FINITE ELEMENT ANALYSIS OF KNEE IMPLANTS MANUFACTURED BY FDM TECHNOLOGY

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Abstract. Knee prostheses are used in knee replacement surgery in patients who have or develop some type of disease in this joint. The prostheses currently on the market have the femoral component in a metal body and have been used for many years. Problems of metallic implants such as patient sensitivity, adaptation to existing models of prosthesis and cost of prosthesis are some of the factors that influenced the study of non-metallic prosthesis materials. The finite element method will be applied in the study of prostheses made in 3D by Fused Modeling Deposition (FDM) in ABS and PLA materials, and its orthotropic nature will be evaluated. In order to achieve this objective, the prosthesis was modeled graphically, in which the load and boundary conditions to simulate the activity of an individual walking with the prosthesis were applied and the Tsai-Hill' and Tsai-Wu' failure theories for composite materials were used to evaluate the functionality of this prosthesis. Thus, several results are obtained, such as failure index and strain rate for these materials.

Keywords: Knee prostheses. Finite Element. Fused Modeling Deposition

1 Introduction

The knee is a joint of the body that joins the thigh with the leg. It is classified as a ginglymus, that is, it allows extension and flexion in only one plane and consists of two connections, one between the femur and the tibia and another between the femur and the patella. A good joint function is critical for the mobility of the human being to perform activities such as standing, walking and running [1].

The knee prostheses are used during knee arthroplasty surgery. Total knee astroplasty (TKA) surgery is recommended when nonsurgical methods are not sufficient to help the patient, and is one of the most successful medical procedures in medicine. There are many types of implants and their choice depends on the type of surgery to be performed, the individual needs of the patient, the cost of the prosthesis and its performance [2].

The prostheses are made mostly of metal, or at least contain metal parts due to their durability and corrosion resistance. Chromium-cobalt alloy (CoCr) is a hard, tough, corrosion-resistant and bio-compatible material and is one of the materials most used in this type of implant. Titanium alloys have similar advantages, as well as unique characteristics such as low density and less elasticity (for this reason titanium and its alloys act as if they were the natural knee joint), but its application is more restricted to implants that do not require high mechanical strength [3].

Lack of success of ATJ may be due to many factors but the main reasons are related to mechanical and biological causes [4] Chronic inflammations following wear of the prosthesis have been recognized as the main biological factor that leads to failure of prostheses [5]. The materials used in orthopedic prostheses are categorized according to their toxicity, hypersensitivity (or allergy) and the presence of carcinogens. For example, significant sensibility is noted for metallic elements, such as Titanium and Vanadium, are also reported [6] and the accumulation of aluminum in the body has been associated with several types of diseases [7]. In dynamic load conditions, such as knee implants, where the interface in contact degrades the surface oxide film on the surface of the prosthesis causes an increase in corrosion [8].

The objective of this work is to create an approach for the study of the mechanical resistance of knee implants manufactured by the Molded Material Deposition Model (FDM) using ABS (Acrylonitrile butadiene styrene) and PLA (Lactic acid) thermoplastics. In addition, we can highlight some specific objectives:

• Check the resistance of the prostheses against the failure criteria of Tsai-Wu and Tsai-Hill by the macromechanical approach.

• Compare the response of the two materials ABS and PLA to the loads suffered in the walking activity.

• Create a methodology to serve as a basis for the study of any material manufactured in FDM beyond those addressed.

2 The manufacturing technology cast material deposition modeling (fdm)

Fused Deposition Modeling, or FDM, is a process of manufacturing objects in three dimensions used in many applications. The creation of this method by S. Scott Crump co-founder of Stratasys in the late 1980s along with new additive manufacturing technologies made a leap forward in the areas of rapid modeling and rapid prototyping in engineering [9].

The additive manufacturing machines are capable of constructing any volume or shape by depositing a series of overlapping slices of a desired material until the desired shape is obtained. It is in this context that the STL file comes in to facilitate this process. This type of file is able to be worked and processed much faster than other files used in additive manufacturing [10].

The FDM manufacturing equipment is powered by a material such as ABS, which is a thermoplastic polymer material with excellent strength and durability at low temperatures, as well as offering good thermal and chemical resistance. [11]. The thermoplastic filament is inserted into the machine nozzle through a feeder where it is semi-fused and extruded into a desired wire shape on a pallet. The platform moves in a plane perpendicular to the axis of the nozzle (alternatively the nozzle may move in one of the orthogonal directions) and the molten thermoplastic is deposited on the table and joining the adjacent filaments in a diffusion process until a layer is formed. At the end of each layer the nozzle moves in the vertical direction so that the process of modeling a new layer restarts until the desired object is formed [1].

3 The mechanical properties of prototypes fdm

In order to determine the effects of the manufacturing parameters on the mechanical properties of the FDM prototypes, [1] determined that the void between the filaments and the deposition angle has an important effect on the tensile strength of these materials, on the other hand, other manufacturing parameters have negligent effect. However, the factors studied by them do not affect the compressive strength in a remarkable way [12].

The difference between the mechanical properties between the ABS material entering the extrusion tube and the fabricated material is mainly due to the welding kinetics of the additive manufacturing machine. The main differences are due to faults present in the fabric structure and its orthotropic nature [13].

Isotropic materials have identical mechanical properties in all directions, examples of isotropic materials are metals and glass. Anisotropic materials on the other hand vary their mechanical properties according to directions. A subdivision of the anisotropic materials are orthotropic materials that have different properties along three mutually orthogonal planes [14]. Objects created by FDM technology of additive manufacture are orthotropic materials [15].

An important feature of an orthotropic material is that there is no shear relationship with the main axes of the material. In other words, normal stresses generate only normal deformations, and shear stresses generate only shear deformations [16].

When one approaches the prototypes in FDM, one can study certain levels of its structure, below shows these levels. The laminate is the first level and the macromechanical approach is used in this case, the laminates that make up the laminate make up the second level. The last level is the analysis of its mesostructure, which takes into account the bond strength of the filaments [15].

The mechanical properties are governed by their mesostructure, which are governed by the manufacturing parameters and their elastic behavior in the flat state of stresses can be demonstrated by the elastic constants E11, E22, G12 and by the Poisson's coefficient, υ_{12} [17]. A new system of equations was proposed by [17] to determine the elastic constants as will be shown later.

Objects created with FDM can be compared to composite materials by having a mesostructure very similar to the latter [18]. In this work ABS materials and composites will be treated as similar and all considerations from one will be extended to the other.

4 Results

In the software, Hooke's Law must be specified in the case of an orthotropic material or alternatively, the elastic constants can be inserted so that it is not necessary to calculate the constants Cij of the matrix. In the present work, this last option will be chosen.

PLA offers better thermomechanical properties than ABS (Acrylonitrile butadiene styrene), having a higher mechanical strength and a low coefficient of thermal expansion. Moreover, it presents a lower health risk than most types of ABS when manufactured in small and poorly ventilated places, according to Casavola [12]. However, Casavola [12] showed that even though PLA is more resistant it is more fragile, and also showed the fracture deformation of 0.079 mm / mm for PLA and 0.16 mm / mm for ABS.

In order for the object to not fail by the Tsai-Hill fault criterion, it is necessary that equation (1) be less than 1, such that:

$$I_F = \frac{{\sigma_{xx}}^2}{X^2} + \frac{{\sigma_{yy}}^2}{Y^2} - \frac{\sigma_{xx}\sigma_{yy}}{X^2} + \frac{{\tau_{xy}}^2}{T^2} < 1 \quad (1)$$

If $\sigma_{11} > 0$ then $X = \sigma_{tl}$, otherwise $X = \sigma_{cl}$. If $\sigma_{22} > 0$, then $Y = \sigma_{tt}$, otherwise $Y = \sigma_{ct}$. E $T = \sigma_s$.

The same logic can be extended to the Tsai-Wu failure criterion, Eq. (2) must be less than 1 so that the object does not fail.

$$I_F = F_1\sigma_{11} + F_2\sigma_{22} + F_{11}{\sigma_{11}}^2 + F_{22}{\sigma_{22}}^2 + F_{66}{\sigma_{12}}^2 + 2F_{12}\sigma_{11}\sigma_{22} < 1 \quad (2)$$

Abaqus provides fault results through the R index in the color legend. As previously discussed, fault theories are determined by an elliptical surface and failure occurs every time the stress state is outside that surface. R is a scalar factor that measures the proximity of the state of stresses of the fault surface, such that for a state of stress {σ_11, σ_22, σ_12}

$$\left\{\frac{\sigma_{11}}{R}, \frac{\sigma_{22}}{R}, \frac{\sigma_{12}}{R}\right\} \rightarrow I_F = 1 \quad (3)$$

That is, 1 / R is the factor in which we need to multiply all the voltage components simultaneously so that they stay on the fault surface. Values of R <1 indicate that the state of voltages is within the fault surface. For values of R≥1 the fault occurs.

4.1 Prosthesis made of ABS

The model was assigned as a continuum shell section with the composite feature to take into account the layers of the FDM material. This type of section has three-dimensional appearance but the kinematics and behavior of a shell section. The number of layers was adjusted according to the size of the mesh elements that will be defined later. A surface -to-surface contact was inserted between the lower surface of the femoral component and the upper surface of the plastic spacer highlighted in red and purple as shown in Fig. (1), and a normal and tangential behavior was inserted in that contact between the interaction surfaces.

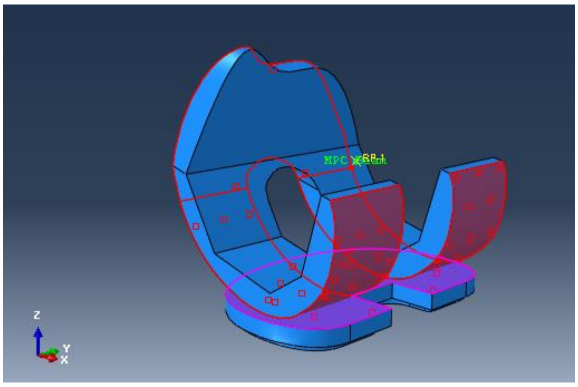

Figure 1 – Contact surfaces.

Before the mesh of the femoral component was generated, the model was partitioned into several 2 mm slices so that the direction of the layers in each element is better defined horizontally. The element SC8R, a quadrilateral with 8 nodes to analyze plane problems, was chosen for the model and applied to the mesh.

The analysis was submitted to the ABS material for all angles of Table (1) and the most critical point was found for the angle of 20 ° as shown in Fig. (2). Figure 2 (a) shows the results for the Tsai-Hill failure criterion and (b) for the Tsai-Wu criterion, it being possible to observe that the elements located at the ends of the flaps are subjected to higher load and have the maximum R index equal to (a) 0.7988 and (b) 0.7995, respectively, according to the legend. This means that the stress state is within the failure surface in the two analyzes and the fracture does not occur.

Table 1 -Load and flexion angle as a function of the walking activity cycle

Runtime	Charge F_x (N)	Bending Angle (º)
0	1118	0
0,10	2556	13
0,15	2794	16
0,20	2690	13
0,30	2391	5
0,40	2762	5
0,50	3318	20
0,60	1453	43
0,70	470	57
0,80	315	50
0,90	345	25
1,00	1085	0

Figure 2 - Results of the MEF analysis for the 20 ° angle for ABS material according to the criteria of (a) Tsai-Hill and (b) Tsai-Wu

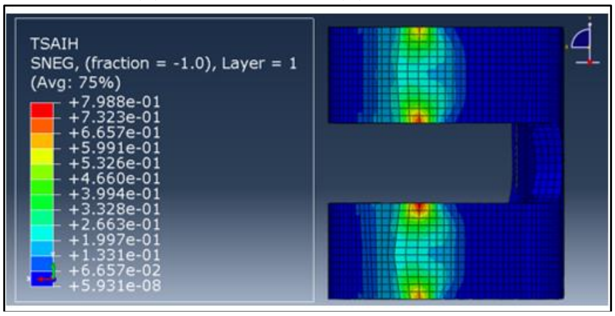

Figure 2 (a)

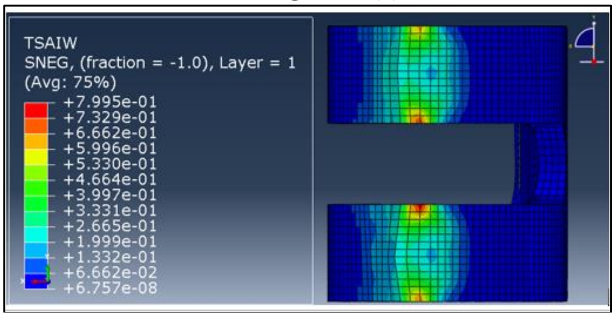

Figure 2 (b)

Although the R index is within the failure surface, we are considering mean values of individuals' weight and mean values of load acting on the prosthesis. The problem in working with the average is that there are observed values that are above and below it, and these variations impact the value of R increasing and decreasing this index. The lowest safety factor found was 1 / 0.7988 = 1.25 which may not be enough to guarantee the safety of the prosthesis in these cases.

Bergmann [19] showed that individuals running lightly show average loads-Fz in the range of 5000 N and for such activities the ABS prosthesis probably can not guarantee safety against failure, and it is necessary to carry out more analysis to verify this.

Figure (3) below shows the maximum von Mises stresses observed in the prosthesis by the percentage of the activity cycle. We observed that for 50% of the activity cycle the prosthesis is submitted to a maximum tension of 14.02 MPa.

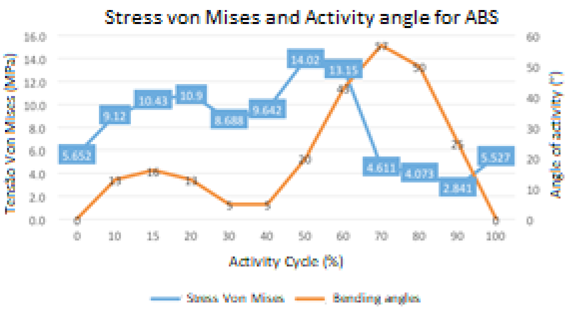

Figure 3 – Stress von Mises and Activity angle for ABS.

When analyzing the 0 ° and 57 ° bending angles, the orthotropic behavior of the ABS material can be observed. For the 0 ° angle the compressive force exerted by -Fz = 1118 N acts perpendicular to the direction of deposition of the longitudinal fibers as already shown in Tab. (1). For the 57 ° angle the force Fz = -470 N acts inclined in the longitudinal fibers and at that angle the index corresponds to R = 0.2005. But if a load of only -Fz = 750N acts at this angle its index has the value of R = 0.31 (which is greater than R = 03078). Thus it is possible to observe that the angles that are most sensitive to stress are the angles that the force acts on the fibers in an inclined way and this is due to the fact that in the FDM prototypes the shear strength between the planes is low being one of the main disadvantages of this type of manufacturing process against the injection molding process.

The Tsai-Wu and Tsai-Hill criteria show very close results as shown in Fig. (4) below. This can be explained by the fact that the data used in the simulation were obtained by the study of Rodriguez [20] who considered the tensile and compression strengths the same for ABS materials manufactured by FDM with unidirectional fibers.

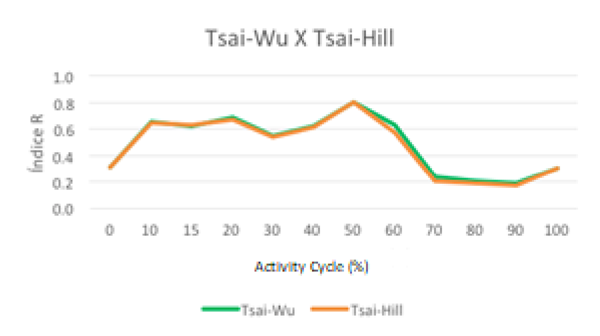

Figure 4 - Comparison between the two failure criteria for ABS

4.2 Prosthesis made of PLA

The analysis was re-used using the PLA material to predict its behavior under the same load and activity conditions. The most critical angle was found to be 20 °, and von Mises tensions were close to the finding for ABS material. The maximum value of the R index for the Tsai-Hill and Tsai-Wu criteria were 0.3531 and 0.3864, respectively. The maximum values are also located in the lower flaps of the prosthesis, as well as in the ABS, which indicates a point of concentration of tension that can be reevaluated and improved, either by means of a fillet to diminish the living corner, or by means of a material in these sensitive areas.

Figure 5 - Results of the MEF analysis for the 20° angle according to the criteria of (a) Tsai-Hill and (b) Tsai-Wu

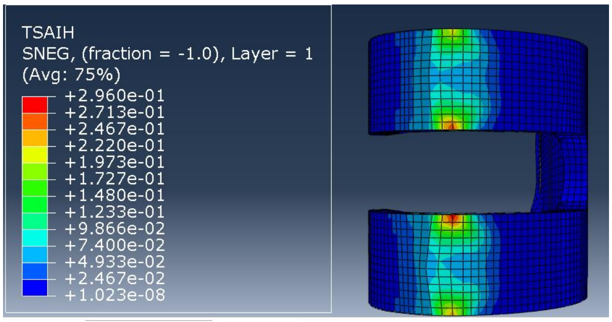

Figure 5 (a)

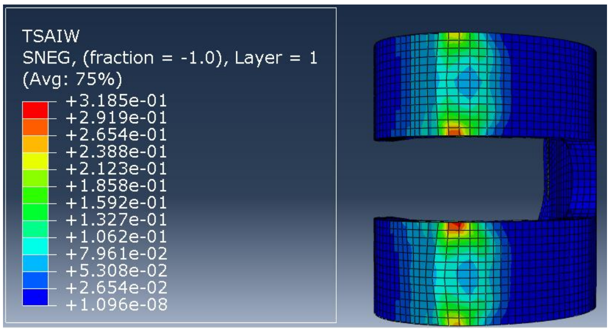

Figure 5 (b)

It can be seen that the values of the Tsai-Wu and Tsai-Hill indices for the PLA material vary more than for the ABS material of the previous topic. This is easily explained by the fact that the study by Song [21] considers different values for the compressive strength and tensile strength of these objects.

The ABS and PLA materials have different resistances in their isotropic form and it was expected that after passing through the manufacturing process by melting of material they also had different resistances in their orthoprop form. The difference between the two materials goes beyond their chemical composition, the fusion dynamics and the type of technology implemented to manufacture the objects in FDM for each of the two materials also influences its resistance. Figure (6) below shows the comparison of the Tsai-Hill fault R index for the two materials, following the manufacturing technology used by Rodriguez [20] for ABS and PLA materials respectively.

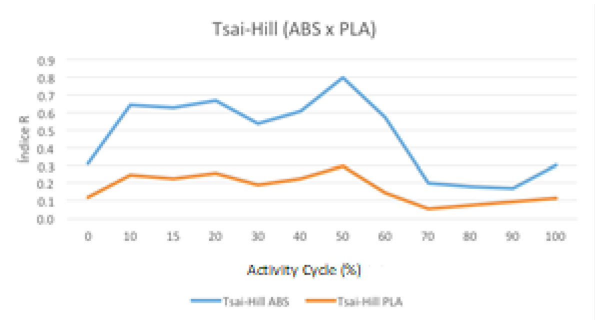

Figure 6 - Comparison by the Tsai-Hill failure criterion for ABS and PLA

The following figure (7) shows the same comparison for the Tsai-Wu criterion and, as expected, PLA is a very resistant material than ABS and therefore its applications have greater safety advantages.

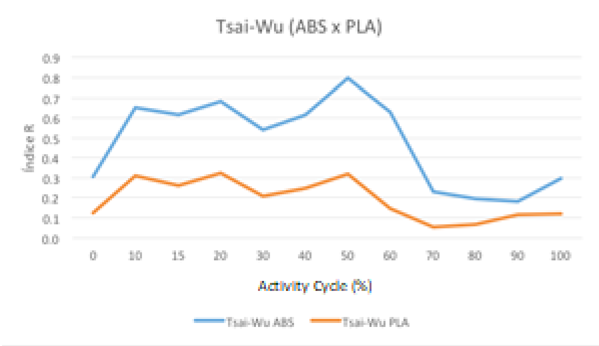

Figure 7 - Comparison by the Tsai-Wu failure criterion for ABS and PLA

Figure (8) below shows the response in the elastic regime of the deformation as a function of the stress applied in the materials analyzed.

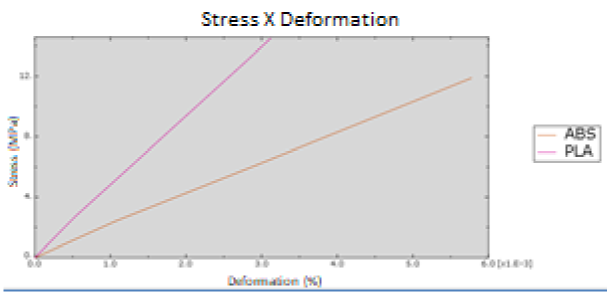

Figure 8 - Graph Stress x Strain for ABS and PLA materials

The two curves seem to approach a perfectly elastic behavior, but they are not straight. Looking at Hooke's law and the elastic constants presented in this paper, it is easy to understand the difference between the two curves. The ABS material has a more elastic behavior by deforming more to an applied voltage, than the PLA material has undergone the same tension. This elastic characteristic of the ABS material is also in agreement with the study of Casavola [12], showing ABS material with a feature less brittle than PLA.

5 Conclusion

The present work shows that the finite element method can also be used in biomechanics to evaluate the behavior of 3D-made prostheses by the technology of cast material deposition (FDM) in ABS and PLA thermoplastic materials. The macromechanical analysis was reflected in this work, and therefore the mechanical resistances were analyzed considering the loads that act on the walking activity.

It was possible to observe that the prototype is more sensitive when the loads act inclined with respect to the plane of the filaments and was remarkable the superiority of the PLA in relation to the ABS in relation to the reliability and safety to have a lower index R, that is, a greater resistance mechanics. The PLA presented as a lower safety coefficient the value of CS = 3.378, well above the ABS, CS = 1.25, which shows that this material, besides being satisfactorily inside the fault surface, can be studied further considering other loads and other activities besides those approached in this work.

The Tsai-Wu and Tsai-Wu criteria were used for the two materials and it can be observed that they showed very close R values for the ABS material, while for the PLA material the Tsai-Wu criterion was more conservative than the ABS material. Tsai-Hill. The Von-Mises voltage, although it is used for isotropic materials, follows a behavior similar to the variation of the R index during the activity cycle.

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