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ORIGINAL RESEARCH PAPER

Optimal material selection based on finite element method for manufacturing hip implant

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ABSTRACT

The objective of this study is to simulate material selection for fabricating hip joint prostheses from light-weight, low-cost materials which are also strong and durable. In this study, Co-Cr alloy CoCrWNi (F90), stainless steel ASIS 410, and titanium alloys (Ti6Al4V) material selection as the potential candidate for the suggested implant to manufacture a joint that is characterized by lightweight, low cost, does not react chemically with the human body and can bear the weight of the patient without mechanical failure. With this study, it was concluded the stainless steel ASIS 410 was selected as the best material selection since it passed engineering analysis, acceptable weight, and low cost compared to other proposed materials.

KEYWORDS

hip joint, implant, replacement, prosthesis

1. INTRODUCTION

Patients who suffer irreparable hip joint deterioration due to calcification, age, or accidents must have hip joint replacement surgery with an artificial replacement. The goal of hip joint surgery is to alleviate severe arthritis pain that interferes with everyday activities [1]. Total hip replacements are designed to treat or minimize pain, rectify deformity, restore function, reconstruct joint architecture, and improve functional mobility in injured joints [2]. The number of total hip replacement operations is growing each year [3]. In the last years, several researchers developed multiple suggestions for improvements of the hip joint implant. Abdullah Tahir sensoy et al. [4] studied the best material for a total hip implant. In Their Research, H. F. El-Sheikh et al. [5] and Dhyah Annur et al. [6] concentrate on the material selection using the finite element method in customized iliac implants. Yunus E Delikanli et al. [7] worked on light-weight hip implants' design, manufacturing, and fatigue analysis. S. L. Gavali et al. [8] experiment with stress analysis of a hip joint implant to see if it may be fractured. In the commercial market, there are several different types of prosthetic hip joints. To suit the needs of patients, a variety of material types and design forms are available on the market. This research aims to find the best materials to produce long-lasting, low-cost, harmless, light-weight hip joint prostheses.

2. METHODOLOGY

2.1. Hip joint design

The implanted hip joint is designed based on the natural dimensions of the pelvic joint. Solid works 2020 was used to build a three-dimensional model of the hip joint. Eastern Asians' morphometry is taken into account while designing hip implants.

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2.2. Finite element analysis

The designed model of the hip implant was transferred to ANSYS 14.5 software for analysis of a static load test and to find the Von-Misses stress and deformation with the safety factor of the joint when applying the boundary conditions As it is shown in Fig. 1, the boundary conditions applied to the joint include applying the patient's weight at the top tip of the joint and fixing support at the base region of the hip joint. The value of the applied load depends on the patient's weight, so if the patient weighs 60 kg, then a load of 600 N will be applied. In this study, to analyze the joint assume the value of the load applied to the upper tip of the joint is 900 N. Tetrahedrons were used as the meshing method, as illustrated in Fig. 1. Mesh convergence experiments were previously performed to determine the best mesh size. Based on the convergence analysis, a mesh size of 2 mm was chosen for this study.

3. MATERIAL SELECTION

Co-Cr alloy CoCrWNi (F90), Titanium Ti6Al4V, and ASIS 410 were selected to manufacture the hip joint implant. The materials that were selected are characterized by strength and biocompatibility. In addition, the material was considered to be homogenous, isotropic, and linearly elastic. The materials were tested by tensile and fatigue tests to know the mechanical properties of each material. ASTM B557m - 02a [9] is dependent on determining the dimension of tensile test specimens as it is shown in Fig. 2. The standard specimen dimension for the fatigue test is shown in Fig. 3 [10].

4. RESULT AND DISCUSSION

The result of the tensile test for selection material is illustrated in Figs 4–6 for Co-Cr alloy CoCrWNi (F90), ASIS-410, and Ti6Al4V, while the result of the fatigue test is illustrated in Figs 7–9 for Co-Cr alloy CoCrWNi (F90), ASIS-410, and Ti6Al4V, respectively.

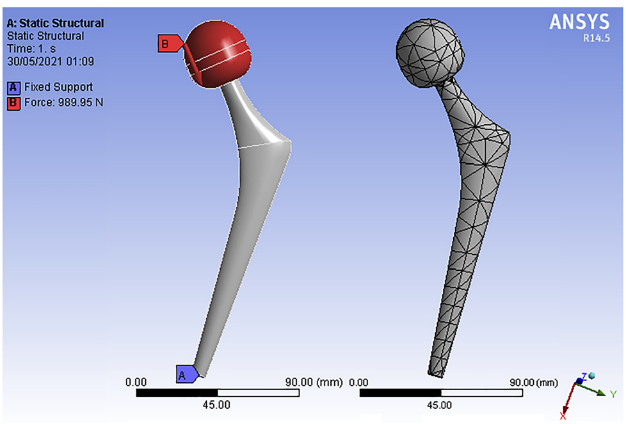

Fig. 1. The boundary condition and mesh applied to the model

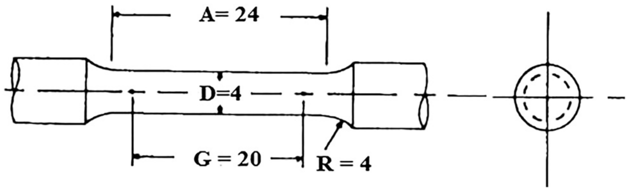

Fig. 2. The dimension of the tensile specimen according to ASTM B557m - 02

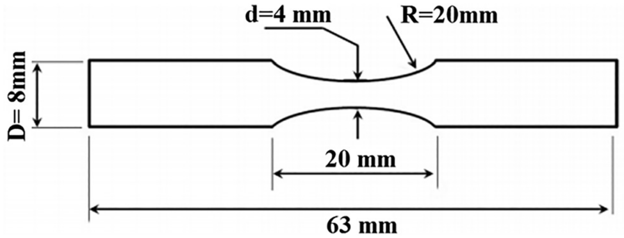

Fig. 3. Standard specimen dimensions for fatigue test

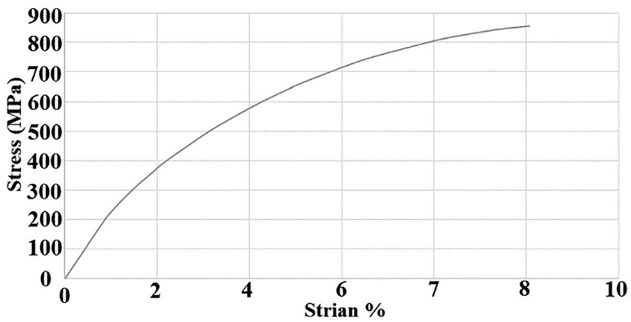

Fig. 4. The stress-strain curve of Co-Cr alloy

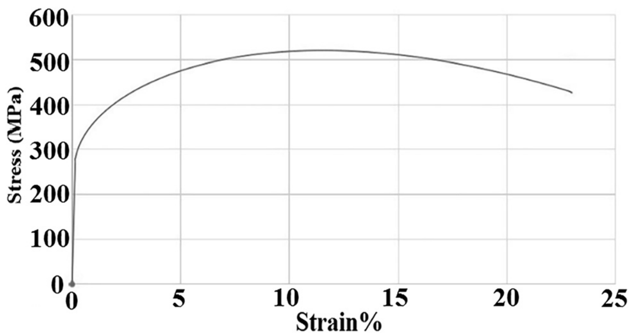

Fig. 5. The stress-strain curve of ASIS-410

A summary of the results of mechanical tests can be listed in Table 1.

The mechanical test results of the chosen materials were utilized as information for joint analysis methods to determine the values of produced stresses and deformations caused by the patient's weight on the joint, as well as clarifying the safety factor for each joint's material as a consequence of repeated stress created in the joint to determine, which material is better among the chosen materials that can

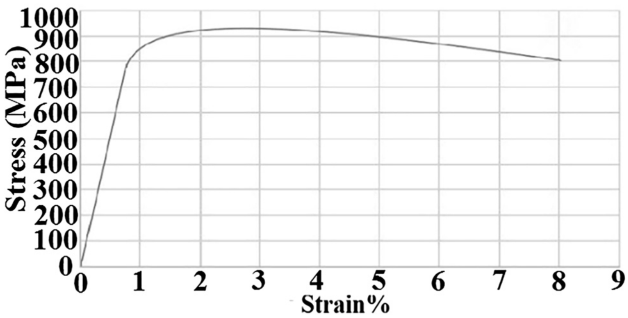

Fig. 6. The stress-strain curve of Ti6Al4V

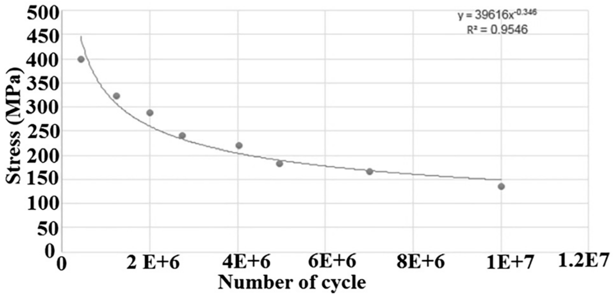

Fig. 7. S-N curve of Co-Cr alloy

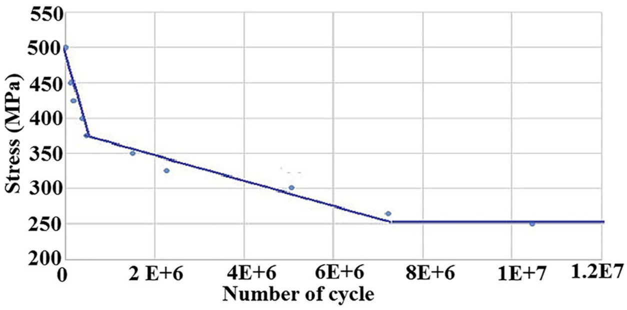

Fig. 8. S-N curve of ASIS-410

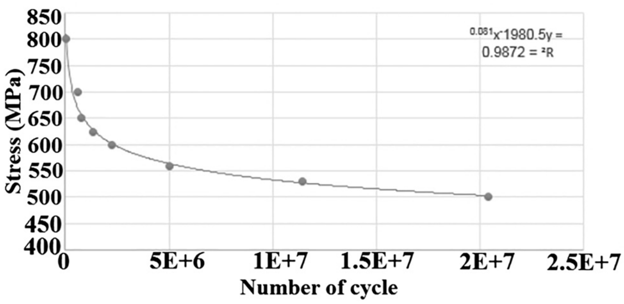

Fig. 9. S-N curve of Ti6Al4V

be depended on to achieve the study's goal. As for the Von Mises stress, results showed that the joint's maximum stress value equals to 119.81 MPa as it is demonstrated in Fig. 10. It has to be noted that the value of the difference is large between the joint stress and the yield stress of the selected materials. That indicates the success of the materials selected to be candidates for the manufacture of the joint.

While the deformity resulting from applying the patient's weight on the joint recorded the maximum deformation equal to 0.81 mm for the model using Co-Cr alloy as it is shown in Fig. 11. In contrast the highest deformation

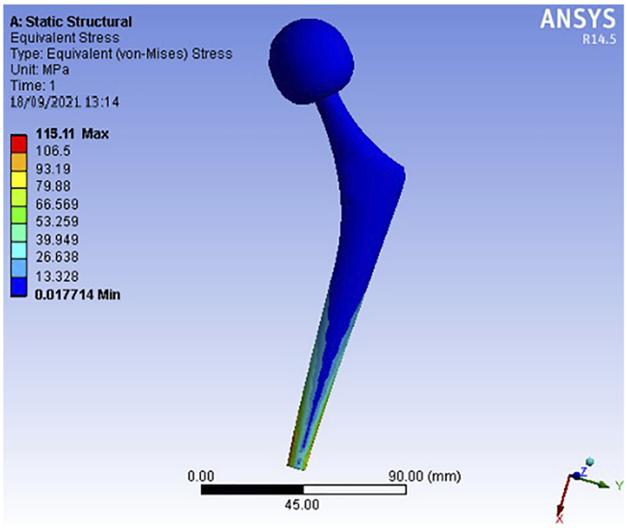

Fig. 10. The Von Mises stress analysis of the hip joint model

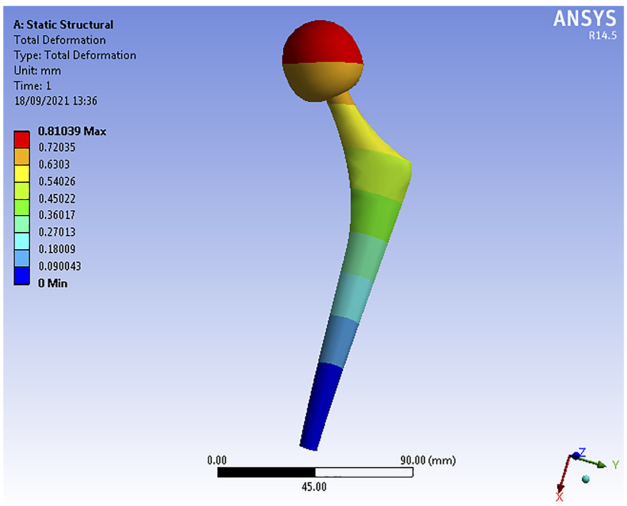

Fig. 11. Deformation of the hip joint using Co-Cr alloy

Table 1. The mechanical properties of selected material

Material	Density (g cm^{-3})	Yield stress (MPa)	Ultimate stress (MPa)	Modules of elasticity (GPa)	Endurance stress (MPa)
Ti-6Al-4V	4.42	880	930	110	500
ASIS 410	7.78	310	517	200	250
CoCrWNi	10.00	320	870	230	310

recorded equal 0.93 mm for the model using ASIS-410 material as it is shown in Fig. 12, and the maximum deformation equal to 0.717 mm for the hip joint using Ti6Al4V material as it is shown in Fig. 13.

The Finite Element Method (FEM) was used to analyze the hip joint models to compute the fatigue safety factor. The value of the safety factor varies by region, based on the distribution of stresses created and the endurance stress for each material used. Figures 14-16 show the value of the safety factor is greater than 1.25. Therefore, the design will be safe if the fatigue safety factor equals or greater than 1.25 [11–13].

After obtaining the results of the mechanical tests and the results of the FEM, to compare the results and determine the best material for the implanted hip joint, the results are summarized in Table 2.

When the summary results are reviewed, it is concluded that the preferred material to choose for the manufacture of the hip joint is ASIS 410 material due to its lower joint weight, its acceptable weight of 0.37 kg, and the ASIS 410

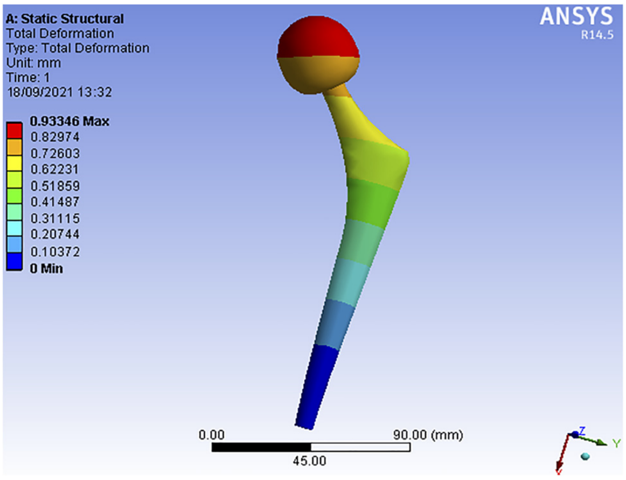

Fig. 12. Deformation of the hip joint using ASIS-410 material

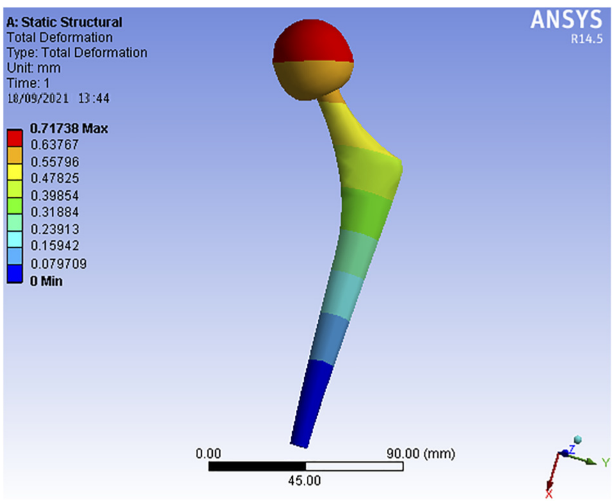

Fig. 13. Deformation of the hip joint using Ti6Al4V material

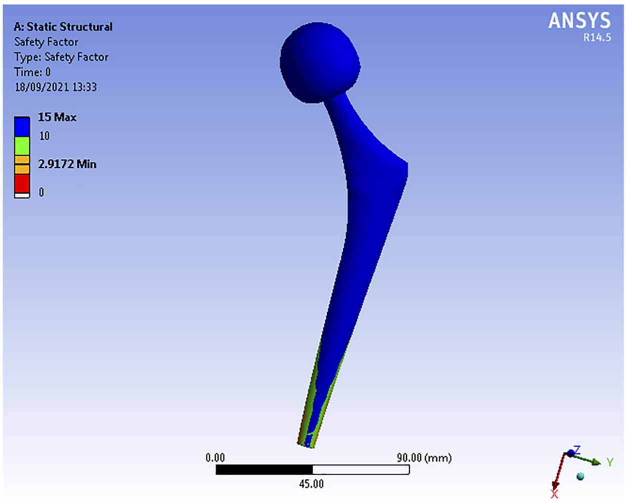

Fig. 14. The safety factor of the model using Co-Cr alloy

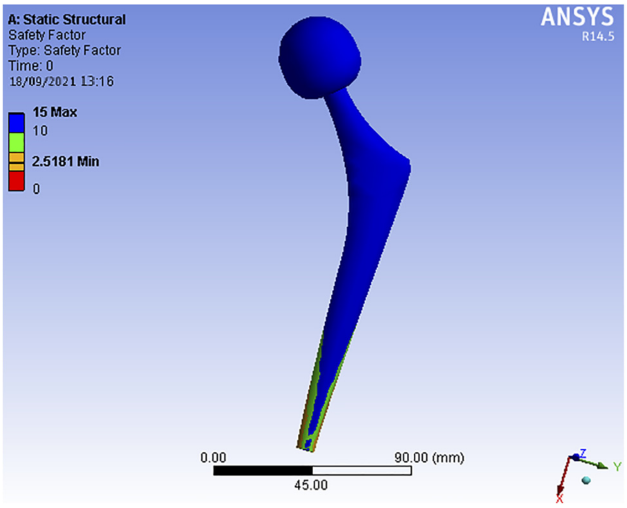

Fig. 15. The safety factor of the model using ASIS-410 material

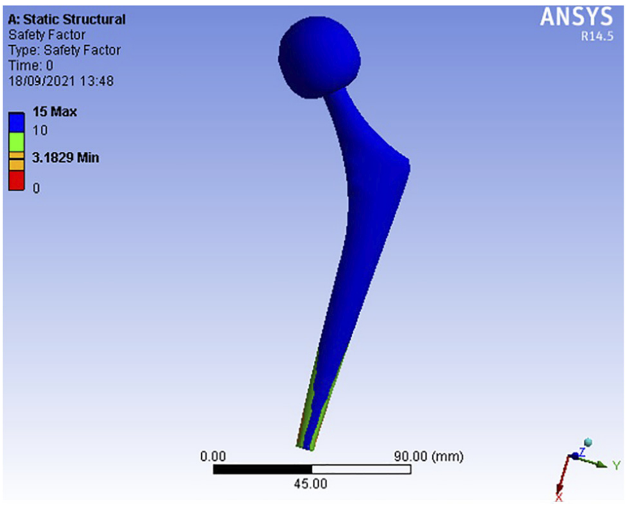

Fig. 16. The safety factor of the model using Ti6Al4V material

Table 2. The summary of the mechanical analysis for the selected material

Material	Von Mises stress analysis (MPa)	Yield stress (MPa)	Maximum Deformation analysis (mm)	Safety factor	Weight (kg)	Cost of raw material
Ti-6Al-4V	115	880	0.717	3.18	0.21	higher
Co-Cr alloy		335	0.810	2.91	0.48	high
ASIS 410		310	0.930	2.51	0.37	Low

price is the lowest among the other selected materials in addition to passed in design.

5. CONCLUSION

- All of the selected materials have a safety factor of fatigue of more than 1.25;
- The results showed that there is a big gap between maximum Von Mises stress analysis and yield stress of selected material;
- All selected materials passed in design;
- The ASIS 410 material was chosen as the optimal material in terms of the ratio of cost to its weight, which is acceptable compared to the cost to the weights of other materials.

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