Effects of Initial Crack Length and Specimen Thickness on Fracture Toughness of Compact Bone*

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This paper deals with the determination of fracture mechanics parameters, such as critical stress intensity factor, K_c , and critical strain energy release rate, G_c , of compact bone. Haversian bone samples taken from fresh bovine femurs were machined into small compact tension (CT) specimens with various initial crack lengths and thicknesses, and then tested under quasi-static mode I loading condition at room temperature. Factor K_c was determined following the ASTM standard E399-90, and the compliance method was used for the determination of G_c . The values of K_c and G_c were larger in the specimens with transversely oriented initial cracks than in those with longitudinally oriented initial cracks. Both K_c and G_c were dependent on initial crack length as well as specimen thickness, and these fracture characteristics could be interpreted by a hypothesis based on the observation of damage accumulation, or microcracking ahead of the main crack front.

Key Words: Bone Biomechanics, Fracture Mechanics, Compact Bone, Cumulative Damage Model

1. Introduction

Compact bone plays a very important role in the human skeleton as one of the support bones, or main structural component to bear external loads from a biomechanical point of view. Many small pores, such as Haversian and Volkmann canals, canaliculi, and osteocyte lacunae, are found in compact bone, in which vigorous cells live in order to control bone function. Recent histomorphometric studies on the microscopic aspects of bone turnover have revealed that microcracks can be easily initiated at the cement line interfaces around osteons even under physiological loading condition in daily life, and the rate of bone remodelling can be accelerated by these defects⁽¹⁾. On the other hand, inhibition of normal bone remodelling

could cause an accumulation of unrepaired fatigue damage that, over time, could lead to fracture. It is important to understand, however, that the prevention of fatigue failure is not entirely dependent on repair or remodelling. The growth of microdamage or microcracks is also controlled by the lamellar structure of bone. Therefore, from the clinical viewpoint of prevention and prediction of bone fracture, the structural integrity of bone should be assessed not only by conventional tensile, compressive, bending and torsional tests but also in terms of the fracture mechanics approach which considers pre-existing cracks as the main cause of reduction in strength of structural components. At this point, fracture toughness of bone, derived from fracture mechanics analysis, should be considered as a measure of its resistance to fracture or of its fragility. Since Melvin and Evans⁽²⁾ applied fracture mechanics to the evaluation of strength of compact bone for the first time, many studies on fracture toughness of compact bone under quasi-static mode I loading condition have been carried out. Bonfield and coworkers performed a series of experiments to determine fracture toughness of bovine compact bone using various specimen

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configurations, and revealed the validity of the fracture mechanics approach to the analysis of compact bone fracture^{(3),(4)}, the effects of bone density and crack propagation velocity on fracture toughness⁽⁵⁾, and the orientation-dependent behaviour in fracture toughness⁽⁶⁾. Norman et al. measured the crack resistance curve (designated as R curve) of human compact bone⁽⁷⁾, and Vashishta et al. found that damage extension due to microcrack accumulation could be directly related to the R curve⁽⁸⁾. In addition to these basic engineering approaches, Bonfield indicated that the fracture mechanics characteristics of bone should be required for the optimum design of implant materials for prostheses in order to establish favourable mechanical compatibility with natural bone tissue at the bone-implant interface⁽⁹⁾.

Compact bone is a semibrittle material. Hence, stable crack growth or equivalent damage extension may take place before catastrophic fracture occurs, and this may affect the determination of fracture mechanics parameters, such as critical stress intensity factor, K_{Ic} , and critical strain energy release rate, G_c . Although microscopic failure behaviour on the bone surface during a fracture toughness test for the determination of the R curve was observed as mentioned above⁽⁸⁾, limited quantitative discussion on the relationship between damage extension and fracture mechanics parameters has been made so far. Therefore, in this study, we attempt to experimentally determine fracture toughness, K_{Ic} and G_c of compact bone in conjunction with microscopic damage extension prior to unstable fracture, that is, the objectives of this study can be explicitly stated as follows:

(1) to determine fracture toughness, K_{Ic} and G_c as a function of initial crack length and as a function of specimen thickness, and

(2) to discuss qualitatively the nature of damage accumulation due to microcracking prior to unstable macroscopic fracture, in particular, its effect on fracture toughness.

To this end, fracture toughness tests on compact tension (CT) specimens with various initial crack lengths, actually machined notches with a sharp notch tip radius of curvature as will be mentioned later, and thicknesses taken from bovine compact bone, were performed under quasi-static mode I loading condition. The term "initial crack length" is clearly distinguished from the term "crack length" throughout this study. CT specimen with an initial crack length was used for the measurement of a single value of critical load at which the initial crack length started to propagate, while the crack length was the instantaneous crack length as the crack extended across the specimen. Microcrack initiations on the specimen surface

near the main crack tip were also observed during fracture toughness tests, using a scanning electron microscope.

2. Materials and Methods

2.1 Materials

Haversian bone samples were taken from the mid-diaphyseal anterior cortices of fresh frozen bovine femurs, stored at -20°C for 48 hours after slaughter, of an average age of seven or eight months. CT specimens were then wet machined into thicknesses of 3, 5 and 7 mm, with overall dimensions of $17.5\text{ mm} \times 16.8\text{ mm}$ (Fig. 1). Six- and 8-mm-thick specimens were also machined for specimens with an initial crack length of 7 mm. Machined notches of 6, 7, 8, 9, 10 and 11 mm with a notch tip radius of curvature of $50\text{ }\mu\text{m}$ and a tip angle of 30° were introduced as initial cracks at angles of 0° or 90° (designated as T-L and L-T specimens, respectively) with respect to the long axis of the bone (Fig. 2). Side grooves 1 mm deep were introduced into each L-T specimen to produce controlled crack propagation parallel to the machined notch, or the initial crack⁽⁶⁾. The specimens were machined within 24 hours after obtaining the bone and tested within 24 hours after machining. All specimens were kept moist at all stages of the machining process with physiological saline solution, and then stored in the saline solution before testing at 3°C . Ten specimens from each initial crack direction at given thicknesses and initial crack lengths were used to collect test data for K_{Ic} and G_c determination (five for K_{Ic} and five for G_c).

2.2 Experimental methods

Fracture toughness tests were performed at a

Fig. 1 Compact tension specimen configuration

crosshead speed of $3.3 \times 10^{-6} \text{ ms}^{-1}$ (0.2 mm min^{-1}) at room temperature (20°C) using an Instron-type materials testing machine (Autograph AG-25TD, Shimadzu Co., Ltd., Japan). A low-vacuum-type scanning electron microscope (JSM-5300LV, JEOL Ltd., Japan), which allowed us to observe biological materials without any pretreatment, was used to observe specimen surfaces of a part of the T-L and L-T specimens, 7 mm thick and with an initial crack length of 7 mm, before and during fracture toughness tests. To carry out this observation, some fracture toughness tests were stopped at around the critical load in their loading sequence, and the specimens were then removed from the testing machine. The specimens were kept moist during fracture toughness tests by spraying saline solution on their surfaces.

2.3 Determination of critical stress intensity factor, K_c

Load, P , and crack opening displacement, v , during crack propagation were recorded for each specimen. Factor K_c was determined following the ASTM standard E 399-90⁽¹⁰⁾. All specimens showed typical P - v curves designated as Type I in the ASTM standard, independent of initial crack direction. Therefore, the critical load, P_{cr} , associated with the onset of crack growth was determined as the load at the intersection of a secant line (the line with 95% slope of the elastic region of the recorded P - v curve) with the test record, and K_c was then given by

$$K_c = \frac{P_{cr} Y_2}{B^* \sqrt{W}}, \quad (1)$$

where P_{cr} is the critical load, Y_2 , the shape factor as a function of crack ratio, W , the specimen width and

B^* , the specimen thickness. Note that $B^* = B$ for ungrooved specimens and $B^* = (B B_n)^{0.5}$ for grooved specimens, where B is the overall thickness and B_n the thickness between the grooves (See Fig. 1)⁽¹¹⁾.

2.4 Determination of critical strain energy release rate, G_c

The value of G_c was determined from the compliance method⁽¹¹⁾. Three specimens, 3, 5 and 7 mm thick, for each initial crack direction were used to determine the compliance (Fig. 3). Distance markers were placed on the specimen surface with a lead pencil at distances of 6, 7, 8, 9, 10 and 11 mm from the loading line. After the attachment of the specimen to the testing machine, the crosshead speed was manually controlled in a manner similar to the previous study⁽¹¹⁾ to perform compliance calibration by unloading and reloading when the crack reached the distance markers on the specimen surface. Crack growth in each specimen was monitored using a travelling microscope with the magnification of $\times 40$. The microscope was in close proximity to the manual displacement control, so that it was possible to view the crack during unloading and reloading. The operator paid special attention not to propagate the crack too quickly, particularly for reloading sequences, by adjusting the manual displacement control properly. This resulted in the establishment of unloading and reloading curves at crosshead speeds of less than approximately 2 mm min^{-1} . Specimen compliance, C , was determined from the continuously recorded unloading and reloading P - v curves for any given crack length, a , as the average reciprocals of their slopes

Fig. 2 Initial crack orientations. Crack was introduced at angles of 0° (longitudinal) or 90° (transverse) with respect to the bone axis.

Fig. 3 Compact tension specimen for compliance measurement. Distance markers were placed on the specimen with a lead pencil at distances of 6, 7, 8, 9, 10 and 11 mm from the loading line.

(Fig. 4). Figure 5 shows a plot of the raw data for the compliance calibration specimens with respect to specimen thickness along with the resulting curves of third-order polynomial regression of the data. Once the results of Fig. 5 were obtained, the value of G_c for each specimen was determined from its critical load as

$$G_c = \frac{P_{cr}^2}{2B^*} \left(\frac{\partial C}{\partial a} \right), \quad (2)$$

where B^* is specimen thickness; $B^*=B$ for un-grooved specimens and $B^*=B_n$ for grooved specimens.

Fig. 4 Unloading and reloading curves from load-deflection testing of 7-mm-thick T-L specimen

Fig. 5 Typical compliance curves for specimens of various thicknesses

3. Results

3.1 Relationship between critical load, P_{cr} , and initial crack length, a_0

The critical load P_{cr} monotonically decreases with increasing a_0 , independent of initial crack orientation and specimen thickness (Fig. 6).

3.2 Effect of initial crack length, a_0 , on critical stress intensity factor, K_c

The value of K_c ranges from 1.3 to 1.6 MPa m^{1/2} in T-L specimens and from 2.5 to 4.2 MPa m^{1/2} in L-T specimens. Factor K_c appears to decrease with increasing a_0 , independent of specimen thickness and initial crack orientation (Fig. 7). This result is in contrast to the previous study on the same bovine Haversian bone by Vashishta et al., in which larger K_c at longer crack length (designated as the rising R curve behaviour) was observed⁽⁷⁾.

3.3 Effect of initial crack length, a_0 , on critical strain energy release rate, G_c

The value of G_c ranges from 50 to 700 Nm⁻¹ in T-L specimens and from 100 to 1700 Nm⁻¹ in L-T specimens. Characteristics similar to those of K_c can be seen, that is, G_c appears to decrease with increasing a_0 , independent of specimen thickness and initial crack orientation (Fig. 8). This is also in contradiction to previous studies on G_c ^{(7),(12)}.

Fig. 6 Critical load (P_{cr}) plotted against initial crack length (a_0) for specimens of various thicknesses

Fig. 7 Effect of initial crack length on the average K_c for T-L and L-T specimens of various thicknesses. Each datum point represents the mean of five specimens.

Fig. 8 Effect of initial crack length on the average G_c for T-L and L-T specimens of various thicknesses. Each datum point represents the mean of five specimens.

3.4 Effect of specimen thickness, B , on critical stress intensity factor, K_c , and critical strain energy release rate, G_c

The relationships between K_c and B (Fig. 9) and G_c and B (Fig. 10) were determined with respect to the initial crack length of 7 mm. A one-way analysis of variance (ANOVA) revealed no significant effect of specimen thickness on K_c ($F=0.65$, $p>0.05$) and G_c ($F=0.60$, $p>0.05$) in T-L specimens, while both K_c and G_c decrease with increasing specimen thickness in L-T specimens.

3.5 SEM observation of microcrack initiation near initial crack tip

A part of T-L and L-T specimens was used for SEM observation, and special attention was paid to microcrack initiation on the specimen surface near the initial crack tip during fracture toughness tests.

Fig. 9 Effect of thickness on the average K_c for T-L and L-T specimens of various thicknesses with an initial crack length of 7 mm. Each datum point represents the mean of five specimens.

Fig. 10 Effect of thickness on the average G_c for T-L and L-T specimens of various thicknesses with an initial crack length of 7 mm. Each datum point represents the mean of five specimens.

Each specimen surface was inspected before testing (Fig. 11(a)) and at a slightly smaller load than the critical load (approximately 90% of P_{cr}) (Figs. 11(b) and 11(c)). Microcrack initiation from Haversian canals and lacunae and at the cement line interfaces around the osteons can be easily recognised even below the critical load. These microscopic failure behaviours suggest that a fracture process zone due to microcracking could be produced and developed before main crack growth is initiated.

4. Discussion

Notched specimens were used in this study instead of naturally cracked ones for the determination of K_c and G_c . Actual aspects of the stress or strain field around the microcracks initiated at the cement line interfaces and micropores are, therefore, thought

Fig. 11 Typical surfaces near the initial crack tip: (a) before testing, (b) T-L and (c) L-T specimens at 90% load level of P_{cr}

to be different from those near the notch tip in this study. However, Bonfield demonstrated that a variation in the radius of curvature of the machined crack tip from 0.19 to 1.25 mm did not alter the derived K_c value, and concluded that fracture probably propagated from a similar submicroscopic crack at the periphery of the machined radius and therefore could be considered as approximating to the ideal condition of an atomically sharp crack tip⁽¹³⁾. In this study, a smaller machined notch tip radius of curvature (50 μm) than the radii used by Bonfield was used and microcrack initiation was also confirmed at around the critical load, as shown in Fig. 11. Consequently, the machined notches used in this study could give us good approximations to natural cracks.

Both K_c and G_c were smaller in T-L specimens than in L-T specimens. This orientation dependence of fracture toughness agrees qualitatively well with the previous result, but the values of K_c and G_c obtained in this study were remarkably low compared with those in the previous study⁽⁷⁾. For instance, the values of K_c were approximately 50 to 70% of those obtained by Behiri and Bonfield for the same kind of compact bone⁽¹⁶⁾. This is probably due to a difference in the bone structure among individuals rather than a difference in the determination of critical load between the present study and a previous one in which Bonfield et al. considered the maximum loads in the P - v curves as the critical loads and derived the values of K_c from such critical loads⁽⁶⁾. As mentioned in section 3.5, the initiation of a fracture process zone was obviously recognised at a load smaller than the critical load determined following the ASTM standard, and consequently, the present study gave us safer values of K_c from a clinical point of view. A similar behaviour was found in the values for G_c that were much lower than those obtained by Bonfield et al.⁽⁴⁾ and Norman et al.⁽¹¹⁾ (approximately 10 to 60%), and

Fig. 12 K_c and cumulative number of secondary cracks (N) plotted against crack length (a) for bovine Haversian bone specimen (redrawn from Vashishth et al., 1994)

this is also due to the same reason as discussed above.

Factor K_c appeared to decrease with increasing initial crack length, independent of initial crack orientation (Fig. 7). This characteristic is assumed to be associated with the initiation or extension of a fracture process zone ahead of the main crack front as mentioned in section 3.5. Vashishth et al. performed fracture toughness tests on bovine Haversian bone, and found the relationship between K_c and damage accumulation ahead of the main crack front in the stable or slow crack growth region⁽⁸⁾. The cumulative number of secondary cracks, N , as well as K_c increases linearly with increasing crack length (or slow crack propagation), and therefore, a positive correlation between K_c and N can be easily found (Fig. 12). It should be emphasised that Vashishth et al.⁽⁸⁾ used a single specimen for successive determination of K_c values at given crack lengths during stable crack growth while separate specimens with various initial crack lengths were used in this study. Less damage was assumed to be accumulated in specimens in this study in comparison to their result, as shown in Fig. 12. In addition to this, the cumulative damage model (CDM) proposed by Carter and Caler⁽¹⁴⁾ suggests that a larger number of microcracks can be initiated anywhere in the specimen under a larger applied load irrespective of the presence of macroscopic crack or defect. A summary of these findings for damage accumulation yields the following hypothesis, and the result of Fig. 7 can be qualitatively interpreted.

Hypothesis:

As the critical load decreases with increasing initial crack length (Fig. 6), damage at the crack tip is assumed to be reduced at larger initial crack lengths (CDM by Carter and Caler). Since K_c and damage are directly related (Fig. 12), an increase in initial crack length eventually results in the reduction

of K_c (Fig. 7). In other words, the greater the damage is, the greater fracture toughness is, and conversely, lower damage means lower fracture toughness.

The crack length dependence of G_c obtained in this study showed the same tendency as that of K_c , which contradicts previous results. This characteristic can be related not only to the initiation of a fracture process zone but also to the procedure of its determination. The compliance calibration and G_c determination in this study as well as in the other previous studies^{(5),(7),(11),(12)} were performed using different specimens. Therefore, the compliances of the specimens used for G_c determination might be different from those used for compliance calibration. In other words, we cannot guarantee that all specimens have the same compliance since a comparatively large difference in material properties of living tissues is usually observed among individuals. Furthermore, the critical loads required for G_c calculation were determined from several specimens at various initial crack lengths while the compliance was successively measured for a propagating crack in the specimen. That is, the compliance was affected by damage accumulation but the critical load was not. Thus, the influences of damage and difference in material properties among individuals on G_c cannot be avoided as long as the conventional method is used. However, compact bone is an orthotropic solid and the use of G_c as the resistance to crack growth in such orthotropic material is more reasonable than that of K_c to investigate anisotropic fracture behaviour. The method of analysis for G_c should be further discussed.

5. Conclusions

Quasi-static mode I fracture toughness tests on bovine Haversian bone were performed, and the effects of initial crack length and specimen thickness on the critical stress intensity factor, K_c , and the critical strain energy release rate, G_c , were discussed. The results obtained are summarised as follows:

(1) The value of K_c ranges from 1.3 to 1.6 MPa m^{1/2} in T-L specimens and from 2.5 to 4.2 MPa m^{1/2} in L-T specimens.

(2) The value of G_c ranges from 50 to 700 Nm⁻¹ in T-L specimens and from 100 to 1 700 Nm⁻¹ in L-T specimens.

(3) Both K_c and G_c are dependent on initial crack length, that is, they decrease with increasing initial crack length in both T-L and L-T specimens.

(4) Specimen thickness does not affect both K_c and G_c in T-L specimens, while they decrease with increasing specimen thickness in L-T specimens.

(5) Microcrack initiations were easily recognised near the initial crack tip even below the critical load.

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