Abstract

Fatigue tests of bovine cortical bone were carried out. Compressive stress was applied along longitudinal axis of bones and fracture surfaces were parallel to the loading direction. Damage accumulation during tests was monitored by the measurements of acoustic emission (AE) signals and ultrasonic wave velocity. For the static compression test, specimens fractured catastrophically and the most of AE signals were detected close to final fracture. On the other hand, AE events increased and wave velocity decreased gradually during fatigue fracture of bone. A majority of AE signals were detected during unloading and they formed characteristic ‘AE bands’. AE wavelet analysis demonstrated that the peak frequencies of unloading AE, as well as loading AE, were equivalent to the resonant frequency along the specimen thickness. Finally, it is strongly suggested that microcrack extension due to wedging effect of debris took place during unloading in the fatigue process of cortical bone.

Keywords: Fatigue, Cortical bone, Microdamage accumulation, AE wavelet analysis, Wave velocity

Introduction

Bone is the primary structural material and has the role of supporting load in a human body. Bone can be classified into two types of structure. One is cancellous bone with sponge-like structure, and the other is dense cortical bone that consists of hydroxyapatite matrix and collagen fibers aligned along the long axis and have the microstructure similar to unidirectionally reinforced composites [1, 2]. During the life, damages were initiated and accumulated in bones, which result in the degradation of bone. When bone is subjected to excessive cyclic loading, fatigue fracture will take place similar to fatigue in metals [3]. The microfracture process must be clarified for the early diagnosis of fatigue fracture of bone. Previously, various studies on fracture behavior of human or bovine bone under cyclic loading were carried out; since the bovine bone has the mechanical properties similar to human bone, it is frequently used for the investigation on mechanical behavior of bone, as in this study. The damage accumulation or mechanical property degradation of bone under cyclic loading was characterized by means of the measurement of stiffness or wave velocity during fatigue fracture [4 - 6]. However, few AE study has been reported and microscopic understanding of fatigue fracture processes of bone has been inadequate.

In the present study, compressive fatigue tests of bovine cortical bone were carried out. The purpose of this study is to understand the mechanism of bone fatigue fracture for the development of detecting technique of fatigue damage in bone. Damage accumulation during fatigue fracture of bone was characterized by AE monitoring during fatigue test. The longitudinal wave velocity was also measured and compared with AE generation behavior. In particular, the nature of AE sources was investigated by AE wavelet analysis. Finally, the degradation process of bone under cyclic loading was discussed.
Experimental Procedures

Bone Specimens

Bovine cortical bone was used in this study. The microstructure of the bovine cortical bone is classified into two tissues, plexiform and haversian bones. Here, the plexiform bone was investigated. Figure 1 shows the schematic structure of diaphysis and microstructure of bovine cortical bone (plexiform bone). Diaphysis consists of a tubular cortical bone and the interior marrow, as shown in Fig. 1(a). The radial, tangential and longitudinal directions are x₁, x₂ and x₃, respectively, as indicated. An optical micrograph of typical cross-section, perpendicular to longitudinal axis, of the plexiform bone is shown in Fig. 1(b), which shows that lamellae are aligned along longitudinal direction, resulting in the orthogonal elastic properties. A number of lacunae were also observed among lamellae. These act as flaws under loading.

Specimens of 5 mm x 5 mm x 12.5 mm were cut from the diaphysis of bovine femoral bone. The specimens were kept frozen at −20°C, cut under flowing water and kept wet during the mechanical tests. The mechanical load was applied along longitudinal direction (x₃) as in the body.

Static Compression Tests

Static compression tests of bovine cortical bone (plexiform bone) were carried out in air at room temperature. Uniaxial compressive load was applied along the longitudinal (x₃) axis of bone specimen under constant crosshead speed of 0.1 mm/min. Testing system of static compression test is shown in Fig. 2, schematically. During the tests, longitudinal strain was measured using a strain gage attached directly on the specimen. Microfracture process of bone under compressive stress was evaluated by AE technique. A wideband AE sensor (NF; AE-900M) was attached on the specimen. Detected AE signals were amplified by a preamplifier (Gain; 60 dB) through the bandpass filter with a range of 100 kHz to 1200 kHz. The threshold level was 43 dB (= 141 µV at the input terminal of the a preamplifier). Amplified AE signals and strain were then recorded by an AE analyzer (PAC; Mistras), while load and strain were recorded by another PC.

Cyclic Compression Tests

In order to investigate the fatigue fracture behavior of bone, cyclic compression tests were performed in air at room temperature. The bone specimen was subjected to sinusoidal loading at 3 Hz along the longitudinal (x₃) axis of the bone. Stress ratio (minimum stress divided by maximum stress) was 0.05. For the convenience, compressive stress is taken as positive in this study.
The variation of mechanical property of bone is large, because bone is not industrial but natural material. Therefore, the stress amplitude (a half of the sum of maximum and minimum stresses), $\sigma_a$, was normalized by the initial Young’s modulus, $E^*$, of each specimen, which was determined from the linear part of the stress-strain relationship at the first cycle.

The damage accumulation in bone under cyclic loading was monitored by AE measurement. AE measurement system for the cyclic compression tests is shown in Fig. 3(a). The system was almost same as the static compression test (Fig. 2), but a resonant type AE sensor (PAC; Pico, resonant frequency $= 400$ kHz), which is more sensitive than the broadband sensor, was additionally used since the AE signal level during fatigue fracture was expected to be lower than static compressive fracture. Threshold level was $45$ dB ($= 178$ $\mu$V), which was higher than static compression test because of higher mechanical noise of a fatigue testing apparatus.

In order to examine the degradation in mechanical properties of bone, Young’s modulus and longitudinal wave velocity were also measured at every 300 – 400 cycles. Figure 3(b) shows the measurement system of wave velocity schematically. Two AE sensors were used as a transmitter and a receiver. Rectangular wave (frequency: $1$ MHz, amplitude: $10$ V) was transmitted along the radial ($x_1$) axis and wave velocity was determined as the specimen thickness divided by transit time.

Results and Discussions

Static Compression Tests

Figure 4 shows a typical result of stress-strain relationship and the behavior of cumulative AE events and energy for the static compression test. The stress-strain curve is almost linear except for the slight deviation from linearity at the final stage. Most of AE events and energy was
detected close to the final fracture. These results suggest the catastrophic fracture without damage accumulation during static compression tests. Average strength, fracture strain and Young’s modulus were 139.2 MPa, 0.0061 and 24.1 GPa, respectively.

After the static compression tests, most of the specimens were fractured along the $x_3$ (longitudinal)-$x_2$ (tangential) plane, i.e., fracture surfaces were parallel to loading direction. It is then suggested that the final fracture of bone under longitudinal compression derived from the nucleation and propagation of microcracks, which might be induced by lacunae, among lamellae shown in Fig. 1(b).

![Stress-strain relationship and AE behavior during static compression test.](image)

**Fig. 4.** Stress-strain relationship and AE behavior during static compression test.

![Distribution of AE events during compressive fatigue test.](image)

**Fig. 5.** Distribution of AE events during compressive fatigue test [$\sigma_a/E^* = 0.0024$].

**Cyclic Compression Tests**

A number of AE signals were detected during compressive fatigue test of bovine cortical bone. Figure 5 shows the distribution of AE signals detected during the fatigue test at $\sigma_a/E^* = 0.0024$ ($E^* = 26.7$ GPa). AE events detected during loading and unloading were discriminated and plotted in the figure. The figure indicates the normalized stress and cycle when each AE signal was detected. It can be seen that the majority of AE events were detected during unloading.
and AE events during loading were detected around peak stress. It is also observed that most of loading AE events was detected at the initial and final stages. It is worth noting that several characteristic ‘AE bands’ consisting of many AE signals are found in the figure. Those ‘AE bands’ can possibly correspond to specific features of fatigue fracture.

Cumulative number and energy of AE events detected during loading and unloading are shown in Fig. 6(a) and (b), respectively. In the figure, cumulative AE events and energy are normalized by each maximum and the rapid increase at final fracture for loading AE is omitted. For the loading AE (Fig. 6(a)), most of AE events and energy were detected just before the final fracture. On the other hand, cumulative energy of unloading AE increases gradually until ~200 cycles followed by nearly a steady state and rapid increases at final fracture.

The longitudinal wave velocity measured during fatigue tests is also plotted in Fig. 6. The wave velocity decreased gradually, which suggest that the strength of bone decreased during fatigue test due to microdamage accumulation [6]. Comparing with generation behaviors of loading and unloading AE, it is important that decreasing behavior of wave velocity has a tendency similar to generation behavior of unloading AE. It appears that gradual decrease in strength during fatigue resulted from the microfracture during unloading.
AE events detected during loading and unloading correspond to crack opening and closure, respectively. The nature of the AE sources was investigated using AE wavelet analysis. Figure 7 shows the wavelet patterns of loading and unloading AE signals detected during fatigue fracture of bovine cortical bone. Figure 7(a) shows a typical result for the loading AE detected at around peak load. A peak WT coefficient is recognized at ~350 kHz. Since the frequency value is comparable to the resonant frequency of longitudinal wave along thickness (x1-axis) direction, the source of the AE generated a strong signal in that thickness direction. Considering the radiation pattern of AE, the source is suggested as a longitudinal crack parallel to applied compressive load. The WT-coefficient pattern of unloading AE detected at a low stress level, shown in Fig. 7(b), is quite similar to that of loading AE. Therefore, it is strongly suggested that the unloading AE was emitted from microscopic crack propagation at the longitudinal crack tip due to the wedging effect of debris. Thus, it can be suggested that the damage during crack closure is the dominant factor of strength degradation by compressive cyclic loading.

Conclusions

The microfracture process in bovine cortical bone under cyclic loading was investigated in this paper. Microdamage, such as microcracking, was monitored by AE measurement. The wavelet transform analysis of AE signals detected during loading and unloading yields the essential information of fatigue fracture. The following conclusions were obtained.

1. For the static compression test of cortical bone, few damage accumulation was detected.
2. AE signals detected during loading and unloading can be discriminated. The majority of AE signals were detected during unloading, which parallels the decrease in strength during fatigue as suggested by the observed decrease in ultrasonic wave velocity.
3. Unloading AE exhibits ‘AE bands’, which is corresponding to the behavior of individual microcracks. AE wavelet transform analysis suggested that unloading AE indicates the crack propagation parallel to compressive loading.
References