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FEM analysis of drills used in bone surgery

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ABSTRACT

Purpose: The aim of the work was determination of biomechanical analysis of a surgical drill – bone system in simulated conditions of drilling in a bone.

Design/methodology/approach: Geometrical model of the selected surgical drill and simulated femur (cortical bone) was worked out in the Inventor Professional 2008. The value geometry of the edge was point angle ($2\kappa_1 = 90^o$ and $2\kappa_2 = 120^o$). Numerical model was prepared in ANSYS Workbench v. 11. Meshing was realized with the use of SOLID 187 elements. Evaluate boundary conditions to numerical analysis imitate phenomena in real system with appropriate accuracy. Drill was loaded with forces in the range F= 100-200 N and torque T = 0.04 Nm. Calculations were carried out for two kinds of metallic material of the drill.

Findings: The effect of numerical analysis was determination of strains and stresses in working part of the drill. Results of analysis indicate diverse values of strains and stresses distribution in working part of the drill depending on its geometry. The maximum values of strains and stresses were obtained for the drill of point angle $2\kappa_1=120^o$.

Research limitations/implications: In order to simulate phenomena in real system, a simplified model of surgical drill – femur system was worked out. The simplifications concerned mostly geometry of a femur. The femur was represented by disc of height h = 10 mm, corresponding with thickness of cortical bone.

Originality/value: The numerical analysis of the surgical drill – femur system in simulated conditions of drilling in a bone can be a basis for optimization of cutting edge geometry of surgical tools as well as for selection of their mechanical properties.

Keywords: Numerical techniques; Finite Elements Methods; Metallic materials; Mechanical properties

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Medical instruments include very wide range of geometrically and functionally diverse group of products. This group includes both tools and medical devices. An operational surgical instrumentarium is the special group of medical instruments. That group is characterized by irregular and diverse intensity of use. Furthermore, because of a work in chemically active environment (body fluids, drugs) it is necessary to sterilize them after each use. The mentioned working conditions of the surgical instrumentarium determine the selection of material which should ensure reliable utilization. The main group of metallic materials applied in surgical instrumentarium are stainless steels divided into three groups: martensitic, austenitic and ferritic steels.

The main group of tools used in surgical operations are cutting tools. This group includes one-, two- and multiedge tools. The most frequent used multiedge tools are surgical drills and screw taps. They are mainly used in osteosynthesis procedures for example Polfix [1].

Application of drills in bone surgery was forced by development of osteosynthesis methods. Diversity of operation procedures, need of custom design tools and tendencies to simplify operations, bore fruit in variety of drills. Besides standard surgical drills there are also available special design drills, for example drills with guide end and cannulated. As opposed to drills applied in machining, surgical drills have different geometry. This results from different mechanical properties of treated material (bone tissue) [2-8].

Immense demand on surgical instrumentarium causes efforts in development of its working life. The main attention was focused on surface engineering in order to reduce wear of the tools [9]. Biomechanical issues of surgical drills are very limited in the literature. This concerns stress and strain analyses mostly. Those analyses are a basis for geometry optimization as well as for selection of mechanical properties of metallic material. Most of the papers focuses on temperature distribution [10-19]. For that reason in the present work, an analysis of surgical drill during bone drilling with the use of finite element method was carried out.

2. Material and methods

2.1. Geometrical model

Drill used in orthopeadic procedures for diverse geometry of the edge was analyzed in the work. The value geometry of the edge was point angle – $2\kappa_1 = 90^o$ and $2\kappa_2 = 120^o$ – Fig. 1. The diameter and length drill was state and was equal d = 6 mm and l = 70 mm respectively.

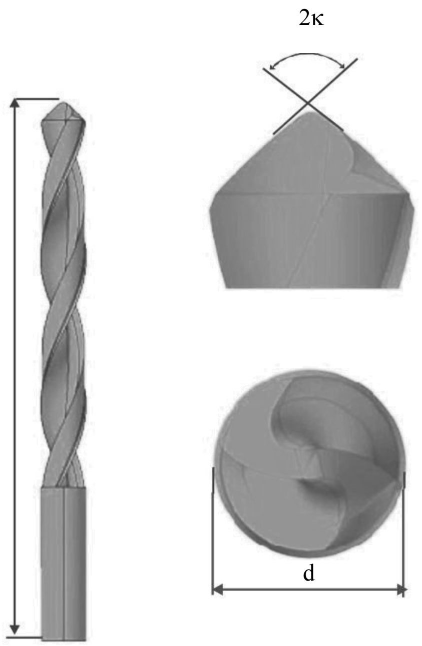

Fig. 1. Geometrical model of the surgical drill

In order to carry out the numerical analysis a simplified geometrical model of femur was worked out. Disc of diameter d_1 = 20 mm and height h = 10 mm was established as the model of the femur. The height of the disc corresponded with thickness of cortical tissue of femur. The hole corresponding with diameter of the drill and representing its edge geometry was simulated in the disc – Fig. 2. The Inventor Professional 2008 software was applied in order to work out the geometrical models.

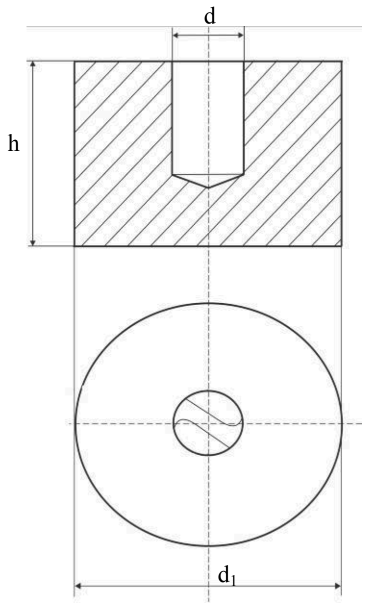

Fig. 2. Geometrical model of the disc simulated of bone

2.2. Numerical model

On the basis of the geometrical models, finite element meshes were generated. Numerical model was prepared in ANSYS Workbench v11. Meshing of the drill for both point angle 2κ and disc was realized with the use of SOLID 187 elements applied in analyses of volumes. Additionally in zones for which maximum strains and stresses were predicted a concentration of mesh was applied – Fig. 3. Meshed model of the surgical drill – bone system was presented in Fig. 4.

In order to carry out calculations it was necessary to evaluate and establish initial and boundary conditions which imitate phenomena in real system with appropriate accuracy. The following assumptions were established - Fig. 5:

- drill was loaded with forces in the range F = 100-200 N and torque T = 0.04 Nm [4],
- directional (X, Y and Z) immobilization of the disc,
- contact drill with disc (simulated bone) was simulated along to the cutting edge and chisel edge.

The scope of the analysis included determination of strains and stresses in working part of surgical grill for point angle ($2\kappa_1 = 90^o$ and $2\kappa_2 = 120^o$) made of martensitic steel and stainless steel. The materials properties were as follows:

- E = 221 000 MPa, υ = 0.35 – martensitic steel (X39Cr13),
- E = 200 000 MPa, υ = 0.33 – stainless steel (grade D),
- E = 18600 MPa, υ = 0.33 – bone.

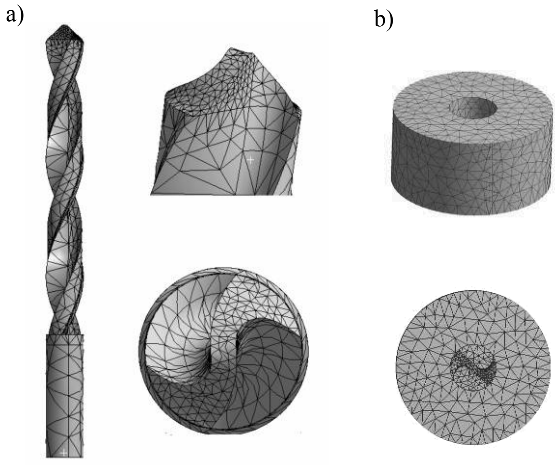

Fig. 3. Meshed model: a – surgical drill, b – disc simulated of bone

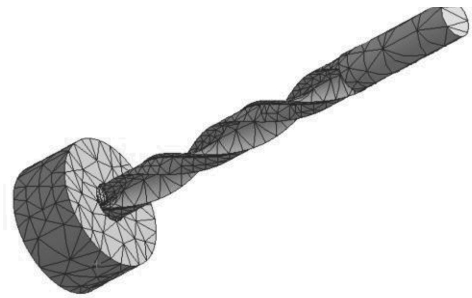

Fig. 4. Meshed model surgical drill – bone system

Fig. 5. Numerical model with boundary conditions F- force, T-torque, 1- fixed support

Strains and stresses obtained in the analysis are reduced values according to the Huber – Misses hypothesis.

3. Results

3.1. Results of the numerical analysis for drills made of stainless steel (grade D)

Results of the numerical analysis for both point angles ($2\kappa_1 = 90^o$ and $2\kappa_2 = 120^o$) are presented in Table 1.

Table 1.
Results of the numerical analysis drill for point angle $2\kappa_1 = 90°$ and $2\kappa_2 = 120°$ made of stainless steel (grade D)

Point angle 2κ, °	Load F, N	Strain ε_{max}, %	Stress σ_{max}, MPa
90º	100	0.15	307
	150	0.22	459
	200	0.30	613
120º	100	0.18	368
	150	0.28	560
	200	0.37	752

Results of analysis indicate diverse values of strains in the working part of the drill. On the basis of the analysis it was affirmed that maximum values of the strains were equal to $\varepsilon_{max} = 0.15\%$ for angle $2\kappa_1 = 90^o$ and $\varepsilon_{max} = 0.18\%$ for angle $2\kappa_2 = 120°$ respectively for the applied force F=100 N. While for force F=200 N maximum strains were equal $\varepsilon_{max} = 0.30\%$ for angle $2\kappa_1 = 90^o$ and $\varepsilon_{max} = 0.37\%$ for angle $2\kappa_2 = 120°$ respectively – Table 1. The values of maximum strains for point angle $2\kappa_1 = 90^o$ were observed in cutting edge nearly of chisel edge while for angle $2\kappa_2 = 120°$ distributions uniformly along to the cutting edge. Independently of the point angle ($2\kappa_1 = 90^o$ and $2\kappa_2 = 120°$) values of strains distribution similar for both cutting edges. Examples values of strains distribution are presented in Figs. 6, 7.

The analysis allowed to determine relations of maximum equivalent strains as a function of the applied loading – Fig. 8. On the basis of the analysis it was affirmed that maximum values of strains were obtained for the drill of point angle $2\kappa_1 = 120^o$.

The next part of analysis included determination of stresses in edge. Results of analysis indicate diverse values of stresses in the working part of the drill. On the basis of the analysis it was affirmed that maximum values of the stresses were equal $\sigma_{max} = 307$ MPa for angle $2\kappa_1 = 90^o$ and $\sigma_{max} = 368$ MPa for angle $2\kappa_2 = 120°$ respectively for the applied force F=100 N.

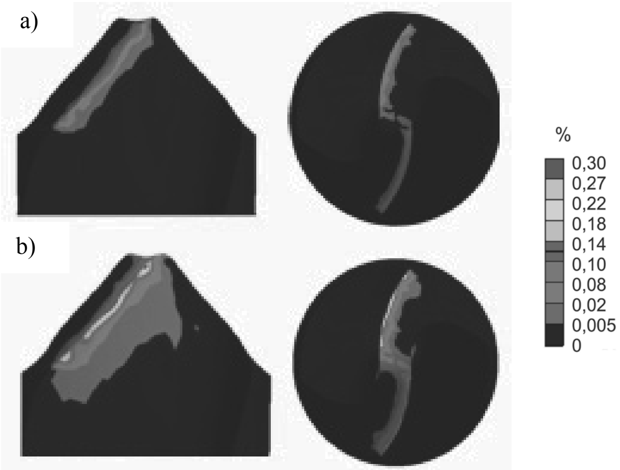

Fig. 6. Example strains distribution in drill for point angle $2\kappa_1 = 90°$ made of grade D loaded with the force a) F= 100 N, b) F= 200 N

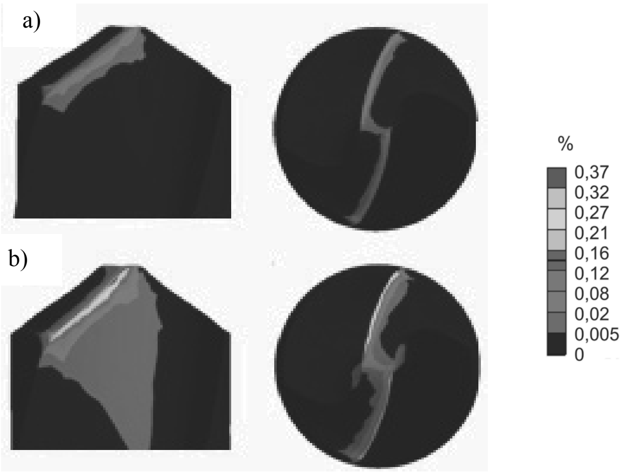

Fig. 7. Example strains distribution in drill for point angle $2\kappa_2 = 120°$ made of grade D loaded with the force a) F= 100 N, b) F= 200 N

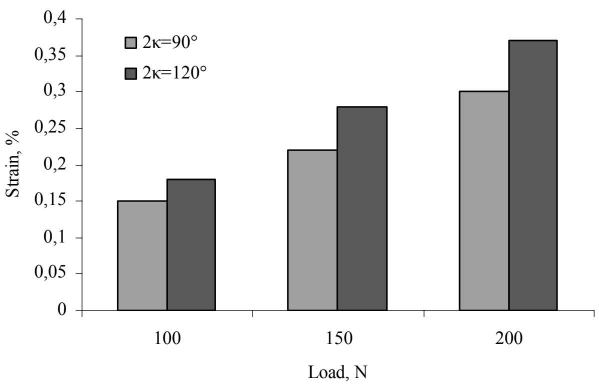

Fig. 8. Relation maximum reduced strains drills point as a function of the applied loading

While for force F= 200 N maximum stresses were equal σ_{max} = 613 MPa and σ_{max} = 752 MPa respectively. The values of maximum stresses for point angle $2\kappa_1 = 90^o$ were observed in cutting edge nearly of chisel edge while for angle $2\kappa_2 = 120°$ distributions uniformly along to the cutting edge. Independently of the point angle ($2\kappa_1 = 90^o$ and $2\kappa_2 = 120°$) values of stresses distribution similar for both cutting edges. Examples values of stresses distribution are presented in Figs. 9, 10.

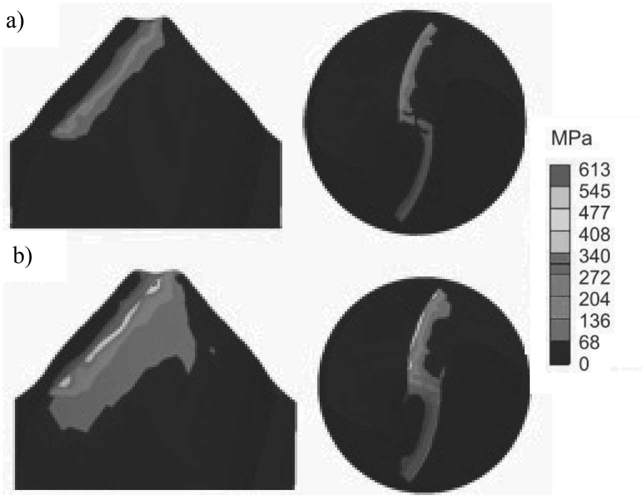

Fig. 9. Example stresses distribution in drill for point angle $2\kappa_1 = 90°$ made of grade D loaded with the force a) F= 100 N, b) F= 200 N

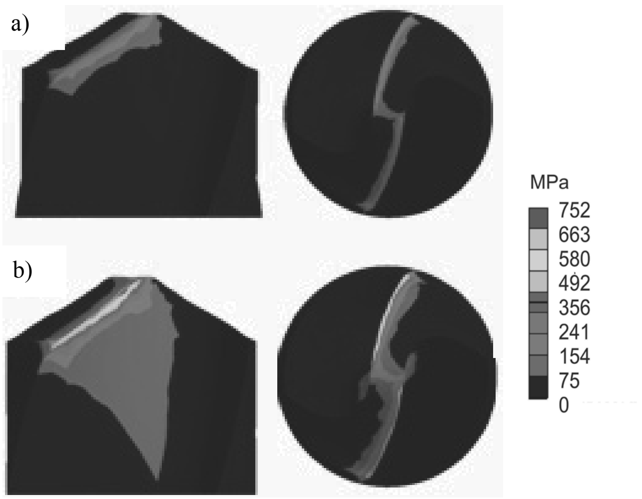

Fig. 10. Example stresses distribution in drill for point angle $2\kappa_2 = 120°$ made of grade D loaded with the force a) F= 100 N, b) F= 200 N

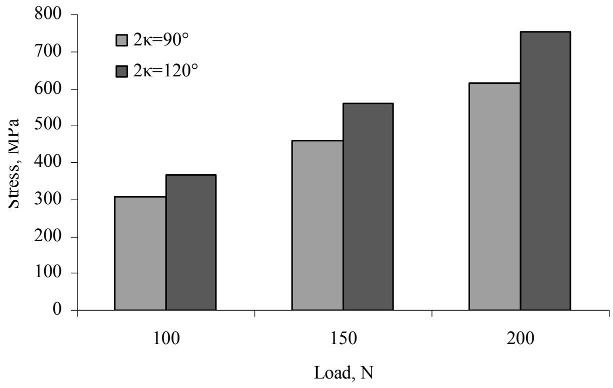

Fig. 11. Relation maximum reduced stresses drills point as a function of the applied loading

The analysis allowed to determine relations of maximum equivalent stresses as a function of the applied loading – Fig. 11. On the basis of the analysis it was affirmed that maximum values of stresses were obtained for the drill of point angle $2\kappa_1 = 120^o$

3.2. Results of the numerical analysis for drills made of martensitic steel (X39Cr13)

Results of the numerical analysis for both point angles ($2\kappa_1 = 90^o$ and $2\kappa_2 = 120^o$) are presented in Table 2.

Table 2.
Results of the numerical analysis drill for point angle $2\kappa_1 = 90°$ and $2\kappa_2 = 120°$ made of X39Cr13 steel

Point angle 2κ, °	Load F, N	Strain ε_{max}, %	Stress σ_{max}, MPa
90°	100	0.13	307
	150	0.2	460
	200	0.28	619
120°	100	0.16	369
	150	0.25	561
	200	0.34	753

Results of analysis indicate diverse values of strains in the working part of the drill. On the basis of the analysis it was affirmed that maximum values of the strains were equal ε_{max}= 0.13% for angle $2\kappa_1$= 90^o and ε_{max}= 0.16% for angle $2\kappa_2$= 120° respectively for the applied force F= 100 N. While for force F= 200 N maximum strains were equal ε_{max}= 0.28% for angle $2\kappa_1$= 90^o and ε_{max}= 0.34 % for angle $2\kappa_2$ = 120° respectively – Table 2. The values of maximum strains for point angle $2\kappa_1$= 90^o were observed in cutting edge nearly of chisel edge while for angle $2\kappa_2$= 120° distributions uniformly along to the cutting edge. Independently of the point angle ($2\kappa_1$= 90^o and $2\kappa_2$= 120°) values of strains distribution similar for both cutting edges. Examples values of strains distribution are presented in Figs. 12, 13.

a)

b)

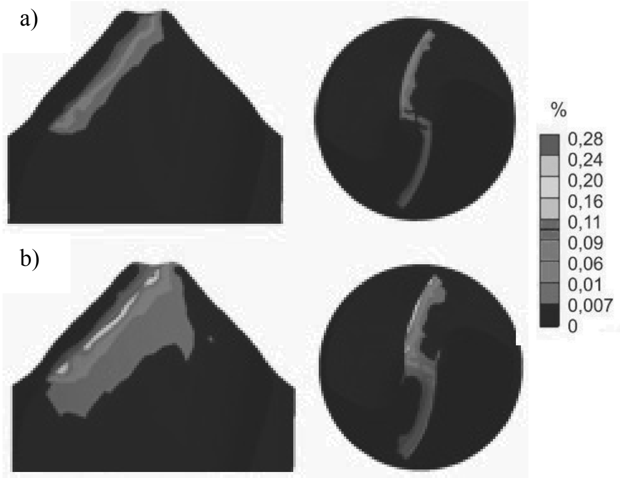

Fig. 12. Example strains distribution in drill for point angle $2\kappa_1$ = 90° made of X39Cr13 steel loaded with the force a) F=100 N, b) F= 200 N

a)

b)

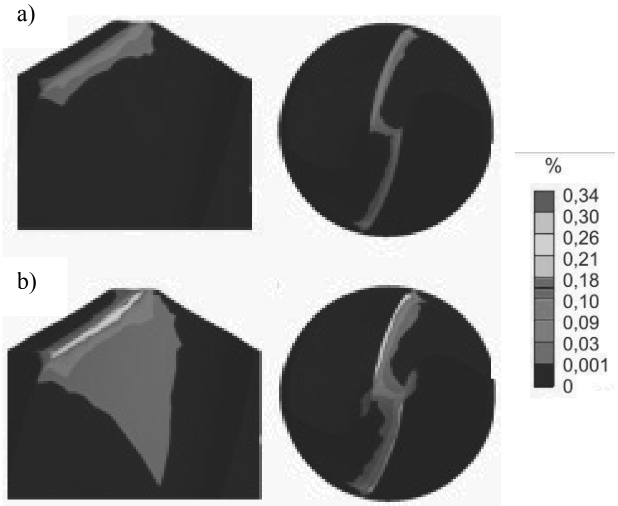

Fig. 13. Example strains distribution in drill for point angle $2\kappa_2$ = 120° made of X39Cr13 steel loaded with the force a) F=100 N, b) F= 200 N

The analysis allowed to determine relations of maximum equivalent strains as a function of the applied loading – Fig. 14. On the basis of the analysis it was affirmed that maximum values of strains were obtained for the drill of point angle $2\kappa_1 = 120^o$

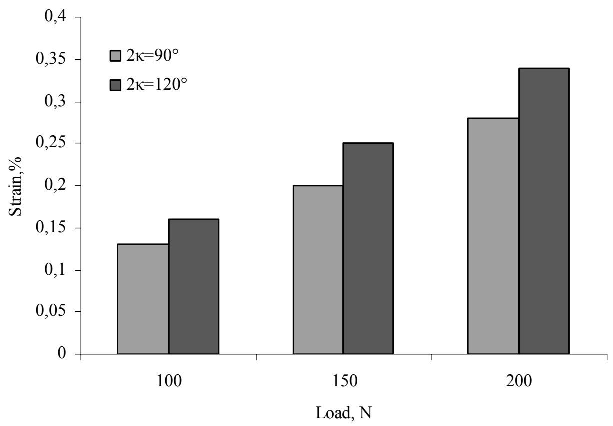

Fig. 14. Relation maximum reduced strains drills point as a function of the applied loading

The scope of the analysis included determination of stresses in edge. Results of analysis indicate diverse values of stresses in the working part of the drill. On the basis of the analysis it was affirmed that maximum values of the stresses were equal σ_{max} = 307 MPa for angle $2\kappa_1 = 90^o$ and σ_{max} = 369 MPa for angle $2\kappa_2 = 120°$ respectively for the applied force F= 100 N. While for force F=200 N maximum stresses were equal σ_{max} =619 MPa and σ_{max} =753 MPa respectively – Table 2. The values of maximum stresses for point angle $2\kappa_1 = 90^o$ were observed in cutting edge nearly of chisel edge while for angle $2\kappa_2 = 120°$ distributions uniformly along to the cutting edge Independently of the point angle ($2\kappa_1 = 90^o$ and $2\kappa_2 = 120°$) values of stresses distribution similar for both cutting edges. Examples values of stresses distribution are presented in Figs. 15, 16.

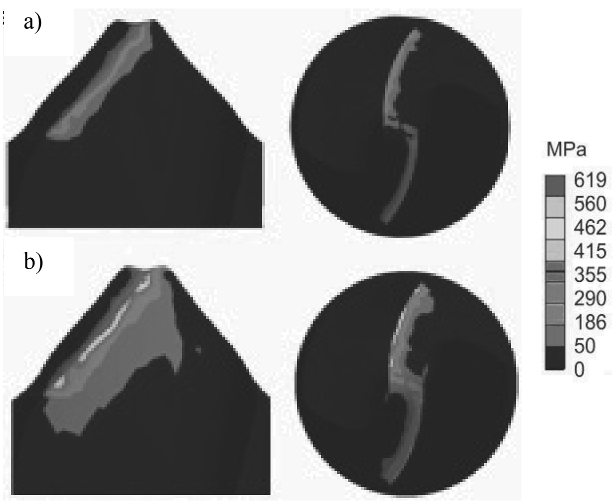

Fig. 15. Example stresses distribution in drill for point angle $2\kappa_1 = 90°$ made of X39Cr13 steel loaded with the force a) F=100 N, b) F= 200 N

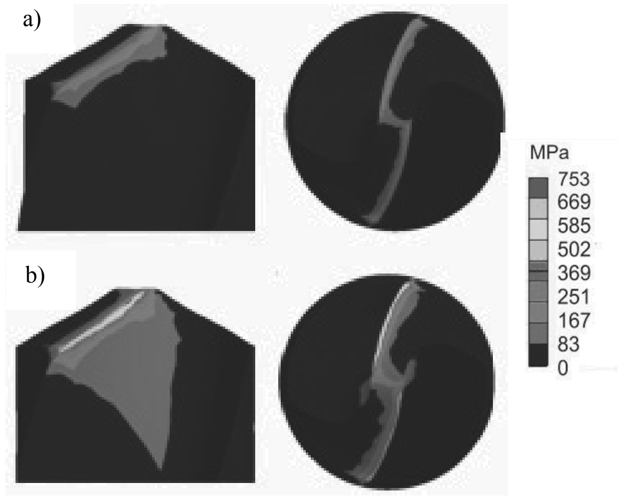

Fig. 16. Example stresses distribution in drill for point angle $2\kappa_2 = 120°$ made of X39Cr13 steel loaded with the force a) F= 100 N, b) F= 200 N

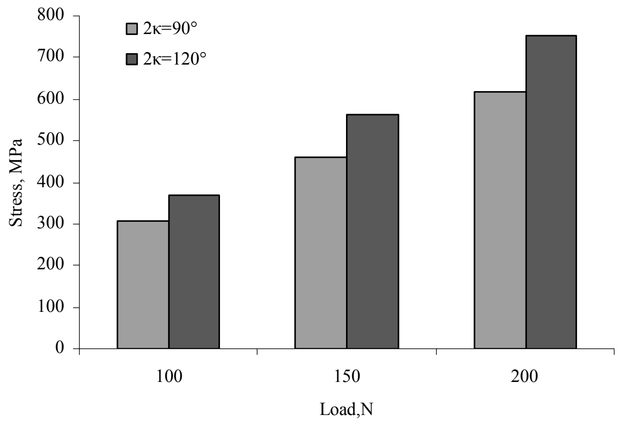

Fig. 17. Relation maximum reduced stresses drills point as a function of the applied loading

The analysis allowed to determine relations of maximum equivalent stresses as a function of the applied loading – Fig. 17. On the basis of the analysis it was affirmed that maximum values of stresses were obtained for the drill of point angle $2\kappa_1 = 120^o$.

4. Conclusions

Forming of usage properties of an operational instrumentarium used in bone surgery is a multistage process. First of all that includes a geometry design stage and selection of mechanical properties of metallic material. With reference to surgical drills, their usefulness is determined by appropriate geometry of edge. The edge geometry is mostly determined by point angle 2κ. The value of point angle for drills used in clinical practice is in the range 2κ= 90°-120°.

The work presents results of biomechanical analysis of a surgical drill used in orthopeadic procedures for two point angles – $2\kappa_1 = 90^o$ and $2\kappa_2 = 120^o$. In order to reflect phenomena in a real system, a simplified surgical drill – femur model and appropriate boundary conditions were established – Figs. 4 and 5. The simplifications in the analyzed system concerned mostly geometry of femur. A disc of height h = 10 mm was established as the model of the femur. The height of the disc corresponded with thickness of cortical tissue of femur. The calculations were carried out for two types of metallic material – stainless steel (grade D) and martensitic steel (X39Cr13).

The analysis of the obtained results show that for the drill of point angle $2\kappa_1 = 90^o$ equivalent strains and stresses are lesser than for the point angle $2\kappa_2 = 120^o$ – Tables 1 and 2, Figs. 6-17. This dependence was confirmed also for both analyzed metallic materials. The values of maximum strains and stresses for point angle $2\kappa_1 = 120^o$ were observed in cutting edge nearly of chisel edge. No significant differences in the results were observed for the analyzed metallic materials of the surgical drill.

The numerical analysis of the surgical drill – femur system in simulated conditions of drilling in a bone can be a basis for optimization of cutting edge geometry of surgical tools as well as for selection of their mechanical properties. Due to breaks of drills observed in clinical practice (especially for tools of diameter d = 2-3 mm) a biomechanical analysis of the wide range of the given instrumentarium will be carried out.

Acknowledgements

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