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Fractography of Human Intact Long Bone by Bending

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Summary. Human intact tibiae were tested using the static bending method to learn about the relationship between the fracture surface and the failure mode. The bending test was applied to test pieces and to whole bones. The fracture surface was observed by scanning electron microscopy. The bone fracture is closely related to the architecture of the bone substance, especially to the direction of the Haversian canals and the lamellae. The failure mode and the sequence of the break line of the bone can be found out by the observation on the fracture surface. Hardly any crushing effects caused by the compressive force is seen. The mechanical properties of the fractured bone can be estimated to some extend by considering the direction of the break line and the failure mode. The strength calculated by the simple beam formula for elastic materials can not be obtained directly because of the plastic deformation of the bone. The results of the tensile test may be applied to the fracture using the static bending moment.

Zusammenfassung. Um die aktuelle Analyse vom Mechanismus des Knochenbruchs deutlich und ausführlich zu erfassen, wurden der Biegungsversuch und die Raster-Elektronenmikroskopische (REM) Untersuchung durchgeführt. Eine enge Beziehung zwischen dem Knochenbruch und den strukturellen Eigenschaften des menschlichen Knochens (Tibia), beziehungsweise der Verlaufsrichtung der Haverschen Kanäle und Lamellen, wurde festgestellt. Die Befunde der Bruchfläche, die mit der Hilfe von REM beobachtet werden, geben sichere Information in Bezug auf den Zerstörungstypus und die Richtungen der Bruchlinien; daraus läßt sich die Rolle des dynamischen Verhaltens des Knochens beim Bruch vermuten. Wegen der komplizierten mechanischen Eigenschaften der Knochenstruktur ist es unmöglich, wie bei der Zerstörung von elastischem Material, das homogen ist, die Fraktur mit einer Formel zu erfassen. Es wird auch erwartet, daß die Theorie von der Zugfestigkeit bei der Analyse des Knochenbruchs durch statische Biegekräfte (d.h. Biegungsfraktur) anwendbar ist.

Key words. Fractography – Fracture of long bone, by bending

Introduction

Bone fracture was studied from the mechanical viewpoint such as by observing the mode of fracture and the measurement of the mechanical properties. The traffic accidents these days make it important to study the bone fracture (Sellier, 1963). Among the many studies on the bone fracture, there has been done little work on the microscopic observation of the fracture surface in relation to the mechanical feature of the bone. Piekarski (1970) measured the resistance of the bovine bone to the fracture and correlated it with the observation of its microstructure. His observation technique included the scanning electron microscopy (SEM). Pope and Outwater (1972) discussed the mechanical properties of bone in relation to the fracture characteristics. They demonstrated the fracture surface of canine tibia by SEM. Carter and Hayes (1976) observed the fracture surface of the bovine bone by SEM in the case of fatigue fracture.

We studied the relationship between the mechanical properties and the failure mode of the bovine bone (Kimura et al., 1975; Tateishi et al, 1976) and of the human long bone (Kimura et al., 1976). The mechanical properties were examined from the viewpoint of the directional differences. The failure mode was able to be estimated from the observation on the fracture surface by SEM. Considering the direction of the break line, the cause of the fracture could be surmised. The mechanical properties of the fractured bone could be estimated to some extend from the results of the tests carried out. The loading tests on the human bone were performed under the normal force on the test pieces. The failure mode of the bone is closely related to the architecture of the bone substance. The microstructure of the human long bone is somewhat different from those of other animals such as bovine and dog (Currey, 1960; Fukushima, 1973). It is necessary to study not only the animal bone but the human bone in order to observe the fracture surface in detail.

In this paper, we examined the whole human bone to learn about the relationship between the fracture surface and the failure mode. We tried the static bending test because the bending moment has the most important role in relation to the strength of the long bone (Kimura, 1974 a). Before examining the intact bone, we performed the bending test on the test pieces to study the mechanical characteristics and the failure mode in several directions of the bone using the bending. The bending test in the directions other than longitudinal was not throughly performed.

Materials and Methods

The material test using the bending was performed on two fresh human adult tibiae. Three specimens were prepared from a single tibia, one in the longitudinal direction, one in the direction 45° to this and one in the transverse direction. The test pieces were rectangular bars 3 mm wide and 3 mm high. One of the bones did not have a thick enough compact substance, so we made the specimen in the 45° and 90° directions of this bone 4.5 mm in width and 1.5 mm in hight. The bending test was carried out using the Instron Type Testing Machine (Shinkoh TOM 500). The specimen was supported on two ends by steel rollers of 2 mm in diameter. The distance between the rollers was 40 mm in the longitudinal direction and 20 mm in the other directions. The middle of the bar was loaded by an edge of 2 mm in radius with a loading speed of 1 mm/min from the outer side of the bone. Ultimate normal strength σ was calculated using the beam theory from the formula:

$$\sigma = \frac{Mh}{2I}$$

where M is the bending moment, h the height of the specimen and I the moment of inertia of the cross section. The stress-strain curve on the tensile side in the middle of the bar was recorded by the strain gage technique.

The intact bones of the human adult tibia were fractured by static bending. Four pairs of macerated dry bones and a fresh wet bone were tested. The methods and the results of the mechanical characteristics of the dry bones were already reported (Kimura, 1974 a and b). The upper and lower ends of the tibia were covered by rectangular polyester plastic blocks of 10 cm wide, 6.5 cm long and 4 cm high. The plastic blocks covered the ends of the bone up to a distance about 2 cm from the articular surface. The blocks were supported on both ends by steel rollers of 8 mm in diameter at the level of the articular surface. The middle of the bone was loaded sagittally by an edge of around 2 mm in radius. The Instron Type Testing Machine was used with the loading speed of 0.5 mm/min for the dry bones and 1 mm/min for the fresh one.

When the tests were completed, the fracture surface were observed by SEM (Hitachi-Akashi MSM 5). The specimens were evaporated with carbon and gold.

All the fresh bones were deep frozen at −20°C while not being used and were kept in a wet condition until evaporation. Tests were carried out at about 20°C.

Table 1. Bending test on the test pieces (n = 2)

Angle degree	0°	45°	90°
Ultimate strength kgw/mm^2	26.6	11.0	11.8
Yield stress kgw/mm^2	16.3	9.3	9.9

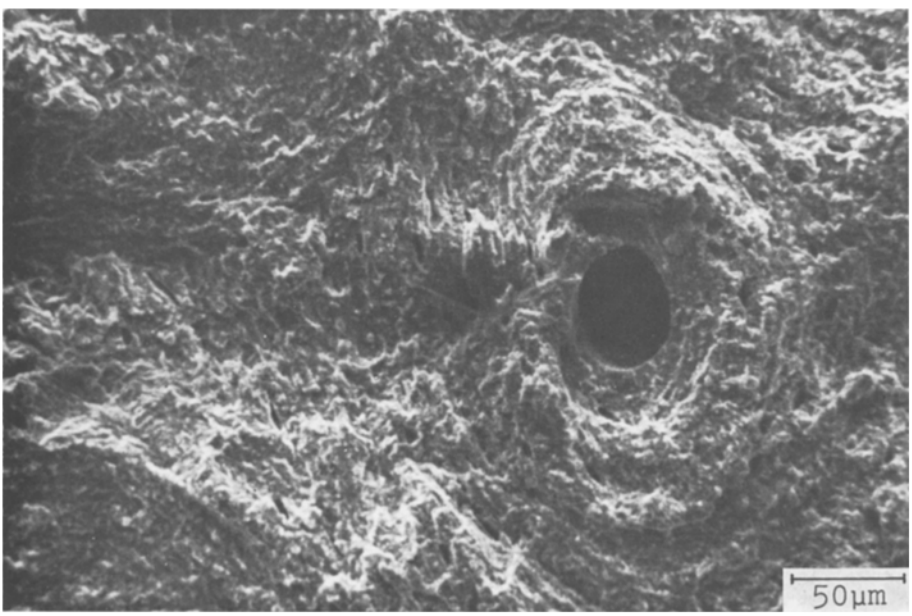

Fig. 1. Tensile ductile fracture on the side opposite the loading point

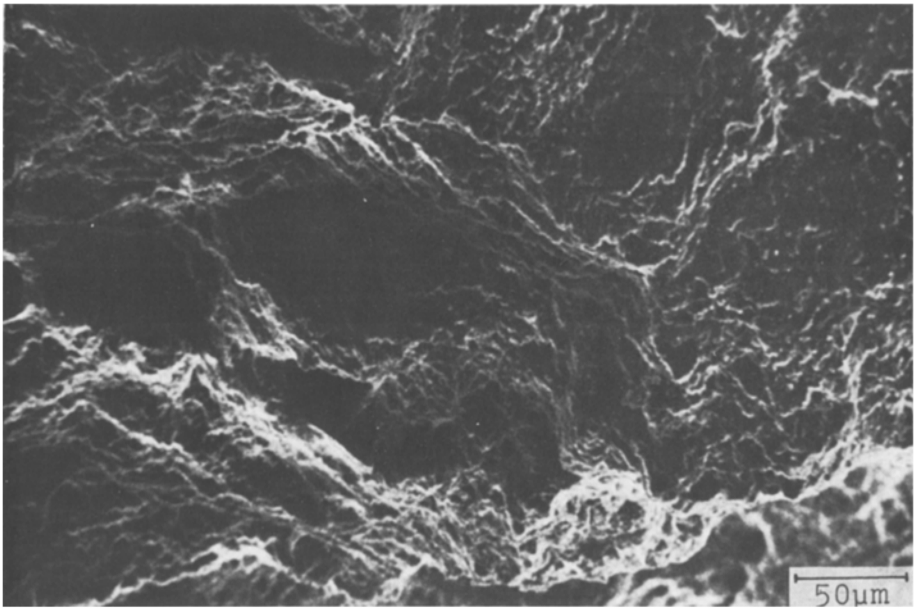

Fig. 2. Obliquely cut lamellae showing a shear fracture

Results of Test Piece

The mechanical properties by the bending test are shown in Table 1. The specimen in the longitudinal direction is much stronger than that in the other directions. Using the simple beam formula, the yield stress is calculated from the load when the plastic flow begins from the tensile side.

The break line of the specimen in the longitudinal direction is usually Y-shaped. The side opposite the loading point fractures transversely to the bone axis (Fig. 1). The surface is rugged. The Haversian canals and the lamellae are cut transversely. The surface shows the same pattern as that of the tensile fracture of the specimen in the longitudinal direction (Kimura et al., 1976). The failure mode here is the tensile ductile fracture. In the middle of the bar, the break line radiates in two directions. The lamellae are cut obliquely by the shearing force (Fig. 2). Then the line runs nearly longitudinally. We can see the cleavage facets caused by the cleavage fracture along the lamellae (Fig. 3). The break lines end transversely to the axis on the loading side, showing the ductile fracture and not the compressive feature.

The specimen in the transverse direction shows a break line crossing the specimen at a right angle. The fracture surface is flat and appears to be a widely spread cleavage fracture as in the tension test on the specimen in the 90° direction (Kimura et al., 1976).

The break line of the specimen in the 45° direction crosses the test piece at an angle of nearly 45°, that is the direction of the axis of the whole bone. We can see the cleavage facets on the surface. There may also exist the ductile fracture by the shearing force cutting the lamellae obliquely. Cleavage steps are sometimes quite high and they form a rugged feature.

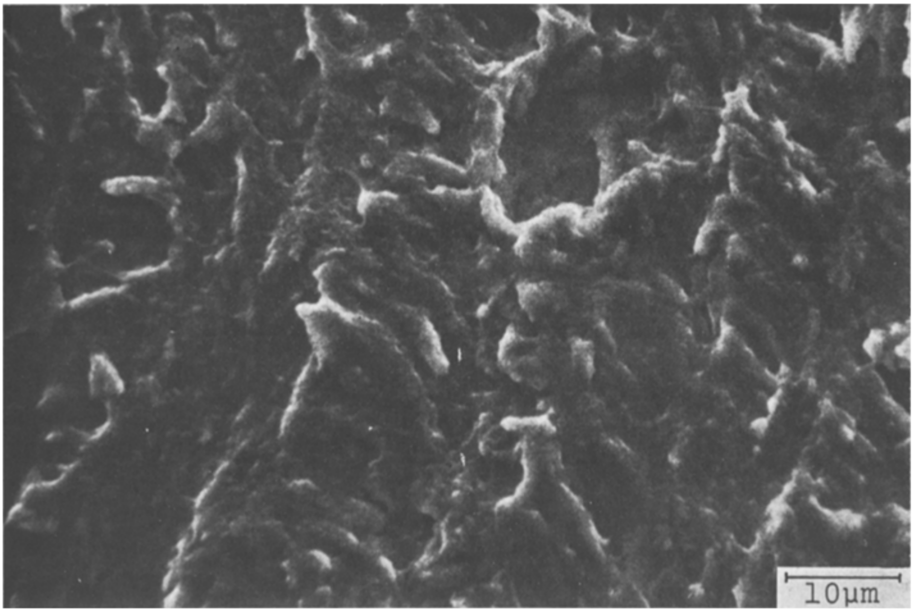

Fig. 3. Cleavage fracture with cleavage facets

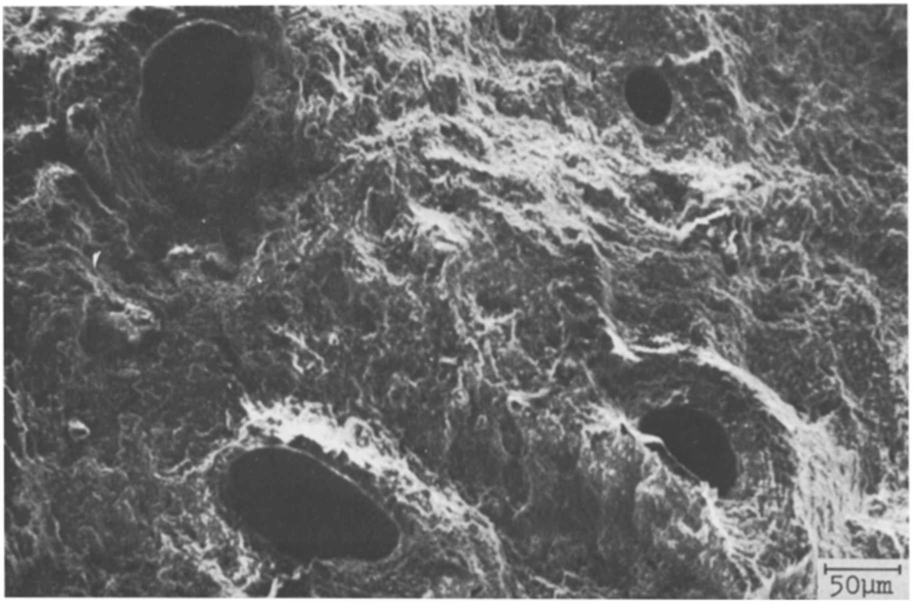

Fig. 4. Fracture surface on the side opposite the loading point of a whole bone

Bending Fracture of Whole Bone

The fresh tibia was fractured transversely at the loading site. Many cracks started to run longitudinally from the cross sectional fracture plane.

The fracture surface of the side opposite the loading point is rugged but nearly at a right angle to the bone axis (Fig. 4). This side is the tensile side of the bone. The surface shows dimple-like patterns and microcracks which pass through the canals and lacunae (Fig. 5). This surface apparently shows a tensile ductile fracture as shown in Fig. 1. Some kinds of ruggedness may show tear ridges.

Midway between the loading point and the back side the break line meanders a little. The surface is wavy and the lamellae is cut obliquely (Fig. 6). This may show a shear fracture.

The loading side of the bone shows a zig-zag pattern appearance. The fracture surface contains both the cleavage and the ductile fracture (Fig. 7). The Haversian canals are cut obliquely. The crushed feature caused by the compressive force (Kimura et al., 1976) can scarcely be seen here.

The crack running nearly in the longitudinal direction shows a cleavage fracture. The Haversian lamellae are torn at the interlamellar site (Fig. 8). The Haversian canal is cut longitudinally.

The dry bones break more dynamically with less time than the fresh one. The break line radiates from the back point of the loading point to the surface on which the load is applied (Kimura, 1974 a and b). The fracture surface shows the same pattern as that of the fresh bone both on the loading side and the opposite side. The break line radiates mainly in the direction oblique to the bone axis. The cleavage fracture can be seen on this surface.

Discussion

The test piece in the transverse direction is much weaker than that in the longitudinal direction. The Haversian canals and the lamellae are arranged in series in the transverse direction. The bone becomes easily cleaved with a small magnitude of stress. On the other hand, the canals and the lamellae are arranged in parallel in the longitudinal direction. The fracture starts on the tensile side where the ductile fracture can be seen by SEM. The lamellae may resist a large plastic deformation and a large breaking energy. The specimen in the 45° direction shows about the same strength and about the same cleavage fracture as that in the transverse direction. The cleavage fracture starts with a small breaking energy in this bone in the direction parallel to the lamellae, that is the direction of the axis of the whole bone.

The bending strength in this experiment is larger than that reported by Tsuda (1957) on the specimen in the longitudinal direction (20.2 kgw/mm^2) and by Dempster and Coleman (1961) on the specimen „parallel-to-grain“ (19.1 kgw/mm^2) and „cross-grain“ (3.3 kgw/mm^2). The tendency that the „cross-grain“ specimen is much weaker than the specimen „parallel-to-grain“ shows the same pattern with our results.

The ultimate strength by bending test of ours and other investigators is not measured directly but derived from the simple beam formula for the elastic materials shown under „Materials and Methods“. The fracture may not occur within the elastic limitation of the material. The fracture surface on the tensile side, where the break

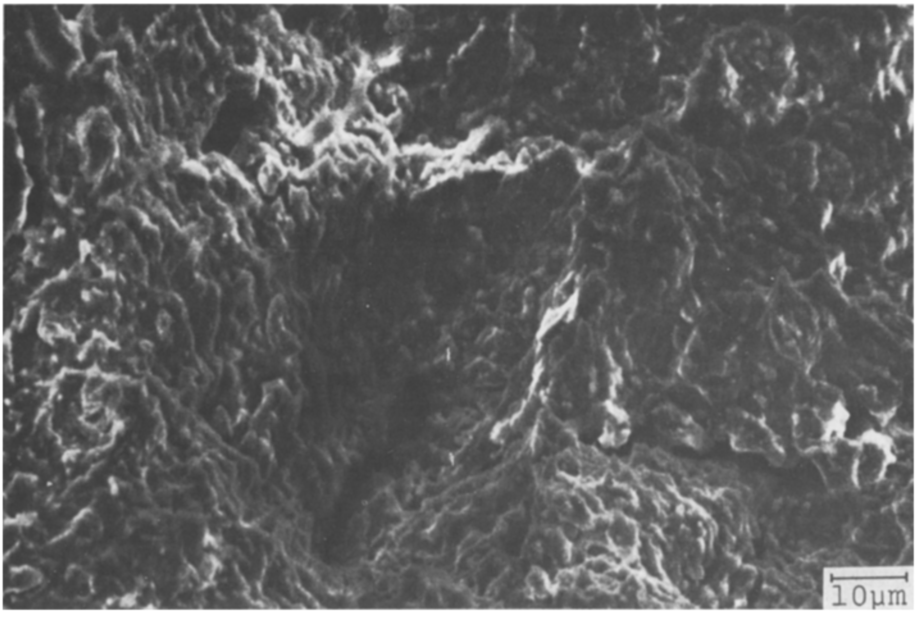

Fig. 5. Dimple-like patterns and microcracks

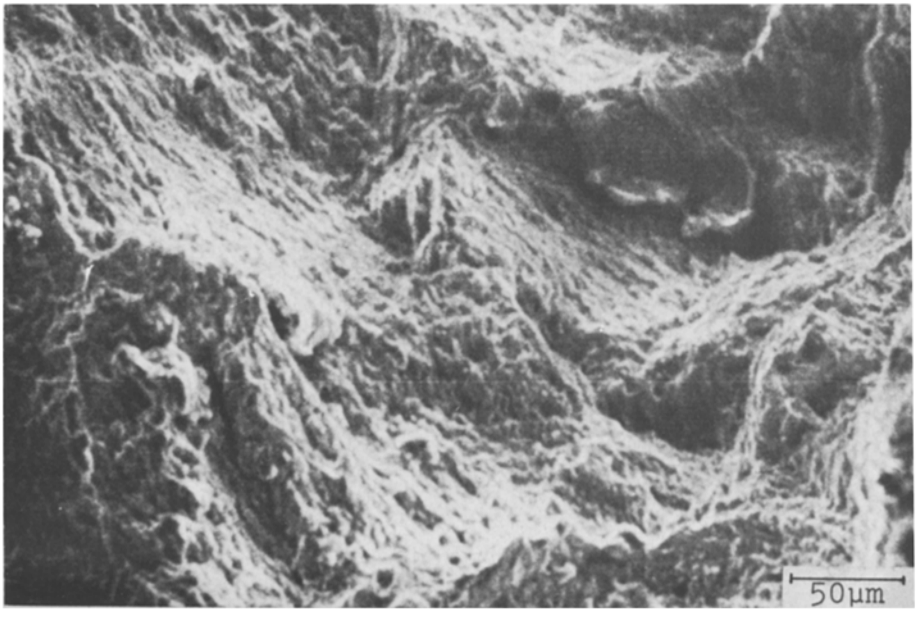

Fig. 6. Obliquely cut lamellae of the whole bone

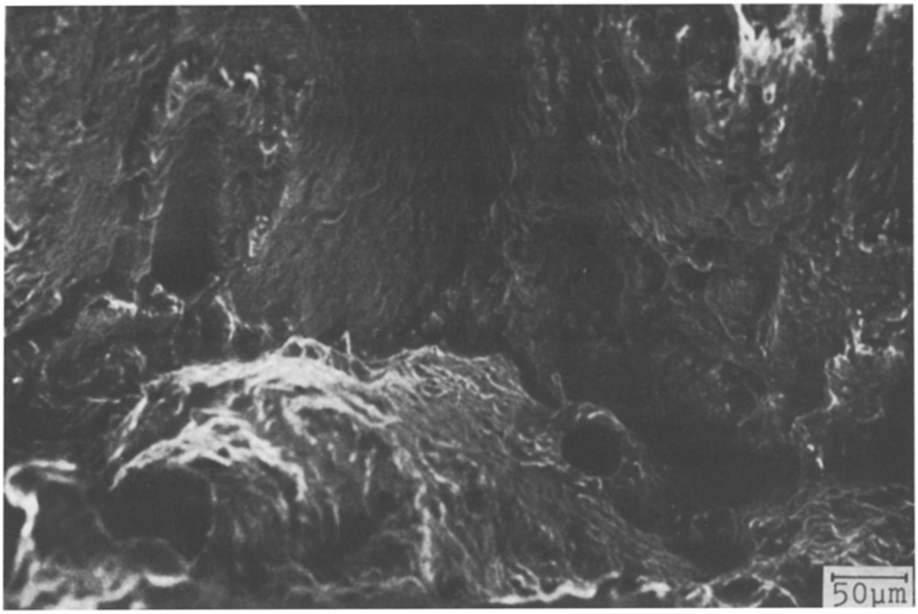

Fig. 7. Fracture surface on the loading side of the whole bone. The cleavage fracture (above) and the ductile fracture (below)

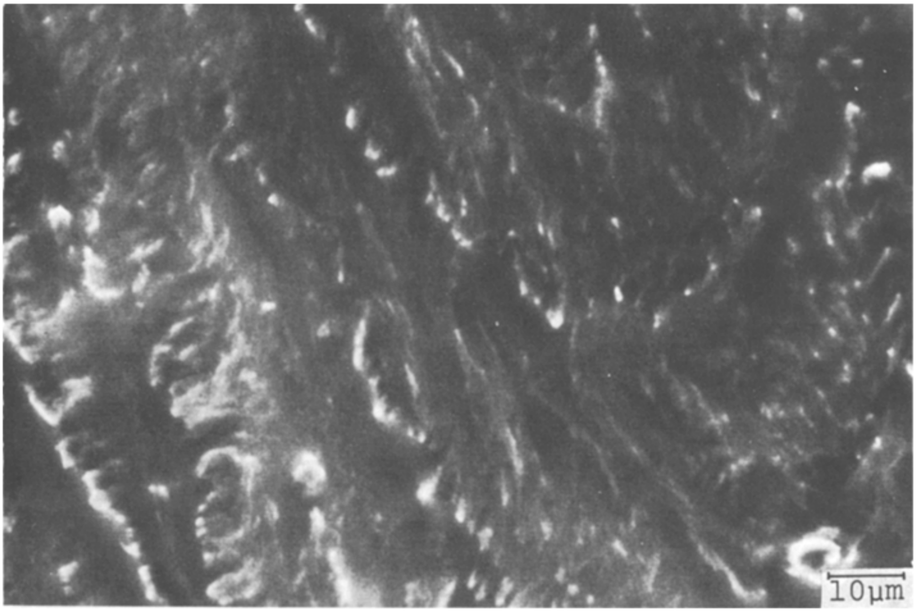

Fig. 8. Haversian lamellae being torn and forming cleavage facets

line starts, shows a large plastic deformation as seen from the stress-strain curve. The ultimate bending moment depends on the size of the plastic zone as described by Burstein et al. (1972). The yield stress in Table 1 is calculated from the load at the time when the plastic flow begins on the tensile side, because until this time the elastic formula on the simple beam can be applied. The yield stress is smaller than the calculated bending strength. The measured tensile and compressive strength (Kimura et al., 1976) also contains the result of the plastic deformation. But the magnitude of them seems to show a more precise value of strength than be bending strength calculated from the elastic formula, as it is difficult now to define the plastic bending of the bone.

The whole intact bone starts to break with the same mode as that of the test piece in the longitudinal direction. The tensile side shows a ductile tensile fracture with a large breaking energy. Then the fracture surface changes to a obliquely running shear fracture. The bone finally breaks by the ductile and the cleavage fracture being alternately applied. On the cracks or the radiated break lines which run neary parallel to the longitudinal direction, we can see the cleavage facets parallel to the lamellae as in the test piece using the bending test. The line may easily grow in this direction with the small energy as seen from the specification tests using the test pieces.

The pattern difference of the break line of the tibia was explained by the concentration of the load by Sellier (1965). Kawase (1965) broke many kinds of long bones by the bending and showed that the break line of many tibiae run transversely in contrast to the Y-shaped break line of the other long bones. The difference in the visco-elastic properties between the wet bone and the dry one may be also related to the difference in the break line.

The mechanical properties of the bone at the fractured place can be estimated to some extent by considering the angle of the break line and the failure mode. There is scarcely a compressive pattern of failure, so the results of the tension test (Kimura et al., 1976) can be applied. The results of the bending test may not directly be applied to the intact bending test as discussed before.

Conclusion

The failure mode of the intact human long bone under the static bending moment can be known by the observation on the fracture surface.

The failure mode depends deeply on the direction of the break line. The angle between the break line and the structure of the bone, that is the arrangement of the lamellae and the Haversian canals, shows a good agreement with the failure mode.

The starting point of the break line and the point where the break ends can be determined from the observation of the failure mode. The break starts by a tensile ductile fracture. On the other hand, the part where the break ends shows both the shearing and the cleavage fracture. There is hardly seen any compressive fracture.

The mechanical properties at the failure point can be estimated to some extent from the results of the tensile test on the test piece by considering the direction of the break line and the failure mode. The results of the bending test on the test piece can not be directly applied.

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