Simulation of the mechanical behavior of a HIP implant. Implant fixed to bone by cementation under arbitrary load

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Abstract. In a previous work a finite elements model was constructed to simulate a fatigue assay according to the norm IRAM 9422-3. Three materials were studied, two of them are the most used in this type of implant (Stainless steel 316L and alloy Ti6Al4V) and the third was a new developed titanium alloy (Ti35Nb7Zr5Ta). Static loads were applied to the model according to the highest requirements of the norm and the stress – strain distribution were determined.

In this study a simplified analysis of the material’s fatigue was done according to the previous work. The best behavior of the titanium alloys vs. the stainless steel was evident.

With the objective of studying the behavior of both: the implant and the femur bone, new finite elements models were realized, in which the presence of the bone was considered. Inside the bone, the femoral component of the implant was placed in a similar way of a cemented prosthesis in a total hip arthroplasty.

The advantage of the titanium implant related to the stainless steel one, was very clear.

1. Introduction

Nowadays the THA (Total hip arthroplasty) is a common practice of reconstruction used when the natural function of the hip articulation and the leg is damaged. The number of THA has been in constant increments, and more or less 800,000 operations are realized every year. This increment is particularly notable in young people, who are more active, because of that more and bigger loads appear on the implants [1]. So, the loads produced on these prosthesis can be 5 or 6 times the patient’s weight and, for a middling active person, the frequency is more than a million cycles a year [2].

Different problems are associated with the THA and some of them are because of the design or the applied materials. Among the principal problems associated to the THA are the fatigue fracture of the implants, the dislocation or loosing of the implant and stress shielding. Some tests and preliminary proofs help the probability of reducing the fault in the THA.

The assay according to norm IRAM 9422-3 specifies the method for a fatigue test on the femoral part of the prosthesis, because this is the principal cause of its mechanical fault. It is important to emphasize that since this kind of tests began, the number of fatigue fault has been reduced and nowadays it is a minor cause of revision and/or replacement of the implant [3].

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Although there has been a great progress thanks to biomaterials, the fastening of the prosthesis to the bone is still a problem. The loosening shows pain on the thigh and on the highest degree with femur fractures because of the reabsorption produced on the bone.

Then, the new implanted prosthesis in the replacement will be subjected to the same service condition, with the aggravate of the loss of bone and of course the support for the new implant.

The finite elements method is a tool that allows realizing the simulation of the response or the real behavior of a component under fixed loads. Thanks to these, it is possible to know the behavior of materials subjected to different types of efforts, before the construction and tests of prototypes. This permits the evaluation of new designs and/or materials economically from the point of view of cost and time.

2. Materials and Methods

Three implant materials were considered for the simulation by finite elements: an stainless steel with very low carbon as it is the 316L, in semi hard condition; the typical titanium alloy Ti-6Al-4V and one titanium beta alloy with low module, Ti 35Nb-7Zr-5Ta [4]. Its mechanical properties are shown in Table 1.

| Material          | E (GPa) | σR (MPa) | σF (MPa) | Poisson Coeff. |
|-------------------|---------|----------|----------|----------------|
| Stainless Steel 316L | 196     | 861      | 620      | 0.30           |
| Ti6Al4V           | 115     | 976      | 847      | 0.33           |
| Ti35Nb7Zr5Ta      | 55      | 596      | 547      | 0.33           |

To characterize the mechanical behavior of the bone all materials were considered as isotropic. For the compact bone the elastic modulus is 16200 MPa and for the spongy bone is 380MPa [5]. The Poisson coefficient for both is 0.3.

2.1. Finite elements models

Finite elements models were realized, in which the hip implant and the femur were represented. (Figure 1). Four nodes solid elements were used in the models, to realize 4 finite elements models. Details are shown in Table 2. Three were developed with the implant and an additional model without the implant was analyzed (Figure 2). This was considered as a control or reference.

| Model | Number of Nodes | Number of Elements | Description               |
|-------|-----------------|--------------------|---------------------------|
| 1     | 22797           | 77977              | Bone without implant      |
| 2     | 74571           | 325919             | Bone with implant Steel 316L |
| 3     | 74571           | 325919             | Bone with implant Ti6Al4V |
| 4     | 74571           | 325919             | Bone with implant Ti35Nb7Zr5Ta |

For 2, 3 and 4 models, the implant was completely fastened to the bone through an interaction in which “slave” nodes are tied to the master surface of the bone. So the degrees of freedom in the exterior side of the implant associates to the degrees of freedom of the bone surface in contact to it.
All the models were created, analyzed and afterwards the results were processed using the program Abaqus for structural analysis by finite elements.

![Finite elements model for a pair bone-implant](image1)

**Figure 1:** Finite elements model for a pair bone-implant

![Finite elements model for bone](image2)

**Figure 2:** Finite elements model for bone [6].

### 2.2. Loads
The results obtained in a previous work were used for the study of material’s behavior in fatigue [7]. In the analysis of the whole bone-implant an arbitrary load of 1000N was applied, on the head of the femur if the bone has not implant and in the acetabular component of the prosthesis if the bone has an implant. The other end was considered as embedded.

### 3. Results and Discussion

#### 3.1. Fatigue of the materials
The Goodman’s diagrams were drawn with the results obtained for the three materials, using the maximum load established in the norm IRAM 9422-3 (Figures 3, 4 and 5). It can be observed that the titanium implants had a higher fatigue safety factor than the stainless steel implant for which the point that corresponds to the stresses of the test is near the limit of the safety zone of the diagram.
Figure 3: Goodman’s diagram. Stainless steel.

Figure 4: Goodman’s diagram. Ti6Al4V.

Figure 5: Goodman’s diagram. Titanium β.
3.2. Bone-implant group

In the first place the results obtained for the femur without implant are presented, which is considered as a control case for models with implants. The maximum Mises stress was produced in the anatomic neck of the femur, being its value 39.7 MPa. The stress components S33 in the middle part of the body were +18.8 MPa and -34.0 MPa (Figure 6). The stresses in the spongy bone were of 0.9 MPa in the anatomic neck and of 0.4 MPa in the zone where the implant was fixed.

The results that were obtained for the models with implants are shown in Table 3. The stresses in the implant were considered in two zones as it is shown in Figure 7. The bending stresses produced in the middle zone of the femur, are shown in Table 4.

### Table 3. Stresses and strains in the implant.

| Model | Equivalent stress of Mises in zone 2 (MPa) | Stress components S33, for flexion in Zone 1 (MPa) |
|-------|-------------------------------------------|--------------------------------------------------|
| 2     | 145.0                                     | + 58.6                                           |
|       |                                           | - 69.4                                           |
| 3     | 145.8                                     | + 43.4                                           |
|       |                                           | - 55.5                                           |
| 4     | 148.2                                     | + 27.1                                           |
|       |                                           | - 41.5                                           |

### Table 4. Stress components S33 for flexion in the middle zone of the femur.

| Model | Stress components S33, for flexion (MPa) |
|-------|-------------------------------------------|
| 1     | + 17.0                                     |
|       | - 21.9                                     |
| 2     | + 15.5                                     |
|       | - 19.8                                     |
| 3     | + 15.5                                     |
|       | - 19.9                                     |
| 4     | + 15.7                                     |
|       | - 20.0                                     |

### Table 5. Displacement components (mm)

| Model | u1 | u2 | u3 |
|-------|----|----|----|
| 1     | 4.7| 1.0| 1.6|
| 2     | 4.0| 1.0| 1.1|
| 3     | 4.1| 1.0| 1.2|
| 4     | 4.3| 1.0| 1.3|

Finally the displacement components in the head of the femur and in the superior extreme of the implant were compared (Figure 8). Results are shown in Table 5. From the obtained results, it can be inferred that, from the point of view of stress and displacements that were produced in the bone, with the titanium β implant, the behavior of the whole bone-implant is nearer to the natural bone.

Considering the efforts on the implant, a lower stress level in zone 1 was obtained for Tiβ. This can be considered positive from the point of view of the interface bone-implant and the cement used.
Figure 6: Stress components S33 (MPa).

Figure 7: Implant’s zones where the stress levels are indicated.

Figure 8: Deformed configuration. Deformations amplified 30 times.
4. Conclusions

Considering this type of implant, and the established loads by the standard IRAM 9422-3, a better fatigue behaviour was obtained from the titanium implants compared with the stainless steel implant. Referring to the behaviour of the group bone-implant, and under the action of the applied load, the use of titanium implants is seen more favorable for the interface bone-implant.

5. References

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