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Numerical modelling of structure and mechanical properties for medical tools

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Analysis and modelling

ABSTRACT

Purpose: In order to design forceps and bowl cutter property, it is necessary to optimise many parameters and consider the functions, which these medical tools should fulfil. Of course, some simplifications are necessary in respect of calculation methodology. In the paper a solution procedure concerning this problem has been presented. The presented solution allows for precise determination of the geometrical dimensions according to the functional requirements that forceps should fulfil. The presented numerical analysis describes a small range of the forceps application but the used algorithm can be applied in any other type of forceps. Also in the paper, the numerical simulation results of the bowl cutter being loaded are presented. Residual stress distribution on the tool surface is presented. A position of the cutting edges and holes carrying away the bone chips is shown as a polar diagram.
Design/methodology/approach: The numerical analysis was carried out using ADINA software, based on the finite element method (FEM). In the paper some fundamental construction problems occurring during the design process of the forceps and bowl cutter have been discussed.
Findings: The iteration procedures in order to optimize the basic construction parameters of the medical tools (forceps and bowl cutter). The calculations allow for determination of the geometrical parameters with reference to the expected spring rate. The charts elaborated on the basis of the calculations are very useful during a design process. The numerical calculations show an essential problem, namely a change in contact surface as a function of load. The observed phenomenon can affect the functioning of the forceps in e negative way.
The numerical simulation make it possible to obtain the suitable geometry, better material properties and the instructions heat treatment of these tools.
Research limitations/implications: These research was carried out in order to improve ergonomics, mechanical properties and work condition of medical tools. For bowl cutter was improve geometrical sharp and distribution of cutting holes.
Originality/value: This paper presents conception to obtain new medical tools, after optimizing the basic construction parameters by numerical calculations. The prepared model could be a helpful for engineering decisions used in the designing and producing forceps and bowl cutter.
Keywords: Fined elements method; Numerical optimization; Medicals tools; Surface engineering

1. Introduction

In these days design of modern medical tools must be supported by interdisciplinary knowledge. Relevant knowledge of such science disciplines as medicine and high tech mechanic engineering is required. Medical tools should have different medical and mechanical properties. The most important of them are durability and reliability. The main designing problem for medical tools is their sterilization during working life [1]. Their durability mostly depends on their material properties and working conditions. As far as the price of multiuse medical tools is concerned, one should have in mind that the more durable they are the more financial benefit they bring. The high quality of good medical care directly depends on organization and effective use of available resources and it is an international problem [2].

In publication [2] Peclitt presents the possibility of wide use of "Engineering support of surgery".

To perform further numerical and structural analysis two test medical tools forceps and bowl cutter have been chosen. First of these has most practical application but the other tool (bowl cutter) has only one medical application for hip joint alloplasty.

Forceps are one of the most popular medical tools. They are used in many medical fields such as: stomatology, laryngology, surgery, pharmacology, genetics etc. Moreover, forceps are applied in other domains such as: electronics, prosthetics, philately, assembly of tiny elements, laboratory tests etc. Generally, shape and dimensions of forceps depend on their application. Anatomical forceps with the flat holder jaws and a classic arm shape are the most representative example of the forceps. These forceps may have different working tips with a thickness of 1÷5 mm. The whole forceps length ranges from 67 to 490mm [3]. In microsurgery and genetics the forceps with a large width of the arms in proportion to the pointed holder jaws are used. Some forceps e.g. laryngological ones have curved working arms in order to secure better observation of the surgical field. There is also a group of the specialist forceps, which are characterised by a special shape of the arms and holder jaws depending on their use. Some forceps have working jaws with the specialistic holder tips, which are designed for execution of the special medical functions [4,5,6]. The forceps can be made of the acid resistant steel, stainless steel, titanium or non-magnetic steel. It depends on the forceps use. Some forceps are covered with TiN layer. The working parts can be covered with diamond or made of sintered carbides.

In this paper a tool for hip joint alloplasty was presented. The surgery was meant to reconstruct a damaged joint.

The two factors that contribute to the successfulness of the operation are: endoprothesis construction and operation technique [7]. To sum up the success in alloplasty of hip joint is directly dependent on the correct design of a medical tool. Medical tools are usually made of special types of steel, which are chosen according to the recommendation in works [8,9,10], and suitable conditions of sterilization and corrosion resistance.

2. The numerical analysis for chosen medical tool

2.1. Numerical analysis of the dential forceps

A numerical simulation of the dental forceps was carried out. Three dimensional geometrical models were created. Three variants of the forceps geometry were analysed. Figure 1 shows these variants. In Figure 1a) a basic geometry of the dental forceps is presented. Next, the geometry was modified. In Figure 1c) and 1d) the views of the forceps parts, which were subjected to modification, were shown. The changes concerned thickness of this part of the forceps where the load was applied. Thickness change aims at receiving more agronomic shape and more favourable load of the forceps. The modification was made only to one forceps arm. – Only one arm was modified.

Thanks to the numerical simulation it is possible to obtain information on the stress state in the forceps elements [11,12]. Additionally, in the numerical model contact elements at the working tips were applied, which allows for more precise analysis of behaviour of the working tips. Analysis results will be used in the design of the forceps geometry and determination of the compressive force and heat treatment. The calculation was carried out for 1.4024 steel (according to EN standards). Table 1 presents some mechanical properties and chemical constitution for the chosen type of steel.

In order to carry out the numerical analyse it is necessary to predetermine performance requirements and working parameters of forceps. According to functional analyses are shown in Figures 2a), 2b), 2c). Elastic properties of the forceps material were assumed in the numerical model. Mesh of the finite elements was created from 27-node 3D elements. In order to model the forceps about 42 000 nodes were used. The assumed number of the elements and nodes secure the right image of geometry and optimum calculation results.

Table 1.
Material data for 1.4024 steel (EN)

Chemical constitution [% mass]				Mechanical properties in room temperature				
C%	Si%	Mn%	Cr%	$R_{0.2}$ [MPa]	R_r [MPa]	E [MPa]	N	Hardness
0,12-0,17	≤1,0	≤1,0	12,0-14,0	250	600	$2{,}2 \cdot 10^5$	0,29	225 HV

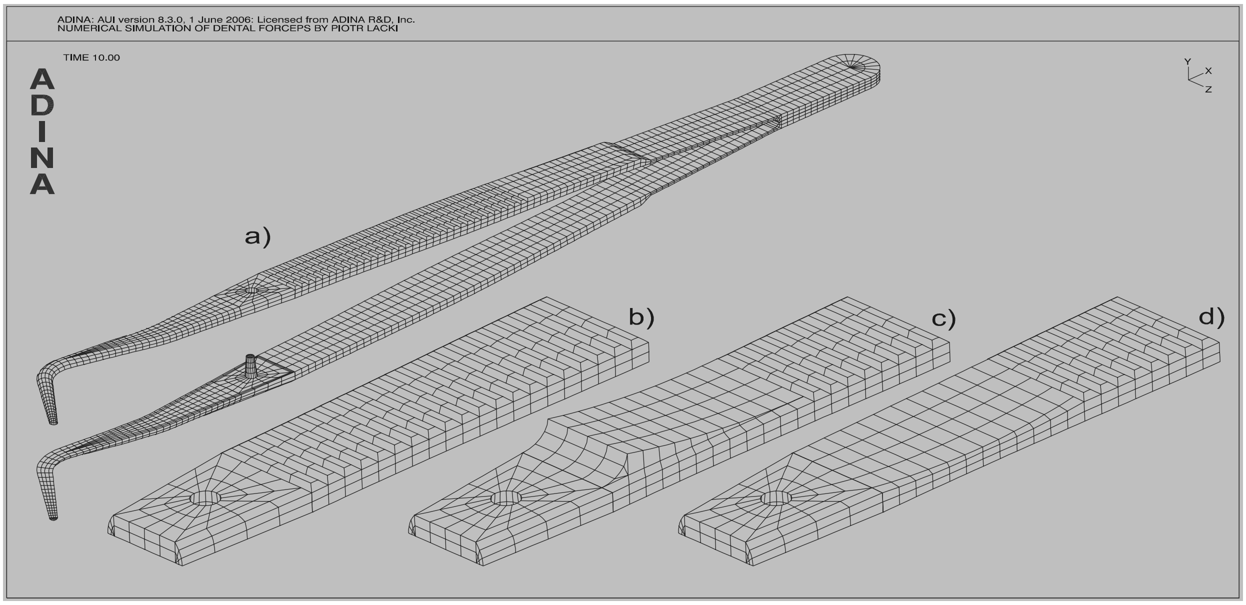

Fig. 1. The analysed forceps geometry a) basic geometry – a view of the whole forceps, b) basic geometry – a view of the forceps part, which undergoes modification, c) thickening in the modified part, d) thinning in the modified part

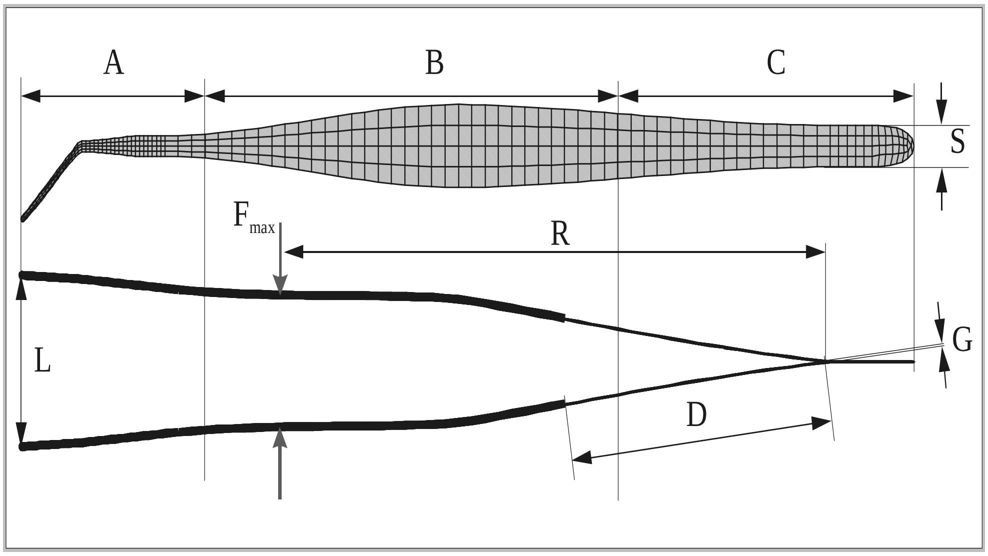

Fig. 2. Characteristic area of specialist forceps

In Figure 3 the stress distribution for the analysed geometry and the way of their load is presented. The force of F=10N was applied to the arm of the forceps. F force was distributed among two nodes of the FEM mesh. According to the calculations there is a difference in stress distributions resulting from the forceps geometry.

Differences in reduced stresses appear only for the modified parts of the forceps. In the area of the compressive force action (in the case of the forceps showed in Figure 1d) an increase of reduced stresses in relation to the stresses for the basic geometry was observed. The increase of stresses resulted from a decrease in the local thickness of the forceps arm. For the forceps shown in Figure 1c) there was no essential change in the stress state. Thickness of the forceps arms was higher than the thickness of the basic forceps. None of the analysed variants exceeded the limit of stresses, which were defined for the analysed material.

Maximum stresses occurring in the working area of the forceps jaws are of about 25% of the tensile strength so they do not present any risk. When the F force is applied at the forceps tips the stresses are also small despite the direct contact between working jaws. It is connected with a slight change in geometry of the working jaws Figures 4 and 5.

Fig. 3. Distribution of the effective stresses for the analysed variants, [MPa]

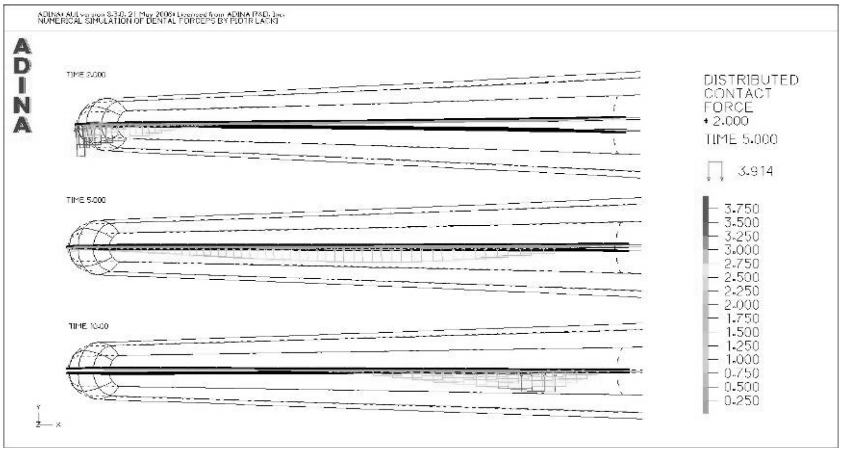

Fig. 4. Contact Forces distribution [N] in surface of working jaws

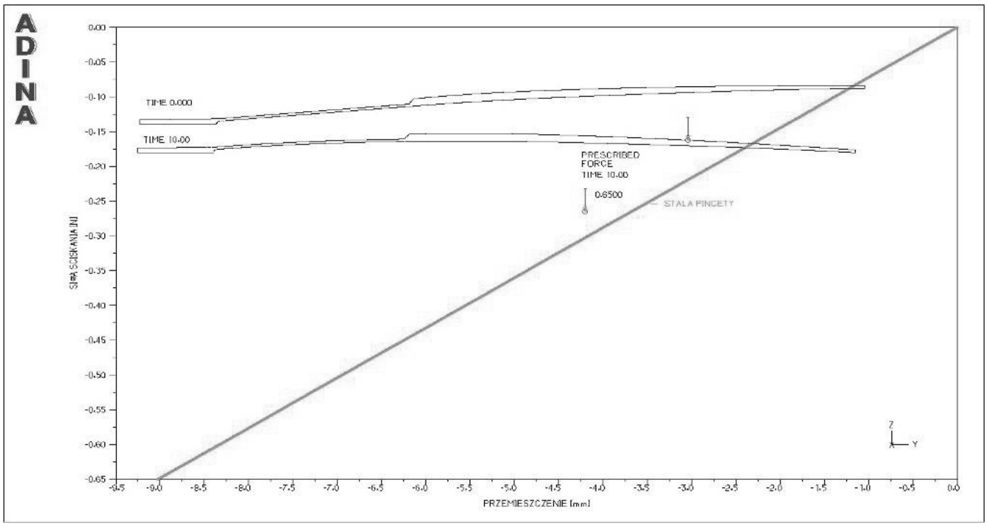

Fig. 5. Curve of changes of applied compressive force in function on the distance between the tips of the working jaws and the point of load

At the end of the working jaws there are: a hole in one arm and pin in the other arm. These elements prevent forceps jaws against shifting. Taking into consideration stress distribution, these elements pose some kind of notch and result in stress concentration. At the forceps surface in the vicinity of the hole there is local concentration of the effective stresses. When the hole is too big as compared to the forceps thickness, this place can be affected by a crack. The other arm with the pin is not affected by crack but it is exposed to corrosion [13,14]. In order to improve corrosion resistance pins are generally made of the material with lower carbon content.

2.2. Numerical analysis of the bowl cutter

In the first part of a bowl cutter designing process distribution of cutting edges was established. Figure 6 shows points, where holes with cutting edges will be made in further stages. These points are arranged along three spirals.

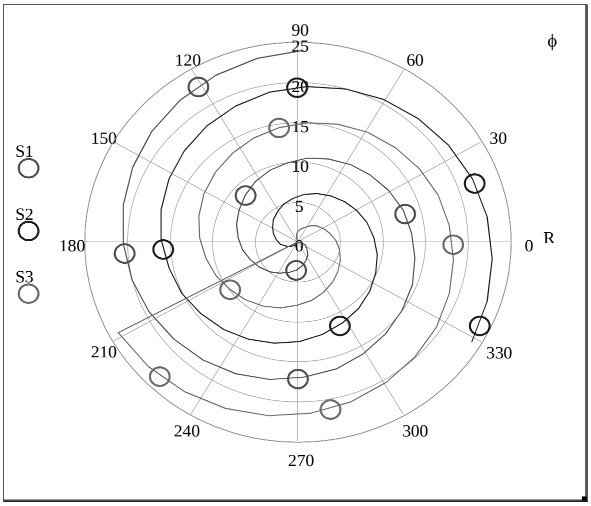

Fig. 6. The design of cutting edge holes distribution on the bowl cutter surface

Cutting edges distribution on the bowl cutter surface is of key importance in the cutting process. Badly designed or inaccurately made cutting edges will have a negative influence on the effectiveness of a bone cutting process. The graph of cutting edges distribution was a base for creating of a numerical model. Figure 7 shows finite elements net put on a geometrical model. The numerical model has been built with 3,348 coating elements and 3,360 solid elements. The first elements are shell type with 6 degrees of freedom and the second of 3D solid type with 3 degrees of freedom. Totally 8,382 nods of MES net were generated. In this work, the modeled bowl cutter was made of 1.4028 steel according to the European Standards. The basic property of this steel has been shown in Table 2.

The results of the numerical analysis presented as a stress distribution (Fig. 7), show state of the stress on the surface of a bowl cutter, which is the result of a static load/force. Its maximum value is on cutting edges and around holes carrying away bone chips. The biggest stress reduction is observed in the middle of cutting edges and $\sigma_{max} = 114$MPa.

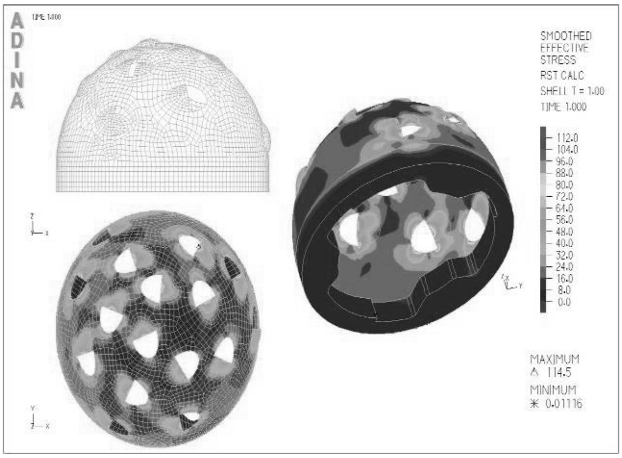

Fig. 7. The numerical model of a bowl cutter. The map of stress reduction on a bowl cutter surface, [MPa]

The stress state on the surface of a bowl cutter in every point does not exceed a yield point, suitable for the type of steel chosen for a numerical analysis.

In accordance with the initial assumptions the edges of the MES net elements were about 3mm long. During further numerical analyses the length of element edges was gradually decreased (MES net was being consolidated) and maximum dislocation was being cooperated with the previous model characterized by less thinness of MES net. These procedures were repeated until the moment when the difference in maximum dislocation was smaller than 0.1mm. The constructed numerical model had optimal number of elements in reference to its required precision. The load of a bowl cutter was chosen in accordance with required proportion between the area of a cutting surface and the resistance of a bone. The place of fixing of the bowl cutter was in the part of a fixing ring.

3. Description of the results achieved during own research studies

3.1. The methods to prolong/increase life resistance of bowl cutter

The numerical analysis showed in this work does not take into account the consumption of cutting edges of a bowl cutter. This problem will be the subject of further research. In Figure 8 state of stress reduction with a wide legend area was presented. The wide legend area is a reason for connecting some of the stress areas, which are situated near holes. During the designing process suitable location/placement of the depending on the size of holes is the most important task.

Design errors and the composite state of stress may sometimes result in buckling of some area of the bowl cutter. This phenomenon is very difficult to analyze using traditional methods, because this effect is caused by stress whose value does not exceed a yield point. The buckling results from reduction of a material tautness in places near holes of a bowl cutter. It is a critical deformation and the tool becomes completely useless. In this case the numerical analysis is helpful in determination of a suitable sheet thickness.

Table 2.
Properties of 1.4028 steel (EN)

Chemical constitution [% mass]				Mechanical properties				
C	Si	Mn	Cr	$R_{0.2}$ [MPa]	R_r [MPa]	E [MPa]	N	Hardness
0,28-0,35	≤1,0	≤1,0	12,0-14,0	250	750	$2{,}2\cdot10^5$	0,29	235 HV

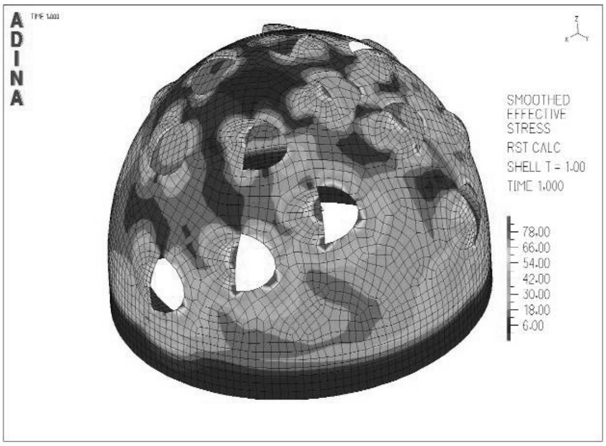

Fig. 8. The state of reduced stress on bowl a cutter surface, [MPa]

For the analyzed bowl cutter the input sheet thickness was g = 1 [mm], which made it possible to obtain the optimal working conditions. During the pressing process the bowl cutter sheet was thinned by about 30%. The thinned sheet was not the same in every areas of a bowl cutter. Because of that, it was necessary to carry out a numerical analysis taking in consideration the change of a bowl cutter surface thickness. The pressing process ought to be the properly designed and carried out. Graphite grease was used in order to guarantee the good condition of a bowl cutter pressing.

Heat treatment is a key element in a bowl cutter production process. Heat treatment enables changes of material structure and its mechanical properties such as: spring rate, yield point, impact resistance and durability. Heat treatment makes it possible to obtain a very hard structure with a high spring rate and a long working life, but these structures are brittle and they tend to crack. The load of a bowl cutter depends on the surgeon's strength and the geometry of a bowl cutter can be affected by non linear change of strength and the bowl cutter structure sometimes is very brittle and sometimes leads to spalling of a cutting edge or cracking of a bowl cutter. On the other hand, too plastic material will be characterized by lower consumption resistance. Taking into consideration what has been mentioned above heat treatment ought to be designed so as to obtain suitable proportions between mechanical properties of steel. In this case, maximum reduced stress $\sigma_{max} = 114$MPa obtained during the numerical simulation is two times lower than limit of a yield point of the research material ($R_{0.2} = 250$MPa) and six times lower than its limit of strength ($R_r = 750$MPa). These parameters guarantee optimal strength properties.

3.2. The ways of improving durability of foreceps

In order to improve working durability heat treatment of forceps has been designed and carried out.

During further research two ways of thermo-chemical treatment have been chosen:

- heat treatment in fluidized bed,
- vacuum heat treatment.

The parameters of these processes have been chosen separately for type of forceps material. The better quality and property have been obtained after heat treatment in fluidized bed. Figures 9 and 10 shows structures of forceps materials before and after heat treatment in fluidized bed.

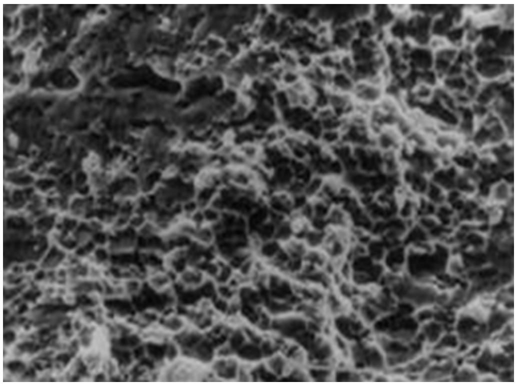

Fig. 9. Microstructure of material before heat treatment, nital etched in scale 1:2 000

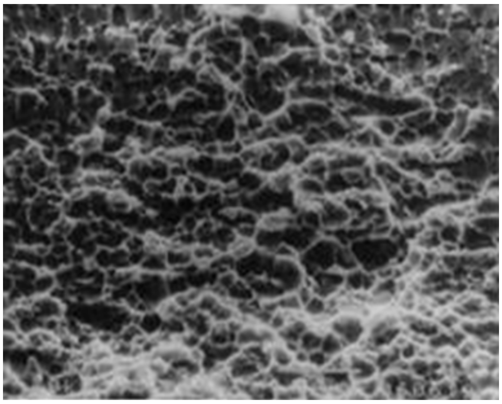

Fig. 10. Microstructure of material after heat treatment, nital etched in scale 1:2 000

In Figures 11 and 12 it is possible to see the distribution of microhardness in surface area of forceps materials before and a after heat treatment in fluidized bed.

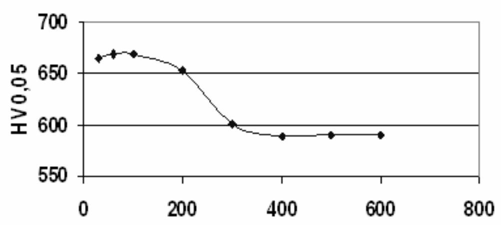

Fig. 11. Characteristic of microhardness HV 0.025 in surface area before heat treatment

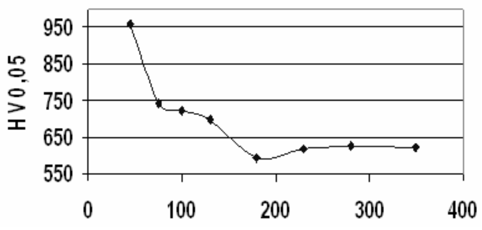

Fig. 12. Characteristic of microhardness HV 0.025 in surface area after heat treatment

The structure of forceps after thermo-chemical process in fluidized bed is characterized by tempered martensite metallic matrix with microhardness 535 HV 0.025 with participation of precipitate of carbides types $Cr_{23}C_6$ and Cr_7C_3). Differences in forceps structure before and after heat treatment depend of the quantity grows of carbides precipitate and is result from the activity of carbonized atmosphere.

4. Conclusions

The environment, in which medical instrumentarium works, imposes new restrictions on the procedure of design. Among other things, material corrosion and resistance to different sterilisation conditions must be just into consideration, of course in agreement with all mechanical parameters.

During numerical analysis in order to improve working properties of bowl cutter the, was carried out optimization procedures enabled to choose a suitable material for a bowl cutter such as 1.4028 steel according to European Standards. This steel after heat treatment gained required mechanical properties, a corrosion resistance and a resistance to the conditions of a sterilization.

To obtain required properties of material used for a bowl cutter pressing 1mm steel was chosen. The selected thickness provided the suitable spring rate of a bowl cutter and also it enabled to take into consideration the change of sheet thickness after pressing.

Depending on a bowl cutter working conditions, the recommend heat treatment ought to guarantee a structural strength to be three times higher than yielded point and not higher than $R_r = 750$MPa with a good impact resistance. The structure of material after the heat treatment process will result in low material consumption and good working life of a medical tool.

On the other hand, in order to improve ergonomics of e.g. the dental forceps, the two following solutions were proposed:

- forceps with thinning in the area of the force action,
- forceps with thickening in the same area.

Calculation results suggest that the stress distribution does not change considerably, but ergonomics of the forceps is better – it is easer and more comfortable to take hold of the forceps by a dentist.

Modification concerns only one arm of the forceps, which gives the possibility to hold the forceps in an easy and proper way without looking away from the operative field. It is especially important in the case of the asymmetric forceps, for which proper position in the hand is essential.

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