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Overload stress and its influence on durability of ceramic elements in hip and knee joints endoprostheses

The paper presents mathematic – statistic methods defining the influence of stress on ceramic elements' durability of hip and knee joints endoprostheses. The paper contains the results of numerical analysis, carried out by the Finite Elements Method in the ADINA System 7.5.1. The FEM is used for computing overload stress in particular elements of tested models of endoprostheses. All presented numerical calculations, state quality conclusions concerning the influence of load of endoprostheses on the values of durability and stress, that are formed in ceramic parts of hip and knee joints endoprostheses. The obtained results help to detect and solve technical problems in examined models and thus, counteract the subsequent effects resulting from premature wear of endoprosthesis elements. Along with numerical analysis, there have been conducted empirical tests on simulator of hip joint endoprosthesis. The model used was "ceramic head - UHMWPE cup" set. The paper also emphasizes necessity of discovering new materials, that will be bio-compliant and wear resistant. Although ceramic materials are brittle and less resistant to load than metallic implants, their improving strength parameters (excellent tribological properties) ceramic materials, like Al_2O_3, are becoming new standard in biomaterials for clinical use. That opens new possibilities especially for hip or knee joints alloplasty.

1. Introduction

Medical ceramics are also widely used in orthopedic applications as a replacement for bone matter. The growing demand for effective bone substitutes in the healthcare sector is likely to be a major driver for the medical ceramics market over the forecast period. Rapid growth in materials research and development is likely to be a key driver for the medical ceramics market, as new materials and production technologies are likely to be developed in the coming years, helping the medical ceramics market achieve smoother operations and higher profit margins. The use of medical ceramics in diagnostic and surgical instruments is also likely to be a key driver for the global medical ceramics market over the forecast period. These materials have a load to scratch that is greater than CoCr, resulting in less wear of the surface and, consequently, less third-body wear of the polyethylene. Among ceramics, zirconia is especially suitable for development of implants because of its tensile stress resistance and the possibility to shape it with a thickness similar to that of CoCr components.

2. Numerical analysis of overload stress and strain in "head – cup" set of hip joint endoprosthesis.

The most common solution offered by endoprostheses 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 material used in endoprostheses 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.
Simulations were conducted by using the ADINA System 7.5.1.
The geometrical model was based on real solutionas of modular set by Aesculap [2].

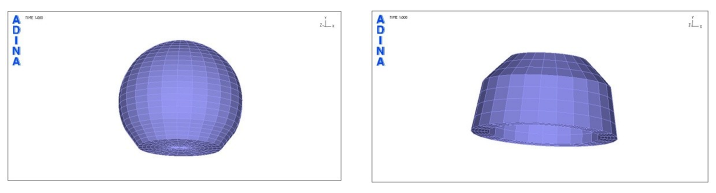

Fig. 1. Geometrical model of "head – cup" set of elaborated solution.

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 N and 900 N.

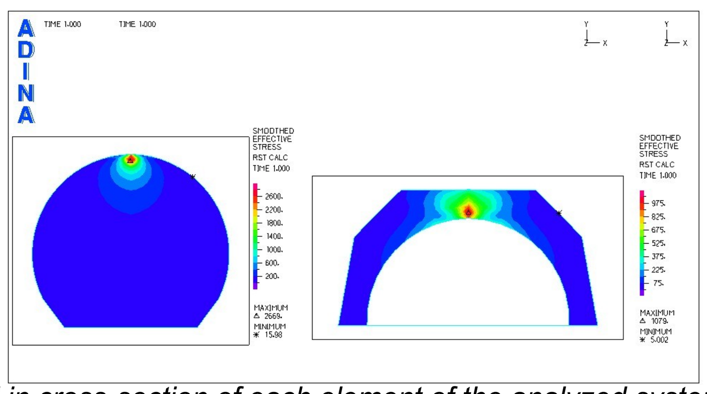

Fig 2. Stress patterns σ_{zr} [MPa] in cross-section of each element of the analyzed system of: ceramic head – ceramic cup, with the load 600N.

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.

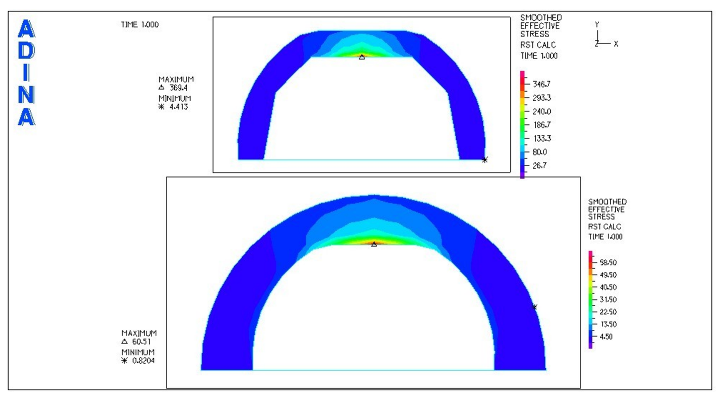

Fig 3. Stress pattern σ_{zr} [MPa] in cross section of casing of core bone in the analysed system, with the load 600 N.

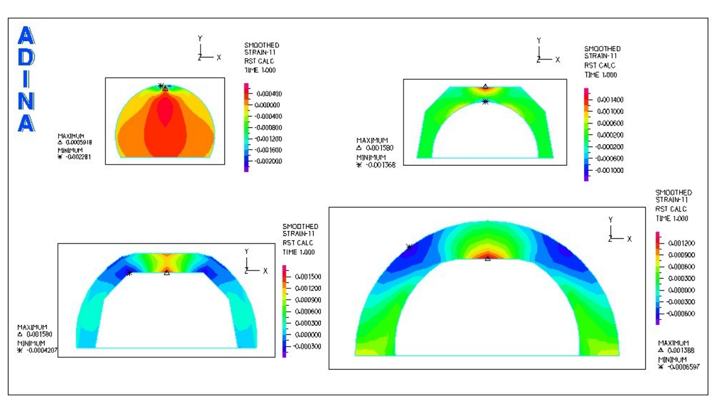

Fig 4. Strain patterns in cross-section for each element of the analyzed system: ceramic head – ceramic cup with the load 600N.

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.

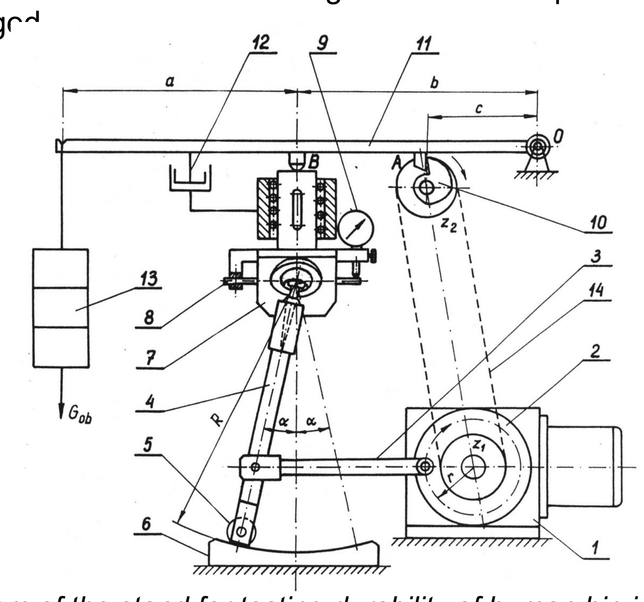

Fig 5. Schematic diagram of the stand for testing durability of human hip joint endoprosthesis [5].

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 N and 900 N respectively, the values of friction coefficient grew significantly for that set run [6]. However that did not cause any damage of the analysed ceramic elements.

3. Knee joint endoprosthesis with polyethylene insert combined with ceramic femoral component

Ceramics have a wide field of application in joint replacements. This chapter is focused on the application of oxide ceramics in joint replacement bearings. The development of alumina (Al_2O_3) and zirconia (ZrO_2) for this application is traced since the early 1970s. The criticalities in the design of ceramic components for joint replacements are described, as well as their main causes of failures in clinical use. The clinical results of the different bearing couples making use of ceramic components are reported, and the future tendencies in this field of application are summarized. Figure 9 presents knee joint endoprosthesis with polyethylene insert combined with ceramic femoral component.

Fig. 6. Ceramic Multigen Plus Knee with BIOLOX® delta ceramic femoral component [8].

3.1. Numerical model of knee joint endoprosthesis

Numerical model is a simplified version of the original endoprosthesis, though the sleds' geometry has been maintained. That enables us to keep the general shape of endoprosthesis and to quite closely imagine the strain distribution on the insert's surface.

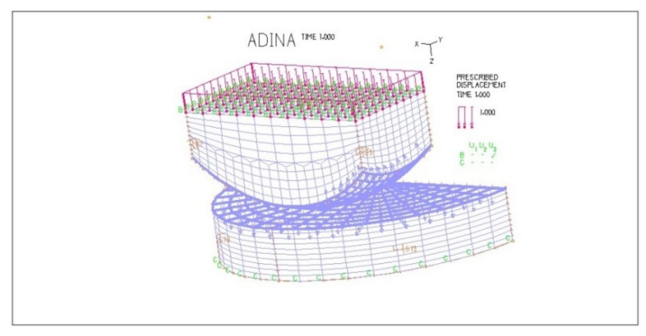

Fig. 7. Simplified sled model used for calculations.

The main purpose of the calculations was to define stress distribution on the surface of the polyethylene insert and right underneath it, where the sled cooperate. There were three heights of polyethylene inserts analyzed: 8, 13 and 22mm, and two sleds of cross section radiuses of 17 and 27 mm, respectively. The analyzed sleds were made of CoCrMo, Ti6Al4V, Al_2O_3.
There were conducted 30 numerical analysis for three various thicknesses of polyethylene inserts cooperating with two geometrically different sleds made of three different materials. Each pair was subjected to load F = 1500[N].
The calculations prove that stress in endoprosthesis is concentrated in the polyethylene insert, right underneath the contact area of both elements, and highest stress is located right underneath the insert's surface.

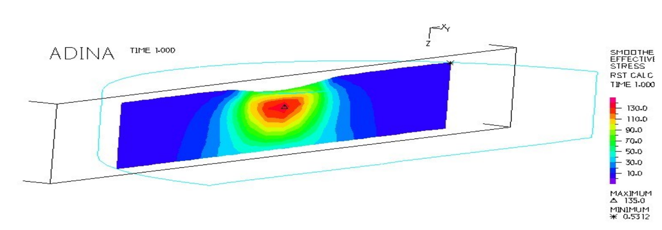

Fig.8. Contact stress distribution occurring in the polyethylene insert. The insert 8mm thick cooperates with a sled of radius 17 [mm]. Load 1500 [N] [8].

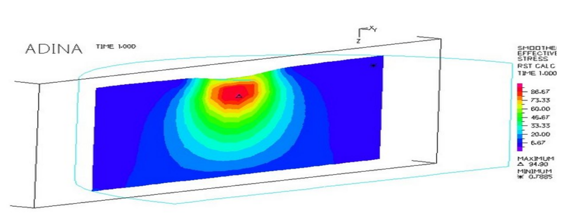

Fig. 9 Contact stress distribution occurring in the polyethylene insert. The insert 13mm trick, cooperates with sled of radius 27 [mm]. Load 1500 [N] [8].

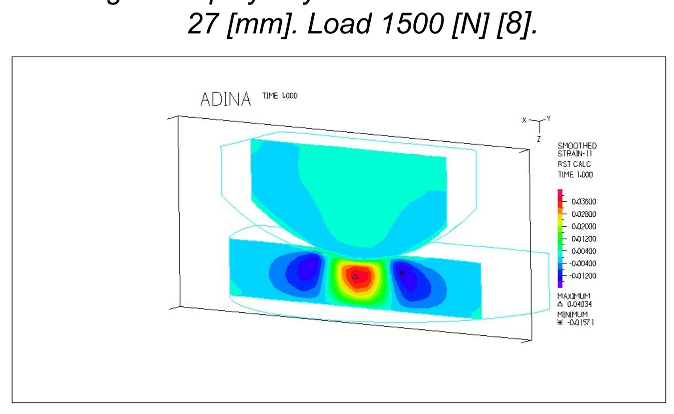

Fig. 10 Strain distribution occurring in the polyethylene insert. The insert 8mm thick, cooperates with sled of radius 27 [mm]. Load 1500 [N] [8].

The lowest reduced stress was achieved for the model where the sled's cross-section radius is 27mm, and the sled is made of Ti6Al4V alloy and valued 9,29[MPa]. The highest stress occurred in the model where the sled was made of ceramic (Al_2O_3), and valued 38,85[MPa], and the sled's cross section radius was smallest and valued 17[mm]. Figure 15 presents the influence of the cross section radius of the sled, thickness of the insert and kind of material which the sled is made of, on the value of the stress generated in the polyethylene insert.

4. Conclusions

1. 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.
2. The obtained stress and strain distribution for the assigned materials prove that the ceramic elements in the analysed system will not be damage
3. The conducted numerical calculations and analysis undaubtedly prove that the future of knee joint alloplastics belongs to a group of new materials including titanium alloys and ceramic elements, which when appropriately selected and combined as far as mechanical features are concerned (low Young's modulus value), may significantly decrease the value of stress generated in polyethylene elements of endoprostheses.
4. Another important element influencing durability of endoprostheses is optimizing of the geometry of the implants both in the friction node and fixing area in the bone.