A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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WAYS OF IMPROVING DURABILITY OF SURGICAL BOWL CUTTER

SPOSOBY POPRAWY TRWAŁOŚCI EKSPLOATACYJNEJ CHURURGICZNEGO FREZA CZASZOWEGO

In order to design bowl cutter property, it is necessary to optimise many parameters and consider the functions, which this medical tool 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 the precise determination of the geometrical dimensions according to the functional requirements that forceps should fulfil. Also in the paper, the numerical simulation results of the bowl cutter 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.

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 bowl cutter have been discussed.

The iteration procedures were performed in order to optimize the basic construction parameters of the medical tools. The calculations allow determination of the geometrical parameters in 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 a negative way.

The numerical simulation make it possible to obtain the suitable geometry, better material properties and the instructions for heat treatment of these tools. These research works were carried out in order to establish mechanical properties and work condition of bowl cutter, conception to obtain new medical tools, after optimizing the basic construction parameters by numerical calculations.

Keywords: Finite elements method; numerical optimization; bowl cutter; surface engineering, mechanical properties

W celu zaprojektowania właściwości freza czaszowego jest konieczna optymalizacja wielu parametrów z uwzględnieniem warunków pracy tego narzędzia do chirurgii tkanki kostnej. Oczywiście podczas obliczeń konieczne są pewne uproszczenia. W pracy tej zostały zaprezentowane procedury dotyczące rozwiązania tego zagadnienia.

Prezentowane rozwiązania pozwalają na precyzyjne określenie geometrycznego kształtu zgodnie z warunkami jego pracy. Praca prezentuje wyniki przeprowadzonej symulacji numerycznej freza czaszowego. Został zaprezentowany między innymi zredukowany rozkład naprężeń występujący na powierzchni freza czaszowego oraz na diagramie biegunowym rozkład otworów i ostrzy skrawających kość miednicy.

Analiza numeryczna została przeprowadzona z zastosowaniem programu ADINA, opierającego swoje obliczenia na metodzie elementów skończonych. W pracy zostały omówione także podstawowe problemy powstałe podczas projektowania freza czaszowego.

Została zoptymalizowana stosowana dotychczas konstrukcja freza czaszowego do skrawania tkanki kostnej. Dodatkowo obliczenia pozwoliły na wyznaczenie parametrów geometrycznych pozwalających na otrzymanie oczekiwanego współczynnika sprężystości. Przeprowadzone badania wykazały, iż podstawowym problemem są zmiany powstające w powierzchni natarcia freza czaszowego podczas wykonywania zabiegu alloplastyki stawu biodrowego, zmiany te zostały zasymulowane numerycznie dla obciążeń dynamicznych.

Przeprowadzone badania pozwoliły na zaprojektowanie odpowiedniej geometrii, lepszych właściwości oraz i właściwy dobór parametrów do obróbki cieplnej narzędzi dla chirurgii tkanki kostnej. Opisane w pracy badania zostały przeprowadzone w celu poprawienia własności mechanicznych i trwałości eksploatacyjnej freza czaszowego, określenia sposobów wytwarzania nowych narzędzi medycznych, także poprawy parametrów konstrukcyjnych przez zastosowaną symulację numeryczną.

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1. Introduction

In these days, a 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 one of 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 e.g. bowl cutter were performed. In the first of these has most practical application but the other tool (bowl cutter) has only one medical application for hip joint alloplasty.

In this paper a tool for hip joint alloplasty was presented. The surgery was meant to reconstruct a damaged joint. Two factors that contribute the success of the operation are: endoprothesis construction and operation technique [3]. 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 [4, 5, 6], and suitable conditions of sterilization and corrosion resistance [7, 8].

2. Numerical analysis of the bowl cutter

In the first part of a bowl cutter, designing process distribution of cutting edges was established. Fig. 1 shows points, where holes with cutting edges will be made in further stages. These points are arranged along three spirals [9, 10].

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. Fig. 2 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 1.

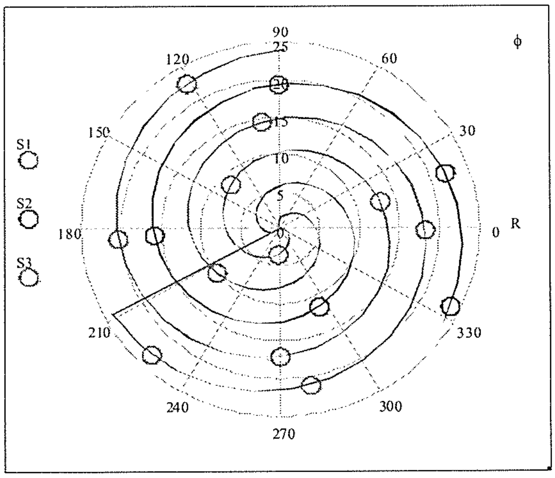

Fig. 1. The design of cutting edge holes distribution on the bowl cutter surface

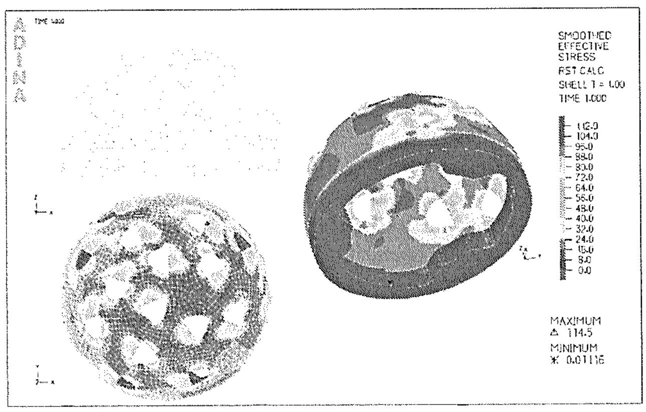

Fig. 2. The map of stress reduction on a bowl cutter surface, [MPa]

TABLE 1

Properties of 1.4028 steel (EN)

Chemical constitution [% mass]					Mechanical properties			
C	Si	Mn	Cr	N	$R_{0.2}$ [MPa]	R_r [MPa]	E [MPa]	Hardness
0.28–0.35	⩽1.0	⩽1.0	12.0–14.0	0.29	250	750	$2.2\cdot10^5$	235 HV

The results of the numerical analysis presented as a stress distribution (Fig. 2), 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 σ_{max} = 114 [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 3 mm long. During further numerical analyses, the length of element edges was gradually decreased (MES net was consolidated) and maximum dislocation was 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 0.1 mm. 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. The methods to prolong/increase life resistance of bowl cutter

The numerical analysis shown 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 3, the 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.

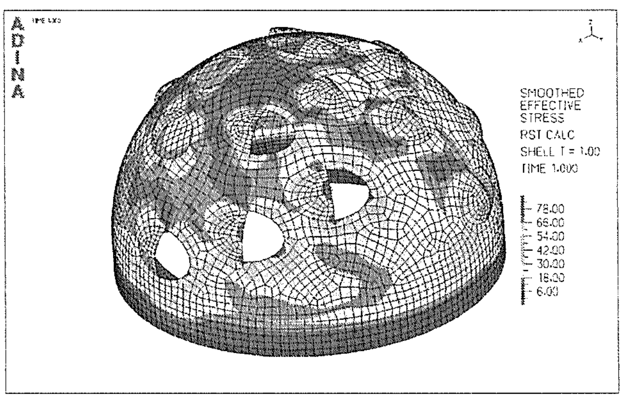

Fig. 3. The state of reduced stress on bowl of cutter surface, [MPa]

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.

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 of 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: 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. 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, the heat treatment ought to be designed so as to obtain suitable proportions between mechanical properties of steel. In this case, maximum reduced stress σ_{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.

In order to improve working durability heat, the treatment of bowl cutter has been designed and carried out. During further research parameters of the thermo-chemical treatment have been chosen:

1. Stress annealing relieving in fluidized bed:
   T = 580°C
   t = 1.5 h
2. Hardening with saturation in fluidized bed
   T = 980°C
   t = 1.5 h
3. Tempering after hardening in fluidized bed
   T = 525°C
   t = 1.5 h

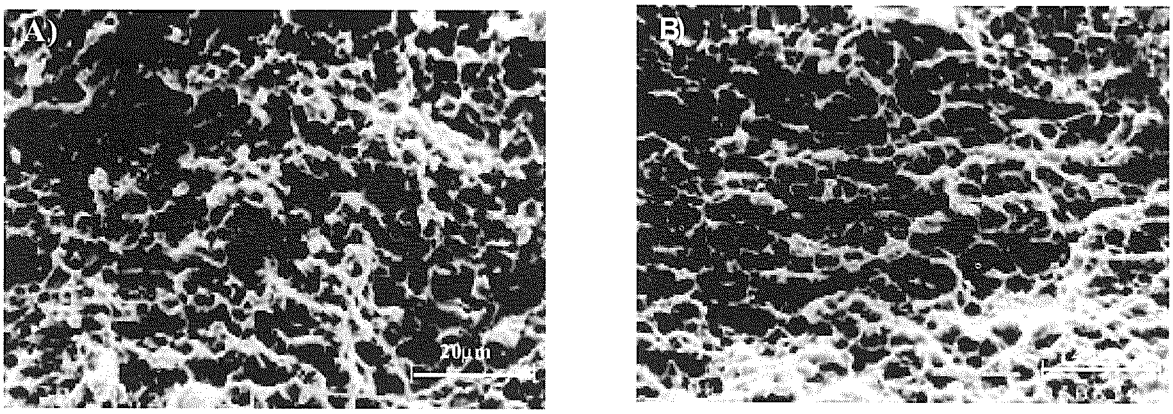

Fig. 4. A. Microstructure of material before heat treatment, nital etched
B. Microstructure of material after heat treatment, nital etched

After the heat treatment the research such as: microstructures, microhardness and durability investigations were carried out. Fig. 4 A,B show structures of bowl cutter materials before and after the heat treatment in fluidized bed.

In Figures 5 and 6 it is possible to see the distribution of microhardness in surface area of materials before and after heat treatment in fluidized bed.

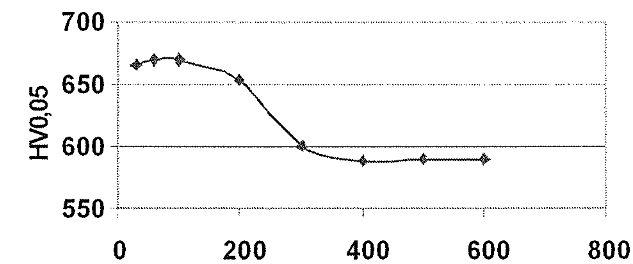

Fig. 5. Microhardnes HV 0.025 in surface area before heat treatment

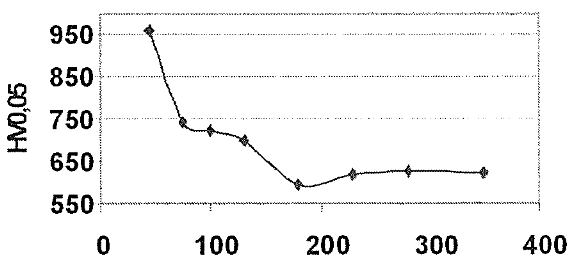

Fig. 6. Microhardnes HV 0.025 in surface area after heat treatment

The structure of material after thermo-chemical process in fluidized bed is characterized by tempered martensite metallic matrix with 535 HV0.025 microhardness with participation of precipitate on $Cr_{23}C_6$ and Cr_7C_3 carbides. Differences in surface structure before and after heat treatment depend on the quantity grows of carbides precipitate and result from the activity of carbonized atmosphere.

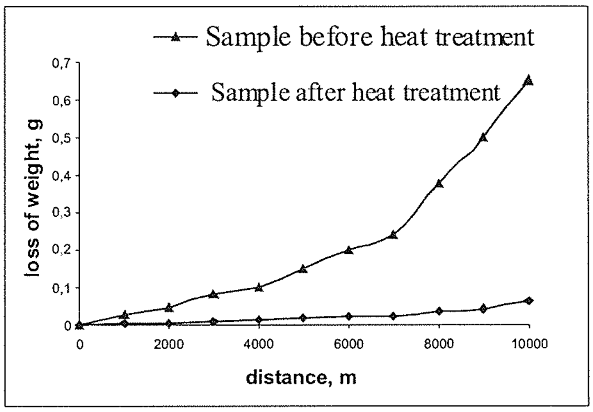

Fig. 7. Results of investigations exploatation with used tester T05 (loss of weight)

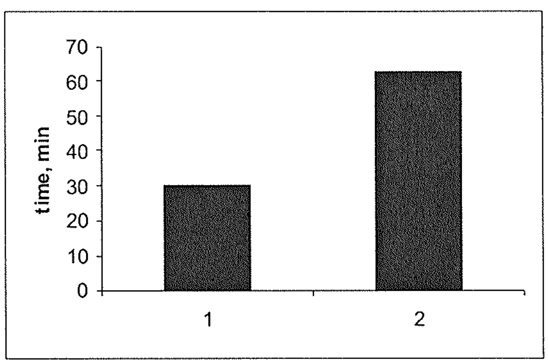

Fig. 8. Results of machine cutting test: 1 – sample before the heat treatment, 2 – sample after the heat treatment

In Figures 7 and 8 results of exploitation research curried out with Tester T05 and machine cutting test bone – steel were presented. These results to allowed find, that suitable selection of parameters of surface heat treatment makes it possible obtain longer working life of bowl cutter.

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, was optimization procedures, which carried out enabled to choose a suitable material for a bowl cutter such as 1.4028 steel according to European Standards.

To obtain required properties of material used for a bowl cutter pressing, 1 mm steel sheet 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 carried out research and heat treatment in fluidized bed make it possible to obtain better durability and twice longer working life of surgical bowl cutter. This fact was confirmed by exploitation research. The structure of material after the heat treatment process will result in low material consumption of a medical tool.

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