Phenomenology of Surface Failure of Poly(methylmethacrylate) Resulting from Rolling Contact Fatigue

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SYNOPSIS

Results of phenomenological study into the forms of surface failure of poly(methylmethacrylate) (PMMA) are presented. Surface failure of the polymer resulted from rolling contact fatigue produced in a model configuration consisting of a PMMA disc with nominally flat surface loaded against three steel balls able to roll free over the surface of the disc. It was found that the performance of the polymer under the test conditions used is influenced by lubricating medium and the main form of failure is of surface fatigue type. © 1995 John Wiley & Sons, Inc.

INTRODUCTION

Polymers, when subjected to strong mechanical and environmental excitation, usually show gradual deterioration of their performance including eventual failure. This behavior is in line with that of other engineering materials. If the changes in properties are mostly due to chemical reactions, one can speak of corrosion or of radiative degradation. The term *fatigue* is used if deterioration in material properties is caused by the repeated cyclic or random application of mechanical stress.

The volume fatigue of polymers has received increased attention in the last 45 years. In addition to a large number of research papers, review articles on this complex subject have been numerous.[1-3]

It is justified to say that, in the case of volume fatigue, failure in repeated loading occurs at load levels which are lower than the stresses sustained under the conditions of static loading (creep) or of monotonously increasing deformation (drawing). The lower the stress level to which a material is exposed, the larger the number of load cycles which are sustained. Three principal mechanisms leading to fatigue may be distinguished: thermal softening, excessive creep or flow, and/or the initiation and propagation of fatigue cracks.

The problem of surface fatigue of polymers, induced, for instance, by rolling contact, has received far less attention,[4,5] although polymers have been successfully utilized in many rolling contact applications.

The main objective of the study reported in this article was to establish the failure modes of poly(methylmethacrylate) (PMMA) when subjected to cyclic loading produced in model rolling contact.

APPARATUS, MATERIALS, AND EXPERIMENTAL PROCEDURES

Test Apparatus

The test apparatus used for the rolling contact experiments is schematically shown in Figure 1. The essential part of the apparatus, namely the cup containing test sample, is shown in more detail in Figure 2. In this apparatus, the top ball is located in a chuck carried by a vertically mounted spindle and is rotated in a loaded contact with three other balls which are free to rotate in the cup. The three lower balls are also in contact with the test piece located at the bottom of the cup. The contact between the lower balls and the test piece is of a transient nature. One revolution of any of the lower balls around the cup

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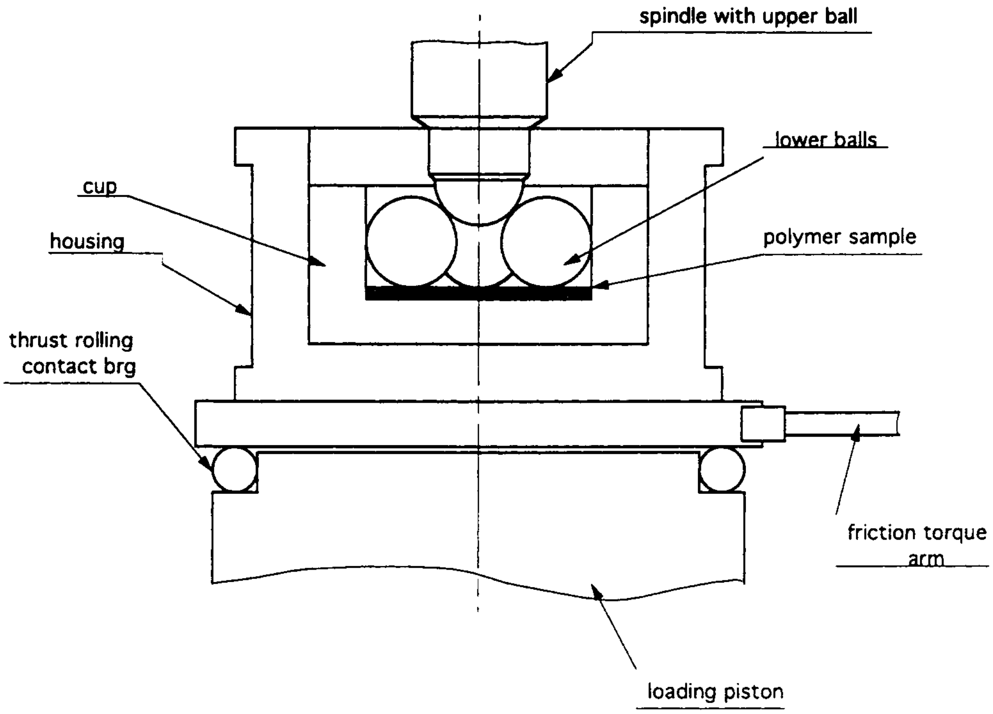

Figure 1 Schematic representation of apparatus used for rolling contact fatigue testing.

produces one loading/unloading event felt by the surface of the test piece. As there are three lower balls, therefore, any given point of the test piece surface is three times loaded/unloaded during one full revolution of the balls around the cup. In this way, cyclic loading acting on the surface of the test piece is generated although the contact as a whole is under a steady load. Details of the loading system are shown in Figure 1. More detailed description of the apparatus is given elsewhere.[6]

Test Materials

Test specimens in the form of flat discs with diameter of 30 mm and thickness of 5 mm were machined from commercially available cast PMMA rods. Some of the more important mechanical properties of PMMA tested were as follows:

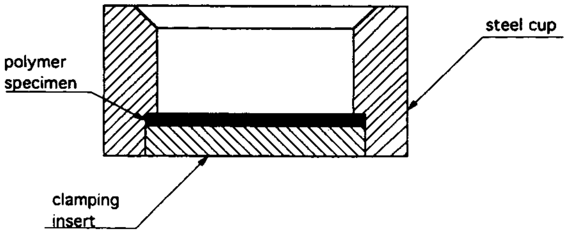

Figure 2 Cup accommodating polymer test sample.

Tensile strength: 80 Nm/m^2
Yield strength: 110 Nm/m^2
Modulus of elasticity: 3300 Nm/m^2
Indentation hardness, HB: 200 Nm/m^2

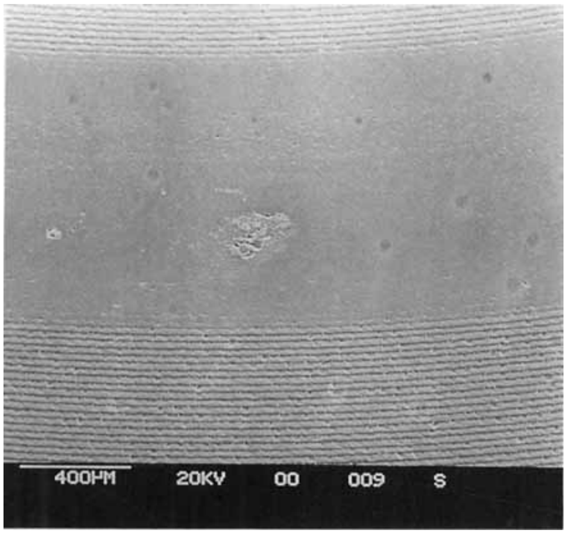

Figure 3 Overview of contact path and adjacent regions with visible machining marks. Damage located within contact zone is also visible. Test conditions: contact stress, 2.9 GPa; upper ball rotational velocity, 2000 rpm; duration of test to failure, 37 h (13.32 × 10^6 load cycles); lubricating medium, base mineral oil.

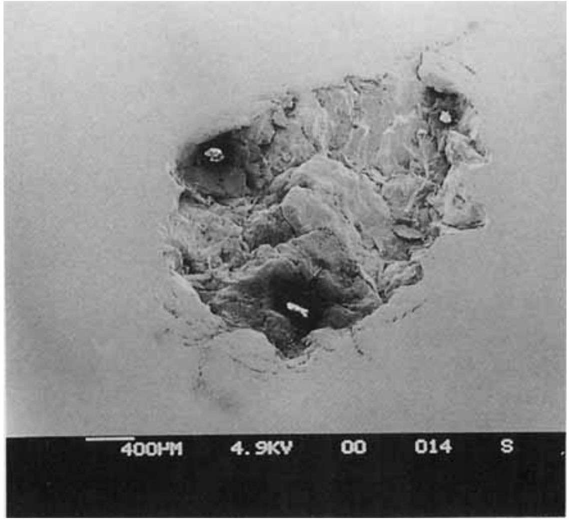

Figure 4 View of pit produced on surface under test conditions specified in Figure 3 legend.

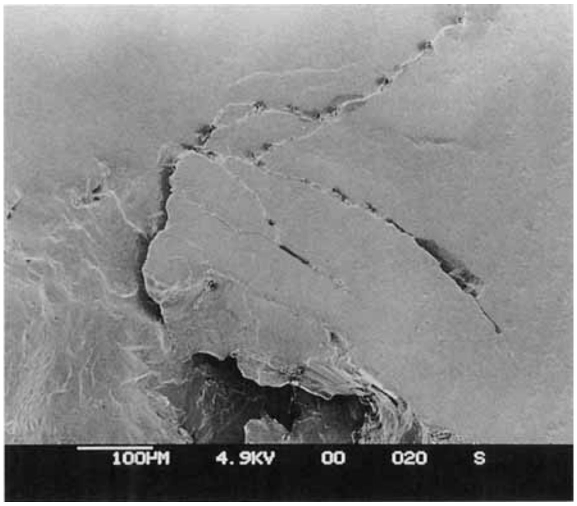

Figure 6 Shelflike feature produced by crack extending into material. Pit visible at bottom of micrograph gives some indication about depth of crack.

Impact strength: 12 kJ/m^2
Notched impact strength: 2 kJ/m^2
Density: 1.18 g/cm^3
Maximum continuous service temperature: 78°C

The cup accommodating the test piece was made of stainless steel. The balls used during testing were commercially available high-grade balls made of special bearing steel. Their surface finish was better than 0.05 μm R_a. Test runs were carried out in the presence of lubricating fluids. The following fluids were used: mineral base oil, Shell Talpa 20 with viscosity of 94.6 cSt at 40°C, and brake fluid with a commercial formulation.

Test Procedure

Before each test run the following general test procedure was implemented:

1. All metal elements were thoroughly cleaned in an ultrasonic cleaning device using general-purpose solvent Genklene.
2. The polymer test piece was assembled in the cup.

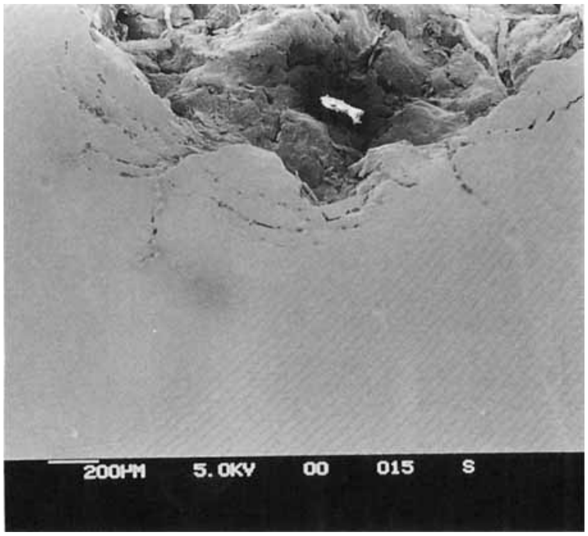

Figure 5 Details of pit of Figure 4 at higher magnification.

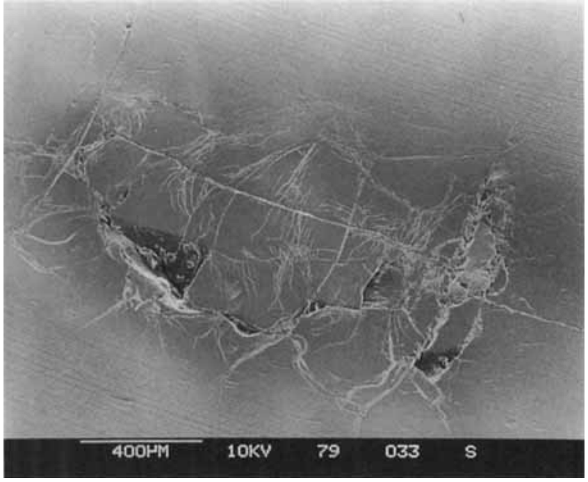

Figure 7 Details of cracks shown in Figure 6 but at higher magnification.

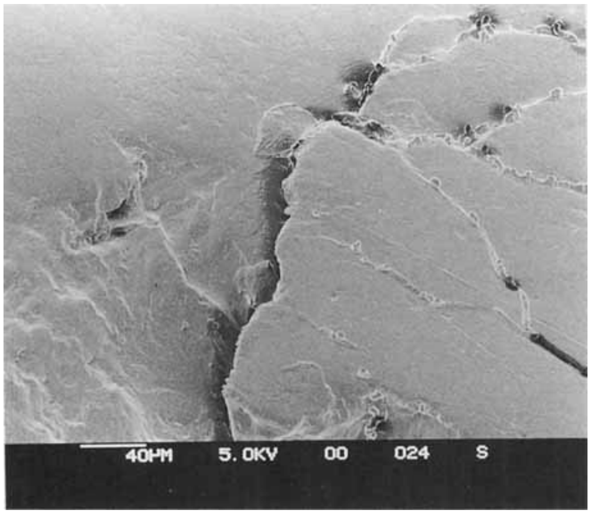

Figure 8 Higher magnification of area shown in Figure 7.

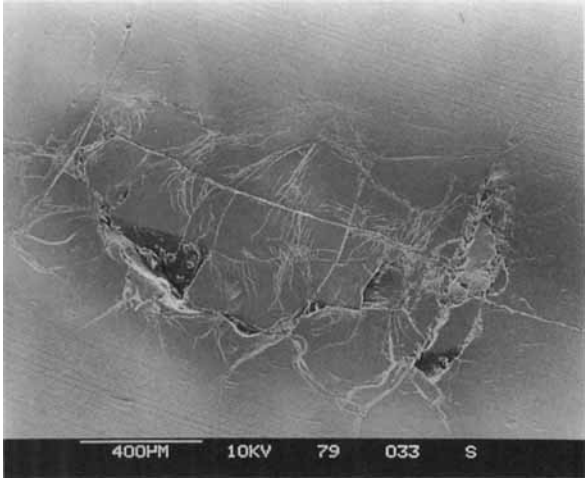

Figure 10 Typical early stage form of surface failure produced under test conditions specified in Figure 9 legend.

3. The upper steel ball was positioned in a spring steel tapered collet. The collet assembly was then pressed into the drive spindle.
4. The polymer sample was inserted into the cup and secured against rotation.
5. The three lower balls were put into the cup and a lubricating liquid poured into the cup until all the lower balls were immersed.
6. The cup assembly was then placed on the loading piston of the apparatus.
7. The spindle motor was started and the speed was gradually increased until it reached the desired level (usually 2000 rpm).
8. Load to the contact was applied and was kept constant throughout the test. The load expressed in terms of contact stress ranged from 2.3 to 4.1 GPa.

The test was interrupted at regular intervals for the inspection of contact path conditions produced by the three lower balls rolling over the surface of the PMMA disc. Depending on the load on the contact, the inspection was carried out every 5 min at the highest loads applied and every 20 min at the lighter loads. Such frequent inspections were necessary in order to capture early signs of surface distress and

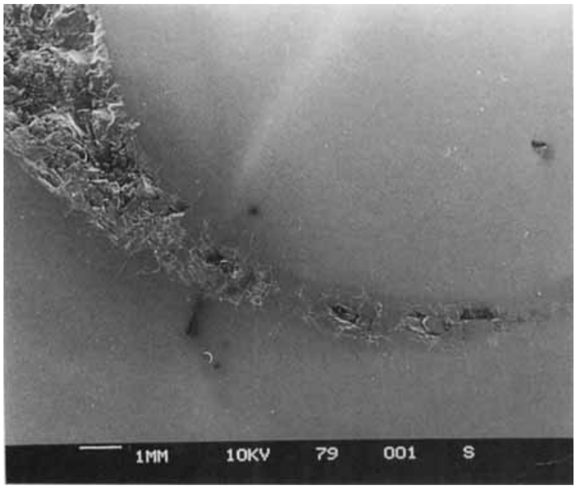

Figure 9 Overview of surface damage produced on surface of PMMA during rolling contact fatigue test under following conditions: contact stress, 2.3 GPa; upper ball rotational speed, 2000 rpm; test duration, 5 h and 55 min (2.13×10^6 load cycles); lubricating medium, brake fluid.

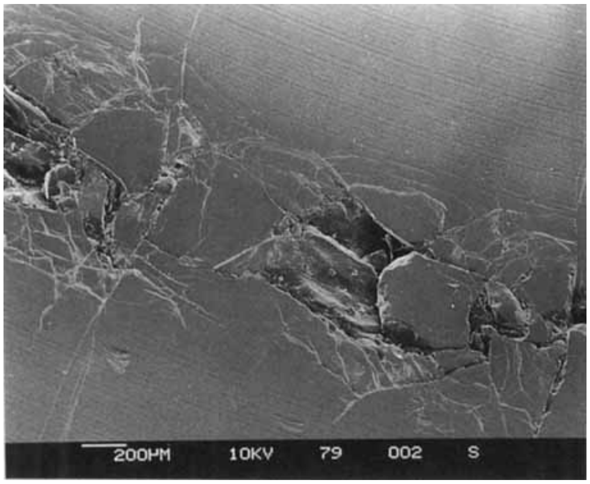

Figure 11 Example of progress in surface failure process (test conditions as specified in Fig. 9 legend).

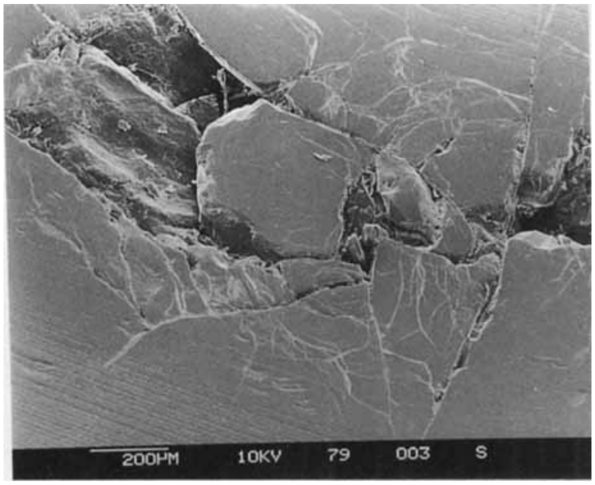

Figure 12 Details of damage shown in Figure 11 but at higher magnification.

the beginning of surface damage development. At this stage the inspection of the contact region was only cursory and the thorough posttest microscopy examinations were performed later. In this way the test continued until clear surface damage was produced. When that was observed, the test for a given load, speed, and lubricating liquid was regarded as being completed. The time to failure varied depending on test conditions used.

RESULTS AND DISCUSSION

As was stated at the beginning of the article, the objective of the studies presented here was to find out the prevailing mode of surface failure of PMMA when exposed to rolling contact conditions. Accordingly, the results will be presented mainly in the form of scanning electron microscope micrographs. For presentation purposes, the results will be discussed separately for the two lubricating liquids used.

Mineral Base Oil

Mineral base oil (Shell Talpa 20) was used to represent a typical and "mild" sample lubricating medium for the PMMA. It did not contain any of the usual additives present in fully formulated oils which are supposed to enhance their lubricating action.

Figure 3 is an overview of a typical appearance of the surface of a PMMA disc tested for 37 h in the presence of Talpa 20 at the speed of 2000 rpm (this is the rotational speed of the upper ball) and the contact stress of 2.9 GPa. Three elements can be distinguished. Clear machining marks are visible on both sides of the contact path, which appears as a smooth band whose width represents the size of the contact region. Approximately in the middle of the contact path surface damage is visible. It is seen that the damage is in the form of an isolated pit and there are considerable stretches of surface where no damage has been produced. This is a characteristic feature of surface fatigue. It can be safely said that the damage was initiated at a point on the surface where some imperfection or weakness existed prior to testing.

Figure 4 shows the surface damage of the previous figure at higher magnification. More details characteristic of surface fatigue emerged. The pit itself is filled with debris of material, and at its edges, a network of cracks has formed. Figure 5 gives even more details about the damage produced. The pit edge region is shown at various magnifications in Figures 6–8. From these micrographs a clear picture of the mechanism responsible for the surface damage of PMMA emerges. Apparently, initial damage is in the form of a pit (see Figs. 3 and 4) and spreads by creation of a network of cracks outside the pit. These cracks eventually merge and create another pit. It is possible that the pits themselves might eventually merge to create large-scale surface failure.

It is important to stress that the failure of PMMA, in the form depicted by Figures 3–8, was confined to the surface only and was produced after 37 h of testing under quite heavy load of 2.9 GPa. In terms of load cycles on any point of surface within the contact region, the time to failure corresponds to 13.32×10^6 load cycles.

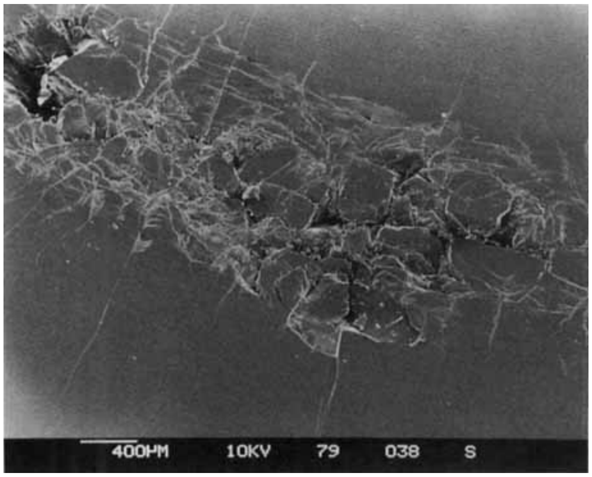

Figure 13 Typical macroscale form of damage characteristic for final stage of surface failure process.

Brake Fluid

The rationale behind the use of brake fluid as a lubricating medium was the assumption that the brake fluid, being a more aggressive liquid than Talpa 20, could accelerate the failure process by means of surface reaction with the polymers detrimental to its performance.

Figure 9 shows a fairly large portion of the contact path which illustrates the type of failure produced in the presence of brake fluid. Unlike the failure obtained in the previous case, this time the damage inflicted on the polymer is much more severe. Figure 10 is an example of an early stage of the failure process. A network of cracks is clearly visible as well as some pits. Figures 11 and 12 show, at different magnifications, characteristic features of the damage. The pits are still isolated from each other. With the progress of the failure process, cracks and pits tend to coalesce and surface damage on a macroscale is produced. This is well illustrated in Figure 13. It took only 5 h and 55 min (2.13×10^6 load cycles) to produce damage to the extent shown in Figure 12. The rotational speed of the upper ball was 2000 rpm and the contact stress 2.3 GPa.

It is obvious, comparing the contact stress and time to failure, that brake fluid had a considerable detrimental effect on performance of the polymer. This detrimental action could be through chemical reaction with PMMA or the greater ability of brake fluid to penetrate tiny cracks, which are usually produced at an early stage in the failure process, and thus facilitate their further growth and propagation. Posttest spectrographic analyses of the contact path did not produce unequivocal evidence to support the first supposition.

CONCLUSIONS

The most important observation emerging from the studies described in this work is that, under the conditions used, the PMMA failed in a manner typical of surface fatigue. The failure, as evidenced by scanning electron microscope micrographs, is characterized by the network of cracks created on the surface of the polymer which coalesce, facilitating the removal of material and emergence of pits. The damage, in the case of both lubricating fluids, was confined to the surface region and affected the material to the depth of approximately 1 mm. The polymer proved to be quite resistant to surface fatigue conditions, especially in the presence of base mineral oil. Brake fluid, being a more aggressive liquid than mineral oil, accelerated the failure process quite considerably.

It is believed that the mechanism of failure consists of crack initiation, at the point on the surface where some sort of weakness or imperfection exists, and subsequent propagation of the crack, its branching, merging, and eventually material removal and pit creation.

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