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ANALYSIS OF THE FRACTURING PROCESS OF NATURAL COMPOSITE ON EXAMPLE OF THE CORTICAL PART OF BONE

ABSTRACT

The short characteristics of the natural composite-bone is given. The parameters which characterised the bone mineral density (BMD) such as DEXA and QCT are presented. Furthermore, based upon the concept of cortical index CI, the characteristics of this one and short discussion about them – with possibility to predict the bone strength and fracture resistance – are made. Finally, the information about capability of the used fracture mechanics parameters such as K and δ to quantitative assessment of the fracture of cortical part of bone are presented.

Key words*: natural composites, bone, density, strength, fracture parameters.*

INTRODUCTION

The modern materials science in connection with biomechanics to create the new area of search the mechanical properties of the natural composite whose classical example are the bones. Understanding how the bone fractures has basic meaning to predict the damage of the bone. This is mainly associated with age or disease of the patients – for example in case of the osteoporosis disease of bones. The osteoporosis of bones is the metabolic disease and it is characterised by [1]:

- decrease of mass of bone tissue,
- change of the external and the internal geometric dimension of the traverse section of bone (*Fig.1*).

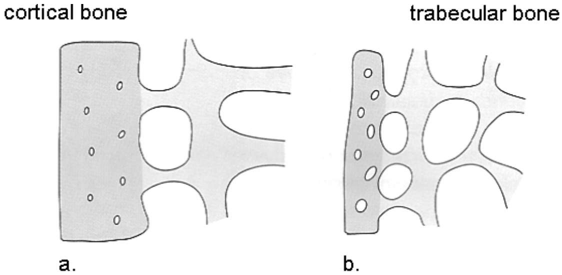

Fig. 1. Process of loss of the bone mass and micro architectural deterioration of bone tissue: cortical and trabecular [1].
a) correct bone, b) result of osteoporosis disease

Mostly common parameter used for the assessment of decrease of mass is the bone mineral density (BMD). The techniques for measuring bone mineral density is mainly used dual X-ray absorptiometry (DEXA) or quantitative computed tomography (QCT). DEXA can be used as an accurate and precise method to monitor the changes in bone density in form of the "surface densities" in (g/cm^2). QCT technique is unique, in that it is provided for true three-dimensional imaging and reports BMD as true volume density measurements in (g/cm^3).

Let's consider the influence of change of the geometric and BMD feature on the mechanical properties of natural composite – bones. As a measure of the influence of change of geometric feature we will use the cortical index (CI). However, as a measure of the influence of change of BMD and structure of bone tissue we will use the fracture mechanics parameters.

CORTICAL INDEX WKT AS A MEASURE OF CHANGE OF GEOMETRIC DIMENSION

Particularly, the neuralgic areas of bones' fractures are the femoral bones. Especially it concerns the end of the femoral bone in the area of the neck. One of the recognised parameters, which is used to estimate the mechanical properties, is the cortical index CI – *Fig. 2*.

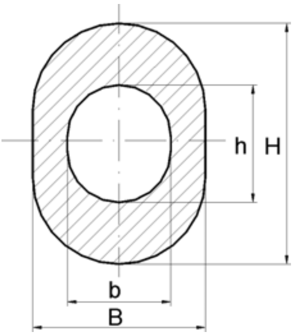

Fig. 2. Section of the femoral bone

The index CI for the cortical part of femoral bone is as follows [2]:

$$CI = \frac{\frac{H-h}{H} + \frac{B-b}{B}}{2} \tag{1}$$

where:

H, B – external dimension of the section of the femoral bone,
h, b – internal dimension of the section of the femoral bone.

While further analysing the cortical index CI, we can transmit the equation (1) in the following form:

$$CI = \frac{g_H}{H} + \frac{g_B}{B} \tag{2}$$

where:

$$g_H = \frac{H-h}{2} \quad ; \quad g_B = \frac{B-b}{B} \tag{2 a, b}$$

By reason of above statement the cortical index CI defines the normalised change of thickness of cortical part of bone in place of the measurement of geometric dimension b, B, h, H. As result of this fact there should take a stand definite relation among CI and mechanical feature of bone such as strength, elastic modulus, fracture resistance [2]:

$$\sigma_g = 0.040\ CI^2\ (r = 0.72,\ v = 21\%) \tag{3}$$

$$E_g = 3.23\ CI^2\ (r = 0.49,\ v = 33\%) \tag{4}$$

$$K_c = 0.092\ CI^2\ (r = 0.66,\ v = 24\%) \tag{5}$$

where:

σ_g – bending stress, MPa,
E_g – elastic modulus under bending, MPa,
K_c – fracture resistance, $MPa(m)^{1/2}$,
r – degree of statistic correlation,
v – coefficient of variability.

Moreover, the selection of proper mechanical parameters is also important. In modern bone biomechanics, the bone tissue is treated mainly as a elastically deformed solid which is characterised by Young's modulus E, the Poisson's coefficient ν, Lame elastic constants λ, μ etc. In this model the bone is treated as continuous material in which the local uncontinuities such as voids and microcracks are omitted. Thus, the correction of this model is indispensable in order to introduce the fracture mechanics parameters for estimation of bone's effort degree.

BASES OF ESTIMATES OF THE FRACTURE PROCESSES OF CORTICAL PART OF BONE IN ASPECT OF FRACTURE MECHANICS

Modelling the mechanical behaviours of natural composites – bones is not a simple task. The cortical part of bone are heterogeneous and are characterised by the presence of several types of inherent flaws such as voids and microcracks.

Till now employment of principles of fracture mechanics has had a great success in analysing the fracture behaviour of metallic and ceramic materials by introducing a dominant macrocrack. The most popular fracture mechanics parameters K and δ (K-stress intensity factor, δ-crack tip opening displacement) allow to define the fracture criterions as:

$$K_I = K_C \tag{6}$$

$$\delta = \delta_c \tag{7}$$

The left side of the eq. (6) depends on:

a. the applied stretching load – symmetric and normal to the surface of macroscopic crack,
b. the crack length and the geometrical configuration of the body (bone).

The right – hand site of the eq. (6) is a material parameter and it defines the plane stress fracture toughness. K_C transform to K_{IC} at plane strain fracture toughness.
In eq. (7) the δ is the crack opening displacement and δ_c is its critical value.
Furthermore, it is assumed that δ_c is a material constant independent of specimen configuration and crack length. To obtain an analytical expression of eq. (7) in terms of applied and other fracture parameters, the Irwin or Dugdale models are invoked [3]:

– Irwin model

$$\delta_c = \frac{4}{\pi}\frac{K_C^2}{E R_e} \tag{8a}$$

– Dugdale model

$$\delta_c = \frac{K_C^2}{E R_e} \tag{8b}$$

where: R_e – yield point, MPa.

Incrementation of the discontinuity in material such as crack will not follow if:

$$K_I < K_C \tag{9a}$$

$$\delta < \delta_c \tag{9b}$$

The application of the same procedure as above to characterise the toughness of cortical bone by ignoring the heterogeneity and hierarchical microstructure of the material and the existing flaws has had limited success to understand the bone fractures.
Firstly, cortical bone has a complex hierarchical microstructure that affects the initiation and propagation of cracks, which leads, ultimately to fracture.

The bone structure can be considered at many dimensional scales. The bone is composed of collagen fibres bound and impregnated with the carbonated apatite nanocrystals. The mineralised collagen fibres are further organised into a lamellar structure, with roughly orthogonal orientations of adjacent lamellae – 3÷7 μm thick. Permeating this lamellar structure are the secondary osteons with large vascular channels and other discontinuities.

The vascular channels are oriented roughly in the growth direction of the bone and surrounded by circumferential lamellar rings. The characteristics of microstructure are presented in *Tab. 1*.

Table 1. *Dimension of components of bone microstructure*

No	Component of microstructure	**Dimensions**			
		length	width	diameter	thickness
1.	collagen fibres	up to 15 μm	–	50–70 nm	–
2.	carbonated apatite nanocrystals	10 nm	10 nm	–	3–7 nm
3.	lamellar structure	–	–	–	3–7 μm
4.	osteons	–	–	200–300 μm	–
5.	vascular channels (Haversians)	–	–	50–90 μm	–

Ritchie and his co-workers have established that fracture in bone is strain – controlled [4]. Scanning electron micrographs of the fracture paths in human bone, specifically indicating how the crack interacts with the microstructure, are shown in *Fig. 3* and *Fig. 4* [5]. A roughly 1mm long crack propagating out of the notch is in the *Fig. 3* are presented. For crack emanating from the notch, the crack path appears influenced by the osteons.

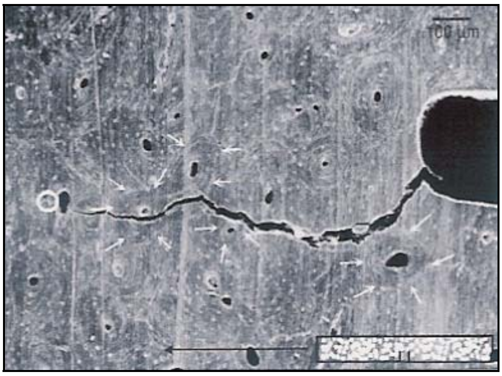

Fig. 3. The crack path influenced by the osteons [5]

Furthermore, a stronger influence of microstructure is evident for the "transverse" orientation with respect to the direction of the osteons, where cracking ahead of the notch is shown at a Havesian canal (dark region within each osteon), although the actual initiation process is at the notch itself – *Fig 4*.

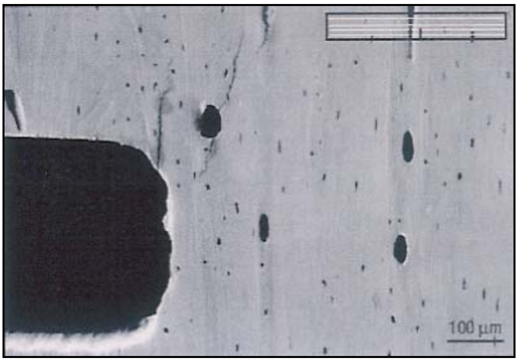

Fig. 4. Characteristic of the microstructure ahead of the notch [5]

These micrographs reveal that not only is the fracture strain – based, but also confirm the marked anisotropy in the toughness of bone.

CONCLUSIONS

The following conclusions drawn:

1. There are characterised the main physical parameters such as DEXA and QCT, which describe the bone mineral density BMD. The BMD effects the strength and fracture resistance of the bone.

2. Based upon the concept of cortical index CI, the characteristics of this one and discussion about them there is made. From the physical point of view the cortical index CI is a measure of change of geometric dimension of cortical bone and also effects the mechanical properties of bone.
3. An analysis of the possibility of using the fracture mechanics (FM) such parameters as K and δ to quantitative assessment the fracture of cortical part of bone are made. The preferred model for assessment the FM parameters is based on the assumption that fracture in bone is strain – controlled. Besides, the anisotropy effects the toughness of bone.

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