Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 46
ISSUE 1
May
2011

Mechanical analysis and numerical simulation of modified bone cements in the hip joint alloplasty

J. Nowacki*, A. Sajek
Institute of Materials Science and Engineering, West Pomeranian University of Technology, Al. Piastów 19, 70-310 Szczecin, Poland
* Corresponding author: E-mail address: jnowacki@zut.edu.pl

Received 21.02.2011; published in revised form 01.05.2011

Analysis and modelling

ABSTRACT

Purpose: The paper aims at verifying the stress values in bone-cement-implant system during human movement cycle and determining the amount of bone cement admixture which induces a drop in mechanical properties to acceptable level.

Design/methodology/approach: In the first place, mechanical tests of modified cements were carried out. These tests are a basis for mathematical description of mechanical properties which will be used during numerical simulations. Numerical simulations were carried out using the geometry obtained by computer tomography.

Findings: A drop in mechanical properties induced by modification depends on admixture size. During movement, cement bond is affected by considerable forces. These forces operate cyclically, i.e. momentarily (when setting a foot on the ground) within the elastic range of examined material. From the point of view of mechanical parameters, an optimum admixture of the aqueous solution of biologically active modifying agent is that inducing porosity at a level of 8%.

Research limitations/implications: The paper constitutes a beginning of examinations on modified cement junctures which may be expanded in future by testing the dynamics basing on the analysis of fatigue strength.

Practical implications: Modifying agent amount was determined and verified that does not induce a decrease in the bending strength and the longitudinal modulus of elasticity during bending below the level specified in ISO 5833 standard.

Originality/value: Modification of cement with aqueous solution of salmon calcitionin, as well as examination and verification of the effect of admixture on mechanical properties.

Keywords: Modified bone cement; Implant; FEM; Calcitonin; Mechanical properties; Computer tomography; Porosity

Reference to this paper should be given in the following way:
J. Nowacki, A. Sajek, Mechanical analysis and numerical simulation of modified bone cements in the hip joint alloplasty, Journal of Achievements in Materials and Manufacturing Engineering 46/1 (2011) 57-64.

1. Introduction

Increase of the interest of many laboratories worldwide in research and development of new material technologies for this field generates a considerable inflow of scientific information.

A specific case of using the bonding techniques in medicine is application of cement bonds in hip, knee and shoulder joint alloplasty as well as in plastic and reconstructive surgery. The features of bone cement connections are, in their whole substance, qualitatively similar to those of bonded joints used in construction of machines, mechanisms and tools or in electronic systems and, from the side of macro- and microstructural, mechanical and corrosive properties, they should be considered as binding materials using bonding engineering criteria expanded with requirements referring to biomedical properties.

An interesting example of using the mechanical properties of bio-bonds is implantation of human hip joint by means of bone cements. Bone cements based on polymethyl methacrylate (PMMA) belong to a group of self-polymerising acrylic resin materials. They have been implemented into clinical practice in the mid 50s for fixing joint endoprostheses and belong at present to most frequently used ones in treatment of osteoarticular and muscular system diseases and injuries.

Human hip joint is an example of spheroid acetabular joint characterised by an extensive scale of movements. Hip joint belongs to most exploited carrying joints in human motor organ [1].

Hip joint, having a considerable importance for the mechanics of human movement, is commonly exposed to pathological changes and injuries. In severe degenerative lesions or after femoral neck fractures, it is necessary to implant an artificial part or the whole joint in place of the natural one [2,3].

Appropriate construction of endoprosthesis should ensure a proper joint movement range, load transfer, overload capacity, vibration damping, bone mass stimulation and abrasion resistance as well as a possibility of carrying out a simple surgical operation. In order to fulfil these requirements, an appropriate geometry and type of implantation material should be chosen. The stress pattern in a juncture between a bone and an implant is determined by relations between their elastic properties. Static and fatigue strengths affect the size of transferred stresses and overload capacity whereas surface condition and its physical and chemical features determine the nature and the strength of juncture at the border of bone-implant phases [4,5,6].

Even though implantology gives possibilities of replacing damaged anatomical structures, it restores lost functions only for a certain period of time. A reason of that is a wear and tear of artificial joints, which leads with time to a repeated failure of function.

After operations of joint alloplasty with the use of bone cement, a rather high percentage of cases with prosthesis functionality loss is observed caused by inflammatory and degenerative changes, bone destruction and aseptic loosening. Therefore, research works are being accomplished aiming at improvement of parameters which characterise biofunctionality of implants. Further directions of development are being conditioned by permanently growing number of performed alloplasties, searching for new solutions in dangerous revision surgeries and economic reasons [7,8].

Application of developments from different areas of technical sciences is more and more frequently helpful or simply indispensable in everyday clinical practice, while implantology is one of the fields of medicine in which theoretical and experimental methods of materials science, including mechanics of materials, are particularly useful. This is because the prediction of consequences resulting from introduction of foreign bodies into human organism - like implants - requires knowledge of the effect of their biological and material properties on internal environment. Biological response of organism on graft insertion depends, among others, on their geometrical features, mechanical properties of components and biomechanical systems created this way and in particular on the stress pattern [1,9,10,11].

Exploitation of biocompatible cement junctures is frequently connected with complications induced by reactions of unreacted toxic components, thermal damages and infections. They lead to formation of the phenomenon of aseptic loosening of implants, which is a concern of a substantial number of research works accomplished so far. Implant loosening prevention is being accomplished in many ways. One of them is cement modification [12,13].

Bone cements are modified with many agents that improve their operational properties, with a modifying agent participating in polymerisation reaction or being inactive. Addition of reactive modifying agents, apart from affecting strength properties, can also decrease the intensity of heat released during mixture hardening [14] through extension of reaction time or reduction of the amount of toxic MMA monomer being liberated into human organism after cement hardening [10].

Gentamicin-containing cements used so far show that within a certain time interval a drug is released from them into environment. Part of the authors is of the opinion that gentamicin release takes place by diffusion of compounds through polymer matrix or capillary through empty spaces inside it. Nevertheless, a considerable part of scientists examining the phenomenon of drug release from bone cements think that it strongly depends on surface roughness [9,14,15].

The theme of using bone cements is very extensive and therefore it covers many areas where number of research works is insufficient to describe a full and complete solution of the problem of biomaterials connecting.

Aspects of bone cement modification with reactive and inactive admixtures in the context of a structure change affecting mechanical properties to the highest degree are a subject of significantly smaller number of analyses and surely require a certain extension.

These changes refer, among others, to increasing the porosity of admixture filled with incompressible aqueous solution and the smoothness and roughness of cement bond surface and decreasing the tensile and bending strength.

Data referring to the porous structure of cement bond and its effect on mechanical properties of modified bone cements published in literature are very fragmentary and cannot be a basis for detailed description of the problem.

Numerical simulation of cement bond described in the paper is to give a picture of the effect of modification of cement with aqueous solution on the stress and displacement pattern in microstructure of material.

In order to illustrate juncture operation conditions, it is important to determine the real state of stresses and displacements in bone-cement-prosthesis systems [16,17]. The problem is complex due to biomechanical relations. Accurate determination of the aforesaid features and their expression in simple qualitative-quantitative relations is very difficult and separate for every case. Analysis of the operation conditions of modified bone cement filling in bone-cement-prosthesis system as well as the relation of geometrical features and the loading of system with forces operating during human movement on the stress pattern calls for further detailed experiments and numerical simulations.

Numerical simulation described in the paper refers to exploitation of modified cement juncture in bone-cement-implant system. The stress pattern in juncture was examined, dependent on actual values of the loading force that are characteristic for movement cycle. Juncture strength parameters used in the simulation were calculated based on examinations of mechanical properties.

2. Materials

The examined bond is bone cement which has been modified with a solution of salmon calcitionin CALCITONIN 100.

Samples were made of bone cement Surgical Simplex® P (Howmedica Osteonics, Mahwah, NJ, USA). It is one of the cements most frequently used in hip-joint alloplasties. It was prepared by mixing two components. First of them is a liquid solution of monomer with a characteristic acrylic smell. The second component of cement is a powder consisting mainly of filler and polymerisation initiator.

As a preparation consisting synthetic salmon calcitonin $C_{145}H_{240}N_{44}O_{48}S_2$, a generally available product under the brand name Calcitonin 100 was applied. This preparation is frequently used in clinical practice.

A larger part of the preparation (99.065 % weight) is water therefore only the size of aqueous admixture and its effect on cement porosity should be taken into consideration when examining mechanical properties.

3. Microstructure

Effect of the admixture of preparation containing biologically active modifying agent on total porosity value was determined. The weight method was verified by means of the analysis of microphotograph images taken on sample transverse micro-sections with the application of scanning electron microscope JOEL JSM-6100 (Joel LTD, Tokyo, Japan). Tests were carried out in three representative areas of 160×120 μm for modified samples (Figure 1).

Results of the quantitative analysis of porosity and the morphology of pores were a basis for working out the methods of numerical simulation for the effect of porosity on the pattern of structure stresses and displacements. Also microscopic examinations of impact strength fractures were carried out and results referring to the cracking mechanism were based on numerical analysis of structure stresses carried out at the same time (Figure 2).

Stresses increase slightly together with an increase of porosity, just as deformations. The increase of stresses together with porosity is larger in samples with empty pores.

The pattern of stresses on cross-section strictly depends on the arrangement of pores to each other. Stresses concentrate in pore clusters, reaching maximum values in the material delimiting two adjacent pores. The smaller the space between such pores, the larger is the stress.

a)

b)

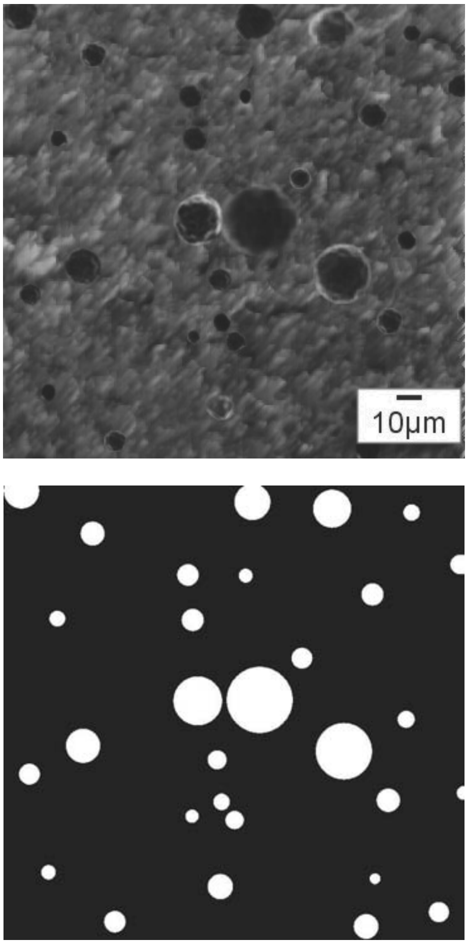


Fig. 1. Pores distrubution in microsection of the specimen (8.3% porosity): a) photography of microsection; b) binary representation

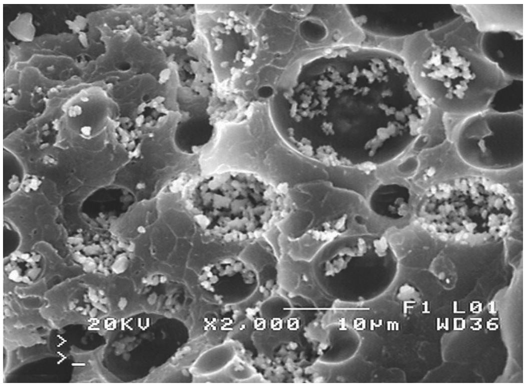
The above-mentioned observations explain results of the microscopic examination of micro-sections in which a tendency was observed towards formation of cracks in the areas between adjacent pores.

Porosity increases together with an increase of the content of aqueous solution of admixture in cement structure. Initially, pores are arranged evenly but then, with large porosity, they cluster together in agglomerations. This causes irregularity in bond properties. With high porosity values, it comes to connection of pores in developing pore agglomerations. Cracks in modified samples with porosity of 8.3% and 13.4% are formed in a thin polymer matrix between pores.

4. Mechanical analysis

Accuracy of the carried out numerical simulations depends on determination of precise mathematical relationships describing variable mechanical properties of bond (Figure 3).

a)



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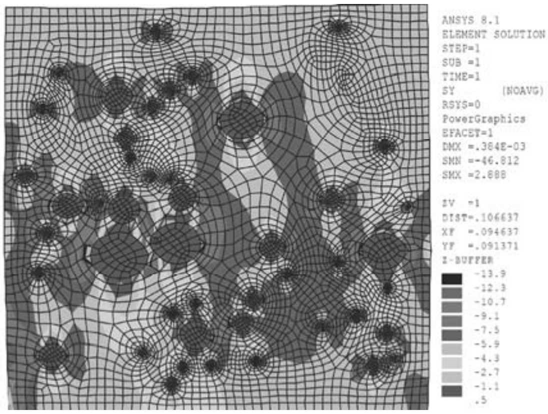


Fig. 2. Modified bone cement microscopic examination: a) fracture microphotography, porosity 13.4%, magnification x2000; b) numerical simulation of the stress distribution in porous microstructure

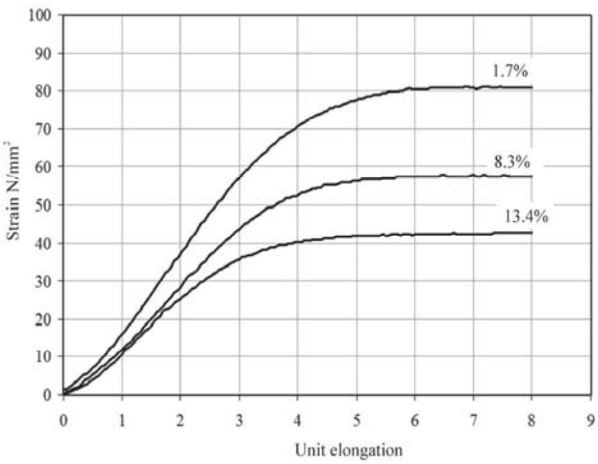


Fig. 3. Results of static compression test in porosity function (strain rate 2mm/min, ambient temperature 22ºC)

The carried out tests of mechanical properties were a basis for determining mathematical relationships between porosity and mechanical strength (Figure 4). They were performed based on an experiment covering examination of the strength features of modified bone cements during static compression and bending. It was decided to apply a three-level design. Independent variables in the experiment were as follows:

- cement porosity P, %;
- strain rate v, mm/min;
- ambient temperature T, °C.

As a result, 27 experiments were received for compression and bending tests each. The obtained mathematical relationships were applied for numerical simulation of bone-cement-implant system.

Exemplary regression dependence for the Young's modulus at the bending E on independent variables P, v and T had the following form:

$$Y(P,v,T) = 20.40615 - 0.84111 \cdot P \quad (1)$$

Square of correlation coefficient $R^2 = 0.98$

Analysis of the coefficient values in the determined equations allows to state that mechanical properties of cements during compression decrease together with increasing porosity. Major influence on properties has the strain rate.

Temperature is the least significant factor. During cement juncture operation in living organism environment, the amplitude of changes of that variable is small and therefore the effect of temperature changes can be omitted. This is confirmed by the results of dependence for the Young's longitudinal modulus of elasticity on temperature, where temperature effect was statistically non-significant for the adopted level of significance α.

5. Numerical simulation

Elaboration of the loading model of hip joint aims at verification of the usefulness of modified cements. The loading of human hip joint depends on the phase of foot contact with the ground. Human body movements accompanying these phases cause reconstruction of the complete real model of hip joint loading to be impossible. It was decided to apply models taken from the literature describing the joint loading during human movement [18, 19, 20]. This gives a chance of calculating the loadings and displacements of cement bond in respective phases of human movement (Figure 5).

Test femur is an anatomical specimen coming from a 50-year old woman weighing about 50 kg. The specimen was obtained from the Chair and Department of Normal and Clinical Anatomy of the Pomeranian Medical University in Szczecin (Figure 6).

The place of making an incision on the femoral neck was determined after making an endoprosthesis stem gauge. Also a rectangular hole penetrating into the marrow cavity was made in cancellous bone tissue.

For calculations, geometrical features were used of a cement endoprosthesis OSTEONIC OMNIFIT® size 4 (Figure 7) that was obtained from the Chair and Clinic of Orthopaedics and Traumatology of the Pomeranian Medical University in Szczecin. At present, this endoprosthesis is being used in clinical practice.

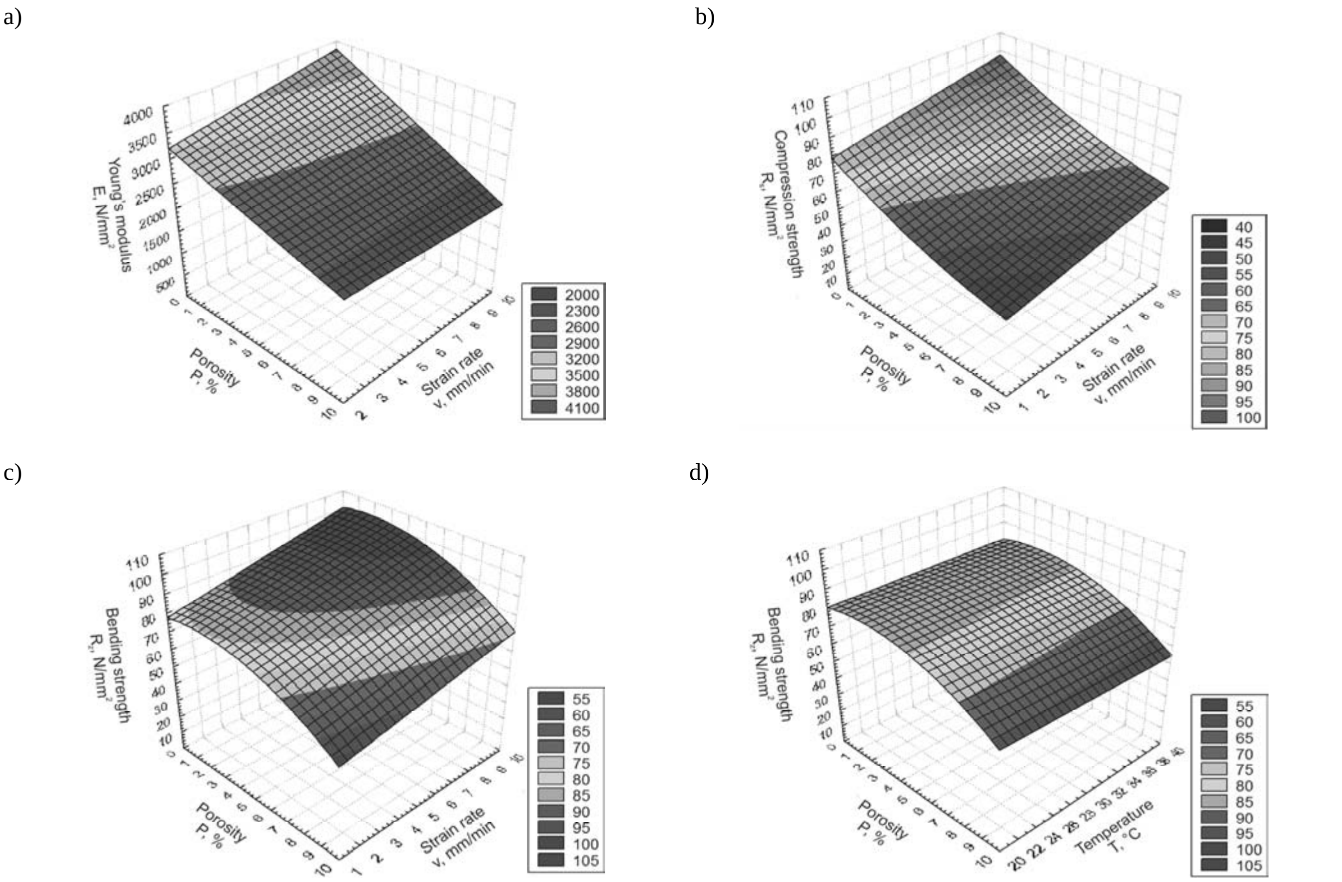


Fig. 4. Bone cement mechanical properties models: a) porosity and strain rate influence of Young modulus during bending; b) porosity and strain rate influence of compression strength; c) porosity and strain rate influence of bend strength; d) porosity and ambient temperature influence of bend strength

Basic mechanical properties of the elements of junction under examination are the Young's longitudinal modulus of elasticity E and the Poisson's ratio ν (Table 1). These features for bone tissues and prosthesis were adopted based on literature. In case of bone cement, values of the longitudinal modulus of elasticity are from tests of mechanical properties carried out earlier.

Table 1.
Mechanical properties of the materials used in numerical simulation [21,22]

Material	Young Modulus E [N/mm^2]	Poisson ratio ν
Alloy ASTM F620	$2{\cdot}10^5$	0.3
Cancellous bone	300	0.2
Compact bone	$2{\cdot}10^4$	0.3
Cement D = 1.8 %	$3.9{\cdot}10^3$	0.3
Cement D = 8.8 %	$2.9{\cdot}10^3$	0.3
Cement D = 13.7 %	$2.2{\cdot}10^3$	0.3

Numerical simulation was carried out for three porosity variants of modified cement (1.7%, 8.3% and 18.4%).

Numerical simulation in bone-cement-implant system was carried out in the function of cement juncture porosity and time period corresponding to one cycle of human movement.

Differences in stresses and deformations between porosities have been presented in diagrams (Fig. 9, Fig. 11).

Considering the weight of human subject, from whom the bone specimen comes (i.e. 50 kg), a value of the force Y was calculated according to the Pauwels model [19]

The tested system was entered into MES-ADINA software package environment. System geometry was limited to the area being most interesting from the point of view of testing (Fig. 8). The system was mounted in an intersection plane depriving it of all degrees of freedom. Calculations were carried out in 97 time steps corresponding to respective stages of human movement.

As a result of testing, no significant differences were found between the pattern of stresses and deformations in cements with different porosity. To limit the volume of results, simulations referring to most representative porosity, amounting to 8.3%, have been presented in figures below (Figure 10).

The stress and deformation values depend proportionally on the applied force and show concentration in the upper and central part of bone-cement-implant system.

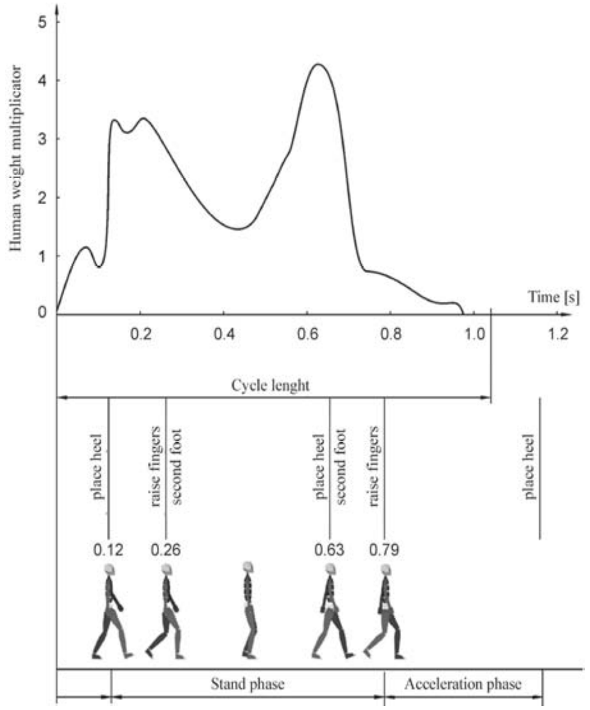


Fig. 5. Loading of hip joint depending on the phase foot contact with ground

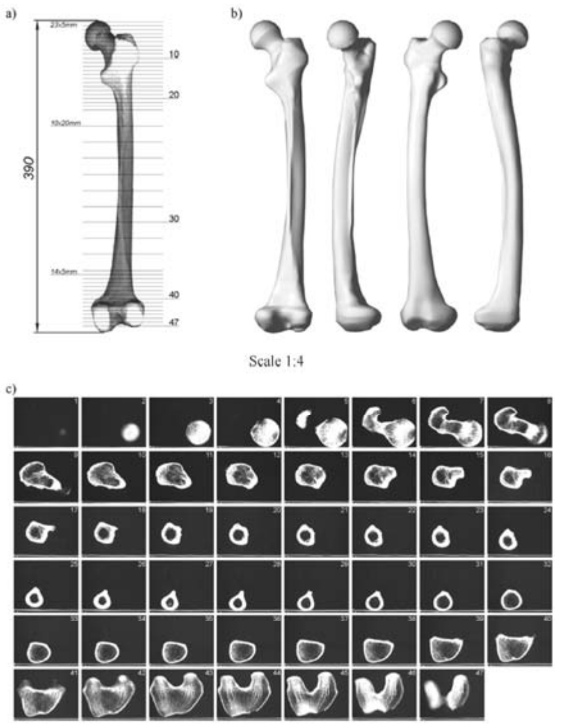


Fig. 6. Hip bone geometry transfer using computed tomography: a) bone division procedure; b) transferred geometry; c) tomographic images

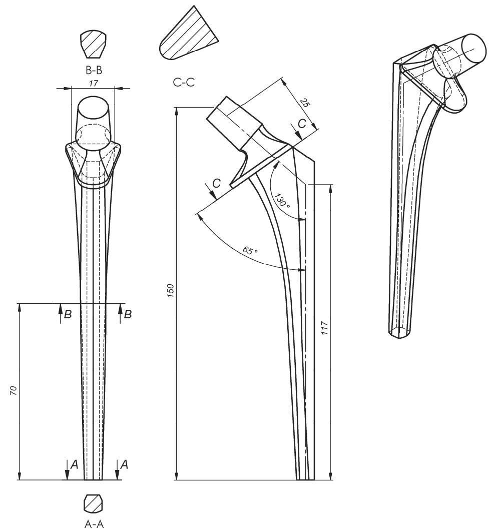


Fig. 7. Main dimensions of OSTEONIC OMNIFIT® endoprosthesis size 4

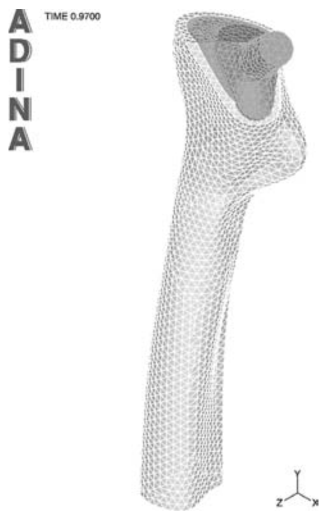


Fig. 8. Meshed model of bone-cement-prosthesis system

Stresses are the highest in endoprosthesis stem and decrease when passing through cement juncture, reaching the lowest values in bone tissue.

The stress values in bone cement are within the elastic range for each porosity variant. Cement juncture porosity affects the developed stresses to a minimum. Stresses in the analysed system depend to a large extent on prosthesis geometry.

Direction of stresses strictly depends on the area of analysis. Normal stresses assume a negative sign near the axis of acting force (cement juncture compression occurs), whereas those in system areas being in the farthest locations from the force axis assume a positive sign (tension occurs). Differences between compressive and tensile stresses point to predominance of compressive stresses in the juncture.

Displacements in the analysed system are distributed as expected, i.e. they are the largest at the point of force application, while the least in the mounting point. A fairly significant influence of cement modification on displacement values was observed.

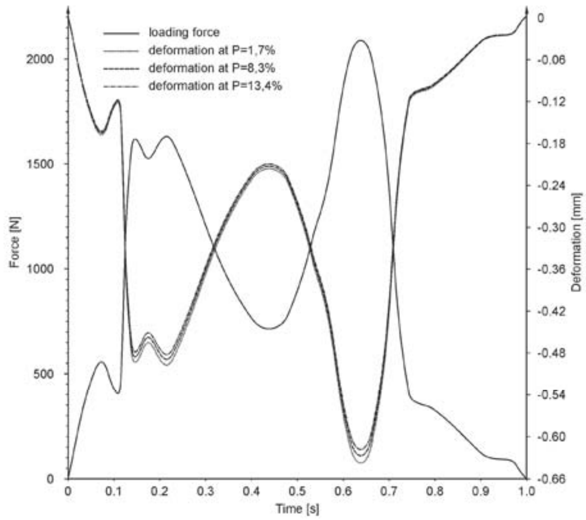


Fig. 9. Comparison bone cement deformations (mm) - force Y fixed point of porosity function

6. Conclusions

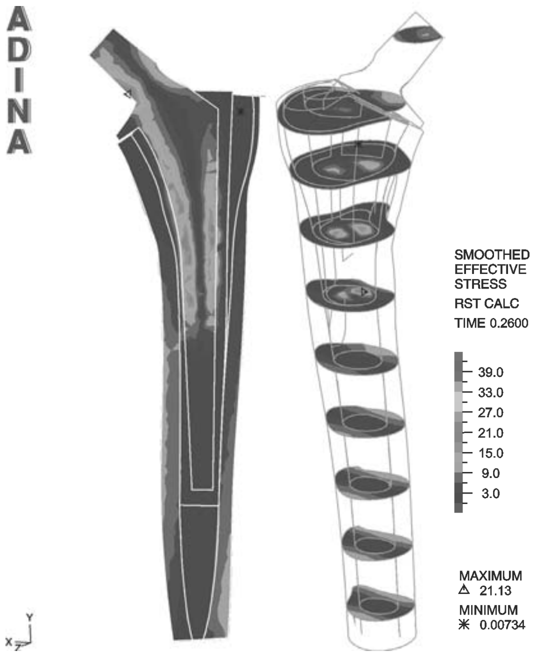
To evaluate the usefulness of modified cement, a simulation of cement filling operation in bone-cement-prosthesis system was carried out. Particular attention was paid to fidelity of the representation of geometrical features of the tested elements and to proper system loading, which has a large effect on the stress pattern. The focus was set on the loading of tested system with forces acting during human movement. The applied Pauwels model shows that largest loadings during human movement operate on cement filling momentarily, i.e. with a large strain rate. Previous mechanical tests showed a large dependence of strength parameters on the strain rate, which also increase as a result of its increase. Taking the dynamic influence of force into consideration, stress values in cement filling are always within the elastic range.

The obtained results show that cement filling is subject to very complex stress conditions. Largest stresses operate on cement filling in the contact place with endoprosthesis metal stem. Stresses decrease together with coming closer to bone tissue. Cement juncture undergoes both compression and tension.

Irrespective of the applied force, no significant differences were found in the filling stresses and deformations in the function of porosity.

When analysing the operation conditions of cement juncture, it should be noticed that it is loaded statically with small forces for over most time (sitting, lying). It is not until movement when significant forces operate on cement filling. These forces operate however cyclically, i.e. momentarily (when setting a foot on the ground), within the elastic range of tested material. The water filling pores offers a larger resistance during dynamic deformations, causing compensation of stresses.

a)



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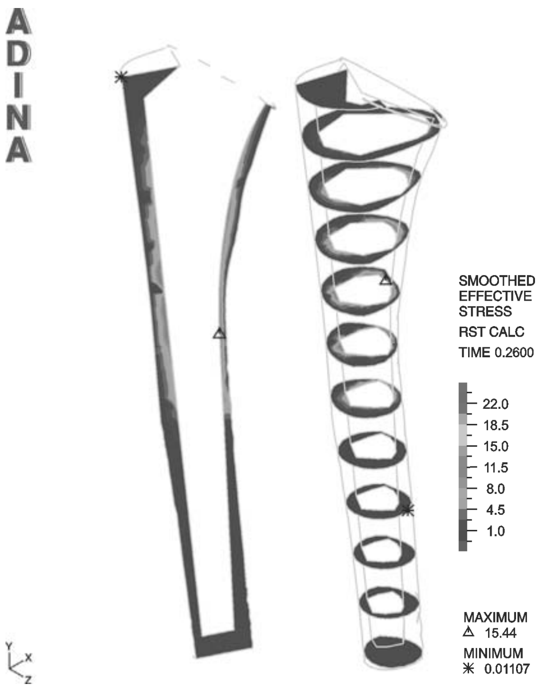

Fig. 10. Reduced stresses (N/mm^2) distribution in time 0.26 s: a) bone-cement-implant system, b) bone cement

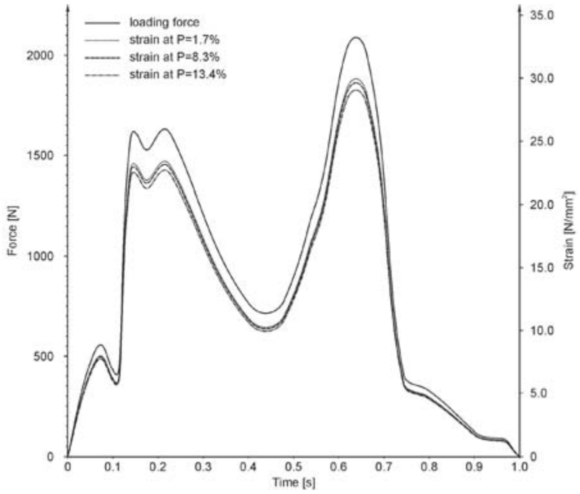

Fig. 11. Comparision bone cement maximum reduced stresses (N/mm^2) of porosity function

An optimum admixture of the aqueous solution of biologically active modifying agent from the point of view of mechanical parameters is that inducing porosity at a level of 8%. In the presented study, this admixture does not cause deterioration of the bending strength and the longitudinal modulus of elasticity during bending below the level specified in ISO 5833 standard.

Different situation is with the compression strength which, although being within the standard, is low, even for unmodified cement. Admixture causes a decrease in this parameter below the established level. Nevertheless, long-term clinical practice has verified provisions of the standard, changing the overestimated level of compression strength to a value that is typical for cancellous bone with which cement cooperates. Taking the aforesaid arguments into consideration, the value of compression strength for cement with 8.3% porosity fulfils requirements.

References

[1] A.S. Baker, L.W. Greenham, Release of gentamicin from acrylic bone cement. Elution and diffusion studies, Journal of Bone and Joint Surgery 70 (1988) 1551-1557.

[2] A. Balin, Mechanical and material conditions of the artificial hip joint stability and durability endoprosthesoplasty - study of the problem, Materials Engineering 2 (1998) 44-52.

[3] J. Kubacki, T. Gazdzik, Endoprosthesoplasty of the hip-problems, Biomaterials Engineering 2 (1998) 12-16.

[4] M. Žitňanský, Ľ. Čaplovič, Ľ. Rehák, F. Makai, Investigation and implantation of endo-prosthesis in biological experiment on animals, Journal of Achievements in Materials and Manufacturing Engineering 24/1 (2007) 146-152.

[5] A.M. Gatti, D. Zaffe, Bioactive glasses and chemical bond, Biomaterials - Hard and tissue repair and replacement, N-H, 1992.

[6] J.F. Osborn, The reaction of bone tissue to hydroksyapatite ceramics coatings, Biomaterials- Hard and Tissue Repair and Replacement, N-H, 1992.

[7] M. Balazic, J. Kopac, Improvements of medical implants based on modern materials and new technologies, Journal of Achievements in Materials and Manufacturing Engineering 25/2 (2007) 31-34.

[8] M. Boujelbene, P. Abellard, E. Bayraktar, S. Torbaty, Study of the milling strategy on the tool life and the surface quality for knee prostheses, Journal of Achievements in Materials and Manufacturing Engineering 31/2 (2008) 610-615.

[9] N. Greene, P.D. Holtom, C.A. Warren, R.L. Ressler, L. Shepherd, E.J. McPherson, M.J. Patzakis, In vitro elution of tobramycin and vancomycin polymethylacrylate beads and spacers from Simplex and Palacos, The American Journal of Orthopedics 27 (1998) 201-205.

[10] P.J. Herzwurm, S.L. Simpson, S. Duffin, S.G. Oswald, F.R. Ebert, Thigh pain and total hip arthoplasty, Clinical Orthopaedics and Related Research 336 (1997) 156-161.

[11] A. Nzihou, L. Attias, P. Sharrock, A. Ricard, A rheological, thermal, and mechanical study of bone cement - from a suspension to a solid biomaterial, Powder Technology 99 (1998) 56-6.

[12] I. Knets, V. Krilova, R. Cimdins, L. Berzina, V. Vitins, Stiffness and strength of composite acrylic bone cements, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 135-138.

[13] A. Balin, G. Junak, Low-cycle fatigue of surgical cements, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 211-214.

[14] M.K.D. Nicholas, M.G.J. Waters, K.M. Holford, G. Adusei, Analysis of rheological properties of bone cements, Journal of Materials Science: Materials in Medicine 18 (2007) 1407-1412.

[15] B.A. Masri, C.P. Duncan, C.P. Beauchamp, Effect of varying surface patterns on antibiotic elution from antibiotic loaded bone cement, Journal of Arthroplasty Arthroscopic Surgery 10 (1995) 453-459.

[16] J. Okrajni, M. Plaza, S. Ziemba, Computer modelling of the heat flow in surgical cement during endoprosthesoplasty, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 311-314.

[17] A. Krauze, W. Kajzer, J. Marciniak, Biochemical characteristic of bone nail - femur system using MES method, Proceedings of the 12th Scientific International Conference "Achievements in Mechanical and Materials Engineering" AMME'2003, Gliwice, 2003, 80-82.

[18] N. Passuti, F. Gouin, Antibiotic-loaded bone cement in orthopedic surgery, Joint Bone Spine 70 (2003) 169-174.

[19] F. Pauwels, Der Schenkelhalsbruch, Stuttgart Enke, 1935.

[20] M. Rocca, M. Fini, T. Greggi, P. Parisini, A. Carpi, R. Giardio, Biomaterials in spinal fixation. An experimental animal study to improve the performance, The International Journal of Artifical Organs 12 (2000) 824-830.

[21] N.J. Dunne, J.F. Orr, Influence of mixing techniques on the physical properties of acrylic bone cement, Biomaterials 22 (2001) 1819-1826.

[22] Standard ASTM F136-98, Standard Specification for Wrought Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) Alloy for Surgical Implant Applications (UNS R56401), USA, 1998.