CRACK CLOSURE AND INTERFACIAL FRACTURE TOUGHNESS TEST OF BONE-IMPLANT SYSTEMS UNDER MIXED MODE LOADING CONDITIONS

+WANG, X, ATHANASIOU, KA, AGRAWAL, CM. Musculoskeletal Bioengineering Center, The University of Texas Health Science Center at San Antonio, Texas 78284: (210)567-6495; FAX (210)567-6504; wangx@uthscsa.edu

INTRODUCTION The strength of the bone-biomaterial interface is an important factor in the design of load-bearing orthopaedic prostheses. Since the bone-implant interface is usually subjected to complex loading conditions, it is important to know how the failure mechanism of the interface varies with external loading conditions. However, current tests of interfacial bonding strength of bone-implant systems are usually performed under either tensile or shear modes and there are no effective methods for assessing the interfacial bonding strength under mixed-mode loading conditions. To address this issue, in a previous study we proposed a sandwich specimen for assessing interfacial bonding strength under mixed external loads.[3] However, it was found that as the shear component of the external load becomes dominant, the crack faces in the vicinity of the crack tip tend to close and subsequently create direct contact between the crack faces. Since the stress field around the crack tip can be significantly affected by the crack closure, further investigation is needed to address this issue. The objective of the present study was to modify the previously developed mixed mode interfacial fracture toughness test by taking into account crack closure to ensure accurate interpretation of experimental results. In the present study, finite element models were generated using contact element at the crack tip to simulate the crack closure process, and a correction was made to the equations used to calculate the interfacial fracture toughness using the sandwich test specimen.

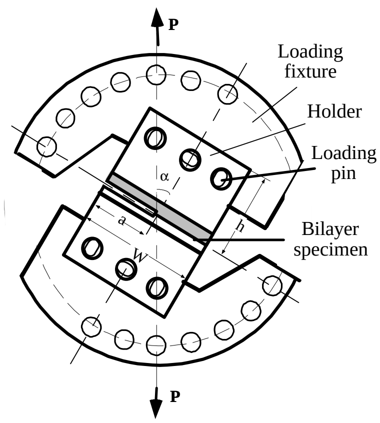

Figure 1. Mixed Mode Sandwich specimen

METHODS AND MATERIALS Previous studies have shown that for specimens with sandwich configurations there exists a universal relationship between interfacial fracture toughness, K_C, and the apparent fracture toughness K_C , which is measured for a homogeneous specimen with the same geometry but no interlayer present: [1]

$$K_C = p\,|K_C^{\infty}|\,e^{i\phi} = p\left(K_{IC}^{\infty\,2} + K_{IIC}^{\infty\,2}\right)^{0.5} e^{i(\omega+\theta-\varepsilon \ln h)} \qquad 1$$

where, p is the scale factor, K_{IC} and K_{IIC} are tensile and shear components of K_C , respectively, ω is a phase angle tabulated elsewhere,[1] $\theta=\tan^{-1}(K_{IIC}/K_{IC})$, ε is a constant determined by material properties, and h is the interlayer thickness. The previously developed specimen is shown in Figure 1, and the fracture toughness, K_C , is determined by the critical load and the specimen geometry as described elsewhere.[2] The loading angle α is measured with respect to the direction vertical to the crack plane.

2-D finite element (FE) models were generated using a mixture of 8-node and 6-node structural solid elements for the mixed mode sandwich specimen as shown in Figure 2. The crack tip was meshed with quarter-point crack tip elements. The accuracy of the FE models was verified in a converging test and against known theoretical solutions, and the error was estimated to be less than 2%. In the FE analysis, the interlayer thickness (h) and material combinations were varied to investigate the effects of the specimen geometry and material mismatch at the interface on the measurement of the interfacial fracture toughness. h was varied from 0.2 mm to 3.0 mm, and three pairs of materials were used in the analysis (Bone-PMMA, Bone-CoCr, and PMMA-Polyester). Table I shows the constants for the different material combinations. FE models without contact elements between the crack faces at the vicinity of the crack tip were first analyzed to determine how crack closure affects the crack-tip stress field under different loading modes. Then, the contact elements were introduced in the FE models to acquire true fracture toughness when crack closure occurs. Finally, the theoretical solution was modified to take into account effects of crack closure.

Table I Parameters used in the analysis

Holder/interlayer	p	ω (degree)	ε (degree)
CoCr/Bone	0.39	-11.5	-0.0950
Bone/PMMA	0.514	-10.5	-0.0507
Poly/PMMA	0.819	-3.4	-0.0239
PMMA/Poly	1.158	2.2	0.0239
PMMA/Bone	1.337	4.0	0.0507
Bone/CoCr	1.425	2.9	0.0950

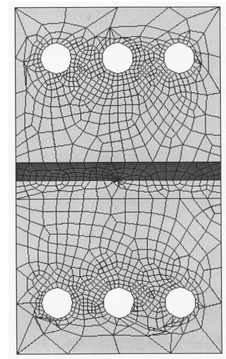
Figure 2. FEM model

RESULTS The interlayer thickness (h) of the sandwich specimen exhibited significant effects on the measurement of the interfacial fracture toughness. Analysis of FE results indicated that the effect of h could be formulated as a power function of scale factor p, and the modified solution can be shown as follows:

$$K_C = p^{\psi(h/W,\alpha)}\,|K_C^{\infty}|\,e^{i\phi} \qquad 2$$

where, ψ is the function of interlayer thickness (h) and loading angke (α). However, the results of the FE analysis exhibited a significant deviation from the theoretical solution as shear loading increases as shown in Figure 3. Such a deviation was also a function of the mismatch of the materials across the interface showing that the stiffer the interlayer material the greater is the deviation. Such a deviation was associated with the closure of crack faces observed in the FE models. By introducing contact elements at the crack faces near the tip to avoid the overlap between the crack faces in the FE models, it was found that a correction factor has to be used to account for the effect of the crack closure when the shear component of load becomes dominant at the crack tip. Therefore, the final solution was formulated in a form of the following equation:

$$K_C = k(\alpha)p^{\psi(h/W,\alpha)}\,|K_C^{\infty}|\,e^{i\phi} \qquad 3$$

where k is the correction factor determined by the loading angle (α).

DISCUSSION The results of this study indicate that when the shear component of the load at the crack tip becomes dominant, crack closure may occur in the vicinity of the crack tip. Such a crack closure significantly affects the measurement of the interfacial fracture toughness using the proposed sandwich specimen. A correction factor derived in the present study can account for this effect to ensure accurate measurement of interfacial fracture toughness using the sandwich technique.

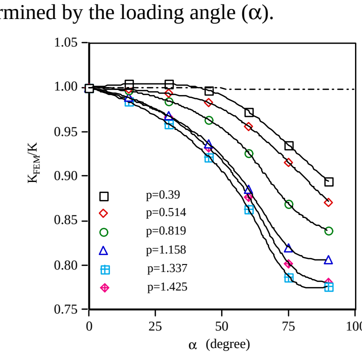

Figure 3. Effect of loading mode

References 1. Suo, Z., et al., (1989) Materials Science and Engineering A107, p.135-143. 2. Richard, H. A., The Int. Conf. on Appl. of Fracture Mechanics to Materials and Structures, Freiburg, F.R.G., 1983. 3. Wang, X and Agrawal, CM, 43rd Ann. Meet. ORS, San Fransisco, CA, 1997.

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