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METAMATERIAL USAGE IN DESIGN OF BILATERAL PROTHETIC LEGS

Abstract: *The paper idea was to investigate is it possible to design running prosthesis with similar design as running blades using only 3D printing technique and ABS, as one of the most used plastic material in the world. This material is very strong and manufactured parts are not very flexible. By using metamaterials some models of human running prosthesis were created and a number of simulations were made through SolidWorks Design Study package. Used approach allows finding of the best solution for custom-made human running prosthesis with the best characteristics.*
Present paper gives the evidence that using of smart geometrical design of inner structure of various parts and models to reduce its mass and improve their mechanical characteristics is possible. Also, obtained model is suitable for 3D printing and it can be opportunity to product cheap prosthesis for a large number of people with disability.

Key words: *Metamaterials, Simulation, Design study, Design optimization, 3D printing, SolidWorks.*

1. INTRODUCTION

In the last few years 3D printers have become well-pointed in the field of production, maintains and usage. Because of the mentioned 3D printers became available to large number of scientists especially in engineering. Usage of 3D printers opens the new possibilities for manufacturing parts of different shapes, as well as complex geometries and materials. Type of used material allows varies of the price of the final part. For example, the production of the metal part using 3D printers implies complicate techniques for laser sintering of metal powder and significantly raise the price of final part, compared to the parts manufactured using different types of plastics, such as PLA and ABS, since they are cheaper than other plastic manufacturing techniques, especially if they are used for individual parts and small batches [1].

Popularity of 3D printers using plastic and printing material has increased utilization of 3D printed parts in variety of areas. One of the areas is custom made prosthetics for human limbs. Custom made prostheses are very expensive, and their availability to a large number of people decreases because of the price. A lifetime healthcare cost for humans with limb loss is about $510,000, compared to $361,000 for people without limb loss [2]. Most of these people cannot afford any prosthetics (active or passive), therefore they need help in everyday life. Quite number of these people need a simple prosthesis that can be cheaply manufactured using 3D printers and can significantly improve their life. Example of how simple 3D printed mechanic prosthetic hand can positively impact on quality of user’s life is shown in Fig. 1. [3], [4]. These types of cheap 3D printed prosthesis are especially interesting for children since they require small and inexpensive prosthetics that can be changed as child grow up. On the other hand, 3D printing is a cheap method to produce many different variations and sizes of the type of prosthesis according to specific patient requirements.

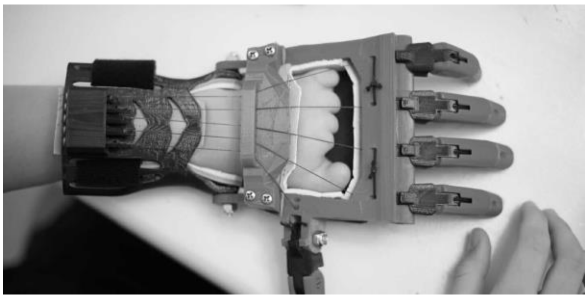

Fig. 1.Simple 3D printed prothesis that patient without hand [3].

Other examples are various leg prosthesis (Fig. 2.). Most of these are made from plastic and used just as a cover for metal parts, in other words 3D printed plastic parts are combined with metal support and functional parts. Other problem that can occur is adequate size of plastics prosthesis that can support human body weight, due its lower mechanical strength and lower wear resistance. Some prosthesis can be completely metal 3D printed, but that significantly increase final price.

Fig. 2. 3D printed leg prothesis [5].

To utilize a full potential of 3D printing technique and to achieve high flexibility of prosthesis that can be adjusted to patient's needs, a good CAD model is required. Various CAD software opens up possibility to create new geometrical structures with more natural curves compared to standard mechanical parts, and most of these structures are almost impossible to produce without 3D printing, as it is shown on Fig. 2. Some of these structures can be utilized with aim to design better or "more natural" prostheses.

Involvement of 3D printers brought out easy creation of the new types of materials with different internal geometries that could have significant impact on their physical characteristics [6], [7]. This type of new materials, called the metamaterials could be created by repeating pattern of basic cells, which have some simple geometrical shape, in its internal structure. Features of metamaterial will depend on sizes and shape of basic cell. Basic cell could have shape of triangle, rectangle, hexagon, cubic, spherical, cylindrical or any other geometrical form that can improve metamaterial characteristics [6], [7] and [8]. The first produced metamaterial was with negative light refraction index [9]. In the last few years, development of metamaterials that can replace some mechanisms or with improved mechanical characteristics has begun [6], [10].

2. PROBLEM FORMULATION

To help people without one or both legs a lot of different prosthesis are developed over last several years. Majority of these prosthesis are specially adapted to the need of the patient, but in general it can be divided into two groups from human activities point of view [11, 12]:

- Walking prosthesis – standard prosthesis for everyday life, and
- Running prosthesis – specially designed prosthesis, also called "Running blades"

These kind of prosthesis have different designs according to its usages. Walking prosthesis are typically made with same number of joint as real leg and therefore they can be used for everyday life. These prosthetics elements can handle weight of the patient body, and provide over all stability of human body when patient walk or stand, (Fig. 3.). Also, these type of prosthesis must resemble to real human leg in order to achieve desired appearance.

Fig. 3. Walking leg prosthesis for everyday use [13].

On the other hand, there are "Running" prosthesis that are specially designed for athletes competing in running, Fig. 4. These type of prosthetics aids are without any moving part and specially designed in the way to absorb feet impact on the ground, but they don't provide standing stability. These characteristic of "Running" prosthesis is achieved with a usage of composite materials used in production of its geometrical shape.

Fig. 4. Running proshesis – Running blades [14].

The paper investigates is it possible to design running prosthesis with similar design as running blades using only 3D printing technique and ABS, as one of the most used plastic material in the world. This material is very strong and manufactured parts are not very flexible.

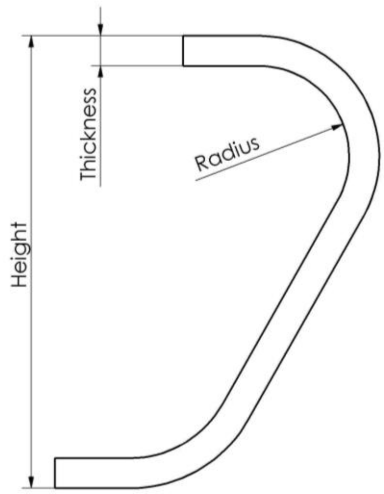

Fig. 5.Basic shape of CAD model.

Basis shape of the modeled prosthesis is showed at Fig. 5. This simplified CAD model is used only for testing, with aim to prove design methodology through simulations, and do not represents the shape of real prosthesis. Defined dimensions, Fig. 5. (Height, Thickness and Radius), are tweaked until maximum stress is minimized. After testing of the basic shape, metamaterials are incorporated into prosthesis (Fig. 6.) and their impact on stresses in model were analyzed while maintains flexibility was tried. For metamaterial two tweaking parameters are define: metamaterial thickness and metamaterial angle.

3. SIMULATION

Modeling of the CAD models and simulations were done is SolidWorks 2018.
To simplify modeling process and reduce simulation of computation time, the following assumptions have been introduced:

- All models have planar geometry. In this case it is possible to simulate stress stain state in the plane and to calculate stresses for complete model.
- Material used for simulation has linear stress strain curve (Material characteristic used in simulation, Table 1)
- Resulting stresses will be calculated using Von-Misses hypothesis.
- Force of 3000N was used as testing load for each model, Fig. 7, 8.
- Same boundary conditions were used for each model, Fig. 7, 8.
- Stress simulations were done using Finite element analysis (FEA) module within SolidWorks 2018. Mesh parameters used in both simulations are shown in Table 2.
- Analyzing impact of dimension changes of the model was conducted on the maximum stress using "Design study" module from SolidWorks. Design study was used to automatize model simulation when it is necessary to analyze influence of dimension changes on model strength. To create simulations with this module it is necessary to choose range and increment steps for every dimension, whose influence was investigated on model stresses. Design study module run FEA simulation for all possible parameter combinations that were chosen for analysis, and tried to find best possible set of parameters which will satisfy defined criteria, such as maximal stress, lowest mass, maximal deformation, etc.

Table 1

. Material properties used in simulations

Material	ABS plastics
Yield strength	30 MPa
Tensile strength	20 MPa
Elastic modulus	2000 MPa
Passion's ration	0.3
Mass density	1020 kg/m3

Table 2

Mesh parameters used in simulations

Mesh type	Planar 2D Mesh
Mesh used	Standard mesh
Maximum element size	5mm
Minimum element size	0.25m
Mesh quality	High

Two models were created, one with incorporated metamaterial mesh and other without it. First analysis was made due to preparation of M. Sc. Paper of student Milan Popovic at Mechanical Faculty, Belgrade. That analysis give idea to prepare new concept of human running prostheses for this paper. Simulations were done in several step. First model without mesh was tested, as it is shown on Fig. 7, then model with metamaterial structure on Fig. 8. For model with metamaterial structure first simulation were done to find best angle of metamaterial, Fig. 6. and then thickness of basic cell were analyzed.

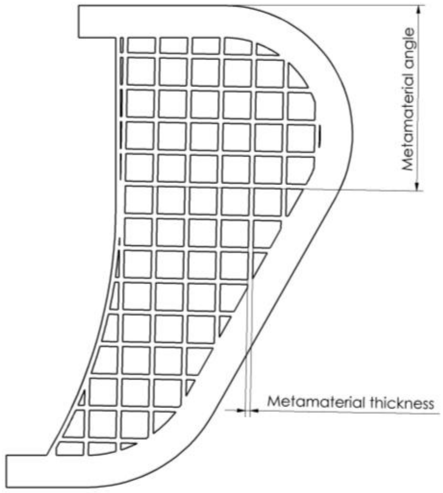

Fig. 6.Basic shape of CAD model.

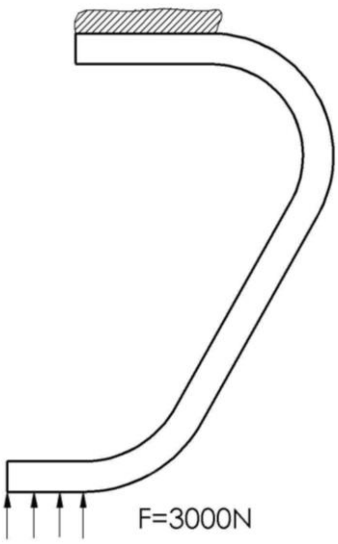

Fig. 7. Loads and fixtures – CAD model without metamaterials.

4. RESULTS

Automated process of design and simulation were done in three analysis steps, in more than 67 simulations. For the first step, after checking of 47 combinations of parameters, maximal stresses were higher in the yield strength of material and the best result was obtained for thickest model, Table 3 and Fig. 9. Across all 47 simulations, range of stresses on prosthesis were from 85MPa up to 260MPa. As it was expected, the lowest stress was on thickest model, but even that model have three times bigger stress then yield strength of ABS. To reduce this stress result even more, it was necessary to increase model thickness.

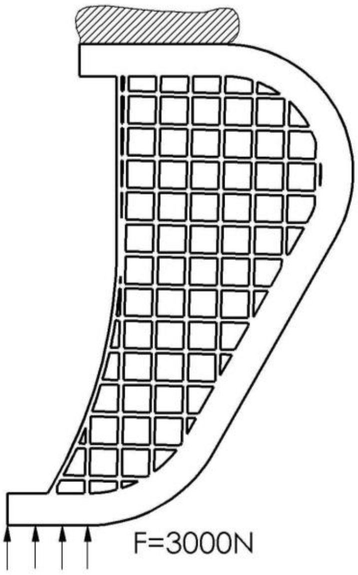

Fig. 8. Loads and fixtures – CAD model with metamaterials.

Table 3

Results for model without metamaterials

Design study parameters without metamaterials					
Parameters	Start	End	Step	No. sim.	Best
Height	200	300	50	45	300
Thickness	20	40	10		40
Radius	40	80	10		60

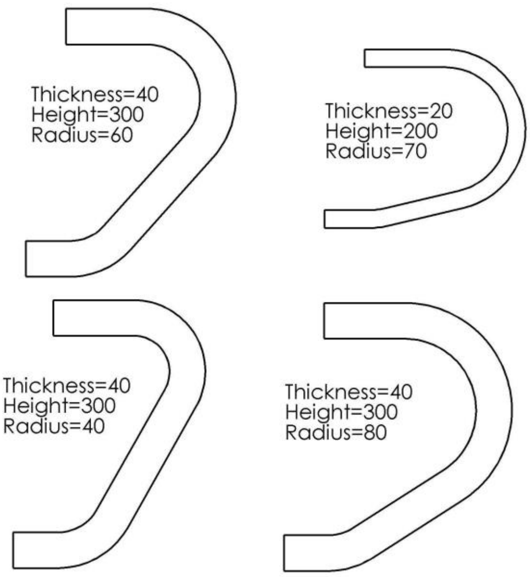

Fig. 9. Examples for first step in analysis.

For step number 2, metamaterial mesh was added into model to improve its characteristics, thickness was reduced to 20mm with idea to reduce overall mass. The result showed significantly reduce of overall stress. For further improvement of the model it was necessary to find optimal angle of metamaterial mesh. It was separate into two design studies, to reduce overall calculating time. In first study, metamaterial angle was tested in range of 0 – 90 degrees, with step of 10 degrees, and overall stress on model was within the range from 32MPa at 0 degrees up 45MPa at 30 degrees, Table 4 and Fig. 10. Second design study was used to check stress changes near 0 degree, where the lowest stress occurs, with steps of 1 degree. This simulation tested angles from -3 to 3 degree and best solution was obtained at 1 degree, and stress was in the range from 28MPa at 1 degree up to 40MPa at -3 degrees.

Table 4

Design study parameters for angle of metamaterial

Design study – angle of metamaterial - large step					
Parameters	Start	End	Step	No. sim.	Best
Angle	0	90	10	10	0
Design study – angle of metamaterial – small step					
Parameters	Start	End	Step	No. sim.	Best
Angle	-3	3	1	7	1

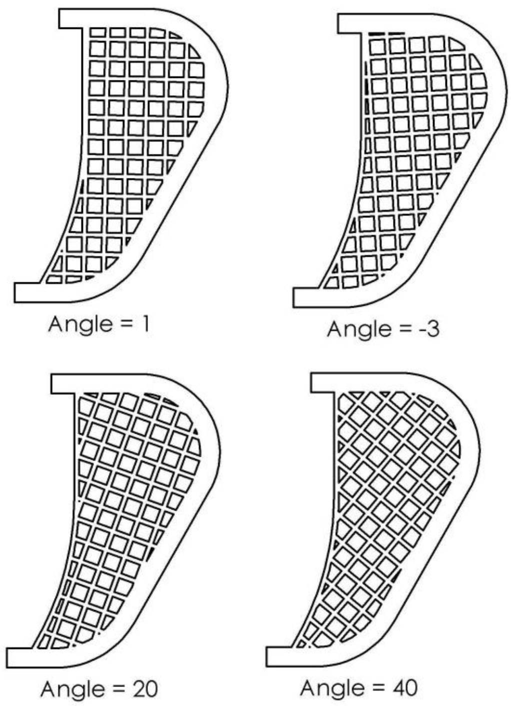

Fig. 10. CAD models for different angle of metamaterial.

In third, last step of analysis, the influence of metamaterial thickness was analyzed. This step was necessary for further improvement of the prosthesis strength and new simulation goal, to minimize mass, was added. Thickness of metamaterial was tested in range from 1mm up 5mm (Table 5 and Fig. 11.) and best result was received with minimal mass for metamaterial thickness of 3mm and stress of 28MPa.

Table 5

Design study parameters for metamaterial thickness

Design study parameters - metamaterial thickness					
Parameters	Start	End	Step	No. sim.	Best
Thickness	1	5	1	5	3

5. CONCLUSION

As it shown [6], [7], with changing of metamaterial geometry (basic unit cell size and thickness) it is possible to create specific response of metamaterial, such as increase of overall strength of part with relatively small increase in mass and relatively low loss in flexibility. Likewise [6], [7], it is possible to see that loading direction of metamaterial have significant impact on overall part response.

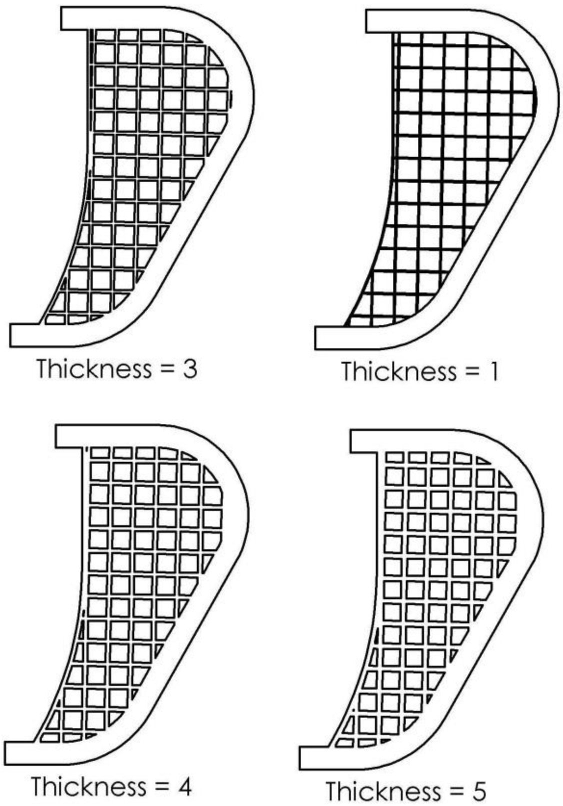

Fig. 11. Different thickness of metamaterials.

In this paper only one base of unit cell was used, rectangular, with changes in its thickness and loading direction. SolidWorks module for automatization of model optimization (Design study) was applied, and its methodology for improving model characteristics using metamaterials achieved final model, that can withstand desired loads of 3000N.

In model without incorporate metamaterial, there is no dimension combination that can lower maximal stress under 85MPa. This stress is almost three times greater than yield strength of ABS material, even if the thickness of prosthesis is 40mm. Model with incorporated metamaterial, was tested with base thickness of 20mm, and after running design studies final model was chosen. This chosen model has lowest mass where maximal stresses do not exceed yield strength of ABS, and its parameters are: 20mm base model thickness, 300mm height, 60mm radius, 3mm metamaterial thickness and metamaterials orientation 1 degree, Fig. 12 and 13. Highest stress on final model was 28MPa, with maximum deformation of 13mm under load of 3000N (Fig. 14.). Also, the mass of model was reduced more than 1.5 times compared to best model without metamaterials.

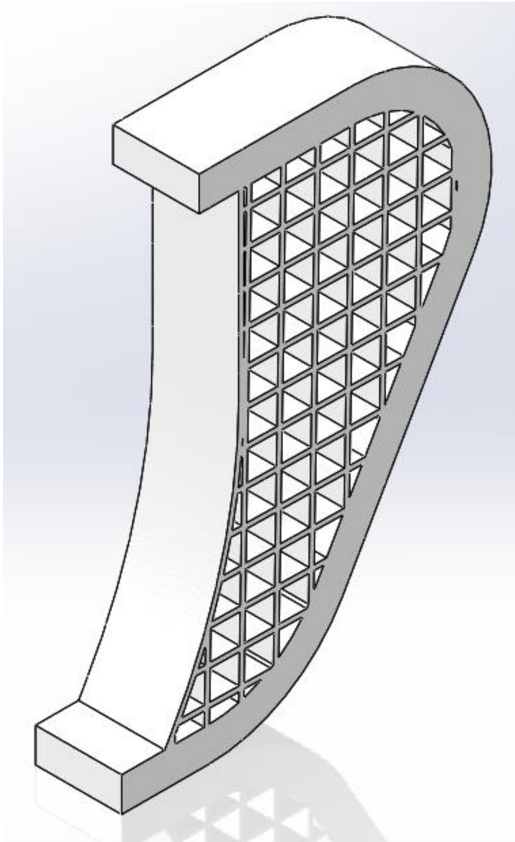

Fig. 12. Final model – 3D model.

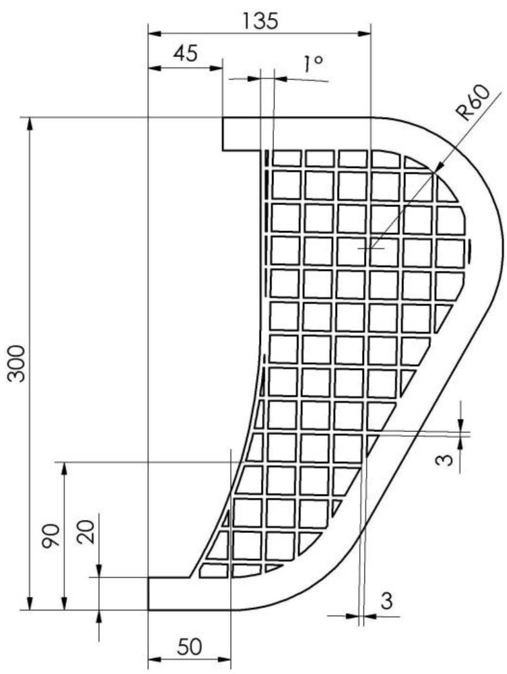

Fig. 13. Final model - dimensions.

From this paper it can be concluded that it is possible to use smart geometrical design of inner structure, of various parts and models, to reduce mass and improve mechanical characteristics. As well, obtained model is suitable for 3D printing production which can lead to cheap production of prosthesis for large number of people with disability.

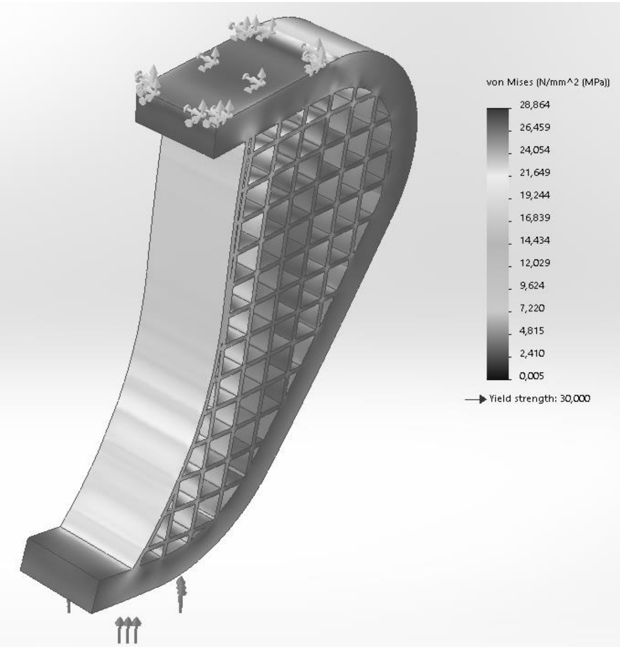

Fig. 14. Final model – FEA simulation result.

Further research in application of metamaterials prosthesis geometry and overall in aesthetics of the product is necessary with aim to obtain prosthetic legs suitable for every patient.

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