

THE INFLUENCE OF OVERLOAD STRESSES ON DURABILITY OF CERAMIC ELEMENTS IN HIP JOINT ENDOPROSTHESES

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Abstract. The paper raises the problems connected with the durability of ceramic elements used in technology. It presents mathematic - statistic methods defining the influence of stress on ceramic elements durability. The paper also contains the results of numerical analysis carried out by the Finite Elements Method in the ADINA system, considering a ceramic elements. The above analysis is confirmed and proved by the experimental tests on a “head - cup” set, carried out on the hip-joint simulator.

Keywords: *durability, stress, numerical analysis*

1. Durability of ceramic elements

The most common solution offered by endoprotheses producers as far as joints construction is concerned, is the application of replaceable cup in metal casing. That solution decreases the range of surgery when the friction elements of endoprosthesis are worn. The cups in such systems usually consist of a metal casing made of titanium alloy Ti6Al4V and an appropriate insert. The replaceable internal element can be made of UHMWPE, bio-ceramic or double-layer materials [1].

All the ceramic materials used in endoprotheses elements are subjected to high loads. It is important that due to the specific shape of tribologically cooperating surfaces, the point of contact is formed.

All the data concerning the durability of ceramic materials can be gained i.e. by mathematic - statistic methods. In this case, the tests are conducted on chosen samples with the same kind and size of defects as the analysed parts. Based on the obtained measurements the conclusions concerning the parameters of whole group of parts, can be drawn. It is mandatory to perform a strength analysis which can lead to assigning the most dangerous fracture by using the pattern:

$$a = \frac{K_I^2}{\sigma^2 Y^2} \quad (1)$$

where:

- K_{Ic} - critical coefficient of stress intensity,
- σ - strength,
- Y - shape coefficient,
- a - apparent length of fracture.

The value of shape coefficient Y is usually approximate [2].

Having the sub-critical increase of fractures it is possible to define the durability of mechanically loaded ceramic elements. Durability t of the ceramic element constantly subjected to load can be calculated as follows:

$$dt = \frac{1}{A(\sigma\sqrt{a}Y)^n} da, \quad (2)$$

and after integration:

$$t = \frac{2}{(n-2)A\sigma^n Y^n} \left(\frac{1}{\sqrt{a_a^{n-2}}} - \frac{1}{\sqrt{a_c^{n-2}}} \right) \quad (3)$$

where:

- a_a - length of the most dangerous fracture before subjecting to load,
- a_c - critical length of fracture.

Using non-destructive methods, it is currently possible to primarily assign length of the most dangerous fracture. When ceramic Al_2O_3 is used in endoprosthesis, the constant values A and n are as follows:

$$\lg A = -40$$

$$n = 60$$

If for the randomly chosen sample the destructive stress distribution is assigned and recalculated by:

$$\frac{\sigma_{b(3-p)}}{\sigma_{b(4-p)}} = \left(\frac{m+2}{2} \right)^{\frac{1}{m}} \quad (4)$$

where for ceramic Al_2O_3 :

$$m = 7$$

$$\sigma_0 = 330 \text{ MPa.}$$

It is possible to define the durability by the equation (3). When the above calculations are made for various stress values σ , the SPT (Strength - Probability - Time) graph can be presented. Based on that - we can settle the amount of samples that have been damaged before the durability time t expires.

When the minimum durability value is required, the method of proof testing can be used.

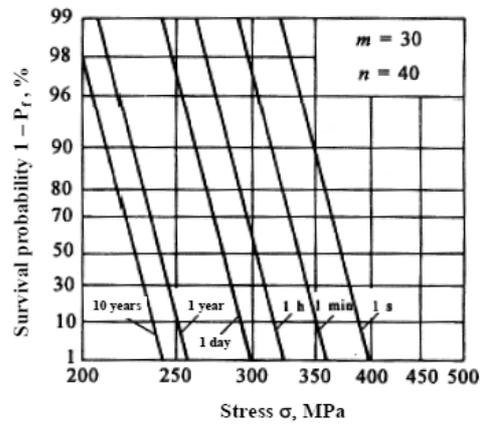


Fig. 1. Graph SPT, dependence of survival probability on stress in various time of load [3]

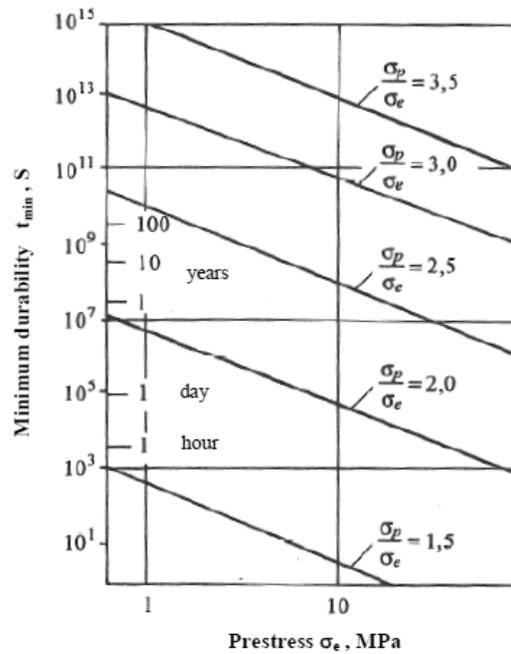


Fig. 2. Graph Proof - test, dependence of minimal durability t_{min} on functional stress s_e for various overloads relations σ_p/σ_e [3]

When using the above method, the tested samples must be initially subjected to stress σ_p , which is higher than stress σ_e , which occurs when the samples are in use. When subjected to the initial load, the samples are not led to damage due to:

$$K_{Ic} > \sigma_p \sqrt{a_p} Y \text{ lub } a_p < (K_{Ic} / \sigma_p Y)^2. \quad (5)$$

assigning that limit defines minimal durability t_{min} :

$$t_{min} \geq \frac{2}{(n-2)A\sigma_e^2 Y^2 K_{Ic}^{n-2}} \left(\frac{\sigma_p}{\sigma_e} \right)^{n-2} \quad (6)$$

Some ceramic parts require initial tests. That eliminates the parts with significant internal defects from the lot. All the remaining ones are considered as of higher durability than σ_p , assigned in initial trial [3].

2. Numerical analysis of overload stress and strain in “head - cup” set of hip joint endoprosthesis

Simulations were conducted by using the ADINA program owned by the Institute of Mechanical Technologies at the Technical University of Czestochowa.

The geometrical model was based on real solutions of modular set by Aesculap [4].



Fig. 3. Geometrical model of “head - cup” set of elaborated solution

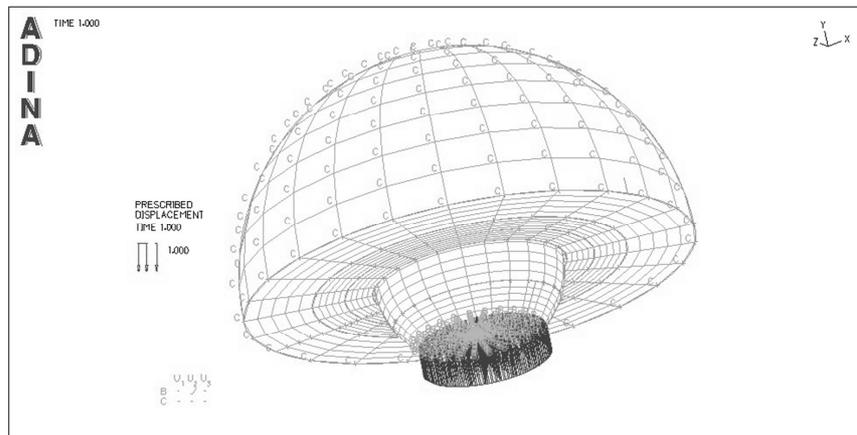


Fig. 4. Model of discretized elaborated solution

Discreet model consists of 10000 cubic elements distributed on 10292 nodes. 8 node elements 3D Solid were used to build up the model.

Strength parameters of the materials and bone tissue used in analysis are presented in the Table 1.

Table 1

Mechanical features of biomaterials and bone tissue [6]

Element of the model	Young's module [MPa]	Poisson's coefficient ν
Core bone	1.7×10^4	0.35
Alloy Ti6Al4V	1.1×10^5	0.3
Ceramics Al_2O_3	3.8×10^5	0.22

In the discreet model of “head - cup” both elements are ceramic. In the tested set the load refers to the load to which the head is subjected in the plain XY with strength 600 and 900 N.

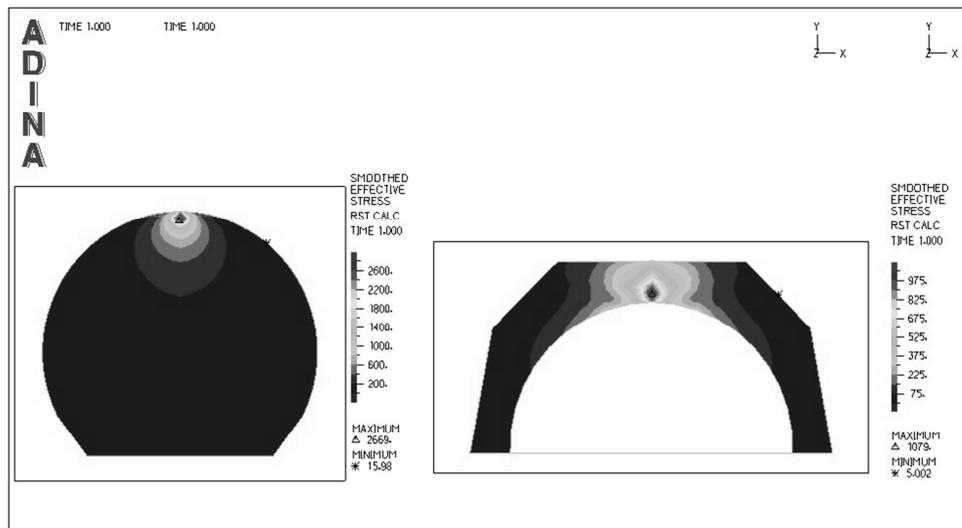


Fig. 5. Stress patterns σ_r [MPa] in cross-section of each element of the analyzed system of ceramic head - ceramic cup, with the load 600 N

The obtained results proved that due to the cooperating elements' parameters, the contact point occurs. It concentrates the stress which can reach in the surface area 2669 MPa when the load is 600 N, and 2900 MPa when the load is 900 N. The contact point between the cooperating surfaces transfers the stress onto the cups.

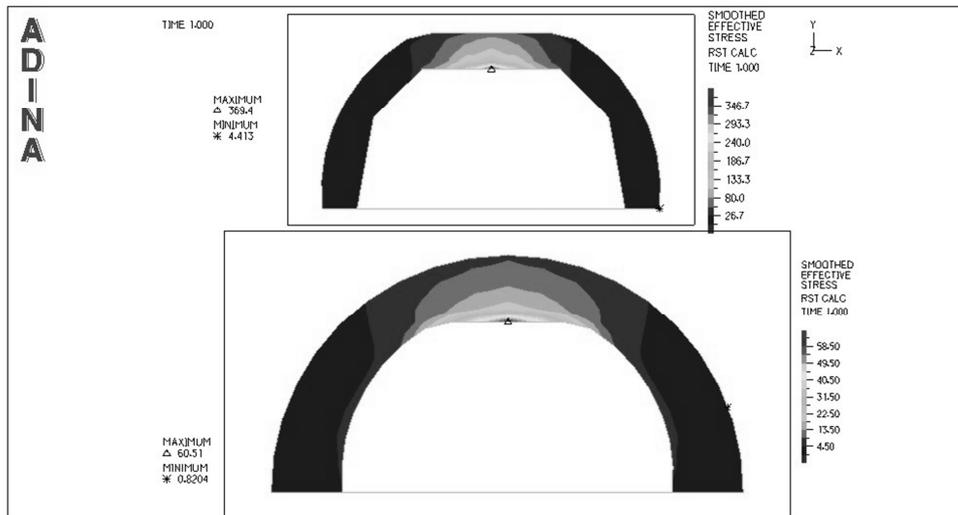


Fig. 6. Stress pattern σ_{τ} [MPa] in cross-section of casing of core bone in the analysed system, with the load 600 N

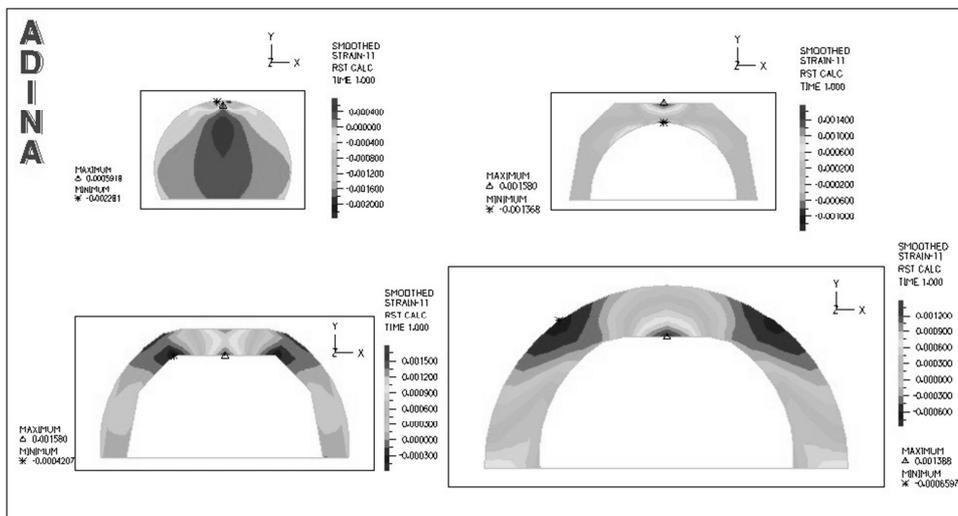


Fig. 7. Strain patterns in cross-section for each element of the analyzed system: ceramic head - ceramic cup with the load 600 N

The strain distribution showed that biggest ones occur in the area where the cup is connected with the casing, and that the pelvis bone was deformed.

The obtained stress and strain distribution for the assigned materials prove that the ceramic elements in the analysed system will not be damaged.

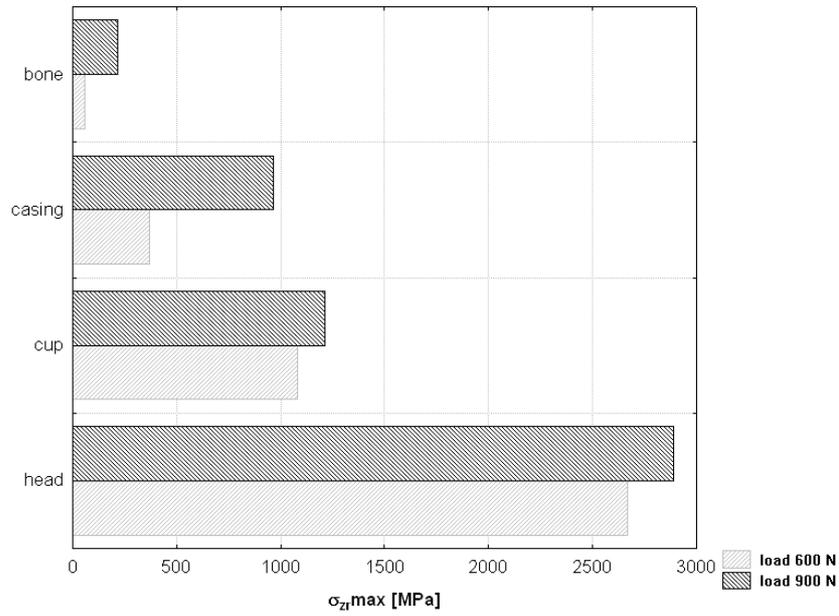


Fig. 8. Statement of the maximum values of stresses in the elements of the analysed system with the load 600 and 900 N

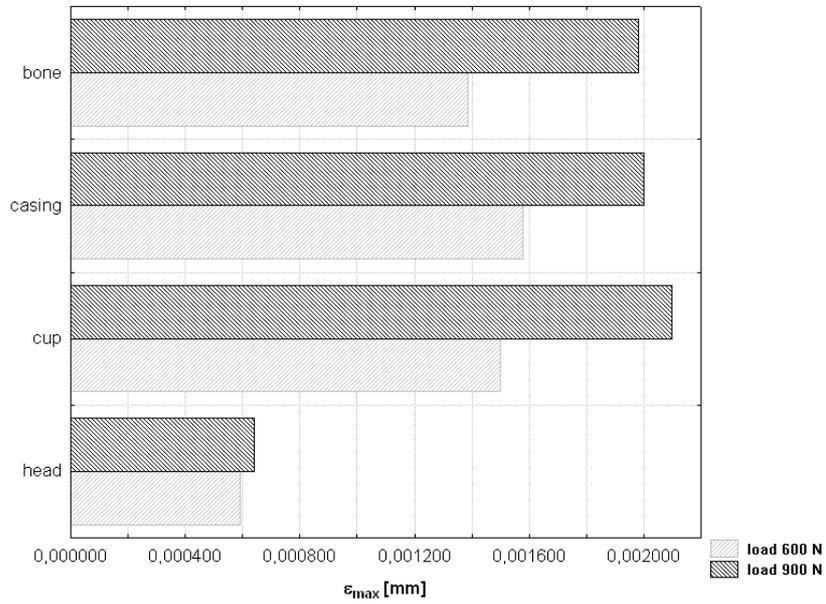


Fig. 9. Statements of the values of strain in the analysed system with the load 600 and 900 N

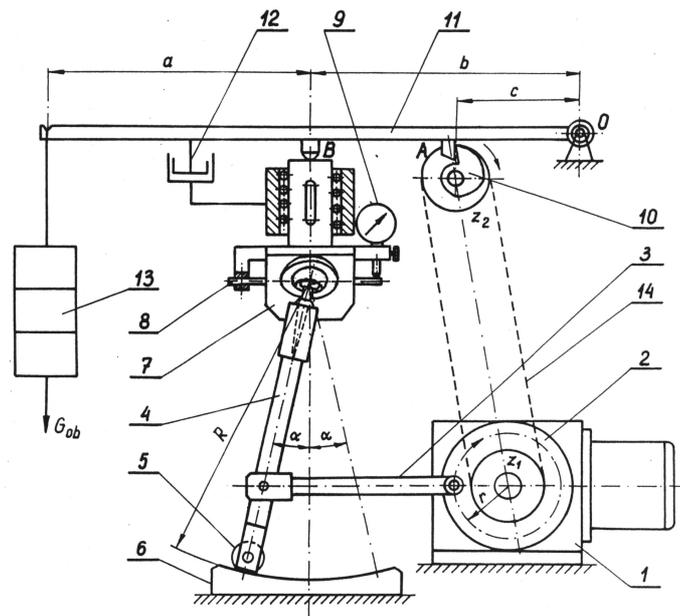


Fig. 10. Schematic diagram of the stand for testing durability of human hip joint endoprosthesis [7]

All the above results were positively confirmed in the empirical tests carried out on the hip joint simulator in the biotribology laboratory in the Institute of Mechanical Technologies. When the real set “ceramic head - ceramic cup” was subjected to load 600 and 900 N respectively, the values of friction coefficient grew significantly for that set run [8]. However, that did not cause any damage of the analysed ceramic elements.

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