Available online at www.sciencedirect.com

ScienceDirect

NDT&E International 40 (2007) 378–389

NDT&E international

www.elsevier.com/locate/ndteint

Experimental–computational solution to fatigue induced microcrack source localization in cemented hip arthroplasty models

Gang Qi[a,b,*], Jihui Li[b]

[a]Medical Acoustic Research Laboratory, Department of Mechanical Engineering, The University of Memphis, TN 38152, USA
[b]Department of Biomedical Engineering, Joint program of The University of Memphis and University of Tennessee Health Science Center, Memphis, TN 38152, USA

Received 5 October 2006; received in revised form 20 December 2006; accepted 10 January 2007
Available online 30 January 2007

Abstract

The present work examined the effects of signal velocity models, system equation damping, number of sensors, and system singularity on experimental–computational solutions to locate fatigue-induced microcracks in cemented total hip arthroplasty (THA). The following results were found. (1) Variable velocity model is a better approach for localizing microcracks in THA constructs. (2) The optimal range of system damping is between 0.001 and 0.002. (3) The rounding error of the final solution can be limited to the level of 10^{-2} when the numerical precision is taken to six decimal places for each element in the system matrix. In addition, proper use of system damping can reduce system singularity.

Keywords: Microcrack source localization; Cemented total hip arthroplasty; Femur fixation; Acoustic emission

1. Introduction

Localization and characterization of crack sources have long been the interests of evaluating the performance of engineering materials. In the literature, early works reported crack source localization and material behavioral characterization of aluminum [1–4], concrete [5–7], and glass fiber composite materials [8] using acoustic emission (AE) techniques. The common themes of these early works are as follows. (1) The materials under investigation were isotropic. (2) Most of these works involved simple structures. (3) The test objects were subject to relatively high stress levels to failure. (4) Fatigue tests were accomplished within relatively small cycle numbers at low sampling frequencies, which allowed extensive signal waveform analysis to take place. Although these works established a profound and solid foundation for crack source localization techniques, little work has been done on engineering structures involving one or more of the following characteristics: (a) anisotropic materials, (b) structure with multiple layers of materials; (c) low stress level; and (d) extensively long fatigue loading period.

When localizing crack sources, four unknowns are to be determined: three spatial coordinates (x, y, z) and the initiation time t. In spite of various crack localization algorithms [9,10], signal travel velocity (determined by material property and signal waveform modes) is the key parameter used in the computation. When encountering structures with multiple material layers and or materials with anisotropic properties, the selection of signal velocity is not a simple task due to unpredictable signal wave travel path and or multiple wave reflections and refractions. Making things worse, the difficulties are entangled with the signals of interests from 100 kHz to over 1 MHz frequency range as to insufficient time for precise waveform analysis taking place. Additionally, when the materials are subject to low stress levels, i.e. 5–10% of its strength, a single microcrack is unlikely to endanger significantly the structure in early fatigue stage.[1] Especially, the difficulties

---

*Corresponding author. Tel.: +1 901 678 3437; fax: +1 901 678 5459.
E-mail address: gangqi@memphis.edu (G. Qi).

[1] Accumulation of microcracks and especially crack debris have been proved to be a significant source to simulate macrophage formation, which is the leading reason to cause aseptic loosening of THA.[11,12].

0963-8695/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.ndteint.2007.01.001

involved in evaluating fatigue performance of THA as follows. (a) "One size" of constant signal velocity model does not fit "all". (b) The equation system is largely ill conditioned due to the experimental–computational nature of the problems involved. (c) The system equation is often divergent or slowly convergent.

To address these difficulties, the authors developed an AE-based methodology [13–18]. This method can automatically tally the number, visualize the distribution, and animate the progression of microcrack formation in cemented total hip arthroplasty (THA) via a variable velocity model. The present work is to explore the effects of velocity models, system damping, sensor numbers, and singularity of system equations on microcrack source localization solution as well as their cross-correlations. In this work, two special specimens with known defects were used. According to the data from these two specimens, the trends of computed results with respect to the suspected real solutions were observed. The effects of the mentioned factors on microcrack source localization as well as their correlations were examined.

2. Materials and methods

We prepared a set of standard cemented femoral stem model constructs. The stems were those from two commercially available designs (Spectron®, Smith & Nephew, Memphis, TN, and Precoat®, Zimmer, Warsaw, IN). The bone cement was Palacos® R (donated by Smith & Nephew, Inc.). These stems were cemented into synthetic femurs (Sawbones®; Pacific Research Laboratory, Vashon, WA). Through the post preparation X-ray examinations, two of these model constructs (herein, designated as S1 and S2) had defects in the cement mantles. The defect in S1 was in the proximal region, with dimensions of 6.5 mm in the anterior–posterior (AP) direction, 2.5 mm in the medial–lateral (ML) direction, and 14.0 mm in the distal–proximal (DP) direction (Fig. 1). The defect in S2 was in the distal region, with dimension of 6.0, 2.2, and 35.0 mm in AP, ML, and DP directions, respectively (Fig. 2).

The AE instrument was an AMSY-5 8-channel system (Vallen-Systeme GmbH, Munich, Germany).

The specimens, S1 and S2, were hinge–hinge mounted onto a universal materials testing machine (MTS, Inc., Minneapolis, MN) as shown in Fig. 3. They were subjected to an axial compressive cyclical load, 267–2670 N, at 2 Hz, for over 2 million cycles (5 and 2.5 million for S1and S2, respectively). Eight piezoelectric sensors (Nano 30; Physical Acoustic Inc., Princeton, NJ) were adhesively bonded to the surface of the specimen to monitor the microcrack activities.

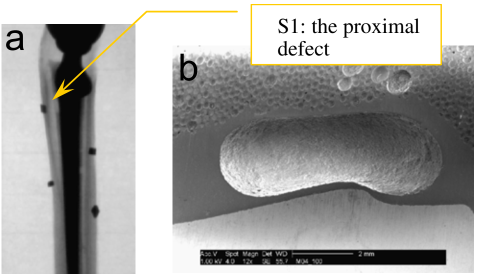

Fig. 1. (a) Specimen, S1, with a proximal defect. (b) Defect section view.

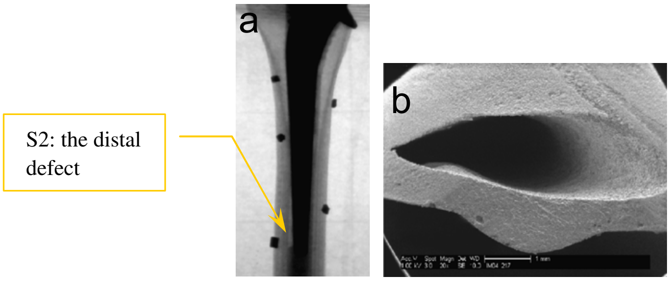

Fig. 2. (a) Specimen, S2, with a distal defect. (b) Defect section view.

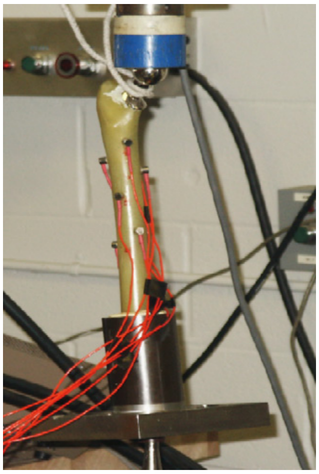

Fig. 3. Test setup and sensor installation. The sawbone specimen was hinge–hinge on both ends of the specimen. Eight AE sensors were installed to the surface of the specimen. The origin of coordinate system that was used to determine the sensor locations was at the top plane center of the metal fixture.

At the end of the fatigue tests, both S1 and S2 were sectioned using a low speed diamond saw at multiple height along the DP direction according to the indication of computed microcrack distribution, at least one section was cut through the defect areas. These sections were then examined using an environmental scanning electronic microscope (ESEM, Model XL30; Philips, Achtsewed, The Netherlands) operated at an accelerating voltage of 1 kV.

The Geiger's iterative method is the main algorithm utilized in this work to localize microcrack sources. The four unknowns, as specified previously, are the source location, $S(x_s, y_s, z_s)$, and the origin time of a crack, t_s. The relationship between these unknowns and locations of sensor are as follows. The distance between a microcrack and the sensor j is [13–15]

$$L_j = \sqrt{(X_j - x_s)^2 + (Y_j - y_s)^2 + (Z_j - z_s)^2} = v_j \times \tau_j, \tag{1}$$