JOURNAL OF MATERIALS SCIENCE: MATERIALS IN MEDICINE 10 (1999) 779–781

Measurement of non-linear microcrack accumulation rates in polymethylmethacrylate bone cement under cyclic loading

B. P. MURPHY, P. J. PRENDERGAST*
Bioengineering Group, Department of Mechanical Engineering, Trinity College, Dublin 2, Ireland
E-mail: pprender@tcd.ie

Damage accumulation in the cement mantle used to fixate bone prosthesis is one failure scenario for joint reconstruction. It can be described as the phenomenon of numerous microcracks initiating and propagating within the material. Microcracks grow in the cement mantle causing it to gradually lose its mechanical integrity, leading to loosening of the prosthesis. In this study microcracking within acrylic bone cement was quantified over the course of a fatigue test. Identification of new cracks and the growth of pre-existing cracks was monitored at intervals during fatigue testing of five specimens at a mean cyclic stress of 7.5 MPa. Given these measurements, an average damage evolution curve was derived for acrylic bone cement. It was observed that the initiation sites for microcracks were the pore perimeters; therefore, the number of microcracks present in a sample is dependent on porosity. Variability was found within the results and the majority of the variability was accounted for by the difference in the porosity of each sample. Results have identified non-linear damage evolution. On a simplified level a power law equation can be used to describe the damage evolution process.

1. Introduction

Damage accumulation is a process whereby numerous microcracks continuously initiate and propagate within a structure [1]. The structure of interest in this study is the cement mantle surrounding a prosthesis. As microcracks grow in the cement mantle it begins to lose its mechanical integrity. Degradation of the cement mantle occurs, leading to loosening of the prostheses, by the so called ''damage accumulation failure scenario'' [2].

Jasty *et al.* [3] studied retrieved femora at post-mortem from patients who had had a satisfactory hip replacement; a fractographic analysis shows fatigue crack features within the cement mantle showing that the cement had undergone fatigue failure under normal use. Further evidence of damage accumulation and cracks initiated under dynamic loading in retrieved cement mantles can be observed in Culleton *et al.* [4] and Topoleski *et al.* [5]. Previous experimental models [6] focused on bending and torsional models involving interfacial damage and damage within the cement mantle. McCormack and Prendergast [7] confirmed that damage accumulation commences early on in the life of a cement mantle and continues for the duration of loading. The results found that the majority of cracks initiated from pores within the bulk cement mantle rather than at the interfaces. This failure scenario has been confirmed in computer simulation studies of total hip replacements by Verdonschot and Huiskes [8] where a linear rate of damage accumulation was used.

This study focuses on the measurement of microcracking within the bulk cement mantle caused by tensional loading. From these results an empirical law to describe the non-linear nature of damage accumulation in acrylic bone cement can be derived.

2. Materials and methods

The cement used in this study was Cemex^{TM} (Tecres, Verona, Italy) translucent, high-viscosity bone cement. The cement was vacuum mixed with the OPTIVAC^{TM} cartridge system (Scandimed A.B., Sjobo, Sweden). The cement was mixed according to the manufacturer's instructions.

Tapered specimens of polymethylmethacrylate (PMMA) bone cement (see Fig. 1) were produced from a flat polyethylene mold. The mold consisted of two aluminum external plates, two polyethylene internal plates, and one polyethylene central plate with the profile of the specimen machined from it. The mold was sealed using eight bolts. Pressure relief holes allowed excess cement to escape. The design of the specimen incorporated three zones of equal area (256 mm^2), each with a different applied mean stress. Damage could be

*Author to whom correspondence should be addressed.

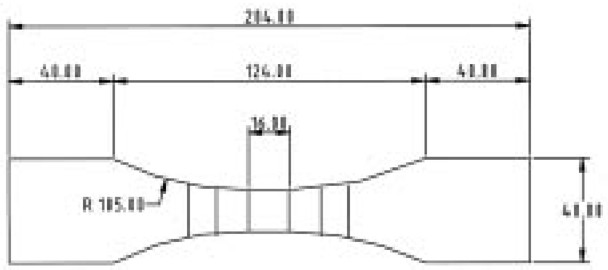

Figure 1 Specimen dimensions.

observed in these different sections over the course of a fatigue test to observe the effect of stress on damage accumulation. This design allows the effect of inter specimen variability on the damage accumulation process to be studied.

Immediately after removal from the mold, alignment holes were drilled in the specimens to ensure the specimen could be aligned in pure tension in the materials testing machine. Rough edges were removed by a light sanding. The specimens were stored in a water bath at 37 °C for a minimum of 2 weeks prior to testing. This allowed a specific moisture concentration of more than 95% to be achieved [9].

McCormack and Prendergast [7] have previously described a method used for monitoring damage accumulation. The method involves dying the specimen to label any pre-existing pores or cracks. The specimen is cycled to a certain fraction of its fatigue life. Interruption of the fatigue test allows new cracks to be observed and crack growth rates can be recorded. This procedure was repeated until fracture of the specimen.

Testing was performed in a rig consisting of four main parts (see Fig. 2): an aluminum base, a Perspex tube, a set of stainless steel grips and a polyethylene vented tap. The tube is sealed around the base by means of double o-rings and silicone sealant. All fatigue testing was performed on an Instron servohydraulic testing machine (Model 8501). Fatigue tests were performed in pure tension at an R-ratio of zero under load control. Testing was performed in a water bath maintained at 37 °C for the duration of a test. Pins were placed through the alignment holes in the specimen and a tensile load of 100 N was applied to ensure that the specimen was aligned in the direction of the load. The frequency of testing was 5 Hz. No thermal softening is reported at this testing frequency [10]. Five specimens were tested.

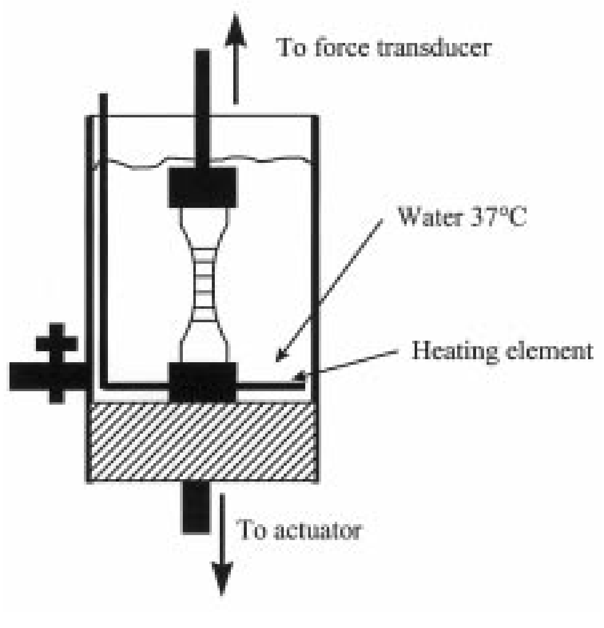

Figure 2 Schematic of the experimental configuration.

3. Results

A non-linear damage evolution process is found, with a significant inter-specimen variability. To account for this variability, normalization of the damage and number of cycles at a point in time is performed. As a first approach, a power law equation can be used to model the damage evolution process within the cement. The form of the equation is as follows: $\omega = (N/N_f)^{\alpha(\sigma)}$ where ω is a non-dimensional measure of damage defined as; sum of crack lengths/sum of crack lengths at failure

$$\text{i.e. } \omega = \left(\sum_{i=1}^{n_c} a_i\right) \Big/ \left(\sum_{i=1}^{n_c^f} a_i\right)$$

where a = crack length, N is the number of cycles at any time, N_f is the number of cycles to failure, n_c is the number of cracks present at any time during the fatigue test, n_c^f is the number of cracks present at failure, and α is a stress-dependent constant. Using this definition of damage, damage growth curves for all five specimens as shown in Fig. 3 can be drawn. These results correspond to the central region of the five specimens, which is subjected to a stress of 7.5 MPa.

To predict the most likely damage evolution law, a suitable probability distribution to model damage evolution must be chosen. From this distribution, the most suitable parameter can be chosen as the stress dependent constant in the damage evolution equation. A two-parameter Weibull probability distribution for α was chosen. The damage evolution curve and equation for acrylic bone cement subjected to a mean cyclic stress of 7.5 MPa is shown in Fig. 4.

4. Discussion and conclusion

As the tests were performed under pure tension it can be stated that tensile loads initiate damage accumulation

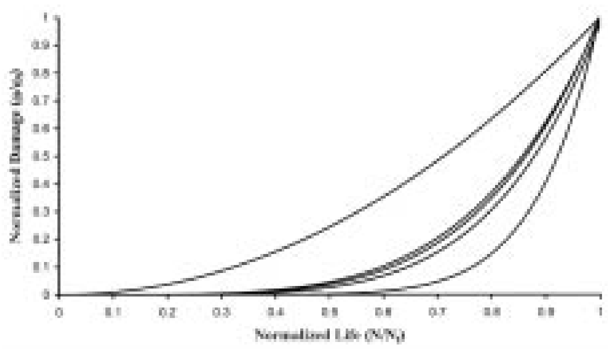

Figure 3 Damage evolution measured in five specimens subjected to 7.5 MPa. The different curves show the variability in damage accumulation.

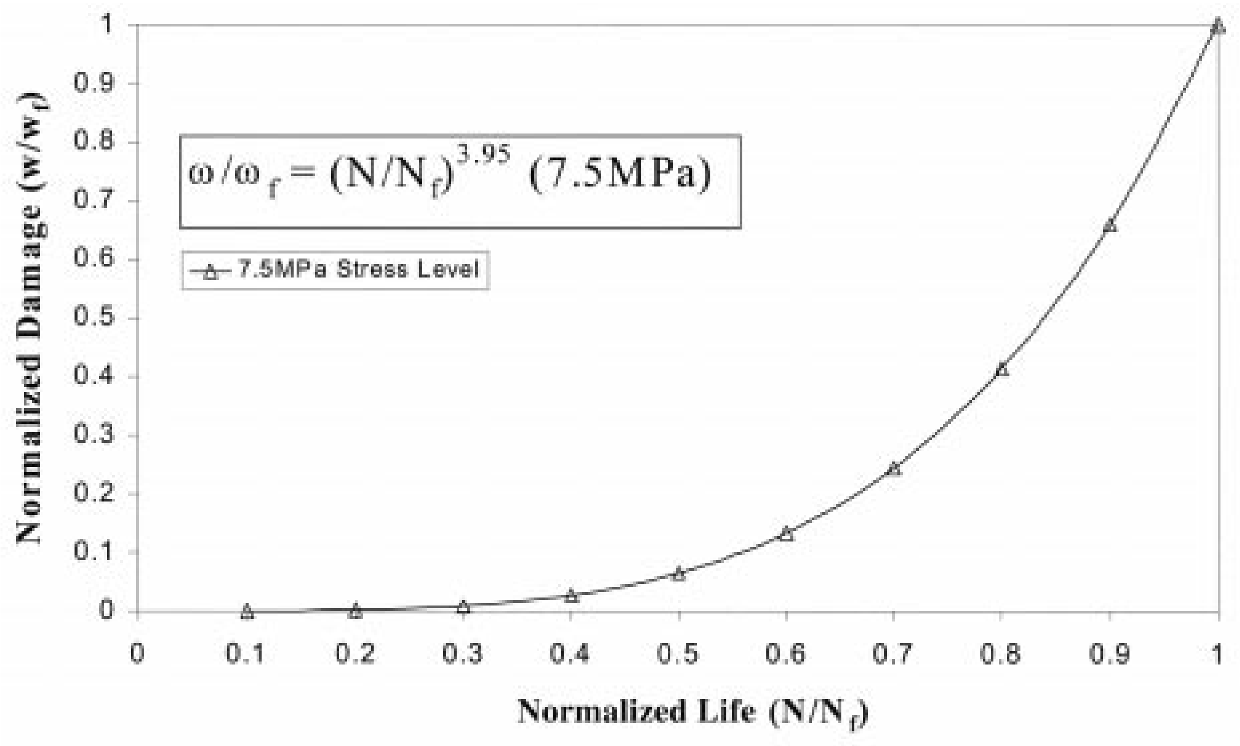

Figure 4 Damage evolution in acrylic bone cement at 7.5 MPa.

within acrylic bone cement. The cracks that were observed in the study were surface cracks, the assumption that cracks grow into the depth of the specimen is reasonable as cracks observed near the edges of the specimen could be seen to grow into the depth of the specimen. Observed cracks in the cement can vary in length from 40 μm to 2 mm (see Fig. 5). The cracks observed in this study replicate microcracks observed in a study on post-mortem-retrieved cement mantles [3].

An empirical equation to describe non-linear damage evolution in PMMA bone cement used in orthopaedic surgery has been produced. Using a Weibull probability distribution, the most likely damage evolution law was generated for a particular stress level. Taking the above factors into account, the equation is in a suitable form for use in iterative finite element analysis, of the sort proposed by Verdonschot and Huiskes [8] for preclinical testing of orthopaedic implants.

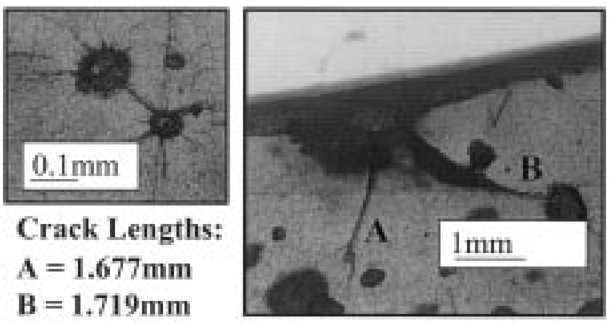

Figure 5 Microcracks in translucent acrylic bone cement observed under a light microscope.

Acknowledgments

Thanks are due to Tecres, Verona, Italy for the donation of bone cement, Mitab for the donation of vacuum mixing cartridges and the Standards Measurements and Testing Program of the European Commission, contract no. SMT-CT96-2076

References

1. J. LEMAITRE and J.-L. CHABOCHE in "Mechanics of solid materials" (Cambridge University Press, Cambridge, 1990).
2. R. HUISKES, *Acta Orthop. Scand.* **64** (1993) 699.
3. M. JASTY, W. J. MALONEY, C. R. BRAGDON, D. O. O'CONNOR, T. HAIRE and W. H. HARRIS, *J. Bone Joint Surg. [Br]* **73-B** (1991) 551.
4. T. P. CULLETON, P. J. PRENDERGAST and D. TAYLOR, *Clin. Mater.* **12** (1993) 95.
5. L. D. T. TOPOLESKI, P. DUCHEYNE and J. M. CUCKLER, *J. Biomed. Mater. Res.* **24** (1990) 135.
6. B. A. O. MCCORMACK, P. J. PRENDERGAST and B. O'DWYER, *Fatigue Frac. Eng. Mater. Struct.* **22** (1999) 33.
7. B. A. O. MCCORMACK and P. J. PRENDERGAST, *J. Biomech.* **32** (1999) 467.
8. N. VERDONSCHOT and R. HUISKES, *ibid.* **30** (1997) 795.
9. U. SOLTÉSZ, *J. Mater. Sci.* **5** (1994) 654.
10. P. K. HUMPHREYS, J. F. ORR and A. S. BAHRANI, *Proc. Inst. Mech. Eng. Part H* **203** (1989) 167.

Received 10 May
and accepted 17 May 1999