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MODELING OF MECHANICAL PHENOMENA IN THE PLATINUM-CHROMIUM CORONARY STENTS

Abstract. This study discusses the geometrical model of a coronary stent with known design and strength analysis using the finite element method. The coronary stent model was made of platinum and chromium alloy. Static analysis based on compression of the coronary stent was also performed. The aim of the analysis was to examine strength of the stent structure. The study analyzed stresses, displacements and plastic strains after applying a constant load to the stent walls. The mechanical phenomena such as percentage degree of shortening (foreshortening), relative narrowing and area of stent covering were also determined.

Keywords: *mathematics, computational mechanics, platinum-chromium stent, FEM, SolidWorks*

1. Introduction

One of the biggest successes in the field of invasive cardiology was to use endovascular implants termed stents. These implants are designed as small metal wirings with cylindrical design. They are implanted in the location of the narrowed coronary artery in order to expand it and support the arterial walls [1].

The most popular materials used for coronary stents include austenitic steel Cr-Ni-Mo (316 L), cobalt alloys, platinum and iridium alloys, nitinol and titanium and its alloys. Compared to stainless steel (surgical steel 316L), platinum-chromium alloy used in this study allows for a reduction in bending resistance and has better fit. The PtCr alloy is characterized by greater density compared to surgical steel 316L. Therefore, it is more visible in X-ray images despite smaller components in the stent. Studies have also shown that stents made of platinum-chromium alloys are faster covered by the neointima. Its flexibility allows for easier movement through the arteries without causing damages.

Conditions that characterize endovascular implants are:

- longitudinal shortening after expansion of the stent is presented as a percentage degree of shortening. The dimensions of the stents can be modified (shortened) during stent implantation, which has an effect on the final stent length. Knowledge of the shortening parameters is useful in choosing the adequate stent length and using it in the right position in human body,
- relative narrowing (normal strain) - narrowing of the stent diameter caused by compression related to its initial diameter,
- stent coverage area is defined as percentage evaluation between the external surface of metal in contact with the surface of the wall of the cylindrical vessel, which represents the fraction of the stented artery surface segment actually covered by metal.

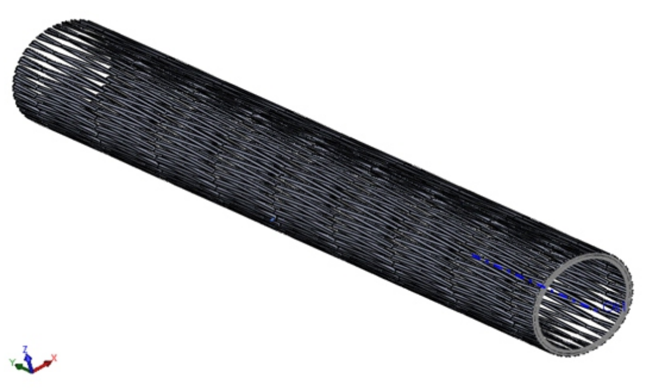

Fig.1. Geometrical model of the coronary stent

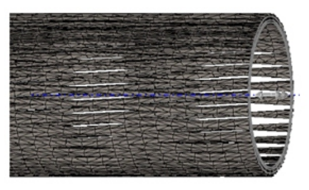

Fig.2. Stent model with finite element grid

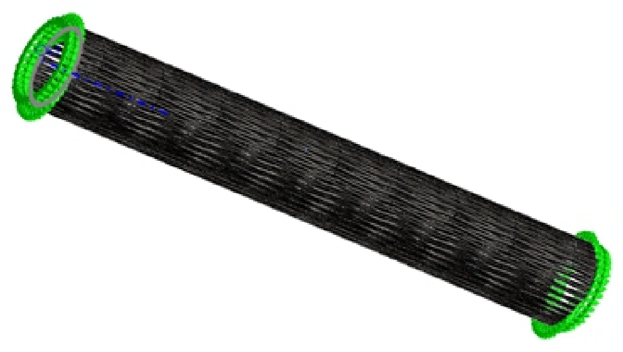

Fig.3. Fixation of the stent model

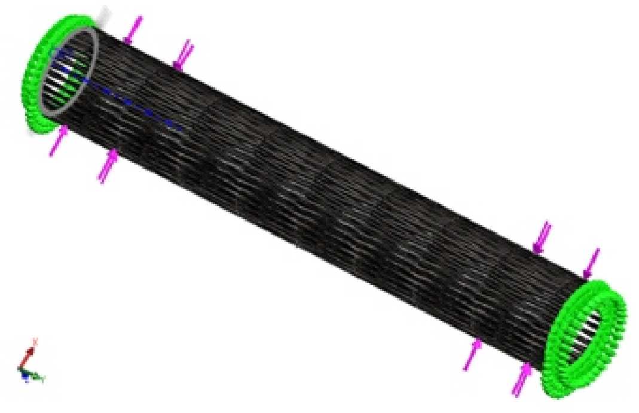

Fig.4. Stent model with applied forces

2. Material and methods

2.1. Stent model

The geometrical model of the stent was developed using the SolidWorks 2014 software (Fig. 1). With regard to its shape, the stent is numbered among net stents. Length of the developed model is 13.03 mm, internal diameter is 2 mm, both thickness and width of walls is 0,06 mm. The stent was composed of 8 segments.

2.2. Model discretization

Static analysis was performed by means of the SolidWorks 2014 software using the finite element method (FEM). A solid grid composed of 91052 nodes and 35711 elements was created for the stent model. Figure 2 presents the geometrical model of the coronary stent with the finite element grid in the expanded stent.

2.3. Material properties of the model

Due to high biocompatibility and strength, mechanical calculations were based on mechanical properties of the material contained in the SolidWorks database for platinum-chromium alloy. Stents made of platinum-chromium alloy have greater density and are faster covered by the neointima compared to the conventional stents made of steel 316 L. Table 1 presents material data adopted in the study.

2.4. Fixation conditions

In order to perform numerical analysis, apart from the adopted material properties, it is also important to define boundary conditions. For this purposes, the stent model was fixed at its two ends. Figure 3 presents stent fixation.

2.5. Stent compression

It is necessary to reduce the initial diameter of the implant in order to ensure proper implantation of the stent in the position of the artery narrowing. Furthermore, an insignificant diameter reduction protects from the possibility of removing from the catheter surface. The aim of the study is to evaluate the stent compression strength. It was adopted that the surgeon acts with a specific force on the external stent surface. Therefore, the stent model was loaded on both ends with the force of 10N on four external walls. Stent model with applied forces is presented in Fig. 4.

For this stent model, stresses, strain, displacement percentage foreshortening, relative narrowing and stent coverage area were determined.

3. Results of numerical analysis

1) Distribution of reduced stresses

For the coronary stent model made of PtCr alloy with applied forces, distribution of stresses was varied. Maximal value of reduced stresses was observed at the end of the external wall in the locations where the force was applied. Maximal value of stresses was 29860 MPa, whereas minimal stresses were around 1,533 MPa.

2) Distribution of displacements

Apart from the distribution of stresses, strain and displacements were also observed for the stent made of platinum-chromium alloy. The highest value of displacement was 0,698 mm, whereas the smallest was 0 mm. The biggest displacement was located on the internal stent wall where the compression force is applied, whereas the smallest displacements are observed on the internal ends of the model.

Tab.1. Material properties of the platinum-chromium alloy

Material properties	Value
Young's modulus E, [MPa]	203000
Poisson's ratio v	0.285
Density ρ, [kg/m^3]	7850
Tensile strength R_m, [MPa]	834
Yield point $R_{p0,2}$, [MPa]	480

3) Distribution of plastic strains

The plastic strains generated during strength test are permanent displacements which do not yield even after removing the load they were caused by. The biggest plastic strain was observed on the external stent walls, next to its fixation and force application point and accounted for 9,7%.

4) Mechanical phenomena during coronary stent compression. Strength tests performed for the stent made of platinum and chromium revealed the following parameters:

- Percentage foreshortening: $Foreshortening = \frac{L - L^{load}}{L} \cdot 100\%$ where: L – initial stent length, L^{load} – stent length at the highest loading $Foreshortening = \frac{13{,}03 - 12{,}67}{13{,}03} \cdot 100\% = 2{,}76\%$
- Relative narrowing caused by plastic strain: $Relative\ narrowing = \frac{D_0 - D}{D_0}$ where: D_0 – initial stent diameter before compression, D - the smallest stent diameter after compression. $Relative\ narrowing\ in\ the\ stent = \frac{2 - 0{,}82}{2} \cdot 100\% = 59\%$
- Stent coverage area: $Coverage\ Area = \frac{Surface\ of\ stent}{Area\ of\ artery}$ $Coverage\ Area = \frac{38{,}36}{82{,}35} = 0{,}47\ mm$

4. Conclusions

Statistical analysis performed using the finite element method allowed for the evaluation of stent strength. Furthermore, based on its value, the percentage foreshortening and relative narrowing caused by plastic strain was determined.

- The examinations revealed that the yield limit was exceeded in the analyzed case, which may lead to irreversible plastic deformation of the geometry of the stent. This condition is necessary for proper process of implantation of the stent in the coronary vessel.
- Maximal value of the reduced stresses was 29860 MPa. These high stresses may lead to emergence of notches on the stent surface. Consequently, the notches can lead to cracking and stent damaging.
- The highest plastic strains are noticed on the external model walls in the locations of slight bending of the stent walls. They can lead to irritation of the internal walls of arteries and inflammatory reactions or complications following the surgery.
- Stent foreshortening may lead to improper implantation of the artery. The numerical analysis of stent foreshortening demonstrated that the obtained values of foreshortening remain within the ranges recommended in the standards.
- The results obtained from the biomechanical analysis of coronary stents carried out in the present study based on finite element method represent information that can be useful for optimization of the geometry, choice of mechanical properties and material properties of the stent.
- The statistical analysis performed using the finite element method allowed for evaluation of stent strength. The stent structures which are the most exposed to risk of damage during model compression were demonstrated. The study showed that an important aspect of stent design is adequate choice of material and model geometry.
- The analysis carried out in the study allowed for identification of the parameters critical to evaluation of clinical usefulness of a specific stent shape.

References

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