Journal of Biomechanics 41 (2008) 2605–2611

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Measurement of transient and residual stresses during polymerization of bone cement for cemented hip implants

N. Nuño *, A. Madrala, D. Plamondon

École de technologie supérieure, Laboratoire de recherche en imagerie et orthopédie, Département de génie de la production automatisée, Université du Québec, 1100 rue Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

ARTICLE INFO

Article history:
Accepted 19 June 2008

Keywords:
Bone cement
PMMA
Residual stresses
Temperature
Polymerization
Hip prosthesis
Experiments

ABSTRACT

The initial fixation of a cemented hip implant relies on the strength of the interface between the stem, bone cement and adjacent bone. Bone cement is used as grouting material to fix the prosthesis to the bone. The curing process of bone cement is an exothermic reaction where bone cement undergoes volumetric changes that will generate transient stresses resulting in residual stresses once polymerization is completed. However, the precise magnitude of these stresses is still not well documented in the literature. The objective of this study is to develop an experiment for the direct measurement of the transient and residual radial stresses at the stem–cement interface generated during cement polymerization. The idealized femoral-cemented implant consists of a stem placed inside a hollow cylindrical bone filled with bone cement. A sub-miniature load cell is inserted inside the stem to make a direct measurement of the radial compressive forces at the stem–cement interface, which are then converted to radial stresses. A thermocouple measures the temperature evolution during the polymerization process. The results show the evolution of stress generation corresponding to volumetric changes in the cement. The effect of initial temperature of the stem and bone as well as the cement–bone interface condition (adhesion or no adhesion) on residual radial stresses is investigated. A maximum peak temperature of 70 °C corresponds to a peak in transient stress during cement curing. Maximum radial residual stresses of 0.6 MPa in compression are measured for the preheated stem.

1. Introduction

Aseptic loosening of cemented hip implants remains the major cause of late failure, leading to the revision of primary total hip arthroplasty (THA) (CIHI, 2004). Debonding of the stem–cement interface and damage accumulation in the cement may lead to long-term failure of fixation (Jasty et al., 1991; Lennon and Prendergast, 2002; Orr et al., 2003). Polymethylmethacrylate (PMMA) or bone cement is used for the fixation of the prosthesis to the bone; it completely fills the space between the implant and the bone and does not chemically bond with the implant or the bone (Nuño and Amabili, 2002). The curing process of bone cement is an exothermic reaction where cement undergoes volumetric changes (Ahmed et al., 1982a; Muller et al., 2002). During this complex phenomenon, porosity and stresses at both interfaces and inside bulk cement are observed (Ahmed et al., 1982a; Bishop et al., 1996; Gilbert et al., 2000; Mann et al., 2007; Nuño and Amabili, 2002). Numerous studies (Bishop et al., 1996; Damron et al., 2006; Iesaka et al., 2003; Wang et al., 2003) have shown significant reduction of stem–cement interfacial porosity by stem pre-heating. Mann et al. (2007) have shown that porosity at the stem–cement interface directly affects stem migration, and is thought to induce implant loosening. Nuño and Avanzolini (2002) have shown the importance of incorporating residual stresses in the cement into finite element (FE) models to better predict load transfer of THA.

Very few experimental studies (Ahmed et al., 1982a; Nuño and Amabili, 2002; Roques et al., 2004) have assessed the stresses generated during PMMA polymerization. Ahmed et al. (1982a) indirectly quantified the cement residual stresses on four specimens. Strain gauges measured hoop strains inside a stainless steel tube. Corresponding compressive radial residual stresses of 0.5 MPa were computed at the stem–cement interface. Nuño and Amabili (2002) also used an indirect method: a 5-mm thick cement mantle was cured around a polished cylindrical stem. Deformations on the outer surface of the cement mantle were measured by strain gauges. Corresponding compressive radial residual stresses of 2.3–3.3 MPa at the stem–cement interface were calculated using a FE model. Roques et al. (2004) measured deformations inside a hollow stem and corresponding hoop

* Corresponding author. Tel.: +1 514 396 8604; fax: +1 514 396 8595.
E-mail address: natalia.nuno@etsmtl.ca (N. Nuño).

0021-9290/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2008.06.030

stresses of 10 MPa at the stem–cement interface were computed using a FE model.

There are relatively few analytical or numerical studies that simulate the polymerization process to assess the residual stresses (Ahmed et al., 1982b; Lennon and Prendergast, 2002; Li et al., 2004; Orr et al., 2003). Using a thermoelastic analysis, Ahmed et al. (1982b) concluded that transient and residual stresses varied with different boundary conditions (temperature and adhesion at interfaces); compressive radial stresses up to 2.5 MPa were calculated. Lennon and Prendergast (2002), also using a thermoelastic analysis, obtained principal residual stresses three times higher when they included porosity in the cement (7 MPa). Orr et al. (2003) used Lamé's equations to analyse shrinkage stresses for different curing temperatures. They found inside-cement hoop stress of 25.2 MPa. In another study, Li et al. (2004) developed a kinetic model of bone cement curing using a FE method. For a stem pre-heated at 45 °C compared to a stem stored at room temperature, the compressive radial stresses increased from 4 to 5 MPa at the stem–cement interface. To date, no agreement exists on the magnitude of these stresses. Analytical relations, or numerical models, have been used to obtain the corresponding stresses from the measured strains, but no experimental study has directly measured the residual stresses.

These transient and residual stresses are influenced by many factors: i.e. initial temperature of system components, bone cement composition, system geometry, mixing method and devices, thermal properties of system components and interface adhesion condition at stem–cement and cement–bone interfaces (Ahmed et al., 1982b; Dunne and Orr, 2001; Vallo, 2002). Cement polymerization normally starts at the warmer cement–bone interface and continues towards the stem–cement interface, creating pores at this interface. Pre-heating the stem modifies the polymerization direction from stem to bone (Bishop et al., 1996; Iesaka et al., 2003; Li et al., 2004).

The objective of this study is to develop an experiment for the direct measurement of transient and residual stresses of cement at the stem–cement interface during cement polymerization. An idealized femoral-cemented implant is devised to measure the compressive radial forces acting on the stem–cement interface, to be converted to radial stresses. The effects of initial temperature of stem and bone as well as the cement–bone interface condition (adhesion or no adhesion) on the cement radial residual stresses are investigated. We hypothesize that preheating the stem will initiate the polymerization process at the stem–cement interface, thus generating larger residual stresses. In particular, this research project aims at quantifying the parameters to be used in a FE analysis to characterize the contact between the implant and the bone cement of hip prostheses.

2. Materials and methods

2.1. Experimental setup

An idealized femoral-cemented implant (Fig. 1) of cylindrical shape, similar to previous experimental studies (Ahmed et al., 1982a; Nuño and Amabili, 2002; Roques et al., 2004), is used. The bone cylinder (40 mm external and 29 mm internal diameter) is 158 mm long; its distal part allows the stem to be centered during insertion resulting in a 5-mm bone cement thickness.

The idealized femoral stem, total length of 175 mm, is made of W1 steel cylinder having a smooth polished surface finish of $R_a = 0.2\,\mu$m. The 19-mm diameter stem has 120 mm in length in contact with bone cement (Fig. 1). The femoral stem consists of a main body, a sliding cap and a positioning guide (Fig. 2). A sliding cap is accurately machined on a computerized numerical control (CNC) turning center Integrex-200-IIIST (Mazak, Florence, KY) to slide perfectly with minimum friction into the femoral stem (Fig. 3a and b). The positioning guide is used to ensure perfect vertical displacement of the sliding cap under the radial force exerted by the cement during curing.

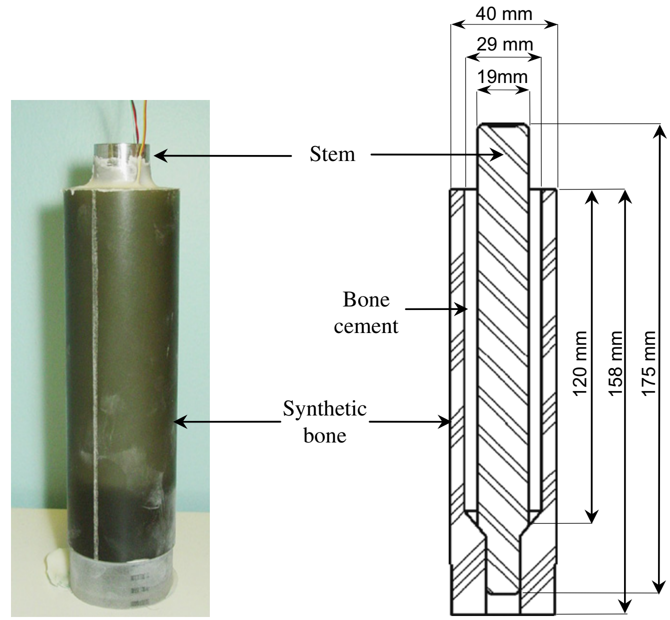

Fig. 1. Idealized femoral-cemented implant.

A synthetic bone cylinder (Sawbones, Pacific Research Laboratories, Vashon, Washington) simulates adhesion at the cement–bone interface, with mechanical properties in the range of natural bone (Cristofolini et al., 1996), while an aluminum cylinder simulates no adhesion at the cement–bone interface.

2.2. Radial stress and temperature measurements

A high-stability subminiature load cell (9.5 mm diameter, 3.2 mm thick) ELFM-B1-50L (Entran, Fairfield, NJ) is placed inside the previously machined stem to receive the load cell (Fig. 2), half-way along its longitudinal axis, to measure the compressive radial force applied on the stem at the interface by bone cement during polymerization. A thin film is placed over the sliding cap to protect the sensor and avoid any cement penetration between the stem and the sliding cap. This high-stability cell, pre-calibrated by the manufacturer, has an operating load of 25–250 N and a temperature range of −50 to 120 °C, with compensated temperatures from 15 to 70 °C. A self-adhesive, super fast-response thermocouple SA1-K/N (Omega Engineering Inc., Stamford, CT) is placed on the stem (diametrically opposed to the load cell) to measure the temperature.

2.3. Specimen preparation

The stem instrumented with the load cell is calibrated inside a pressurized chamber that reproduces a uniform pressure on the stem controlled by a calibrated digital pressure gauge PG-5000 (Omron Scientific Technologies, Inc., Fremont, CA). Known pressures varying from 0 to 500 kPa by increments of 25 or 50 kPa are applied and the corresponding load cell output is recorded. For each instrumented stem, the calibration procedure is repeated three times: the results show good repeatability of the measurements (less than $\pm$0.3% full scale). The compressive radial stresses measured by the stem are underestimated by 12% for pressures above 100 kPa. The stresses presented in the Results section are adjusted according to the calibration data.

Simplex P bone cement (Howmedica Int., Limerick, Ireland) is hand mixed at room temperature (24 °C) according to manufacturer's instructions. After 1 min 30 s of mixing and 30 s of rest, the bone cement is poured inside the bone's hollow cylinder, and the instrumented stem is inserted into the bone. The cemented specimen is kept at 37 °C in a temperature-controlled oven, model 2-140E (Quincy Lab, Inc., Chicago, IL).

The data acquisition program, developed using the commercial software LabVIEW 7.0, starts when the liquid monomer makes contact with the powder at $t = 0$. The radial force (F_{radial}) generated at the stem–cement interface during (transient) and after (residual) bone cement polymerization is recorded. The sliding cap effective area is denoted by $A_{\text{sliding cap}}$ of dimensions 15.73 mm × 15.73 mm (247.44 mm^2 of effective area) as shown in Fig. 3a. The radial stress is computed as follows: $\sigma_{\text{radial}} = c\,(F_{\text{radial}})/(A_{\text{sliding cap}})$, where c is a factor slightly lower than one, to account for surface curvature.

2.4. Measurements

A total of 15 cemented specimens are prepared with different initial conditions (Table 1): (Case 1) $T_{\text{bone}} = T_{\text{stem}} = 37\,°$C with adhesion at cement–bone interface;