Analysis of Stress and Prediction of the Defects of an Ankle Prosthesis Using the Autodesk Inventor Software

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The paper presents stress analysis of an ankle prosthesis and the prediction of the cracks appearance that may occur using the finite element method. The first test was performed using as material for the ankle prosthesis simulation, aluminium alloy 6061, and in the second test were use titanium as the simulation material. Von Mises's basic concept, failure theory, is also analysed, using Autodesk Inventor simulation software, in an attempt to give a perspective on the material from which the ankle prosthesis must be made. In conclusions were presented results for stress, endurance, and safety factors for simulated prosthesis.

Keywords: stress analysis, ankle prosthesis, aluminium alloy 6061, titanium

The nature of the limit conditions used for this prototype of an ankle prosthesis depends on the design requirements. It was desired that the structure remains in the area of the elastic deformations, the loading state being the state of the material flow.

The limit conditions are when material breakage occurs or when of structural stability is lost. Both breaking and loss of stability are the upper limits beyond which the structure cannot be used.

A large number of theories on limit conditions have been developed, corresponding to the different types of criteria. Resistance theories are divided into three categories:

- those predicting the reaching of the flow limit,
- the tearing of the material and,
- the stability loss of the strain [1].

There are several plasticity criteria associated with resistance theories describing the flow conditions for metals and ductile materials.

The most popular are:

- the Rankine criteria of the maximum normal tension;
- the Tresca criteria of the maximum tangential tension;
- the von Mises criteria of maximum distortion energy;
- the Mohr-Coulomb, Drucker-Prager criteria, based on dislocation theory.

Experimental part

Prototype of ankle prosthesis manufacture

As the requirement to improve the natural walk of amputated persons, in order to reduce effort while walking and even in some cases to can practice sports, prosthetic legs have improved significantly over time.

In figure 1 is a prototype of ankle prosthesis manufactured in *Seletron* lab.

In the image engine (1) is used to provide extra energy. The rotation of the engine (1) is transformed in translation motion by the elastic coupling (2). On the threaded shaft (5) moves a nut (6) that acts the lever on which the ankle prosthesis cup is mounted. The lever moves at different angles depending on the walking stage of the foot.

In the study are considered three angles for testing: 5, 15 and 30^o.

While the sole of the prosthesis (7) is considered to be fix, as base, the ankle cup is articulated to the leg for the flexion-extension and prone-supination movements.

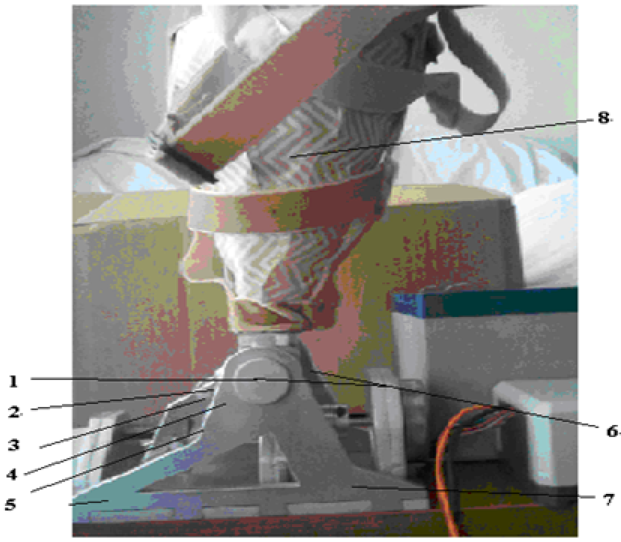

Fig. 1. Ankle prosthesis prototype:
1- engine, 2-elastic coupling, 3-spoke, 4-locking mechanism, 5-threaded shaft, 6-battery, 7-foot, 8-foot prosthesis

In figure 2 is presented the prototype of the manufactured ankle prosthesis.

Fig. 2. The ankle prosthesis prototype

Simulation of forces applied to the ankle prosthesis

Stress analysis is presented through the Finite Element method using Autodesk Inventor software [8].

The main objective of the study is to observe components that are subject to excessive stress and to find out which components are most likely to fail due to

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stresses as the result of the forces applied, depending on the material from which they are manufactured.

The first simulation of the forces applied to the ankle prosthesis cup

The first simulation was made considering as material for the ankle prosthesis the aluminium alloy EN AW 6061 from the Autodesk Inventor software [8] library, because is known as the structural alloy [9].

The characteristics of the material are presented in table 1 [9].

Table 1
CHARACTERISTICS OF ALUMINIUM ALLOY EN AW 6061 [9]

Name	Aluminium 6061	
General	Mass Density	2.700 Kg/m³
	Yield Strength	275 MPa
	Ultimate Tensile Strength	310 MPa
Stress	Young's Modulus	68.9 GPa
	Poisson's Ratio	0.33
	Shear Modulus	25.9023 GPa

In the form of plates, aluminium alloy 6061 is an alloy often used for machine.

Technical or commercial aluminium has a purity of 99.5 ÷ 99.8, the remainder of 0.2 ÷ 0.5 being impurities, in particular, Fe and Si, which have a negative effect on plasticity and corrosion resistance [9].

The application point for the forces that acts to the ankle prosthesis is shown in figure 3.

The mesh used has 14533 knots and 7465 elements defined.

Also, in the simulation, simple geometric shapes were defined in order to simulate the stress induced in the prosthesis cup (fig. 3).

Using Autodesk Inventor software, the individual behaviour of each element was calculated to predict the overall behaviour of the specific component of the prosthesis and whole ensembles.

It was studied von Mises stress or the equivalent stress of stretching, known also the von Mises profitability criteria.

This is a scalar value for stress parameter and can be calculated from the Cauchy stress tensor.

According to von Mises theory, a material begins to break down when von Mises stress reaches a critical value known as flow resistance.

After the simulation of stress analysis, the results are presented in figure 4 and figure 5.

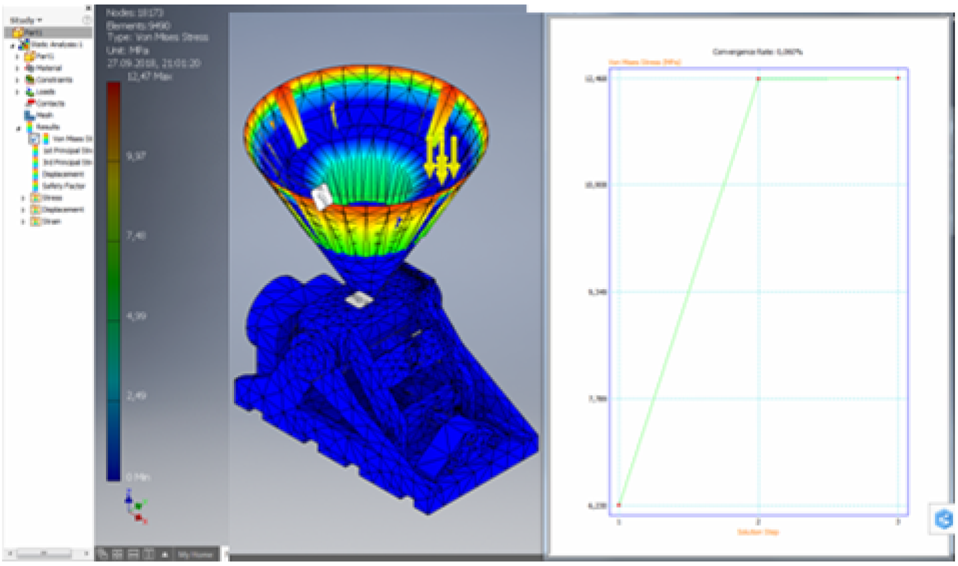

Fig. 3. Simulation of the forces applied to the ankle prosthesis cup

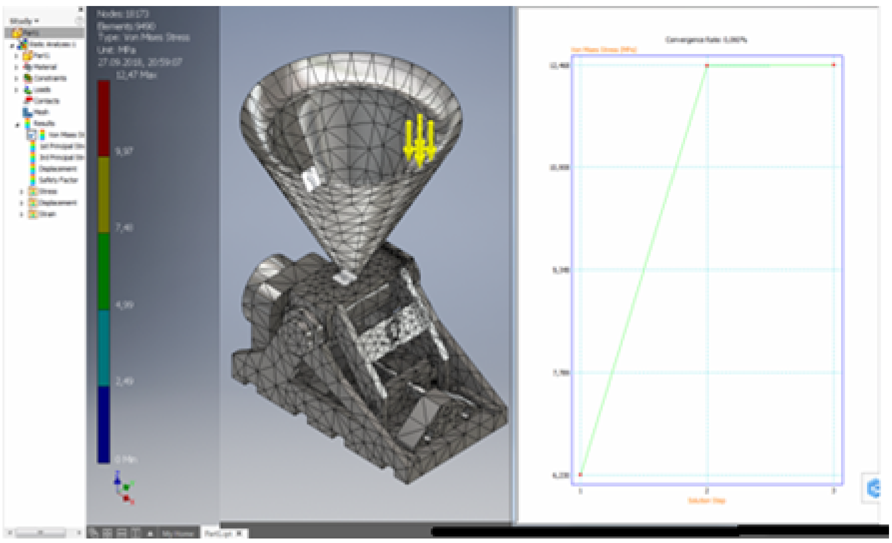

Fig. 4. Type of simulation: Von Mises Stress through the Mesh method

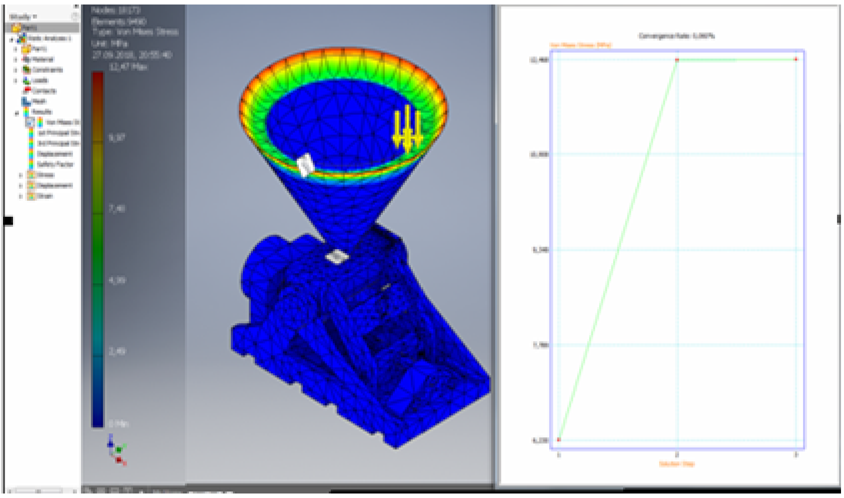

Fig. 5. Type of simulation: Von Mises Stress through the Mesh method in the colour version

The second simulation of the forces applied to the ankle prosthesis cup

The second simulation of the forces applied to the ankle prosthesis was made by decoding the titanium as the material from which the ankle prosthesis is made from the material library of Autodesk Inventor software.

The characteristics of the material are presented in table 2 [10].

Table 2
TITANIUM MECHANICAL PROPRIETIES [6]

Name	Titanium	
General	Mass Density	4510 kg/m³
	Yield Strength	275.6 MPa
	Ultimate Tensile Strength	344.5 MPa
Stress	Young's Modulus	102.81 GPa
	Poisson's Ratio	0.361
	Shear Modulus	37.77 GPa

Titanium properties are a combination of high strength, stiffness, toughness, low density and good corrosion resistance.

From the mechanical properties point of view, titanium and, especially its alloys are characterized by very high values of specific strength (breaking strength / density ratio).

Applying the same principles for the simulation, it was predicted areas with high load demands.

The initiation of plastic deformation as a limit condition of resistance

It this part of the study, the condition was that the all analysed structures of the prosthesis to remain in the elastic deformation domain. For this, the stresses at each point of the structure must be less than a certain critical value.

In the case of the ankle leg support, which the form of a stretched straight bar, the tensile strength is the same at each point of the bar and are equal σ.

In this condition, flow occurs when:

$$\sigma = \sigma_c \tag{1}$$

where σ_c (σ_y) is the flow rate measured in a normal stretch test [1].

In a structure with a complicate geometry, the state of tensile strength is complex and varies from one point to another.

It is known the fact that the material *flows* when it is stretch σ_c the tension [1].

Thus, it was intended to find out what tension value is needed flow when is used a complex tension state. A complex state of tension means a load in which all terms σ are non-zero (the three main stresses σ_1 σ_2 σ_3 are nonzero). The value of complex tension state can be mathematically expressed as a function of the main stresses [1]:

$$f(\sigma_1\ \sigma_2\ \sigma_3) = f_c \tag{2}$$

So, the condition that the material flows, occur when this function reaches a critical value, **fc** [1].

Considering the hypothesis that such a function exists, regardless of the loading mode (of the main stresses) of the prosthesis material, the flow always takes the same value, **fc** [1].

$$\bar{\sigma} = \sigma_c \tag{3}$$

where:

$$\bar{\sigma} = f(\sigma_1\ \sigma_2\ \sigma_3) \tag{4}$$

is known as equivalent tension (for $\bar{\sigma}$ the use of the notation σ_{ech}.) [1]

Criteria of maximum tangential tension, Tresca criteria

According to the maximum tangential stress criteria (Tresca criteria), the flow occurs when the maximum tangential tension, applied to the material, regardless the plane on which the forces acts, reaches a limit value [1]:

$$\tau_{max} = \tau_c \tag{5}$$

For a given state of stress applied $(\sigma_1\ \sigma_2\ \sigma_3)$, the tension maximum value of the tangential strength τ_{max} is:

$$\tau_{max} = \max\left(\frac{|\sigma_1 - \sigma_2|}{2}, \frac{|\sigma_1 - \sigma_3|}{2}, \frac{|\sigma_2 - \sigma_3|}{2}\right) \tag{6}$$

Thus, the critical tangential tension τ_c can be deduced using equation (6) for uni-axial stretching model.

In this case, the flow of the material starts when the condition is described by eq. 7.

$$\sigma = \sigma_c \tag{7}$$

or when

$$\tau_{max} = \sigma_c/2 \tag{8}$$

In consequence, the critical tangential tension can be calculate using the von Mises tensile strength at critical value of material flow

$$\tau_c = \sigma_c/2 \tag{9}$$

So, the Trasca criteria can be written as:

$$\sigma_c = \max(|\sigma_1 - \sigma_2|, |\sigma_1 - \sigma_3|, |\sigma_2 - \sigma_3|) \quad (10)$$

Considering the equation (2), for the complex tension state, can be write the expression:

$$f(\sigma_1, \sigma_2, \sigma_3) = \max(|\sigma_1 - \sigma_2|, |\sigma_1 - \sigma_3|, |\sigma_2 - \sigma_3|) \quad (11)$$

and $$f_c = \sigma_c \quad (12)$$

Equation (10) highlights the independence of material flow the hydrostatic component (uniform pressure, p, in all directions) of the tensile field.

The pressure is calculated as:

$$p = -(\sigma_1 + \sigma_2 + \sigma_3)/3 \quad (13)$$

If the structure is subjected to a pressure condition, then eq. 14 occur and shear stresses are null in all planes:

$$\sigma_1 = \sigma_2 = \sigma_3 = -p \quad (14)$$

Therefore, plastic deformation of the material is not influenced by the value of the pressure. This result is similar with experimental observations on metallic materials: the pressure does not affect the plastic flow of the material. In the real behaviour of the material, the flow under tensile stress is influenced by pressure. But the effect is weak and in most cases is neglected [1].

The von Mises criteria

The von Mises criteria does not include the effect of pressure in producing plastic deformation, namely a pure (uniform) pressure on the material does not determine a plastic deformation.

This criteria is based on energetically considerations.

The specific deformation energy has two components, one related to the variation of the body volume (effect of the spherical tensor, having the components σ 1 = σ 2 = σ 3 = σ m) and another associated with the shape change of the body the deviator tensor [2].

The plastic deformations are mostly determined by the deviator tensor.

The von Mises plasticity criteria can be formulated as follows:

State of Stress	Boundary Conditions	von Mises Equations
General	No restrictions	$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2]+3(\sigma_{12}^2+\sigma_{23}^2+\sigma_{31}^2)}$
Principal stresses	$\sigma_{12}=\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]}$
General plane stress	$\sigma_3=0$ $\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sqrt{\sigma_{11}^2-\sigma_{11}\sigma_{22}+\sigma_{22}^2+3\sigma_{12}^2}$
Principal plane stress	$\sigma_3=0$ $\sigma_{12}=\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sqrt{\sigma_1^2-\sigma_1\sigma_2+\sigma_2^2}$
Pure shear	$\sigma_1=\sigma_2=\sigma_3=0$ $\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sqrt{3}\lvert\sigma_{12}\rvert$
Uniaxial	$\sigma_2=\sigma_3=0$ $\sigma_{12}=\sigma_{31}=\sigma_{23}=0$	$\sigma_v = \sigma_1$

Fig. 6.

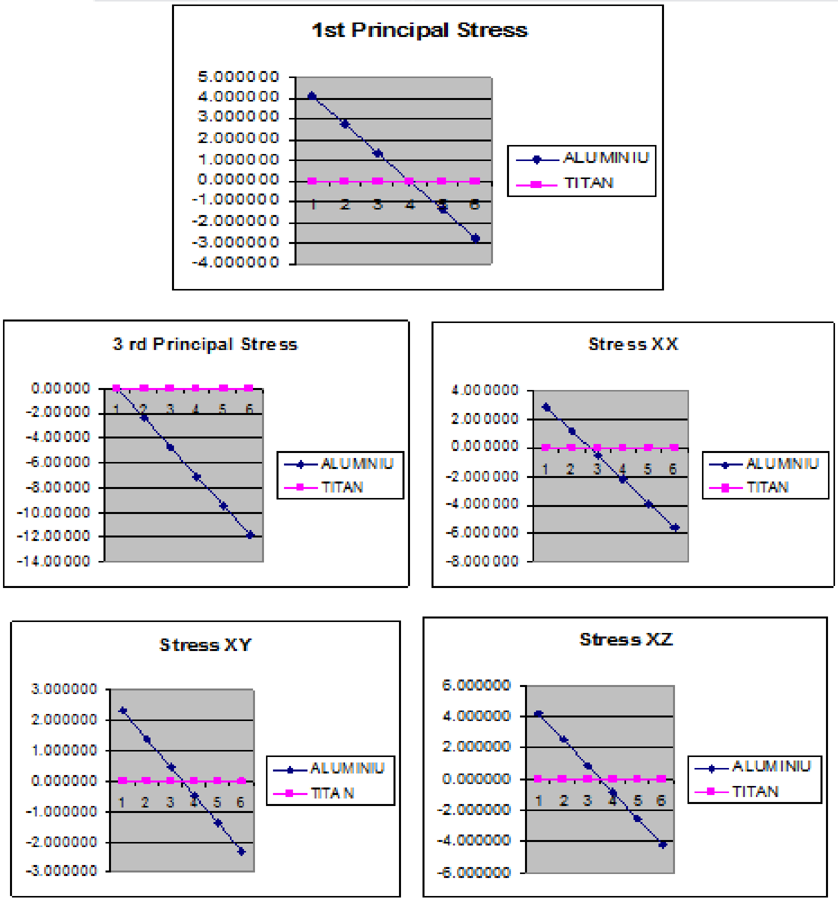

Fig. 7 -11. The distribution of stress is uniform across the bar of aluminium and titanium

In case of a spatial stress condition, flow occurs when the specific energy of changing the body shape (the specific energy of distortion) exceeds the value of the specific distortion energy corresponding to the flow at the single axial tensile strength.

Compare with Autodesk Inventor Software the results obtained for the two materials

Graphic results using Autodesk Inventor software are shown in figure 7-11, where on the OX axis is represented area (m^2) on which the forces acts and on OY axis shear stress (GPa) [8].

The primary main objective of this study is to identify and eliminate weaknesses points before assigning the financial resources to design and manufacture the ankle prosthesis [5].

The results of this study are also useful in determining the duration of use for the prosthesis and critical points of the ensemble or of the component, in order to improve them.

According with the results presented in figure 7-11 we can conclude that ankle prosthesis would not crack as a result of the stresses applied. Stress and travel are so small that they will not cause the ankle prosthesis breakage. All the components of the prosthesis present a high safety factor, except for the upper part, of the ankle prosthesis leg [8].

Anticipation of ankle dentition

The following analysis is to predict cracking of the ankle prosthesis by analyzing stress distribution, on the base ensemble of the prosthesis considering the main components [11].

The most common cause of cracks in ankle prosthesis elements is component-induced stress due to concentrated applied forces [12].

In figure 12 shows the simulation of the force actions and resulting stress on the components of ankle prosthesis.

All the maximum strength values are identified as being located on the white section of the ankle prosthesis.

Conclusions

Predicting and simulating failure is material testing is increasingly bing used, as designing against extreme resistance and fatigue of materials under stress conditions needs to be clearly specified because lab testing is costly. Including multiple simulations shortens design time, which is often an important parameter. A more accurate prediction of maximum strength and fatigue resistance can also lead to more optimized models.

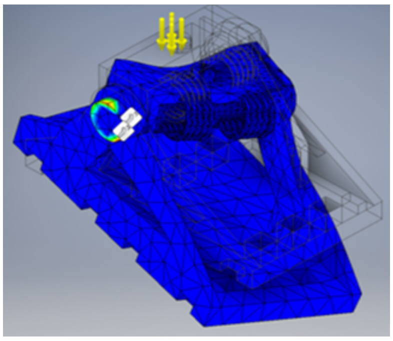

Fig. 12. Simulation of the ankle prosthesis subjected to the stress concentration

These criteria used can often predict when the risk of rupture of the ankle prosthesis begins to increase, and the next simulation will predict whether cracks have developed in an uncontrolled way. In this case, the maximum resistance is reached, but there is often a high residual strength.

When the prosthesis components are in working state thay undergo many physical loads that induce friction, cracking erosion and cracking caused by loading stress induced.

All of these contribute to reducing fatigue life and / or decreasing tiredness.

The failure of the ankle prosthesis can be attributed to existing stretching stresses, which are often generated during the manufacture or loading of stresses generated under heavy operating conditions. The identification of critical areas through the pressure points and shear forces is of particular interest.

Their study leads to the design of prosthesis with an acceptable tolerance in relation to the distribution of pressure, moments and forces at the level of the bust to achieve a high degree of patient comfort.

The simulation was performed at the level of the prosthesis with the application of two types of constraints: the constriction at the level of the prosthesis and the constraints at the level of the ankle rod.

The forces and pressures resulting from these two types of constraints applied to the same prototype are considered additive in a fusion model.

The purpose of the study is to visualize the effects that occur throughout the contact surface between the bust and the prosthesis, knowing that friction can induce stresses that exceed the material's response capacity and produce epithelial wear.

Finite Element Analysis is way to optimize new prototypes, to check the status of existing systems of the prosthesis evaluates new concepts, performance of the prototypes, and to predict defects.

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