Studies on Titanium Hip Joint Implants using Finite Element Simulation

Abhinav Kumar, Apoorv Rathi, Jagjit Singh and N. K. Sharma

***Abstract*—Titanium alloys are being extensively used as an implant material in the medical field due to their excellent biocompatibility and corrosion resistance, low internal stresses, negligible deformation and high specific strength as compared to other metallic alloys that are used for the same purpose. Low modulus of elasticity gives titanium alloy an edge over other materials by resulting in low stress shielding of bone. Titanium alloys used for orthopedic implants belong to one of the two types; α+β type or β type. This paper studies six different titanium alloys in order to propose the most suitable material for hip joint implant, through finite element simulation (FEM). The materials have been studied for equivalent stresses, weight, and deformation.**

***Index Terms*—Biomaterial, Deformation, FEM, Implant, Titanium alloys.**

I. Introduction

MATERIALS used for biomedical implants should possess low modulus of elasticity in order to inhibit stress shielding effect [1]. For implantation materials, researcher have been pursuing materials which can possess all the desired properties [2]. The materials used for implantation especially in the load bearing areas such as legs should have these desired properties such as resistance to corrosion within the body, excellent balance between strength and low modulus, superior wear resistance and fatigue strength and should be non-toxic to the body along with longevity [3]. Over the past few year's metallic materials like stainless steel, cobalt-chromium based alloys and titanium base alloys have been in application for implants. Almost all of these materials have shown a tendency to fail after a long-term use, due to lack in one or the other internal properties resulting in a revision surgery. Other forms of failure include rejection of the implant due to a resulting inflammatory reaction or disease in the human body [4].

Titanium alloys has given an option to medical researchers to use a material with low value of Young's modulus that is close to that of bone along with other properties that include high corrosion resistance due to formation of an oxide layer on its surface, optimum weight, wear strength and good weight to density ratio, thereby rectifying the faults present in other materials and decreasing the risk of failure [5, 6]. Six materials have been employed for the current investigation out of which three materials belong to alpha + beta type and three belong to beta type titanium alloys. The α+β type titanium alloys used are Ti-6Al-4V [2], Ti-5Al-2.5Fe [7] and Ti-6Al-7Nb [8, 9] while, β type titanium alloys used are Ti-12Mo-6Zr-2Fe [10], Ti-15Mo [11] and Ti-13Nb-13Zr [12, 13].

α+β type alloys have an excellent specific strength, corrosion resistance and adaptation to body environment but the alloying elements like vanadium (V) which can alter the mechanism of enzyme activity resulting in an inflammatory response of body cells [14] and aluminum (Al) during long term implantation, increases the chances of origination of Alzheimer disease [15]. Another setback of these type of materials is the high modulus of elasticity due to which the difference in the stiffness values of implant and bone becomes very large giving rise to a physical condition known as osteoporosis [16].

β-type titanium alloys constitute of elements like Nb, Zr, Mo etc. due to which they have a much better combination of mechanical properties, low modulus of elasticity, non-toxic and are totally biocompatible [17]. Further their modulus of elasticity can be drastically reduced by varying the proportion of beta stabilizing elements [18, 19].

The present investigation focuses on identifying the most appropriate material for hip joint implants with least stresses, deformation and weight with the help of commercial software's CATIA V5 used for designing and ANSYS Workbench 14.5 for finite element simulation. All these entities for each material have been obtained and compared to propose the best suited material for the manufacturing of stem implant.

II. Materials and Method

A. Materials

To study both the types of titanium alloys, alpha+beta type and beta type, three material of each type which are used as an implant material are incorporated into this study. The materials are given all the required properties such as Young's modulus, density, longitudinal tensile strength and yield strength respectively. The mechanical properties of the materials [17] used in the modelling and simulation have been illustrated in Table 1.

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Abhinav Kumar is with the Department of Mechanical Engineering, School of Engineering, Gautam Buddha University, Greater Noida, U.P. 201310, India (e-mail: avism007@gmail.com).
Apoorv Rathi is with the Department of Mechanical Engineering, School of Engineering, Gautam Buddha University, Greater Noida, U.P. 201310, India (phone: +91-8506050916; e-mail: apoorv.rathi@gmail.com).
Jagjit Singh is with Glocal University, Mirzapur Pole, Saharanpur, Uttar Pradesh 247122, India (email: jagjit@theglocaluniversity.in).
N. K. Sharma is with the Glocal University, Mirzapur Pole, Saharanpur, Uttar Pradesh 247122, India (e-mail: enksharma@yahoo.com).

TABLE I
MECHANICAL PROPERTIES OF MATERIALS

Material	Density (kg/m^3)	Young's modulus (GPa)	Longitudinal Tensile Strength (MPa)	Yield Strength (MPa)
Ti-6Al-4V	4430	110	965	875
Ti-5Al-2.5Fe	4450	112	1020	895
Ti-6Al-7Nb	4520	114	1050	950
Ti-12Mo-6Zr-2Fe	5000	85	1100	1060
Ti-15Mo	4960	78	874	544
Ti-13Nb-13Zr	4990	82	1037	908

B. *Modelling and Simulation*

Modelling of the hip joint implant has been done using CATIA V5 software. It is the most commonly used size and all the dimensions have been taken from Zimmer's Natural-Hip System [20]. The three dimensional model of Hip joint implant is shown in Fig. 1.

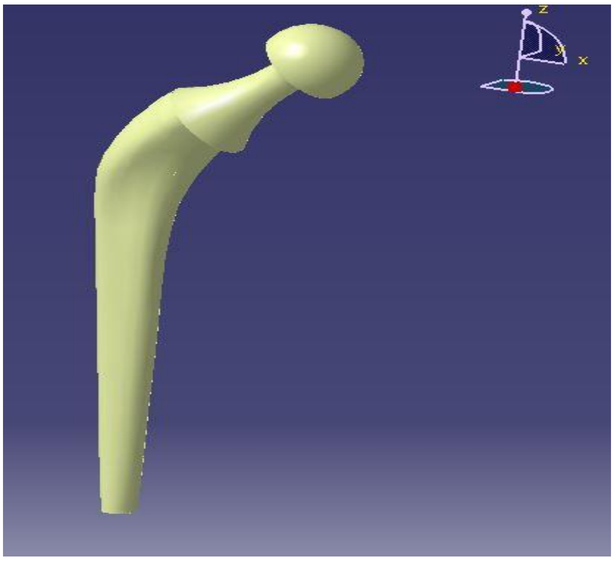

Fig. 1 Three dimensional model of Hip joint implant.

Hip joint implant has been modelled as a solid metal part. The main function of the stem implant is to bear the load of the body when it is inserted into the femur and is made to behave like a whole bone. To achieve results as in case of real life conditions, the boundary conditions of the implant are kept similar to that of a whole femur bone. The stress distribution and deformation is investigated for a weight of 75 Kg male during a normal standing posture [21, 22]. Pressure of 750 Pa is applied on the femoral head of the stem and the base of the stem is fixed. The side walls of the femoral stem is provided with a frictionless support to achieve condition as in that of a real environment.

III. RESULTS AND DISCUSSIONS

The FE model of the hip joint implant of six materials was subjected to a pressure of 750 Pa and was studied for equivalent stresses, deformation and weight. The contour profiles of the implants showing equivalent stresses (Von-mises) and deformation are shown in Fig. 2, 3, 4, 5, 6, 7 and Fig. 8, 9, 10, 11, 12, 13 respectively.

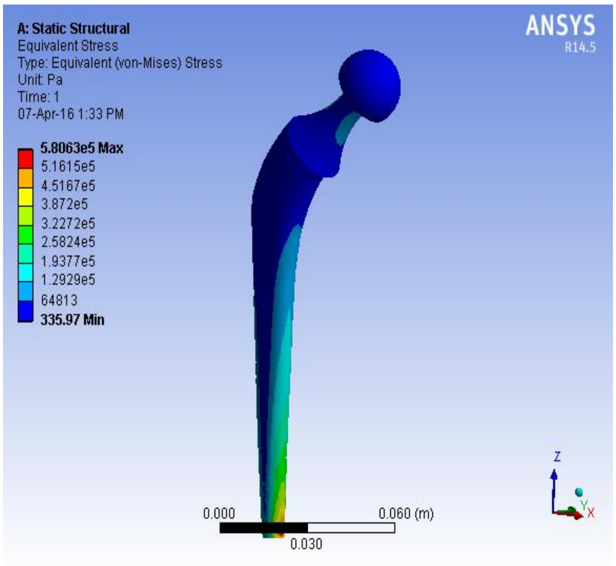

Fig. 2 Contour profile showing equivalent stresses in Ti-6Al-4V

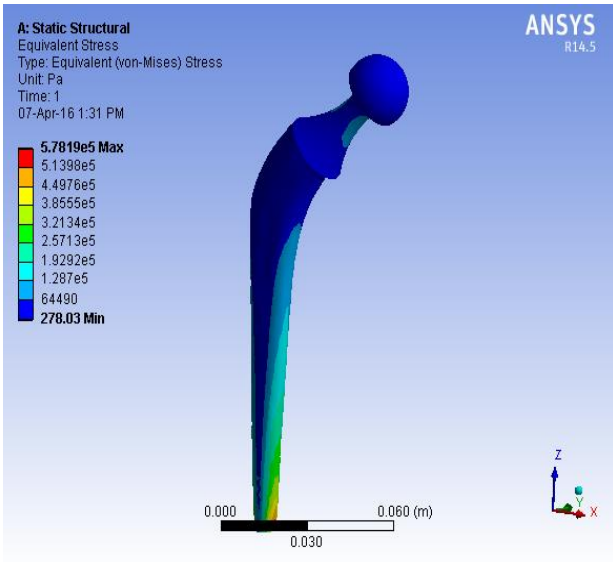

Fig. 3 Contour profile showing equivalent stresses in Ti-5Al-2.5V

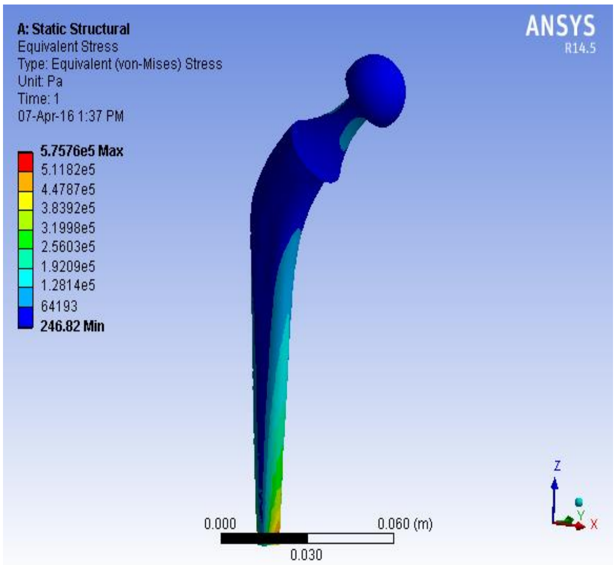

Fig. 4 Contour profile showing equivalent stresses in Ti-6Al-7Nb

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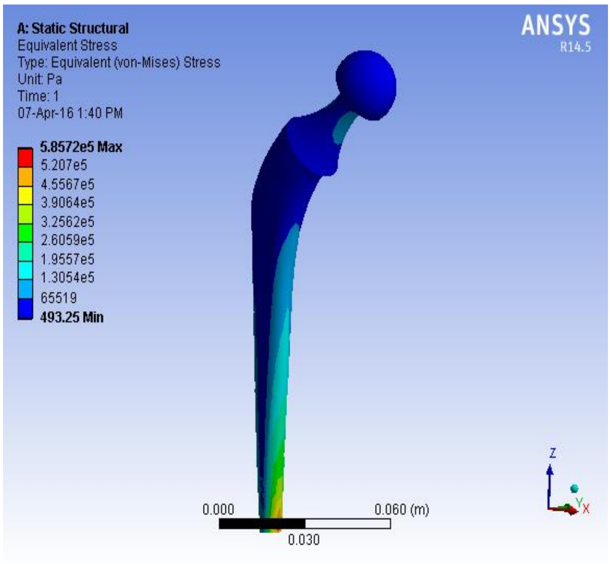

Fig. 5 Contour profile showing equivalent stresses in Ti-12Mo-6Zr-2Fe

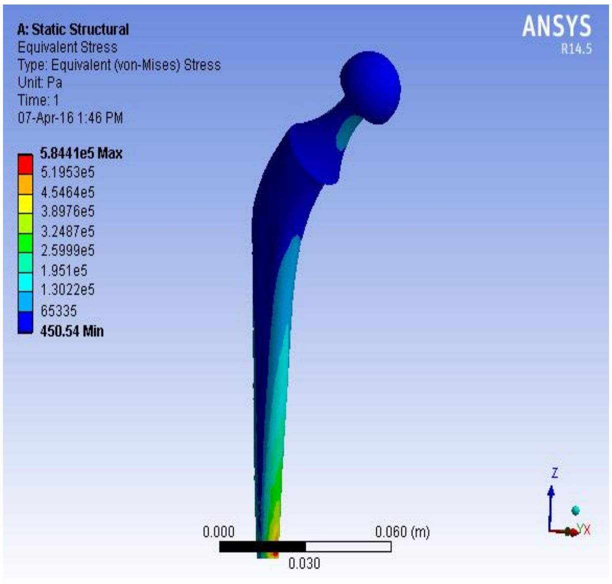

Fig. 6 Contour profile showing equivalent stresses in Ti—15Mo

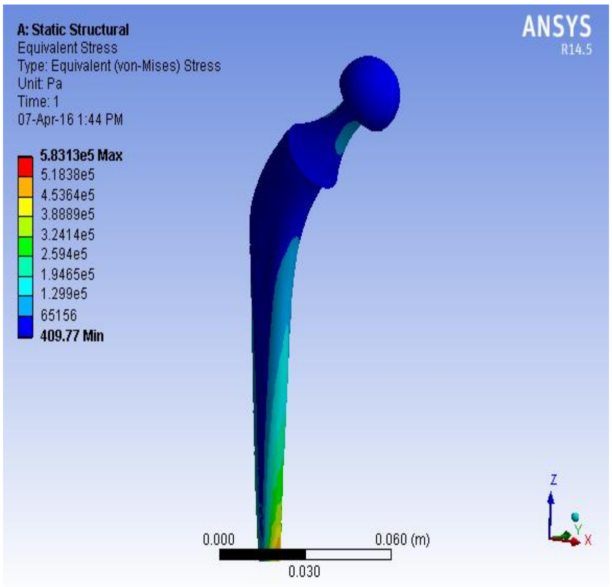

Fig. 7 Contour profile showing equivalent stresses in Ti-13Nb-13Zr

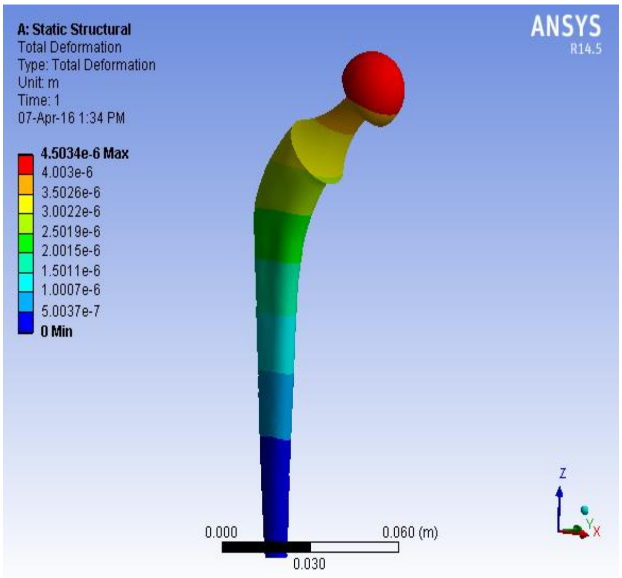

Fig. 8 Contour profile showing deformation in Ti-6Al-4V

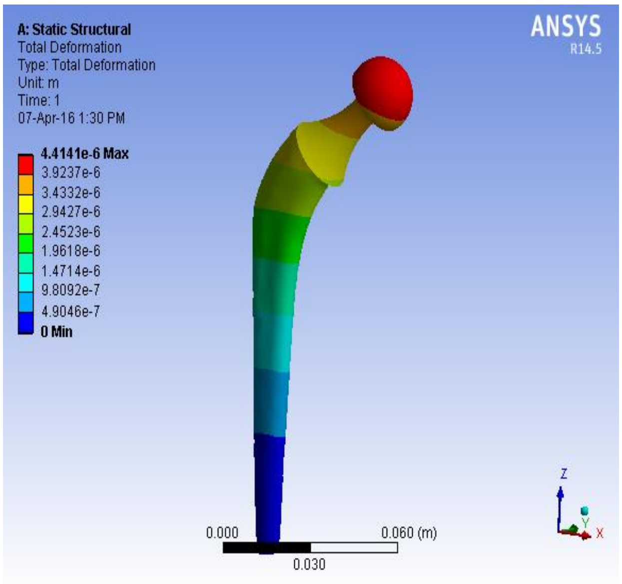

Fig. 9 Contour profile showing deformation in Ti-5Al-2.5Fe

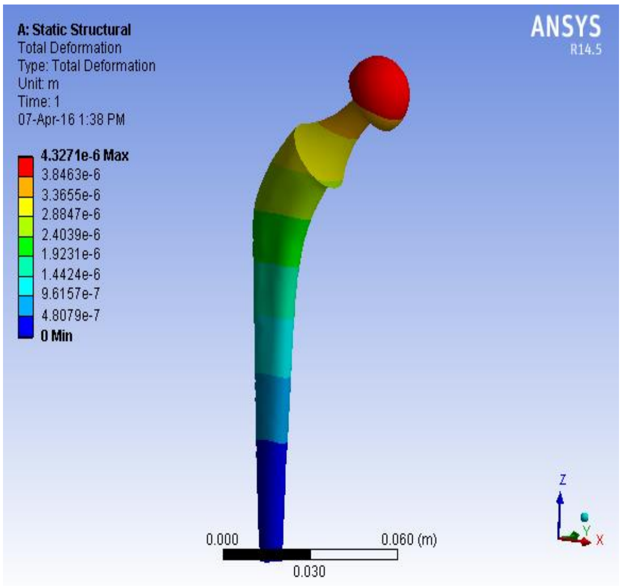

Fig. 10 Contour profile showing deformation in Ti-6Al-7Nb

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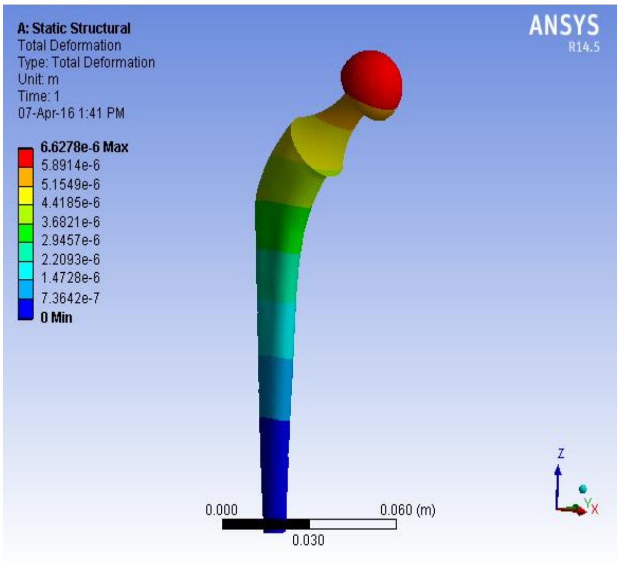

Fig. 11 Contour profile showing deformation in Ti-12Mo-6Zr-2Fe

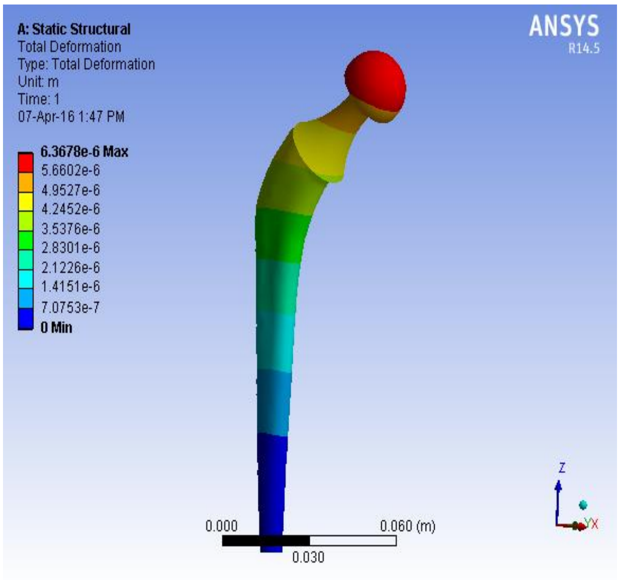

Fig. 12 Contour profile showing deformation in Ti-15Mo

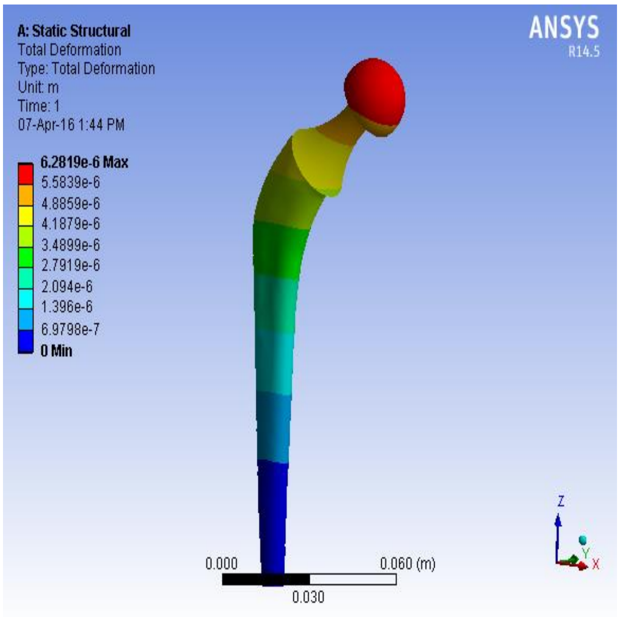

Fig. 13 Contour profile showing deformation in Ti-13Nb-13Zr

The contour profiles of all the six material are used to identify the values of maximum deformation and maximum equivalent stresses respectively. Also weight of each implant is calculated using FE models of every material. These values have been shown in Table 2.

TABLE II
FINITE ELEMENT SIMULATION RESULTS

Material	Maximum Equivalent Stress (Pa)	Maximum Deformation (m)	Weight (grams)
Ti-6Al-4V	5.80×10^{5}	4.5×10^{-6}	111.1
Ti-5Al-2.5Fe	5.78×10^{5}	4.4×10^{-6}	112.6
Ti-6Al-7Nb	5.75×10^{5}	4.32×10^{-6}	113.3
Ti-12Mo-6Zr-2Fe	5.85×10^{5}	6.62×10^{-6}	125.4
Ti-15Mo	5.84×10^{5}	6.36×10^{-6}	123.4
Ti-13Nb-13Zr	5.83×10^{5}	6.28×10^{-6}	124.8

The results obtained from the finite element simulation of a human hip joint stem implant shows that all the results have a very little variation. The maximum equivalent stresses are shown by Ti-12Mo-6Zr-2Fe that is 5.85×10^{5} Pa and least is shown by Ti-6Al-7Nb that is 5.75×10^{5}. Value of maximum deformation is exhibited by Ti-15Mo and least by Ti-6Al-7Nb. Ti-12Mo-6Zr-2Fe has the maximum weight and Ti-6Al-4V is the lightest among all the materials.

As seen from the results, there is a very little variation in the values of each calculated entity. Hence, selection of the best material amongst the six, can’t be done just on the basis of these values and inclusion of their other physical properties and behavior in the working conditions is necessary. Previous work [2-19] identifies the advantages and disadvantages of each material on the basis of properties other than stress, deformation and weight. The present investigation along with previous work done proposes that beta titanium alloys are best for the manufacturing of hip joint implant due to absence of aluminum (Al) and vanadium (V) and low modulus of elasticity which helps in achieving a better compatibility between bone and implant.

Since Ti-13Nb-13Zr has the lowest values of equivalent stress and deformation along with a nominal difference in weight in comparison to other beta titanium alloys, it is definitely the best suited material among all the six.

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