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Ultrasonic Characterization of Damage Accumulation in Cortical Bone under Cyclic Loading

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Damage accumulation in bovine cortical bone under cyclic loading was characterized by AE monitoring and ultrasonic wave velocity measurement. Static and fatigue compression tests were performed and microfracture process was investigated by AE technique. In static test, remarkable AE increase was observed only at final fracture, while continuous AE activity was observed during fatigue test. Longitudinal wave velocity along radial axis of the bone decreased gradually during fatigue loading. Furthermore, the AE signals corresponding crack opening and closure were discriminated. Comparing the AE behaviors during static and fatigue tests, and decrease in wave velocity during fatigue test, it was understood that the crack opening AE emitted from crack propagation and crack closure AE has dominant role for degradation of strength of bone under cyclic loading.

Key words : Cortical Bone, Fatigue Fracture, Mechanical Property Degradation, Ultrasound Characteristics, Acoustic Emission

1. INTRODUCTION

Cortical bone has the role of supporting load in a human body. It consists of hydroxyapatite matrix and collagen fibers aligned along the long axis and has the microstructure similar to unidirectionally reinforced composites [1-2]. When bone is subjected to cyclic loading excessively, fatigue fracture takes place as metals [3]. Previously, various studies on damage accumulation or mechanical property degradation of bone under cyclic loading were carried out [4-5]. However, microscopic fracture process of bone, which is indispensable for the development of accurate diagnosis technique of bone fatigue fracture, has not been understood well.

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. Static and fatigue compression tests of bovine cortical bone were carried out. Especially, damage accumulation process was characterized by AE monitoring during fatigue test. The longitudinal wave velocity was also measured and compared with AE generation behavior. Finally, the degradation process of bone under cyclic loading was discussed.

2. EXPERIMENTAL PROCEDURE

2.1 Specimens

Bovine cortical bone, whose properties are similar to properties of human cortical bone, was used for the materials in this study. The microstructure of the bovine cortical bone is classified into two tissues, plexiform and haversian bone. In this study, the plexiform bones were investigated. An optical micrograph of typical cross-section, perpendicular to longitudinal axis, of the plexiform bone is shown in Fig. 1. It is observed in the figure that lamellae are aligned along longitudinal direction. A number of lacunae were also observed among lamellae, which would 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 as shown in Fig. 2. The specimens were kept frozen at –20°C, then cut under flowing water and kept wet during the mechanical tests. Symbols '1', '2' and '3' refer to the radial, tangential and longitudinal directions, respectively, as indicated in Fig. 2. The mechanical load was applied along longitudinal direction (x_3) as in body.

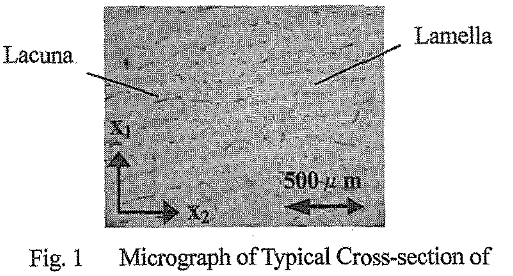

Fig. 1 Micrograph of Typical Cross-section of Plexiform Bone

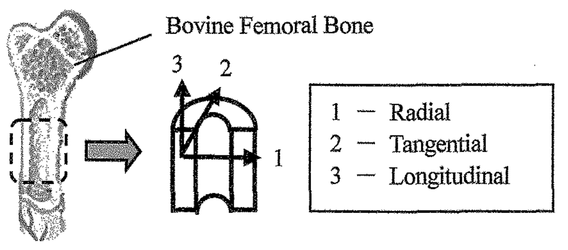

Fig. 2 Specimen Axes Corresponding to Each Direction of Bone

2.2 Static Compression Test

In order to obtain the fundamental fracture behavior of bone, static compression tests were carried out in air at room temperature under constant crosshead speed of 0.1 mm/min. A schematic diagram of compression test system is shown in Fig. 3. Longitudinal strain was measured by a strain gage attached directly on the specimen. The AE signals emitted from the specimens were measured in order to monitor the microscopic fracture behavior during tests. Two AE sensors were attached on the both sides of the specimen. Two types of AE sensors, 'PAC Pico' (resonant frequency of 400kHz) and 'NF AE-900M' (broad-band type), were used. The gain of pre-amplifier was 60 dB, and the band pass filter was used with a range of 100 kHz to 1200 kHz. Threshold level was set to 43 dB (≒141 μV at the input terminal of the a pre-amplifier).

2.3 Cyclic Compression Test

Compression fatigue tests were carried out under sinusoidal cycling loading of 3 Hz and load control in compression-compression mode with a stress ratio of 0.05. Considering the variation of mechanical properties of each sample, the stress amplitude, σ_a, during the test was normalized by the initial Young's modulus, E^*, which was measured under a single loading cycle with frequency of 0.3 Hz before each test. AE measurement condition was same as the static tests, except for the threshold level of 45 dB (≒178 μV).

During cyclic compression test, longitudinal sound velocity in radial direction (x_1) was measured at every 300 - 400 cycles intermittently, in order to monitor the degradation of mechanical properties. Schematic diagram of the velocity measurement is shown in Fig. 4. Rectangular wave with amplitude of 10 V and frequency of 1 MHz was transmitted along redial direction of the specimen. Wave velocity was calculated by dividing the measured distance by the transit time of sound wave.

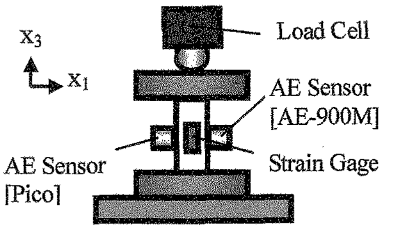

Fig. 3 Compression Test System

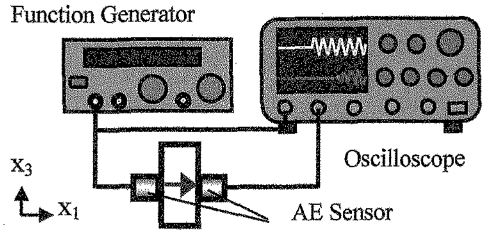

Fig. 4 Wave Velocity Measurement System

3. RESULTS AND DISCUSSION

3.1 Static Compression Test

To investigate fundamental mechanical properties of bone, static compression tests were performed. Figure 5 shows the stress-strain curve and the AE behavior during the static compression test. The linearity of stress-strain relationship is observed in the figure except for slight deviation from linearity at the final short stage. Furthermore, remarkable AE activity was recognized just before final fracture. These results suggest that the damage accumulation is not remarkable during static compression tests. Average strength, fracture strain and Young modulus were 139.2 MPa, 0.0061 and 24.1 GPa, respectively.

For almost all of compression tests, catastrophic fracture of specimen was observed and final fracture surface was parallel to loading axis (x_3) and perpendicular to radial axis (x_1). It is indicated that the strength along radial direction is much lower than the other, since lamellae structure is formed along tangential axis as shown in Fig. 1. It is then understood that the fracture process, such as crack initiation and propagation, among lamellae is dominant in the bone.

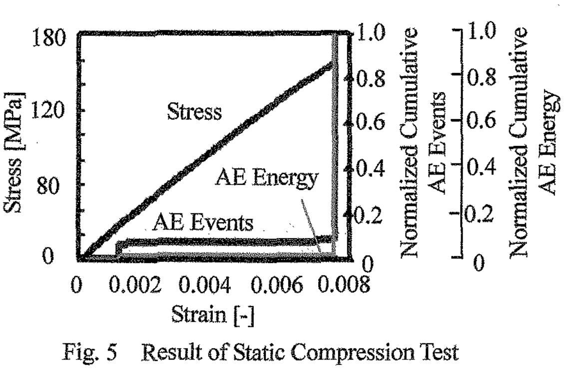

Fig. 5 Result of Static Compression Test

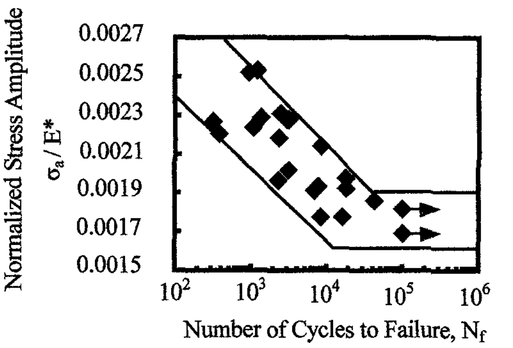

Fig. 6 S-N Curve for Plexiform Bone under Cyclic Compression Loading

3.2 Cyclic Compression Test

Figure 6 shows normalized S-N curve (normalized stress amplitude, σ_a/E^* versus number of cycles to failure, N_f) for bovine plexiform bone. In this study, E^* ranged from 20.9 GPa to 29.5 GPa. Although the wide variation of the data is seen, typical fatigue behavior was obtained. The lower σ/E^* is, the longer the fatigue lifetime is until ~10^4 cycles, while the fatigue limit can be recognized as σ_a/E^* of 0.0016~0.0019. It was reported by Pattin et al. [5] that critical degradation in Young's modulus is observed above σ_a/E^* of 0.002, for the compressive fatigue test of human cortical bone. The fatigue limit was not clearly reported in their work, but their results suggest that fatigue limit exists around 0.002, which is equivalent to the result of this study. Similarly to static compression tests, final fracture took place along lamellae.

Figure 7 shows the distribution of AE signals detected during the cyclic test at σ_a/E^* = 0.0023 (E^* = 23.0 GPa). The figure indicates the normalized stress and cycle when each AE signal was detected. Several characteristic 'AE bands' consisting of many AE signals are found in the figure. Those 'AE bands' might correspond to specific features of fatigue fracture, such as crack opening, closure etc. as discussed in the following section. Since the AE signals at low stress level (σ/E^* < 0.0015 : the area surrounded by dashed line) may not concern with fatigue fracture, those were neglected in the following AE analysis. Cumulative number and energy of selected AE events are shown in Fig. 8. In the figure, cumulative AE events and energy are normalized by each maximum, but the exploding increase at final fracture is omitted. As in the figure, AE events increases gradually until ~1000 cycle followed by nearly steady state and exploding increase at final fracture. On the other hand, most of AE energy was detected at the final fracture. Comparing the AE behavior under static compressive loading, cumulative AE energy shows similar tendency but the different behavior of cumulative events is recognized.

The longitudinal wave velocity measured during fatigue tests is also shown in Fig. 8. The wave velocity decreased gradually. Lee et al. [6] demonstrated that the decrease in wave velocity could be related with the degradation of mechanical properties. Therefore, it is suggested that the strength of bone decreased during fatigue test due to microdamage accumulation.

3.3 Damage Accumulation in Bone under Cyclic Loading

In order to clarify the damage accumulation process in more detail, AE behavior was investigated precisely. AE events detected during loading and unloading were discriminated and their distribution is described in Fig. 9 (σ_a/E^* = 0.0024, E^* = 26.7 GPa). It can be seen in the figure that majority of AE events were detected during unloading and AE events during loading were detected around peak stress. It is also understood that most of loading AE were detected at initial and final stages.

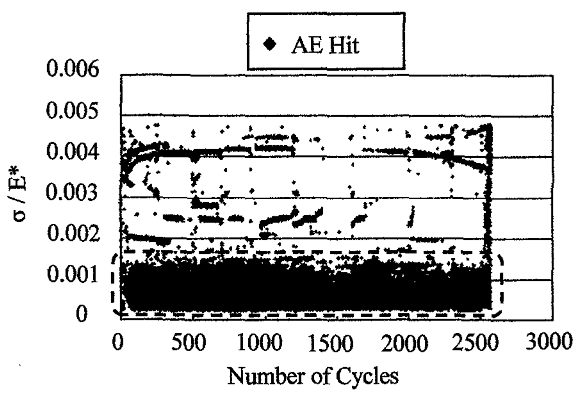

Fig. 7 Distribution of AE Events during Compressive Fatigue Test [σ_a / E* = 0.0023]

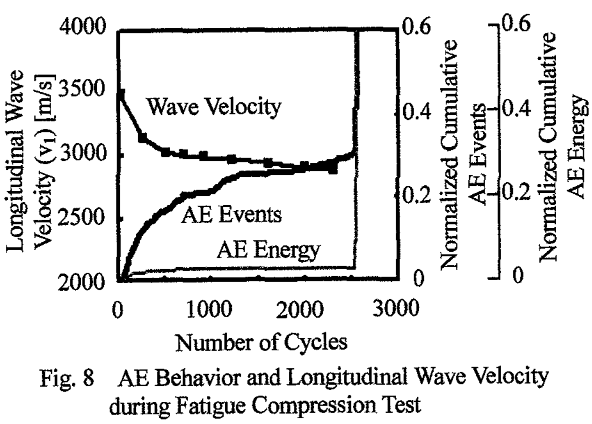

Fig. 8 AE Behavior and Longitudinal Wave Velocity during Fatigue Compression Test [σ_a / E* = 0.0023]

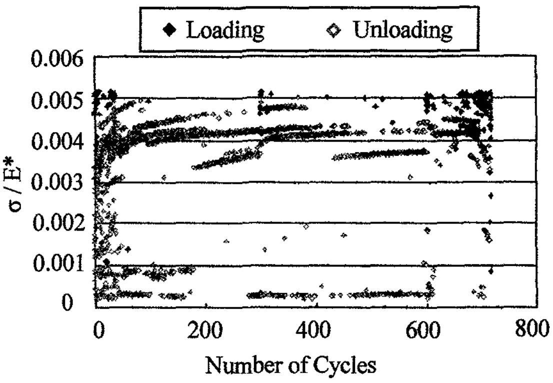

Fig. 9 Distribution of AE Events during Compressive Fatigue Test [σ_a / E* = 0.0024]

Generation behaviors of those discriminated AE and longitudinal wave velocity are shown in Fig. 10. For the AE signals during loading (Fig. 10 (a)), most of AE events and energy were detected just before the final fracture. It is important that the tendency is quite similar to static compression test. On the other hand, generation behavior of unloading AE (Fig. 10 (b)) has a tendency similar to both decreasing behavior of wave velocity and increasing behavior of cumulative events of whole AE (Fig. 8).

AE events detected during loading and unloading correspond to crack opening and closure, respectively. Since the loading AE events and energy increased similarly to static compression test, the loading AE were considered emitted from crack propagation from pre-existing flaws, such as lacunae, during crack opening. On the other hand, unloading AE correspond to microdamage accumulation during crack closure, such as crack propagation due to the wedging effect of debris, because decrease in wave velocity, of which tendency is similar to increase in unloading AE, reflects the degradation of mechanical properties. Consequently, it can be concluded that the damage during crack closure might be the dominant factor of strength degradation by compressive cyclic loading. Although quantitative mechanisms of those processes have not been clarified, the process of damage accumulation under cyclic loading was well described in this study.

4. CONCLUSION

The damage accumulation in bovine cortical bone subjected to compressive cyclic loading was characterized by AE and ultrasound velocity measurements in this study. While the fracture of bone under static loading was catastrophic, damage accumulation in the bone was detected by AE signals and degradation of wave velocity during

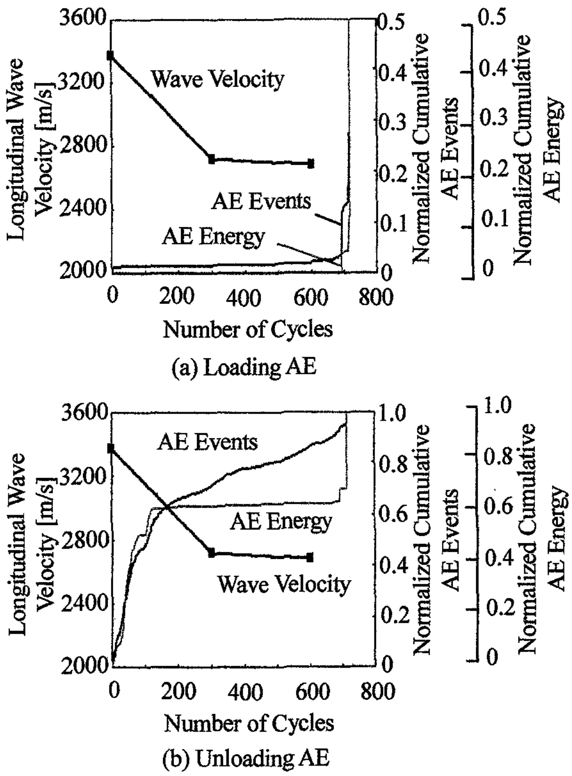

Fig. 10 AE Generation Behavior and Longitudinal Wave Velocity during Fatigue Test

fatigue fracture. Especially, the microdamage during crack opening and closure could be discriminated clearly by AE technique. Damage during loading was crack propagation, similarly to the damage under static loading. On the other hand, the damage during unloading has not been clear yet, but those were dominant in the degradation of the bone under cyclic loading. Finally, the fundamental knowledge for accurate diagnosis of bone fatigue fracture was obtained in this study.

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