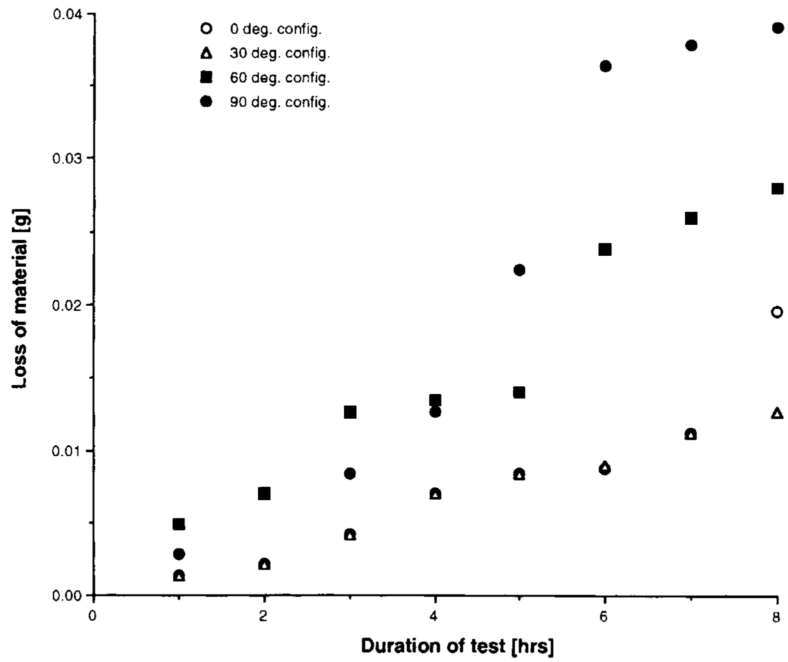

Figure 8 Loss of material as a function of time for cyclic loading.

terial removal. Temperature measurements were taken during testing, but no significant difference was found between contact configurations. In fact, the average temperature measured near the contact zone was around the temperature of the oil bath in which the steel disc was partially submerged. Taking into account very good heat dissipation conditions, resulting from the disc size and the presence of oil, it is not surprising that the measured temperature is rather low. Certainly, what was measured does not represent the so-called flash temperature existing within the contact area during testing. Therefore, temperature checks on the disc do not provide conclusive evidence which could enable explanation of observed wear behavior on thermal grounds. Careful microscopic examinations of worn surfaces tested under cyclic loading did not reveal any signs of fatigue. This observation does not, however, exclude the possibility of surface fatigue occurring under test conditions used because any features characteristic for fatigue could have been worn out before the test was terminated. Anyway, the results obtained indicate that in case of a glassy polymer such as PMMA continuous sliding under cyclic loading produced lower wear rates than did continuous sliding under static loading.

CONCLUSIONS

1. The wear of a PMMA rod in contact with the periphery of lubricated rotating steel disc is significantly lower under cyclic loading in comparison to the wear under static loading of a magnitude equal to the mean load of the cycle.
2. The angle between the axis of the PMMA rod and the axis of the steel disc affects, to a certain extent, the wear. Under both static and cyclic loading, the lowest wear rates were obtained for the 0° and 30° angles.

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