The Effect of Waveform on the Fatigue Crack Propagation Behavior of Ultrahigh Molecular Weight Polyethylene

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ABSTRACT

Ultra high molecular weight (UHMW) polyethylene is used successfully as one of the components in total joint replacements. Damage modes responsible for the generation of significant debris from these components appear to result from a fatigue fracture mechanism. For polymeric materials, the fatigue crack growth behavior can be considered to be a function of a fatigue component and a viscous creep component. The objective of this study was to examine the effect of creep on the fatigue crack propagation behavior of UHMW polyethylene. This was accomplished by performing fatigue tests at three waveforms while maintaining a constant ramp rate. It was found that with increasing time under maximum load, the resistance to fatigue crack propagation decreased. With increasing cyclic stress intensity, the difference in fatigue crack propagation resistance diminished between the three waveforms. These results were interpreted with respect to the contribution of creep to the fatigue crack propagation behavior of UHMW polyethylene.

KEYWORDS

Ultrahigh molecular weight polyethylene; fatigue crack propagation; waveform; total joint replacement.

INTRODUCTION

Ultra high molecular weight (UHMW) polyethylene has been used successfully as one of the components in total joint replacements for more than two decades. In this application, UHMW polyethylene is used as one half of the metal-on-plastic articulation replacing the joint. There is concern, however, that the debris generated from damage to articulating surfaces of UHMW polyethylene contributes to a local biological response, which can result in loosening of the components from the surrounding bone (Wroblewski, 1979 and Mirra *et al.*, 1982). This is expected to be an increasing problem as joint replacements remain in service for longer periods of time.

Finite element analysis of UHMW polyethylene components as used in total knee replacement showed that these components experienced large cyclic tensile and compressive stresses (Bartel *et al.*, 1986). Microscopic examination of UHMW polyethylene components obtained at revision surgery revealed that the damage modes responsible for the generation of significant debris appeared to result from a fatigue fracture mechanism involving the initiation and propagation of surface and subsurface cracks (Hood *et al.*, 1983).

Because a significant amount of the debris is generated through a fatigue fracture process, it is appropriate to use a fracture mechanics approach in the optimization of component design. As part of this approach, it is necessary to establish the fatigue crack propagation behavior of UHMW polyethylene. In a previous study, sinusoidal loading at an R-ratio (the ratio of minimum load to maximum load) of 0.1 was used to compare the fatigue crack propagation resistance of plain UHMW polyethylene to carbon fiber-reinforced UHMW polyethylene (Connelly *at al.*, 1984). However, for polymeric materials, it has been hypothesized (Hertzberg *et al.*, 1975) that the fatigue crack growth behavior can be considered to be a function of a fatigue component and a viscous creep component. Since creep has been shown to contribute significantly to the deformation of UHMW polyethylene total joint components (Crissman *et al.*, 1982 and Rose *et al.*, 1984), the objective of this study was, therefore, to examine the effect of creep on the fatigue crack propagation behavior of UHMW polyethylene.

MATERIALS AND METHODS

Fatigue crack propagation tests were performed on center-cracked specimens machined from extruded UHMW polyethylene (HOSTALEN GUR™ resin, American Hoechst Company, extruded by Westlake Plastics Company). Specimen dimensions were determined according to ASTM Standard E 647-88 and were as follows: thickness (B) = 10mm, width (W) = 35mm, and span = 70mm, measured between the loading pins. For this specimen configuration, the cyclic stress intensity factor, ΔK, is determined by the following expression (ASTM Standard E647-88, 1988):

$$\Delta K = (\Delta P/B)[(a/W^2)\sec(\pi a/W)]^{1/2} \quad (1)$$

where ΔP is the load range (P_{max} - P_{min}), B is the specimen thickness, W is the specimen width, and a is the crack length.

Specimens were loaded cyclically in ambient air on an MTS servohydraulic closed-loop testing machine. The R-ratio was 0.14 and the test frequency was 5 Hz. Three waveforms were examined: sustained high load (in which the high load portion accounted for seventy-five per cent of each load cycle), uniform high and low load (in which the high and low load portions of each cycle were equal), and sustained low load (in which the low load portion accounted for seventy-five per cent of each load cycle), as shown in Fig. 1. In all cases, the ramp rate was the same (0.025 sec). Measurements of crack length were taken with a travelling microscope along with the number of loading cycles, N. An average of both crack lengths extending from the center-line of the specimen was used in the determination of the fatigue crack growth rate, da/dN. Although crack tip temperature was not measured directly, the specimen surfaces at the crack tip were cool to the touch throughout testing.

Following mechanical testing, the fracture surfaces of selected fatigue crack propagation specimens were sputter-coated with a gold-palladium alloy and examined in an Amray 1000A scanning electron microscope at 20 kV.

RESULTS AND DISCUSSION

Fatigue crack propagation results are plotted in Fig. 2 as fatigue crack growth rate, da/dN, versus cyclic stress intensity factor, ΔK. For each waveform, the data presented were collected from two specimens. The sustained high load waveform was the least resistant to fatigue crack growth, while the sustained low load waveform was the most

resistant to fatigue crack growth. However, the difference in the fatigue crack propagation resistance between the three waveforms diminished with increasing ΔK.

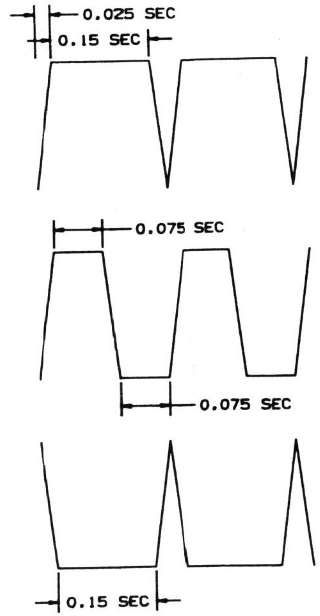

Fig. 1
The three waveforms used in this study: top) sustained high load; middle) uniform high load; and bottom) sustained low load. All three waveforms have the same ramp rate.

The effect of waveform on the fatigue crack propagation behavior of viscoelastic materials such as polymers has been attributed both to a change in the ramp rate (or strain rate) and to a change in the contribution of creep to the overall crack growth rate (Hertzberg, 1980). When the effect of waveform is examined by comparing, for example, sinusoidal, square and triangular waveforms, the ramp rate is different in each case, as is the integrated time-under-load. In such cases, the effect of the ramp rate on the fatigue crack growth resistance cannot be isolated from the effect of creep.

In this study, the ramp rate was the same for all three waveforms. Therefore, it is hypothesized that the different fatigue crack propagation responses of UHMW polyethylene at the three waveforms were due to differences in the contribution of the creep component to the overall fatigue crack growth rate. In the case of the sustained high load waveform, the contribution of creep was increased due to the larger fraction of theload cycle during which the specimen experienced maximum load. This resulted in a decrease in the fatigue crack propagation resistance relative to the uniform high and low load waveform. Conversely, under a sustained low load waveform, the contribution of creep was decreased and, hence, the fatigue crack growth resistance was improved. A similar response to sustained high and sustained low load waveforms was found for poly(methyl methacrylate) (Hertzberg, 1980).

The convergence of the fatigue crack propagation behavior of the three waveforms at increased ΔK can be explained by considering the creep behavior of UHMW polyethylene as a function of applied stress. Crissman *et al.* performed uniaxial tensile creep tests at several stress levels on UHMW polyethylene (Crissman *et al.*, 1982). Creep strain was found to be a nonlinear function of stress at short time periods. However, at long time periods, the creep strain not only increased for each stress, but converged to a common value, independent of stress level. During fatigue crack propagation, the strain at the crack tip increases with increasing ΔK. It is hypothesized that the increase in creep strain at the crack tip with the increase in ΔK becomes independent of time-under-load, and therefore, the fatigue crack propagation data for UHMW polyethylene at the three waveforms should converge with increase in ΔK.

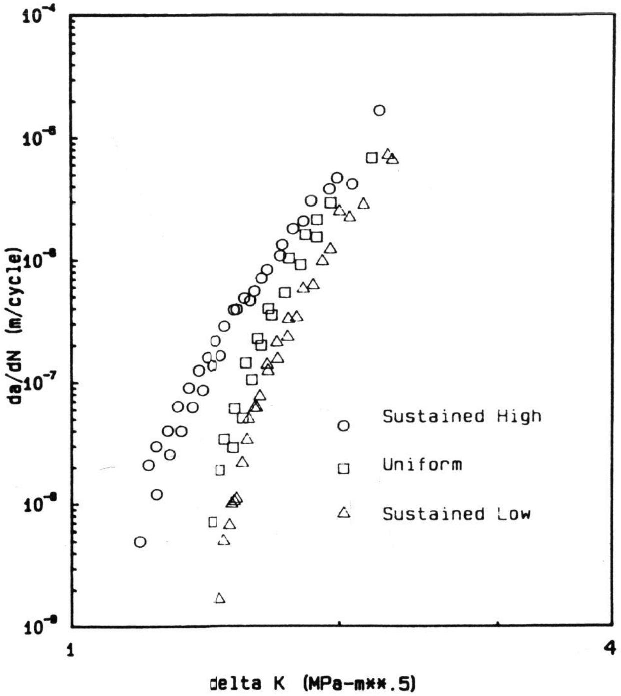

Fig. 2
Fatigue crack growth rate, da/dN, versus cyclic stress intensity, ΔK, for UHMW polyethylene tested using three different waveforms. Test frequency was 5Hz.

The fracture surfaces generated at all three waveforms exhibited a characteristic diamond-like pattern crisscrossing the fracture surface, as well as uniformly spaced lines perpendicular to the direction of crack growth, as shown in Fig. 3a and 3b for the sustained high load and sustained low load waveform specimens, respectively. These fracture surface features have been observed previously in both fatigue crack propagation and static fracture of this material (Connelly *et al.*, 1984, Weightman and Light, 1985 and Rimnac *et al.*, 1988). Due to its high molecular weight (typically exceeding two million), the UHMW polyethylene was able to orient extensively ahead of the crack tip. When the crack tip propagated or extended, the highly oriented and drawn UHMW polyethylene buckled on the fracture surface behind the crack tip. This buckling was most apparent on the edges of the diamonds.

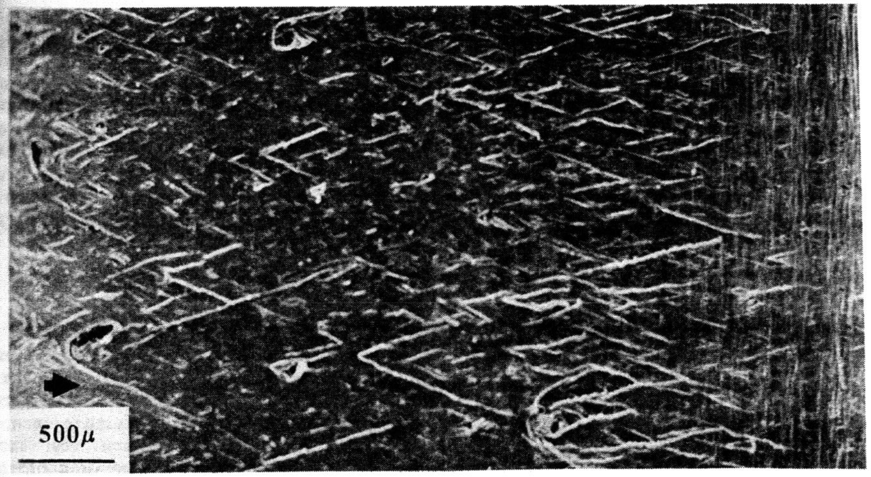

Fig. 3a
Fatigue fracture surface appearance of UHMW polyethylene tested under sustained high load waveform. Arrow indicates direction of crack growth.

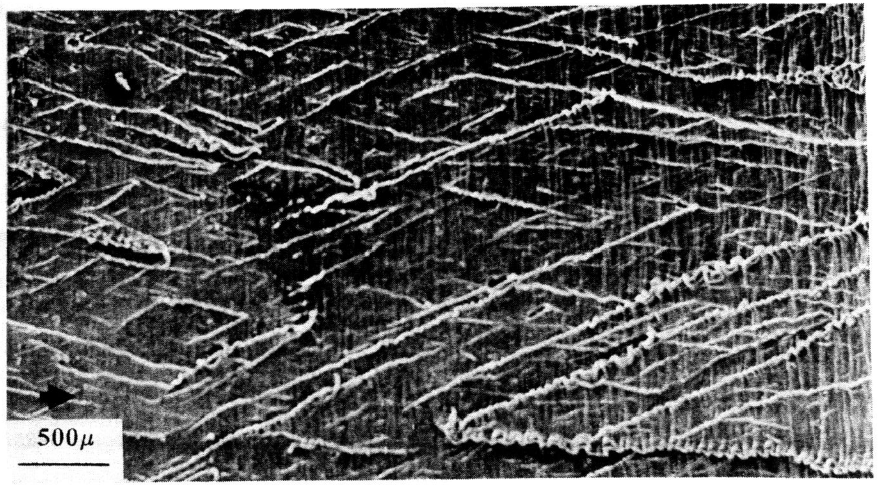

Fig. 3b
Fatigue fracture surface appearance of UHMW polyethylene tested under sustained low load waveform. Arrow indicates direction of crack growth.

The pronounced lines perpendicular to the direction of crack growth were *not* fatigue striations, as has been demonstrated previously (Connelly *et al.*, 1984) in that their spacing remained approximately constant at 5 to 6 microns independent of ΔK across the entire fatigue region of the fracture surface. In addition, these lines were also observed on fracture surfaces generated under static loading conditions (Rimnac *et al.*, 1988). Thus, it appears that physical structure dominates the fracture surface morphology of UHMW polyethylene, rather than the cyclic or static loading conditions.

However, it is interesting that a change in the cyclic waveform modified this characteristic fracture surface appearance of UHMW polyethylene. Specifically, the diamonds appeared to be shorter on the sustained low load specimen (Fig. 3a) compared with the sustained high load specimen (Fig. 3b). The increase in length of the diamonds under the sustained high load waveform may be a reflection of the greater contribution of creep strain at the crack tip due to the longer time under maximum load. The greater creep strain at the crack tip causes more of the UHMW polyethylene to orient ahead of the crack tip. Note that as the crack length (and, hence the cyclic stress intensity) increased for both the low load and the high load waveform, the difference in the length of the diamonds diminished (see the far right of Figs. 3a and 3b). This observation is consistent with the creep strain being independent of time-under-load at high ΔK.

CONCLUSIONS

Test waveform had a pronounced effect on the fatigue crack propagation behavior of UHMW polyethylene. In these tests, the ramp rate was constant for the waveforms examined. With increasing time under maximum load, the resistance to fatigue crack propagation decreased. At higher cyclic stress intensity levels, the difference in the fatigue crack propagation resistance between the three test waveforms resistance diminished. These results were interpreted with respect to the contribution of creep to the fatigue crack propagation behavior of UHMW polyethylene. The fracture surfaces generated at all three waveforms exhibited a characteristic diamond-like pattern crisscrossing the fracture surface, as well as uniformly spaced lines perpendicular to the direction of crack growth. These features are believed to be due to the ability of the UHMW polyethylene to orient extensively ahead of the propagating crack tip prior to fracture.

ACKNOWLEDGEMENTS

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