JOURNAL OF MATERIALS SCIENCE 17 (1982) 2463–2468

Fatigue crack propagation in polymethylmethacrylate bone cements

TIMOTHY M. WRIGHT
Department of Biomechanics, The Hospital for Special Surgery, affiliated with The New York Hospital and Cornell University Medical College, 535 East 70 Street, New York, New York 10021, USA

RAYMOND P. ROBINSON
The Mason Clinic, 1100 Ninth Avenue, Seattle, Washington 98111, USA

The fatigue crack propagation behaviour of a conventional polymethylmethacrylate (PMMA) bone "cement" was examined and compared with those of a low-viscosity PMMA cement and a carbon-fibre reinforced PMMA cement. The low-viscosity PMMA cement, developed for use in cement pressurization systems, did not differ significantly from conventional PMMA cement in its crack propagation behaviour. The carbon-fibre reinforced PMMA cement exhibited crack propagation rates which were approximately an order of magnitude less than those of conventional PMMA at the same range of stress intensity factor. Fractography of the test specimens revealed separation around pre-polymerized PMMA beads and void formation around barium sulphate particles. Examination of carbon reinforced PMMA specimens showed poor mechanical bonding between the carbon fibres and the PMMA with considerable fibre pull-out and evidence of fibre breakage.

1. Introduction

Failure within the polymethylmethacrylate (PMMA) grouting material, used to secure prosthetic components to the surrounding bones, has been recognized as a serious problem in total joint replacement surgery [1, 2]. Previous studies have, therefore, examined the mechanical properties of conventional PMMA bone "cements" and investigated methods for improving these properties [3–6]. Such studies have demonstrated that PMMA exhibits marginal tensile and fatigue strengths when compared to the stresses the material must endure as part of the bone–PMMA–prosthesis composite system [7, 8]. Because PMMA is exposed to cyclic loads *in situ*, the fatigue behaviour of this material deserves further attention.

The mechanism of fatigue failure includes crack initiation and subsequent crack propagation under cyclic loading. With numerous stress concentrations at both the jagged bone–PMMA interface and at voids and seams within the PMMA (resulting from mixing and *in situ* polymerization), crack initiation is easily accomplished. The fatigue behaviour, therefore, may be dominated by the crack propagation behaviour. In the present study, fatigue crack propagation in PMMA cements was examined.

2. Materials and methods

Compact tension specimens were moulded from a commercially available, conventional PMMA bone cement. Specimens were also moulded from a commercially available, low-viscosity PMMA cement and from a carbon-fibre reinforced PMMA cement, which was in a development phase. The low-viscosity PMMA cement contained a more uniform prepolymerized bead size and was developed to provide a lower viscosity while maintaining the same curing time as the conventional cement. The low-viscosity PMMA cement is used in cement guns, which provide pressure injection of cement into the bone cavity. The

0022–2461/82/092463–06$03.22/0

carbon-fibre reinforced PMMA cement was a 2 vol% mixture of carbon-fibres (of average length, 1.5 mm) with conventional PMMA.

All three materials were provided by the same manufacturer (Zimmer USA Inc., Warsaw, Indiana, USA) in the standard form of prepolymerized powder packets and ampoules of liquid monomer. The cements were mixed in the same manner as is employed in the operating room. All mixing was carried out at room temperature with the relative humidity between 50 and 55%. Specimen dimensions conformed to ASTM Standard E647 [9] with a thickness of 10 mm and a depth of 35.6 mm.

Each specimen was instrumented with metal foil gauges (Krak gauge, model KG-A10) used to monitor crack length. Initial specimens were instrumented on both sides to provide measurements at both ends of the crack-front. Subsequent specimens were instrumented on only one side. Signal conditioning of the gauges were performed by a Fractomat, model 1078 (from Hartrun Corp., Chaska, MN, USA), which was calibrated to provide crack-length output in millimeters. Measurement error is stated by the manufacturer to be less than 2%.

Pre-cracking and testing was performed on an MTS* servohydraulic system with a sinusoidal waveform at a frequency of 5 cycles sec^{-1}. Maximum cyclic load was 156 N with a minimum load/maximum load ratio, R, value of 0.06. All testing was performed in laboratory air at room temperature. Crack length against number of cycles was recorded continuously on a chart recorder.

Values of crack-length and cycles were digitized from the chart paper. Crack-length, specimen dimensions, and the applied cyclic load were used to calculate the stress intensity factor range, ΔK, from the expression given in the ASTM Standard. The crack-length, a, against number of cycles, N, data were fitted with a seven-point incremental polynomial [9] to determine the crack propagation velocity, da/dN.

After testing, fracture surfaces were coated and examined in a scanning electron microscope.

3. Results

3.1. Fatigue-crack propagation behaviour

Fatigue-crack propagation in all specimens was within the guidelines of the ASTM Standard with respect to crack-front curvature and deviation of the crack direction from the specimen centre-line. Data were taken only in the range of crack lengths appropriate for the given specimen dimensions [9]. The radius of the plastic zone was calculated to be 0.103 mm at the maximum K for which data was collected [10]. This satisfies the basic requirement that the radius be small compared to the specimen thickness and crack length.

The measured fatigue-crack propagation behaviour for the three materials is shown in Fig. 1. The data conform to the power-law relationship

$$da/dN = C\Delta K^m, \qquad (1)$$

where C and m are constants, first proposed by Paris [11] and found to be common to many materials, including a wide range of polymers [12]. The values of the slope, m, were 6.5 for conventional PMMA cement, 6.5 for low-viscosity PMMA cement, and 7.4 for carbon-fibre reinforced PMMA cement. No statistically significant difference ($P > 0.05$) was found between the results for conventional and low-viscosity PMMA cements. Carbon-fibre reinforcement, however, caused a significant decrease (about an order of magnitude) in crack propagation velocity when compared to conventional PMMA cement at the same ΔK level.

3.2. Fractography

Low-magnification examination of fracture surfaces from conventional and low-viscosity PMMA specimens revealed flat topographies with significant porosity (Fig. 2). At higher magnifications, damage secondary to the propagating crack could be seen in regions through which the crack propagation velocity was slow (of the order of 10^{-8} to 10^{-7} m $cycle^{-1}$). This damage took the form of separation between the prepolymerized beads and the surrounding material and void formation around the barium sulphate particles, added to the cements to render them radio-opaque (see Fig. 3a). In regions through which the crack propagation velocity was more rapid (approaching 10^{-5} m $cycle^{-1}$), this damage was not apparent (see Fig. 3b).

Low-magnification examination of carbon-fibre reinforced PMMA specimen surfaces showed a similar flat topography with a somewhat higher amount of porosity (see Fig. 4). At higher magnifications, the carbon-fibres were evident throughout the surface. The fibres did not appear adherent to

*Material test system.

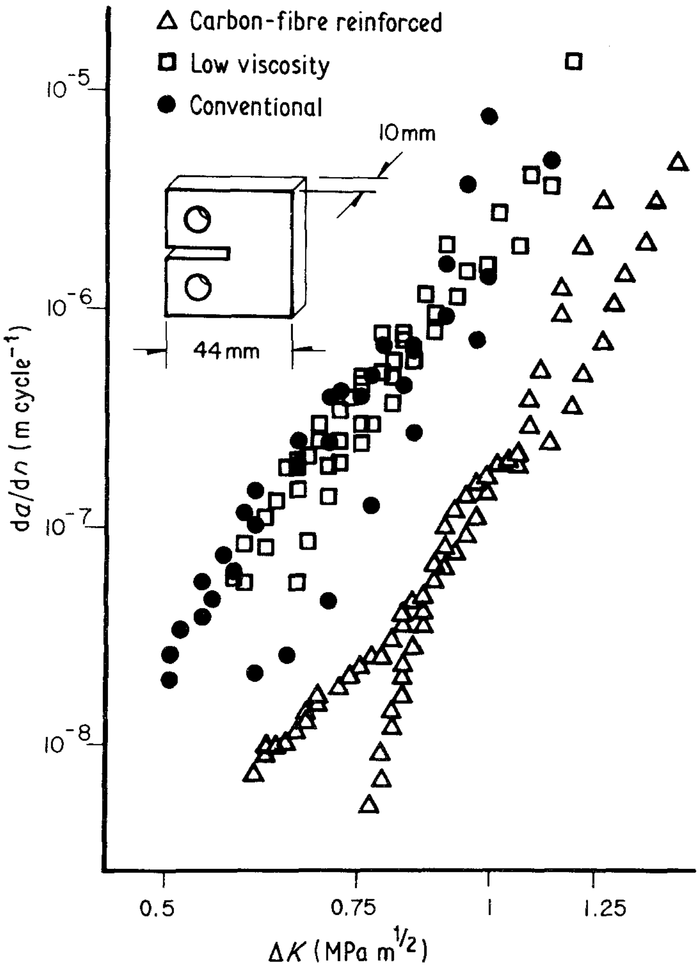

Figure 1 Fatigue crack growth rate, da/dN, plotted against the stress intensity factor range, ΔK, for the three types of PMMA bone cement. Inset shows the specimen configuration used.

the PMMA (see Fig. 5). Evidence of fibre breakage could occasionally be seen.

Fatigue striations were present on all the fracture surfaces examined (see Fig. 6). They did not appear uniformly over the surface, however, and no attempt was made to determine the striation spacing for correlation with the measured crack propagation velocities.

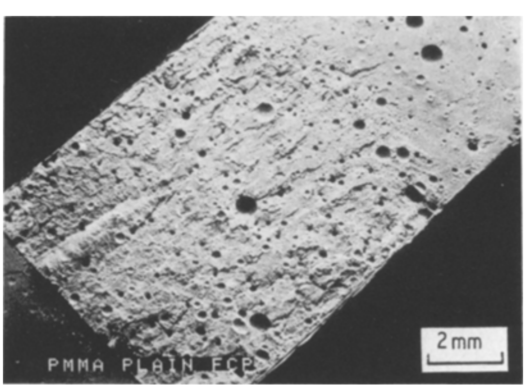

Figure 2 Fracture surface of conventional PMMA bone cement. The starter notch is visible at the bottom left of the figure.

4. Discussion

The application of linear elastic fracture mechanics to PMMA bone cement is a justifiable approach, based on the realization that the material is used in an application in which it contains numerous inherent flaws. Previous investigators have applied fracture mechanics to bone cement to examine the static fracture properties [13] and stable crack growth [14]. More recently, Robinson *et al.* [4] measured the effect of carbon-fibre reinforcement on the fracture toughness of PMMA cement, reporting a 32% increase with fibre additions of 2 vol%.

In the present study, fracture mechanics has been applied to the fatigue behaviour of PMMA cement. The results of the study show a significant increase in the crack propagation resistance with

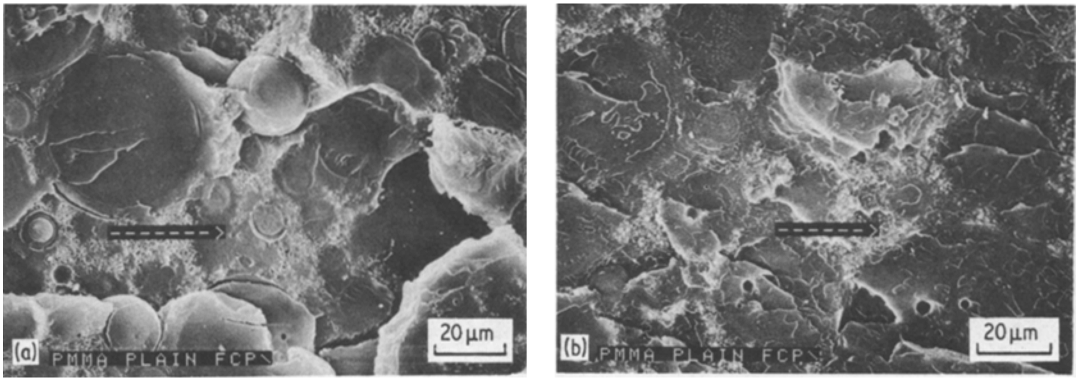

Figure 3 Fracture surfaces of conventional PMMA bone cement in regions of (a) slow and (b) rapid crack-growth rates. The arrows point in the direction of crack propagation.

carbon-fibre additions, similar to the results of Robinson *et al.* [4] for fracture toughness. Furthermore, no significant difference in crack propagation behaviour was found between conventional PMMA and low-viscosity PMMA. This last finding is surprising only in that Robinson *et al.* [4] found low-viscosity PMMA to have a significantly lower fracture toughness than conventional PMMA. The difference in results between the two studies may be due to batch-to-batch variations in the low-viscosity PMMA cements studied.

Pilliar *et al.* [3] performed standard uniaxial fatigue tests comparing conventional PMMA cement and a carbon-fibre reinforced PMMA cement similar to the one used in this study. They found that the fatigue data from both cements could be normalized by plotting the results as applied strain (rather than applied stress) against number of cycles. This lead them to conclude that the fatigue life was strain controlled. A similar approach can be applied to fatigue crack propagation data by normalization of ΔK with respect to the elastic modulus, E, to give a factor, $\Delta K/E$, which should be proportional to the crack-tip strain. This procedure has been used to demonstrate the similarity in fatigue crack propagation behaviour among many metals [15]. However, its application to polymers has been less successful, primarily because of the uncertainty as to the proper choice of elastic modulus [12]. Still, based on the results of Pilliar *et al.* [3], it was tempting to normalize the data from the present study in this manner. Data was normalized using cyclic moduli values for carbon-reinforced and conventional PMMA cements from the literature [16]. The result is shown in Fig. 7. Comparison of the linear regressions through the two sets of normalized data was consistent with the hypothesis that the regressions were, in fact, identical ($P > 0.05$) and supports the previous finding of Pilliar *et al.* [3], at least for the crack propagation phase of the fatigue life.

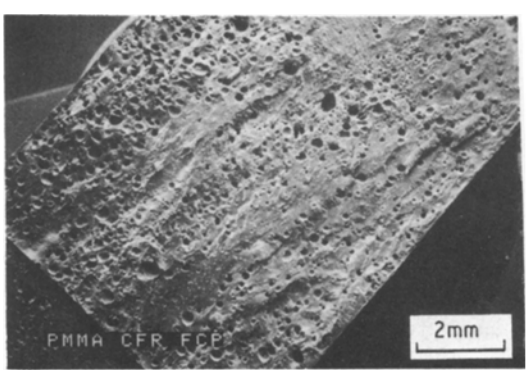

Figure 4 Fracture surface of carbon-fibre reinforced PMMA bone cement. The starter notch is visible at the bottom left of the figure.

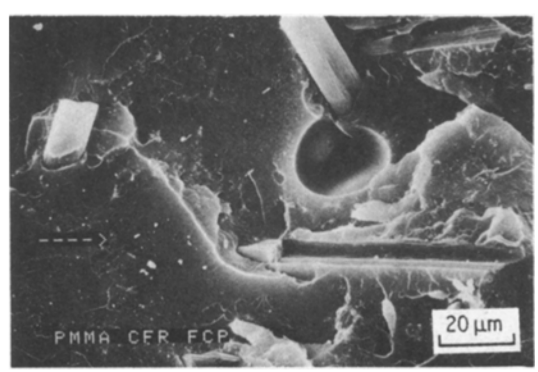

Figure 5 Fracture surface of carbon-fibre reinforced PMMA bone cement. The arrow points in the direction of crack propagation.

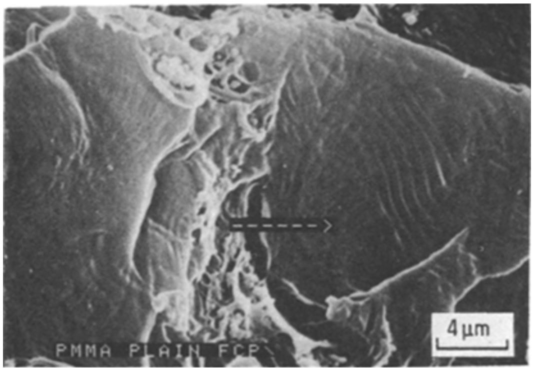

Figure 6 Fracture surface of conventional PMMA bone cement. The arrow points in the direction of crack propagation.

Fractographic examination of the fatigue surfaces of the specimens in this study revealed features consistent with those seen by other investigators. The separation at the interfaces between prepolymerized beads and the surrounding material and the formation of voids around barium sulphate particles were also noted by Beaumont [14] and by Beaumont and Young [17] in investigations of slow, controlled crack growth through PMMA bone cement under static loading.

The lack of bonding between the carbon-fibres and the surrounding PMMA seen in the reinforced specimen surfaces (and leading to fibre pull-out) was also described by Pilliar *et al.* [3] from their fatigue test specimens and by Robinson *et al.* [4] from their fracture toughness specimens. Evidence of fibre breakage seen in this study, however, does not appear to have been noted in other investigations. Such evidence is important in that fibre breakage absorbs more energy than fibre pull-out.

Striations have been noted on fatigue fracture surfaces from the more common form of PMMA, cast or extruded under pressure. The striations, like those seen on metal surfaces, are thought to be due to crack blunting during the loading portion of the cycle and resharpening during the subsequent unloading portion [18]. In the present study, fatigue striations occurred in localized regions on the fracture surface. No attempt was made to correlate spacing in these small regions with the measured crack velocity, however, and it cannot be concluded that these striations correspond directly to each cyclic advance of the crack front.

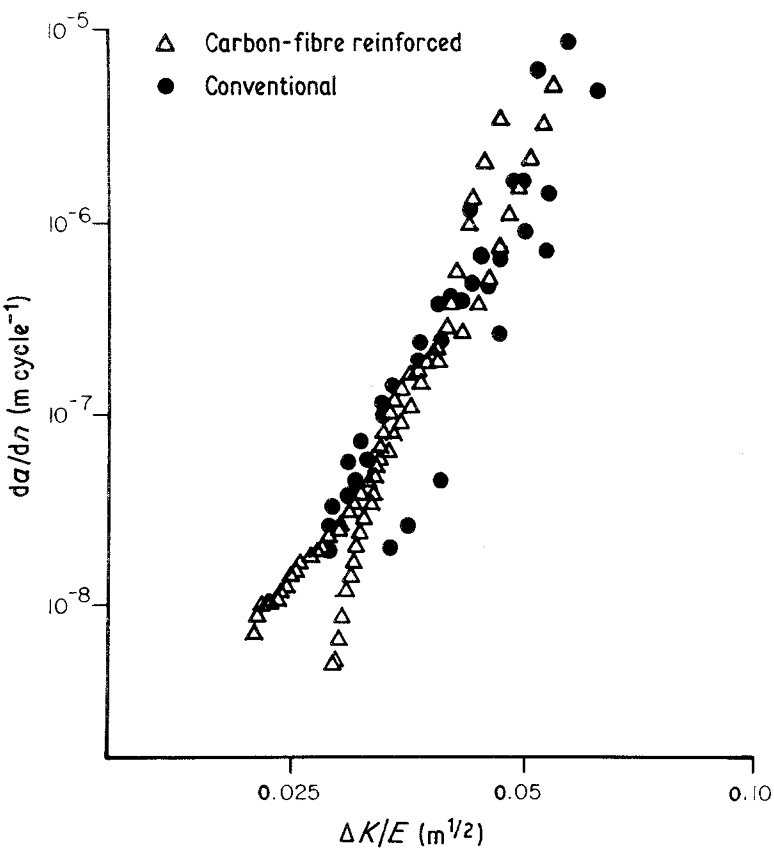

Figure 7 Fatigue crack growth rate, da/dN, plotted against the stress intensity factor range, ΔK, normalized with respect to elastic modulus, E. The moduli used were the cyclic moduli measured in uniaxial tension by Pilliar *et al.* [16] (2650 MN m^{-2} for conventional PMMA bone cement and 4000 MN m^{-2} for carbon-fibre reinforced PMMA bone cement).

Acknowledgements
This work was supported by a grant from the Clark Foundation. The authors thank Zimmer USA Inc. for supplying the materials used in this study and acknowledge the effort of Diane Warner and William Flynn in assisting with the testing and data reduction.

References
1. F. WEBER and J. CHARNLEY, *J. Bone Jt Surg.* **57B** (1975) 297.
2. R. BECKENBAUGH and D. ILSTRUP, *ibid.* **60A** (1978) 306.
3. R. PILLIAR, R. BLACKWELL, I. MACNAB and H. U. CAMERON, *J. Biomed. Mater. Res.* **10** (1976) 893.
4. R. ROBINSON, T. WRIGHT and A. BURSTEIN, *ibid.* **15** (1981) 203.
5. A. CRUGNOLA, E. ELLIS, R. ROSE and E. RADIN, Proceedings of the 39th SPE/AMTEC Conference, Boston, May (1981) (Society of Plastic Engineering, Brookfield Center, Connecticut, 1981) p. 253.
6. J. TAITSMAN and S. SAHA, *J. Bone Jt Surg.* **59A** (1977) 419.
7. R. CROWINSHIELD, R. BRAND, R. JOHNSTON and J. MILROY, *ibid.* **62A** (1980) 68.
8. R. TARR, J. LEWIS, F. GHASSEMI, A. SARMIENTO, I. CLARKE and V. WEINGARTEN, "Finite Elements in Biomechanics" Vol. 2 (University of Arizona Press, Arizona, USA, 1980) p. 511.
9. "Annual Book of ASTM Standards" Part 10, ASTM STD E647-81 (American Society for Testing and Materials, Philadelphia, 1981) p. 765.
10. F. McCLINTOCK and G. IRWIN, "Fracture Toughness Testing and Its Application" ASTM STP 381 (American Society for Testing and Materials, Philadelphia, 1965) p. 84.
11. P. PARIS, Proceedings of the 10th Sagamore Army Materials Research Conference (Syracuse University Press, Syracuse, New York, 1964) p. 107.
12. R. HERTZBERG and J. MANSON, "Fatigue of Engineering Plastics" (Academic Press, New York and London, 1980) p. 74.
13. T. FREITAG and S. CANNON, *J. Biomed. Mater. Res.* **10** (1976) 805.
14. P. BEAUMONT, *J. Mater. Sci.* **12** (1977) 1845.
15. S. PEARSON, *Nature* **211** (1966) 1077.
16. R. PILLIAR, W. BRATINA and R. BLACKWELL, "Fatigue of Filamentary Composite Materials" ASTM STP 636 (American Society for Testing and Materials, Philadelphia, 1977) p. 206.
17. P. BEAUMONT and R. J. YOUNG, *J. Biomed. Mater. Res.* 9 (1975) 423.
18. C. FELTNER, *J. Appl. Phys.* **38** (1967) 3576.

Received 1 December and accepted 15 December 1981