On-line analysis of cracking in cortical bone under wedge penetration

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Abstract

Understanding the mechanism of crack propagation during bone cutting is necessary for the development of realistic bone cutting models. The paper studies the on-line fractural behaviour of cortical bone caused by penetration with a sharp metallic wedge mounted on an on-line loading stage within an X-ray microfocus computed tomography (micro-CT) system. The experimental results demonstrated anisotropy in crack propagation depending on the penetration direction with regard to the longitudinal bone axis and relate the crack growth to the extent of penetration. Scanning electron microscopy (SEM) is performed to analyse the mechanism of cracking in two phase microstructure of compact bone.

Keywords: Bone, Fracture mechanics, Computed tomography, Crack growth, Scanning electron microscopy

1 INTRODUCTION

Bone cutting is the most frequent operation in orthopaedic, neuro and dental surgeries. The last two decades experienced major advances in the development of bone surgical procedures. The cracking of bone due to penetration with a hard, sharp tool is of significance in bone cutting procedures and associated trauma situations. Osteotomes such as hand-driven chisels and mallets, hacksaw and engine-driven alternating rectilinear impactors are commonly used for cutting the bone [1]. Pneumatically-powered ballistic chisels are used in clinical practice to remove cement and cementless prostheses in revision total hip arthroplasty [2]. The metallic tool may also interact with bone in needle-based therapy and biopsy of bone in spinal disorders [3]. One of the important problems in the bone cutting processes is determination of the crack path ahead of a cutting tool. In many bone surgical procedure such as drilling, the cutting is a fast process and visualization of crack propagation ahead of the cutting edge is a difficult task. The study of wedge indentation in bone tissue was suggested for the purpose of exploring the cracking mechanism, which could be an important input into the existing surgical procedures and bone cutting models.

Fracture mechanism in cortical bone tissue under various loading conditions has been the subject of many studies [4-8]. While fracture behaviour of bone has received considerable attention, studies related to the investigation of cracking mechanism in bone under wedge penetration similar to our experimental approach are limited. In an effort to quantify the crack growth and fracture in bone, either indentation fracture experiments were used to measure fracture toughness or relate crack propagation with fracture toughness [9-13]. On-line loading stages found in literature have rather small dimensions, and thus only limited loads can be applied [14, 15]. For the investigation of high strength materials, such as metallic foams or cortical bone, such set-ups becomes inappropriate. Also, most of the measurements taken in previous studies were off-line and obtained for

loading conditions different from cutting. Kasiri [16] experimentally measured the fracture of bovine bone under sharp tool penetration and predicted using the theory of critical distances (TCDs). Sugita [17] has recently observed and analyzed the fracture and crack propagation in machined bones. Crack propagation was observed to depend strongly on cutting direction with regard to the bone axis. It has previously been observed that crack propagation is dependent on the direction of the blade penetration relative to the main axis of the bone [18].

Numerous techniques have been employed to monitor cracking phenomena in bone tissues. These includes acoustic emission [19], sequential labelling [20], nonlinear resonant ultrasound spectroscopy [21], X-ray microfocus computed tomography (micro-CT) [22] etc. Micro-CT is one of such techniques to quantify internal details such as damage, porosity and cracks. De Santis [23] studied crack propagation of short-rod chevron-notched tension specimens (CNT) extracted from bovine cortical bone using X-ray computed micro-tomography. The CNT specimen was tested to relate crack growth resistance (fracture toughness) with crack extension. Zimmerman [24] analysed cracking behavior of human cortical bone using symmetrical four-point bending test equipment coupled with environmental scanning electron microscope (ESEM). The crack-growth toughness was measured while simultaneously imaging the initiation and growth of cracks in real time. When coupled with 3D image analysis, micro-CT can be a reliable tool to characterize cracking phenomena in materials.

The process by which cracks in bone initiate and propagate under a tool penetration up to failure is remained insufficiently understood. In addition, the relationship between the tool penetration depth and crack propagation in the bone tissue is not yet known. The purpose of this study was to address the fundamental question how a crack initiates and propagates in cortical bone. Concerning the mechanical quantification, micro-CT

combined with an on-line loading stage equipped with a sharp metallic wedge for penetration was utilized to image and quantify the cracking phenomena of the cortical bone. This allowed on-line monitoring of the cracking mechanism in bone and possible errors resulting from shifting the specimen from loading stage for CT examination are avoided. The loading stage is able to reach high forces (up to 30 kN) and is free of any tubing around the sample for scanning. Additionally monitoring and/or control of the relaxation are possible. An important and novel feature of these experiments was the possibility to monitor the crack growth during the wedge penetration/advancement at multiple stages. The effect of the penetration direction with respect to the bone's longitudinal axis on the crack propagation direction and extension was studied.

2 MATERIAL and METHODS

2.1 Specimen preparation

Our experimental studies of crack propagation were carried out using bovine femur. The bovine bone is of interest as it is the closest animal bone to replicate the characteristics of human bone [25]. The mean age of the animal was approximately two years. Fresh femoral bones were immediately brought to the lab from a local slaughter house in hard plastic bag surrounded by ice. Epiphysis was removed and the middle diaphysis columns were excised using a hacksaw. The average thickness of the cortical wall of the bones was approximately 9 mm. The specimens were visually free from any significant osteopenia and musculoskeletal disease. A total of fifty specimens were machined for the experiments and were found free from visible flaws (voids, cracks). Test specimens were prepared with the final dimensions of 20 mm × 20 mm × 8 mm after polishing them to a level of six microns. The polished specimens were quickly stored frozen at -10°C before the experiment. The anatomical location of the femur and the sample orientation used in

the experiments are shown in Fig. 1. The chosen X-direction was along the longitudinal axis (osteonal direction) of the bone.

2.2 Experimental setup

In this study, a Philips HOMX 161 (Philips, Eindhoven, The Netherlands) X-ray source upgraded with a CT setup (Tomohawk, AEA Technology, Warrington, UK) was used and operated at a voltage of 62 kV and a current of 0.56 mA. The system is equipped with 30 kN capacity load cell (Sensy model 2965). The components of the loading stage are shown in Fig. 2. The clog-wheels are used to rotate the clamped sample for micro-CT imaging. Both pairs of clog-wheels are equal in diameter to avoid torsional effect on the sample. The technical specifications of the loading stage are summarized in Table 1. An aluminium filter of 1 mm was installed between source and sample. The isotropic voxel size was 15 μm . The μCT system is equipped with a 12-bit 1024 by 1024 detector consisting of an image intensifier (TH 9428 HX, Thales, Vélizy Villacoublay, France) and a CCD camera (MX12P, Adimec, Eindhoven, The Netherlands). The X-ray source has a focal point of $\pm 5 \mu\text{m}$, can operate between 5 and 160 kV and is equipped with a tungsten target. The turntable can rotate in steps down to 0.1° over 180° or 360° . More specifications of the micro-CT device can be found in Table 2. After data acquisition, the cross sectional images of the sample were reconstructed using NRecon [SkyScan NV – Kontich, Belgium]. Fig. 3 shows an image of the loading stage, installed inside the Philips HOMX 161 X-ray system, zoomed in on a cortical bone sample and shows the sharp metallic wedge. Validation of the loading stage was performed for compression testing of porous materials by comparison with INSTRON 4505 universal test bench. No significant difference in the stress-strain curves or global mechanical properties (stiffness, strain) were found for both mechanical testing devices. The wedge was made from

titanium to reduce image artefacts with a cutting angle of 65°. The average cutting edge radius was approximately 10 µm.

The equipment is specifically designed to investigate morphological features and the related mechanical properties of materials, where a combination of micro-CT imaging, image analysis and on-line loading is realized. It allows on-line monitoring and quantification of the relationship between the microstructure and the global mechanical properties employing small steps of loading. Additionally, a relationship between the morphology and the mechanical properties can be quantified. Test can be performed using either load- or position-control modes with relaxation detection and compensation. Also a stepping program for micro-CT scans is incorporated into the system. For SEM investigations, a Philips XL30 ESEM FEG was used.

2.3 Experimental procedure

In all experiments, the wedge penetration direction was in the cortical thickness direction (Z-axis in Fig. 1(c)). Two different penetration orientations were used, namely with the cutting edge parallel and perpendicular to the bone longitudinal axis (osteons). All the penetration tests were run at room temperature under displacement control condition. During the test, the loading machine was periodically stopped in small steps of loading for imaging the specimens. The images were taken after each stage of penetration to allow CT machine to capture the detail when both wedge and the bone were stationary. Imaging the exact location of the wedge cutting edge with respect to osteons during penetration was not possible since those CT images could not differentiate between osteons and interstitial bone.

The initial set of experiments was conducted to determine the amount of wedge penetration necessary for obtaining a progressive crack growth and relate the penetration

depth with crack extension. For this purpose ten samples were used. The cracking mechanism and failure load were found to be independent on the loading rate (between 0.05 and 5 mm/min) in the initial experiments. The cutting edge was sharpened to the required level at the start of each penetration test. These experiments showed failure of the specimen for penetration above 0.8 mm. Thus, a wedge penetration increment of 0.2 mm was chosen for the rest of the experiments to observe the crack propagation at various penetration stages. All specimens were loaded in displacement control at a rate of 3 mm/min. For tomographic reconstruction, 374 transmission X-ray images (radiographs) were acquired over 187° of rotation (0.5° rotation step). The total scanning time of each sample was about 45 minutes; the required memory was approximately 2 Gb.

3 RESULTS and DISCUSSIONS

The crack was resolved in the 3D models based on the difference in X-ray absorption between the bone material and air. All micro-CT datasets of the specimens were acquired prior to final failure (splitting) of the specimen.

3.1 Penetration with cutting edge perpendicular to osteons

As mentioned earlier, a major advantage of the experiments was the possibility for on-line monitoring of the crack evolution under wedge penetration. As a reference, one micro-CT dataset was obtained in a pre-load condition (see Fig. 4a). The first crack was observed to emanate near the wedge edge at a penetration depth of 0.2 mm. This crack was not seen on the outer surface of the specimen and was thus occurring inside the specimen. This was visualised by virtual slicing the 3D micro-CT volume 16 mm from the origin along the plane parallel to the ZX-plane. The crack propagated in a plane parallel to the XY-plane and above a penetration depth of 0.2 mm, it propagated with

gradual extension parallel to the bone axis, as shown in Fig. 4(c and d), and with a sudden extension along the cutting edge parallel to the Y-axis (see Fig. 4e). A similar crack growth behaviour in cortical bone has been reported for the same cutting direction [26]. The crack around the cutting edge was shown to grow along the longitudinal bone axis and perpendicular to the wedge feed direction. Also the crack growth was observed to occur along the lamella interfaces. For both penetration directions fracture cracks grow along the lamella interfaces. The deformation of the material was observed as being piled-up next to the wedge contact edge as shown in Fig. 4(b, c and d). This may be attributed to the bending load on osteons laying in the direction perpendicular to the cutting edge.

3.2 Penetration with cutting edge parallel to the osteons

In the next stage of our experimental study, the specimen orientation was changed so that the cutting edge was parallel to the bone axis. Similar to the case of penetration perpendicular to the bone axis, there was a tendency for the crack to initiate at the first stage of penetration (0.2 mm), which was not visible on the outer surface of the specimens. To visualize this 3D micro-CT volume was sliced 18 mm from the origin along the plane parallel to the ZY-plane (see Fig. 5b). At the next penetration step, up to a depth of 0.4 mm, the crack extension was considerably small and is therefore not shown in Fig. 5. At penetration depth of 0.6 mm, the crack was mainly inclined through the thickness indicating shear failure of the specimen as shown in Fig. 5c. A small length of a horizontal crack was also observed at this stage of penetration. This may be contributed to a local change in orientation of osteons as they are not always parallel to the long bone axis [27, 28]. This may also be due to the increased number of vascular channels at that location. The crack was also seen to extend along the wedge edge with the penetration depth growing from 0.2 mm to 0.8 mm as shown in Fig. 5e.

At the last step of penetration (0.8 mm), an inclined crack through the thickness was observed. This type of response is similar to that found in fiber reinforced concrete [29]. The final crack was formed as a result of coalescence of two initially separated ones. The closed view of the crack when the cutting edge was parallel to the longitudinal axis of the bone is shown in Fig. 6. The orientation of the crack is the same as shown in Fig. 5. The crack growth direction was about 45° with respect to wedge displacement, becoming shallower at larger penetration depth.

At this stage of investigation, we assume that the crack advanced in the interstitial bone and was deflected at the osteonal boundaries (cement line). Our post-fracture surface examinations using SEM confirmed this assumption. These deviations are due to the influence of the microstructure of the cortical bone tissue on the crack propagation, which can progress along, or is deflected by, lamellae.

3.3 Failure load

A typical load-penetration plot obtained from the on-line mechanical experiments is shown in Fig. 7. At the end of each loading step, the force dropped with a certain amount. It is reasonable to believe that the drop in the penetration load was caused by the material relaxation during the period of stopping the loading (and thus fixing the sample) necessary to acquire a micro-CT dataset. The average failure load in penetration perpendicular and parallel direction was 7.8 kN and 5.9 kN respectively. The resistance to penetration, as well as the strength, of the bone was higher in penetration perpendicular to the bone axis, and therefore, more load was required for excision. A similar trend was observed in machining cortical bone in this direction [17].

3.4 Penetration vs. crack growth

One of the acknowledged goals of this study was to look at the crack growth as a function of the penetration depth up to final failure. Since for both penetration directions at final failure the crack was suddenly extended along the cutting edge, the relation between the penetration depth and the crack extension was not established. Fig. 8 shows that the crack length depends on the extent of penetration and its direction, indicating anisotropy of cracking in cortical bone. In Fig 8, all the data points in the graphs are the mean of five consecutive tests. Obviously the crack growth was small up to a penetration of 0.4 mm for both penetration directions. The crack then grew non-linearly with increased penetration. Also, the crack propagation was larger when the cutting edge was parallel to the bone axis than in the case when it was perpendicular to it (see Fig. 8). The resistance to crack growth in penetration perpendicular to the bone axis may be contributed to the increases resistance in shearing of the osteons in that direction. Anisotropic behaviour in cracking has already been reported for bone and dentine [10, 30].

3.5 Post-fracture observations

SEM investigation of the failed (splitted) specimens was performed for closer surface inspection in order to study the failure mechanisms occurring during the penetration experiments (Fig. 9). All the images were taken close to the cutting edge. The fracture surface of the sample was placed perpendicular to the incident electron beam. The post-fracture surface examination revealed some interesting results. The growth of cracks was strongly influenced by the bone microstructure. The cracks were observed predominantly in the interstitial bone, which is consistent with previous observations [31, 32]. The cracks were observed to be deflected at osteonal boundaries as shown in Fig. 10. Each osteon act as a reinforcing fiber as in fiber reinforced composite materials. In the bone microstructure, the osteonal bone is separated from the interstitial bone by a region of cement lines. Cracks can grow easily along the bone axis (parallel to the osteons) through

these regions thus decreasing the fracture toughness of cortical bone in this direction. Wedge penetration perpendicular to the osteons exfoliated a discrete layer of undamaged bone, and the crack direction with the crack front perpendicular to the axes of osteons was almost straight and hardly changed.

The crack direction with regard to the wedge penetration in the bone microstructure is shown in Fig. 11. The crack was confined to the interstitial bone and was inclined to the wedge penetration direction for the condition when the cutting edge was parallel to the bone axis (Fig.11a). The crack direction was observed to be oriented along the bone axis when the cutting edge was perpendicular to the bone axis (Fig.11b). When a crack propagates perpendicular to an osteon, at the cement line (osteonal boundary) it will change direction, resulting in blunting.

4 CONCLUSIONS

Indentation fracture experiments of cortical bone were carried out with the cutting edge perpendicular or parallel to the bone axis. The micro-CT equipment combined with the on-line loading stage used for the penetration experiments allowed quantitative evaluation of induced macro-cracks by means of direct observations of the extension of cracks for a range of wedge penetration steps. The crack propagation in bone was monitored without shifting the specimen from the loading stage for CT imaging. The experimental results confirm that the fracture has a highly anisotropic character. The crack direction and extension are strongly influenced by the orientation of the bone with regard to the cutting edge in penetration. The anisotropic fracture behaviour in bone is due to its microstructural organisation.

The results of the experiments show that for two penetration directions, the cracks initiate at the same penetration depth (0.2 mm for the used indenter shape) but at different loads. In both penetration directions, the cracks were observed to grow at a higher rate above

penetration depth of 0.4 mm. The average failure load for penetration in the direction perpendicular to osteons was 23% higher than that for the parallel direction. SEM examinations revealed that crack propagation is confined only in the interstitial bone and the osteon functioned as a barrier to crack propagation. Thus, this study demonstrated that cortical bone tissue is by no means isotropic in terms of fracture during tool penetration. The assessment of crack status was only possible at the end of each penetration stage. The orientation of the cutting edge with respect to the osteons direction was not tracked due to limitation of the CT images.

The effect of the tool radius of curvature on cracking of bone is not discussed in this paper and requires future attention. The result of this study may be useful in designing and using sharp edge bone surgical tools such as chisels for safe and efficient incision. Further studies are needed to quantify the relation between tool penetration and crack growth with higher penetration speeds similar to those used in actual bone surgical procedures.

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Declaration of Conflicting Interests

The Author(s) declare(s) that there is no conflict of interest

Figure Captions

Fig. 1 (a) Fresh bovine bone, (b) its sample cut from mid-diaphysis and (c) a specimen with wedge. The X-direction is along the bone's longitudinal axis, the Y-directions is the transverse direction and the Z-direction is the cortical thickness direction

Fig. 2 Design of the in-house developed on-line loading stage for the Philips HOMX 161 CT system (black arrows indicate the clog-wheels connecting to the clamps)

Fig. 3 Experimental setup for bone wedge penetration test, showing the on-line loading stage within the micro-CT system, equipped with a sharp metallic wedge

Fig. 4 Reconstructed 3D micro-CT volumes for wedge penetration perpendicular to osteons: (a) pre-load – with the wedge cutting edge (bright colour) touching the bone top surface; (b) penetration depth 0.2 mm, crack emanating from cutting edge; (c) penetration depth 0.6 mm; (d) penetration depth 0.8 mm; (e) crack along cutting edge (penetration depth 0.8 mm). Arrows show cracks

Fig. 5 Reconstructed 3D micro-CT volumes for wedge penetration parallel to osteons: (a) pre-load with wedge (bright colour) touching the bone top surface; (b) penetration depth 0.2 mm, crack initiation; (c) penetration depth 0.6 mm, two cracks; (d) penetration depth 0.8 mm, two cracks coalescing; (e) penetration depth 0.8 mm, crack produced along wedge edge (cutting edge is rendered invisible); (f) crack in the direction parallel to bone axis (penetration depth 0.8 mm)

Fig. 6 Micro-CT longitudinal cross-section showing a crack inclined under an angle of 45° after penetration with the cutting edge parallel to the bone axis and osteons. Penetration depth is 0.8 mm, the crack is initiated along the cutting edge

Fig. 7 Load vs. penetration depth graph. Relaxation at the end of each loading step is due to stopping the loading for intermediate micro-CT scans

Fig. 8 Crack growth as a function of the penetration depth perpendicular and parallel to the bone axis

Fig. 9 Specimen examination using SEM, showing the mounting of the specimen

Fig. 10 SEM investigation of the surface of a specimen after failure, showing crack arrest at osteonal boundaries

Fig. 11 SEM micrographs of typical fracture surfaces: (a) diagonal crack for the parallel penetration direction (arrows denote osteons) and (b) horizontal crack produced in penetration perpendicular to the bone axis

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Fig. 1

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Table 1. Technical specifications of the in-house developed on-line loading stage

<i>Speed of the motor:</i>	1 – 9000 rotations per minute
<i>Crosshead speed:</i>	0.0014 – 12.5 mm/min
<i>Deformation rate:</i>	between 0.005 and 5 mm/min
<i>Maximum sample size:</i>	50 mm diameter, 50 mm height
<i>Theoretical precision of the position:</i>	0.00001 mm
<i>Practical precision of the position:</i>	0.001 mm

Table 2. Specifications of the micro-CT device

<i>Source type:</i>	reflection
<i>Voltage range:</i>	15-160 kV
<i>Maximum power:</i>	32 W
<i>Microfocal spot:</i>	from 5 to 200 μm
<i>Min. voxel size:</i>	$\pm 5 \mu\text{m}$
<i>Detector system:</i>	<i>Image intensifier (TH 9428HX) and CCD camera</i> <i>1024 x 1024 pixels – 12 bit dynamic range</i>
<i>Max. sample diameter:</i>	<i>110 mm</i>