



Surface topography affects the fatigue life of the bone/cement interface in THR

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INTRODUCTION

Total Hip Replacement (THR) is a common surgical treatment for individuals suffering from severe arthritis of the hip. Despite overwhelming success, THR failures are still commonplace. Aseptic loosening of the bone/cement interface is a principle cause of cemented THR failures [1, 2]. Studies show that macroscopic loosening is a result of fatigue and the evolution of micromotion that occurs with degradation of mechanical interlock. In a previous study it was found that bone surface topography affects the interface shear strength [3]. However, fatigue properties of the bone/cement interface and the influence of bone topography are unknown. To increase the fatigue life of the bone/cement interface, it is essential to understand the mechanics of loosening and contributions from the bone surface topography to micromotion.

MATERIALS AND METHODS

Fresh bovine femurs were obtained from a nearby slaughterhouse within 12 hours of sacrifice. The diaphysis of the femur was extracted, cleaned and sectioned to about 65 mm length. The section with thickest wall was identified and then machined to a slice of 12.7 mm wide. The canal side of the bone surface was textured using a specially designed cutting tool to prepare the bone surface with a certain surface topography (Fig.1). The surface topography resulting from machining the bone was quantified prior to cementing. The surface profile was obtained using a contact profilometer (T8000 Hommel America, New Britain, CT) with 5 μm radius diamond stylus. The average surface roughness (R_a), maximum peak to valley height R_{max} and core roughness parameters (R_x family) were estimated from the surface profiles according to ANSI B46.1 and DIN4776. In addition, the volume available for cement interdigitation (V_i) was also calculated [4]. Table 1 lists the specimens prepared and their surface measurements in this study. The final section of prepared femur was 51 \times 12.7 \times 10 mm. Prior to surface preparation all suitable bone candidates were kept at 4°C in saline solution.

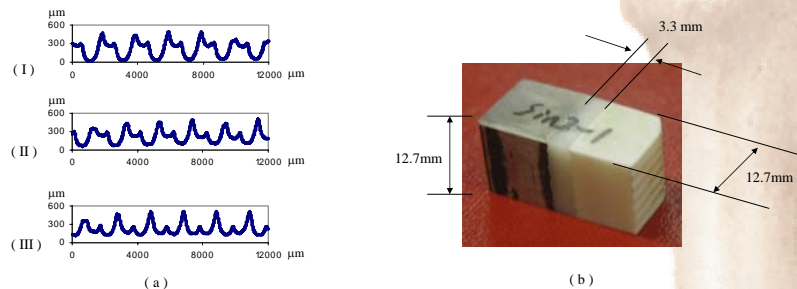
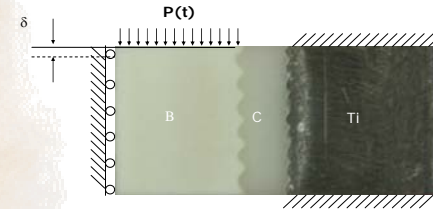


Fig. 1 Bone surface preparation and specimens. a) surface preparation with 2-flute cutting tool and different topographies (I, II and III); b) a specimen prepared for fatigue testing.

A model prosthesis was made of commercially pure titanium (cpTi). One side of a 12.7 \times 12.7 mm square bar was textured with cutting tools so that the prosthesis/cement interface was stronger than the bone/cement interface. The model prosthesis was cemented with the prepared bone section under good ventilation conditions at room temperature (20°C). Before cementing, the model prosthesis and a section of bone were placed into a cementing fixture with 3.3 mm distance separating the two. Bone cement (Endurance® Depuy, Warsaw, IN) was hand-mixed with prepolymerized powder and self-curing methylmethacrylate liquid in the recommended ratio. While still in liquid form, the cement was quickly put into a syringe and squeezed into the "joint space". When cement fully occupied the "joint space", the cementing pressure was sustained at 70 psi until curing was complete.

The model bone/cement interface specimens were subjected to cyclic loading using a universal testing machine (DynaMight™ Instron 8841, Canton, MA). The load and specimen configuration promoted pure shear fatigue of the bone/cement interface. A sinusoidal load was applied under load control with a stress ratio (R) of -0.1 and frequency of 10 Hz. The maximum load was 642 N, equivalent to 30% of the ultimate shear strength obtained from previous push-out tests. After specific periods of fatigue loading digital images were taken of the bone/cement/prosthesis interfaces under a static load to quantify the relative displacement between the prosthesis and bone using Digital Image Correlation (DIC) [5]. The process was continued to a total of 10 million cycles or the relative displacement (δ) between the prosthesis and bone was equal to or greater than 0.5 mm. All specimens were kept in saline solution during the test period to maintain elastic properties and dimension of the bone.

Fig. 2 Schematic representation of fatigue load and boundary conditions. B=Bone, C=Cement, Ti=Titanium



RESULTS AND DISCUSSION

The surface topography of the bone surfaces had an average roughness (R_a) with range of 93 - 191 μm , and the peak to valley height (R_{max}) ranging from 356 to 428 μm . The V_i ranged from 191 - 240 μm and Volume Ratio, $VR_{c/b}$ (cement/bone) were 1.1 - 2.5. Specimens with three surfaces were prepared and the topography of each is listed in Table 1. The Type I specimens did not fail in 10 million cycles. However the Type II and Type III specimens with lower R_a failed within 1.85 million cycles. The displacement history between the cement and bone is shown in Figure 3.

Based on the experimental results the surface topography of bone significantly affects fatigue of the bone/cement interface. As the R_a and R_{max} increased, the fatigue life of the interface also increased. Note that V_i for the bone cement was nearly the same for all these surfaces. However, the volume ratio of cement to bone ($VR_{c/b}$) was not and the fatigue life of the interface increased with decreasing $VR_{c/b}$. An inspection of the failed specimens showed that failure occurred on the bone side and thus an increase in bone volume at the interface increased the interface life. The fatigue strength of bone cement is less than that of bone which indicates that the volume of interdigitation is still an important parameter.

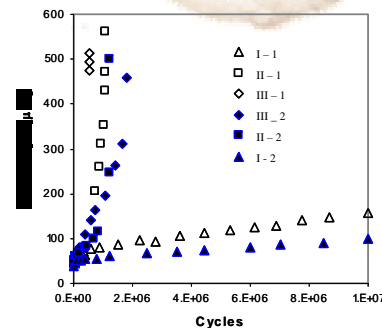


Fig. 3 Relative displacement (δ) evolution with fatigue loading

Table 1 Specimens and their surface roughness parameters

Specimen	Parameters					
	R_a (μm)	R_{max} (μm)	V_i (μm)	$VR_{c/b}$	Fatigue Life (N, cycle)	
I	1	191	403	212	1.1	Not fail
	2	172	428	207	1.2	Not fail
II	1	156	333	209	1.3	1090000
	2	132	391	191	1.5	1232000
III	1	93	359	233	2.5	560000
	2	116	356	240	2.1	1820000

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REFERENCES

- R. N. Stauffer, Ten-year follow-up study of total hip replacement: with particular reference to roentgenographic loosening of the components, *Journal of Bone and Joint Surgery*, 64A:983-990, 1982.
- J. J. Callaghan, E. E. Forest, J. P. Olejniczak, D. d. Goetz, R. C. Johnston, Charnley total hip arthroplasty in patients less than fifty years old: A twenty to twenty-five-year follow-up note, *Journal of Bone and Joint Surgery*, 80A:704-714, 1998.
- D. T. Yang, K. A. Stoffel, D. Arola, "Bone Surface Roughness Parameters Affect the Shear Strength of the Bone/Cement Interface", in Proceedings of First International Conference on Medical Implant, July 25-28, 2003, Bethesda, Maryland, USA
- D. T. Yang, K. A. Stoffel, D. Arola, "Estimating the Apparent Volume of Cement Interdigitation from the Profiles of Bone and Implant Surfaces", The 27th Annual Meeting Transactions of the Society for Biomaterials, April 24-29, 2001, Saint Paul, Minnesota, USA.
- D. Zhang, D. Arola, "Applications of digital image correlation to biological tissues", *Journal of Biomedical Optics*, 9(4), (in press), 2004.