MODELING AND STRUCTURAL ANALYSIS OF ARTIFICIAL ANKLE JOINT UNDER VARIOUS LOADING CONDITIONS

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***Abstract*: Total ankle replacement is a procedure in which an injured ankle joint is replaced with a plastic and metallic material. Presently SS316L, Co-Cr-Mo, Ti-6Al-4V Alloys are used as implant material in ankle replacement surgery. The materials SS316L, Co-Cr-Mo alloys are high in density which fails with in short period. Ti based alloys are used in many applications of biomaterials due to their excellent mechanical, physical and biological performance. Now a days, low modulus β-type Ti-based alloys are still being developed with Young's modules close to that of cortical bone, as they can provide good biological fixation through bone tissue in growth into the porous network potential and preventing stress shielding effect.**

The objective of this work is β-type titanium alloys composed of non-toxic and allergy free elements such as Ti–13Nb–13Zr (TNZ), which is highly expected to be used as a biomaterial for implants. By considering a finite element model of the implant will be developed for the study. The model developed in CATIA V5 software. The analysis of the FE model using ANSYS software of the implant. To obtain the results by considering the different loads exerted by human body weight maximum 2000N,2500N,3000N,3500N on ankle joint implants while walking condition and applying different materials Co-Cr-Mo alloy,Ti-6Al-4V alloy,Ti-13Nb-13Zr alloy.

Then finally we determined Von-Mises Stress and Total deformation from Static analysis and Natural frequencies from Modal analysis.

***Keywords*: Finite element method, Total ankle replacement, Ti-6Al-4V Alloy, Ti–13Nb–13Zr (TNZ) alloy, CATIA V5, ANSYS**

1. INTRODUCTION

An implant is a medical device manufactured to replace a missing biological structure, support a damaged biological structure, or enhance an existing biological structure. Medical implants are man-made devices, in contrast to a transplant, which is a transplanted biomedical tissue. The surface of implants that contact the body might be made of biomedical materials.

1.1 Different Biomedical implants

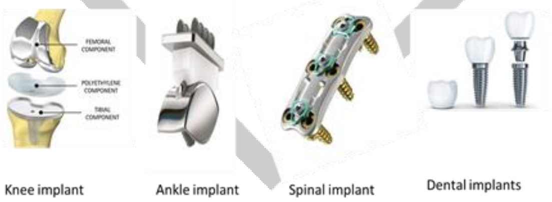


Fig.1.Different types of biomedical implants

Metals and their alloys are widely used as biomedical materials. On one hand, metallic biomaterials cannot be replaced by ceramics or polymers at present. Because mechanical strength and toughness are the most important safety requirements for a biomaterial under load-bearing conditions, metallic biomaterials like stainless steels, Co-Cr alloys, commercially pure titanium (CP Ti) and its alloys are extensively employed for their excellent mechanical properties. On the other hand, metallic materials sometimes show toxicity and are fractured because of their corrosion and mechanical damages [1]

Therefore, development of new alloys is continuously trialed. Purposes of the development are as follows:

- To remove toxic element;
- To decrease the elastic modulus to avoid stress shield effect in bone fixation
- To miniaturize medical devices.
- To improve tissue and blood compatibility

2. TOTAL ANKLE REPLACEMENT [TAR]

Ankle replacement or ankle arthroplasty is a surgical procedure to replace the damaged articular surfaces of the human ankle joint with prosthetic components. This procedure is becoming the treatment of choice for patients, replacing the conventional use of arthrodesis, i.e. fusion of the bones. The restoration of range of motion is the key feature in favor of ankle replacement with respect to arthrodesis

2.1 TYPES OF ARTIFICIAL ANKLE JOINTS PROSTHESIS

There are different types of ankle implants are there

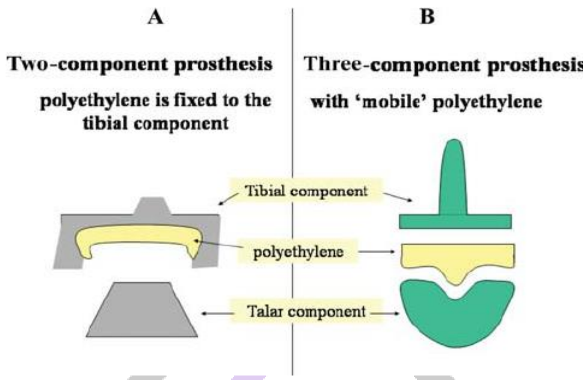


Fig.2 Different types of ankle implants

Modern ankle replacement consists of metallic tibial and talar components, stabilized with or without cement. A 'meniscus-like' polyethylene component is either fixed to the tibial component (A) or is mobile articulating with both components (B) as shown in fig

2.2 The Scandinavian Total Ankle Replacement (STAR)

The STAR is one of the most widely used ankle replacement. The STAR Ankle is a non-constrained, total ankle replacement, surgically implanted to replace an ankle joint. It is non-constrained because the bearing can be free to move in more than one plane along the tibial component [2]

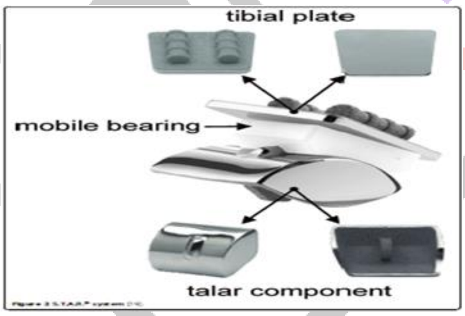


Fig.3 STAR Ankle Implant

Working of STAR: The STAR Ankle has three parts a metal tibial component, a metal talar component and a plastic mobile bearing component. The upper flat surface of the plastic component slides against the flat surface of the tibial plate. The projecting Cylinders of the tibial component serve to fix the device to bone at the distal tibia. The lower surface of the plastic mobile bearing component is concave, fitting against the convex upper surface of the talar component.

2.3 BP ankle replacement

The other leading mobile bearing ankle replacement is Buechel Pappas (BP) ankle (Figure.4).The Scandinavian Total Ankle Replacement (STAR) (Figure.3) manufactured by Small Bones Innovations & manufactured by Endotec are the two leading mobile bearing ankle replacements currently on the market. These two ankles have both been used for approximately 20 years in Europe. The BP is not currently approved for use in the U.S. as it is currently in clinical trials, but the STAR was approved for use in 2009 and is the only mobile bearing device approved in the United States. Both of these designs are unconstrained to anterior/posterior translation and internal/external rotation at the tibial articular surface by having a flat geometry.[3]

Fig.4 BP ankle replacement

They are constrained at the talar surface with a more conforming fit. The talar interface is almost completely conforming which only allows the flexion to occur while any joint rotations are intended to occur at the tibial interface [3]. The conformity of the talar surface also adds medial/lateral stability and prevents the insert from disassociation

3. MATERIALS AND METHODOLOGY

3.1. Problem Identification:

- The conventional materials are, heavier in density and improper which fails within prescribed period
- Steel have low corrosion resistance and high density
- Co-Cr-Mo alloy good corrosion resistance and low cost but heavier than steel
- Ti-6Al-4V alloy is superior to those of other metallic materials but use of vanadium produce toxicity[4]
- Stress shielding effect
- metallic biomaterials require a low Young's modulus, close to that of bone (10–30 GPa) [5]

3.2. Objective of the project:

- Modeling of an Artificial Ankle Joint using existing specifications.[6]
- Obtaining design of Ankle joint using CATIA V5 R20 software and then imported into ANSYS 19.2 workbench
- Meshing of design model using ANSYS 19.2.
- Analysis of ankle joint by using Static analysis and Modal analysis
- Comparing the performance of three different materials (Co-Cr-Mo),(Ti-6Al-4V) ,(Ti-13Nb-13Zr) under static analysis process at different loading conditions are (60kg,75kg,85kg,100kg) and we are taking boundary conditions is 2000N, 2500N, 3000N,3500 Newton's.
- From the Results we identify the suitable material for artificial ankle joint implant.

3.3 Material Properties:

Artificial ankle joint component consists of three parts:

1. Tibial component Material: (Co-Cr-Mo) alloy, (Ti-6Al-4V) alloy, (Ti-13Nb-13Zr) alloy
2. Mobile Bearing component Material:UHMWPE
3. Talar component Material: (Co-Cr-Mo) alloy, (Ti-6Al-4V) alloy, (Ti-13Nb-13Zr) alloy

MATERIAL PROPERTIES	Co-Cr-Mo	Ti-6Al-4V	Ti-13Nb-13Zr	UHMWPE
Density(Kg/m^3)	8300	4430	4720	930
Possion's ratio	0.32	0.31	0.32	0.46
Young's modulus(Gpa)	205	110	79-84	0.894
Yield strength(Mpa)	660	880	836-908	21.4
Ultimate tensile strength(Mpa)	1100	950	973-1037	38.6

Table. 1 Material properties

4. CATIA V5 R20 INTRODUCTION

4.1 Introduction

CATIA (Computer Aided Three Dimensional Interactive Application). As a new user of this software package, you will join hands with thousands of users of this high-end CAD/CAM/CAE tool worldwide. If you are already familiar with the previous releases, you can upgrade your designing skills with the tremendous improvement in this latest release.
CATIA V5, developed by this assault Systems, France, is a completely re-engineered, Next-generation family of CAD/CAM/CAE software solutions for Product Lifecycle Management. Through its exceptionally easy-to-use and state-of-the-art user interface, CATIA V5 delivers innovative technologies for maximum productivity and creativity, from the inception concept to the final product. CATIA V5 reduces the learning curve, as it allows the flexibility of using feature-based and parametric designs.

4.2 CATIA V5 provides three basic platforms:

P1, P2, and P3. P1 is for small and medium-sized process-oriented companies that wish to grow toward the large scale digitized product definition.P2 is for the advanced design engineering companies that require product, process, and resource modeling. P3 is for the high-end design applications and is basically for Automotive and Aerospace Industry, where high quality surfacing or Class-A surfacing is used. The subject of interpretability offered by CATIA V5 includes receiving legacy data from the other CAD systems and even between its own product data management modules. The real benefit t is that the links remain associative. As a result, any change made to this external data gets notified and the model can be updated quickly

4.3 CATIA V5 WORKBENCHES

CATIA V5 serves the basic design tasks by providing different workbenches. A workbench is defined as a specified environment consisting of a set of tools that allows the user to perform specific design tasks. The basic workbenches in CATIA V5 are Part Design, Wireframe and Surface Design, Assembly Design, Drafting.

4.4 MODELLING OF AN ARTIFICIAL ANKLE JOINT IN CATIA V5 R20

There are two bearing surfaces in the artificial ankle implant. The interface between the upper side of the mobile bearing and the facing surface of the tibial plate, and the interface between the lower surface of the mobile bearing and the facing surface of the talar component. The tibial plate has one flat surface and one surface with two raised cylindrical barrels oriented in the anterior/posterior direction. The upper flat surface of the mobile bearing slides against the flat surface of the tibial plate. The projecting cylinders of the tibial plate serve to fix the device to bone at the distal tibia. The lower surface of the mobile bearing is concave, fitting against the convex upper surface of the talar component.

The mobile bearing design of the device is intended to reduce the shear and torque forces on the bearing, which can lead to loosening of either metal component, and to decrease stress at the metal/bone interface. The sloped sides are designed to improve the weight bearing characteristics of the talar component.

4.4.1. Design of Tibial component

In this study, dimensions of tibial component are taken based on The Scandinavian Total Ankle Replacement (STAR) [6] based on talar component dimensions and bone removal rate of distal tibia

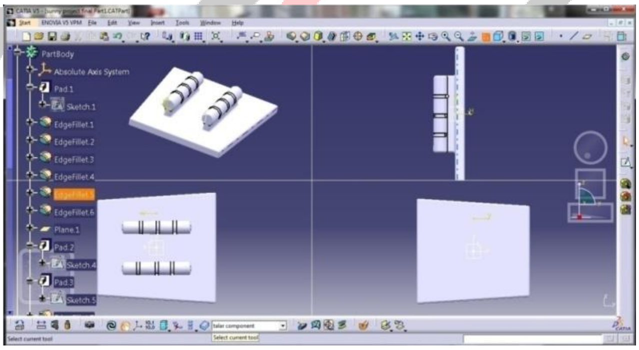


Fig.5 Design of Tibial component

4.4.2. Design of Mobile bearing component

The proximal surface of the mobile bearing is flat. The distal or talar surface is concave and has a central radial groove running from anterior to posterior.

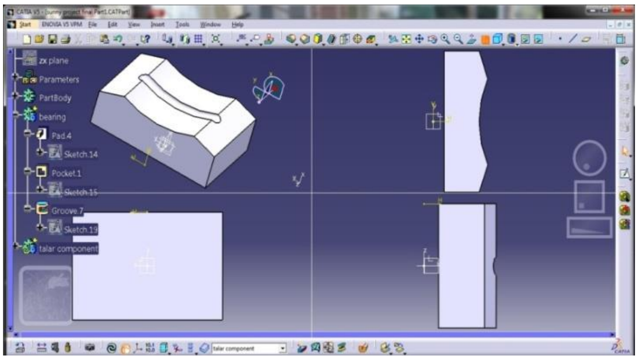


Fig.6 Design of mobile bearing component

4.4.3. Design of Talar component

The talar component is designed as an anatomical prosthesis to cover the talar dome, anterior, posterior, and medial and lateral facets, like the tibial plate. The talar component is designed to minimize the amount of bone that must be removed. From the apex of the dome, the walls slope outwards to conform to the normal bone anatomy.

Viewed from the side, the proximal surface of the talar component is dome-shaped to conform to the talar dome of the normal ankle. A small, raised half-cylindrical ridge runs from anterior to posterior in the medial-lateral center of the dome. The purpose of this ridge is to constrain the medial/lateral motion of the mobile bearing.

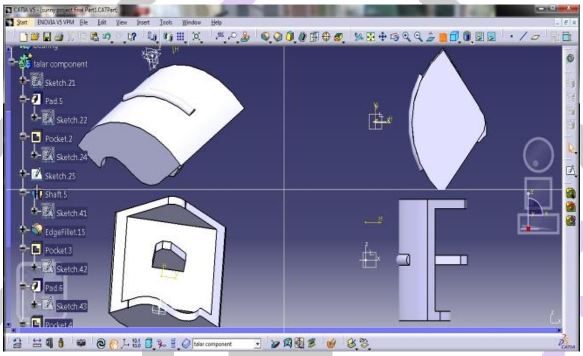


Fig.7 Design of Talar bearing component

4.4.4. Assembly of ankle joint implant

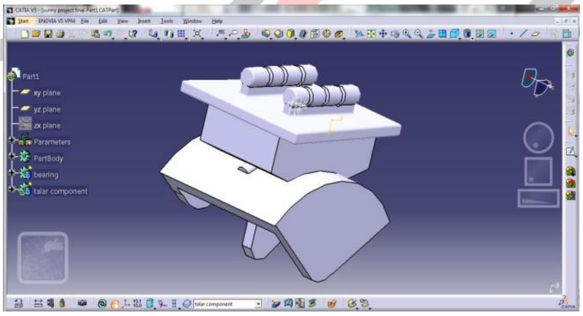


Fig.8 Assembly of ankle joint implant

5. STRUCTURAL ANALYSIS OF AN ARTIFICIAL ANKLE JOINT

5.1. ANSYS INTRODUCTION

Ansys is a general purpose software, used to simulate interactions of all disciplines of physics, structural, vibration, fluid dynamics, heat transfer and electromagnetic for engineers. So ANSYS, which enables to simulate tests or working conditions, enables to test in virtual environment before manufacturing prototypes of products. Furthermore, determining and improving weak points, computing life and foreseeing probable problems are possible by 3D simulations in virtual environment. Also, it can work integrated with other used engineering software on desktop by adding CAD and FEA connection modules.

5.2. Tasks to be done ANSYS

1. Each part in the ankle joint components has to be capable of holding both tensile and Compressive loads successively.
2. Stresses and deflection should be within the permissible limits.
3. Perfect contact pair should be formulated.
4. Parts of the component should always be bonded to each other.

5. Converges of the model should be achieved.

5.3. Meshing

The design that is saved in igs format is imported in Ansys work bench and engineering data is applied and by generating mesh

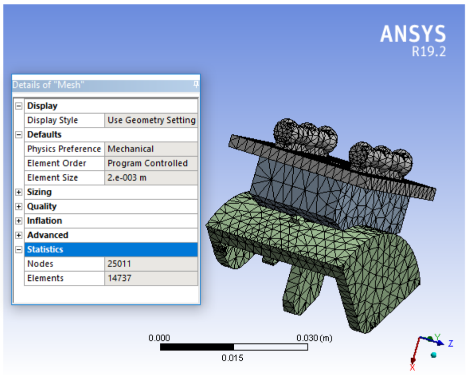


Fig.7 Meshing

5.4. Loads and Boundary conditions:

The boundary condition that are given to the ankle joint in Ansys structural analysis work bench bottom TALAR component is fixed and apply different forces 2000N, 2500N, 3000N, 3500N ON TIBIA component.

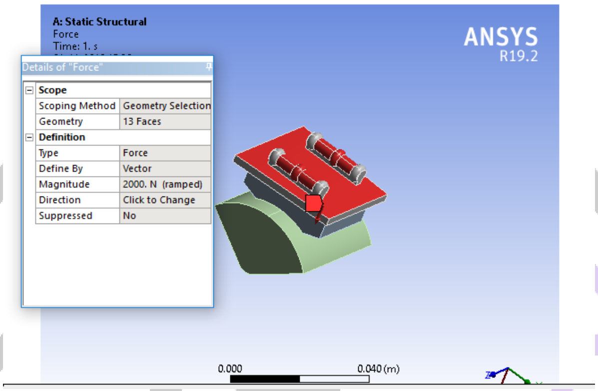


Fig.8 Loads and Boundary conditions

6. RESULTS AND DISCUSSIONS

We are analyzing ankle joint implant and finding Von mises stress and Total deformation at different loading conditions and different materials by Static analysis. The below figures are at max load 3500N position

6.1 At 3500N Co-Cr-Mo Material

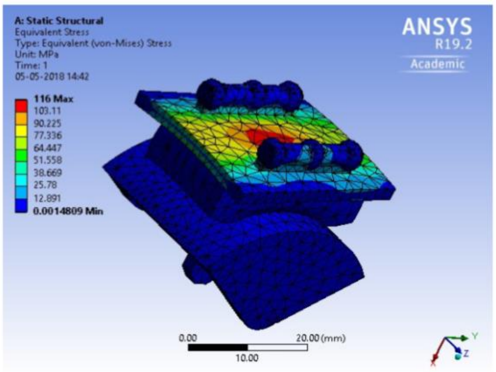


Fig.9 Von-mises stress of Co-Cr-Mo Material

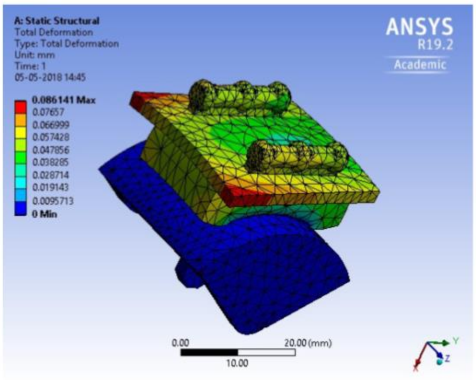


Fig.10 Total deformation of Co-Cr-Mo Material

6.2. At 3500N Ti-6Al-4V Material

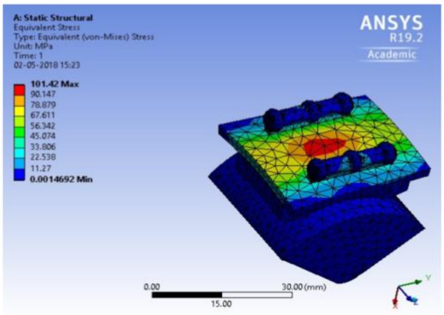


Fig.11 Von-mises stress of Ti-6Al-4V Material

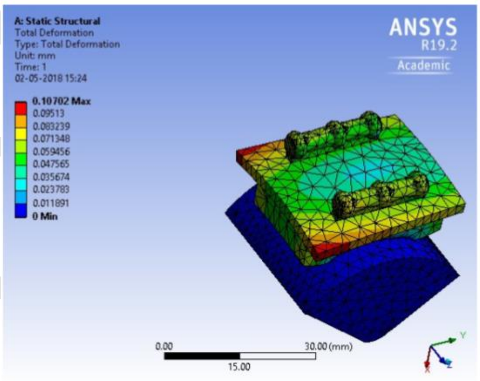


Fig.12 Total deformation of Ti-6Al-4V Material

6.3. At 3500N Ti-13Nb-13Zr Material

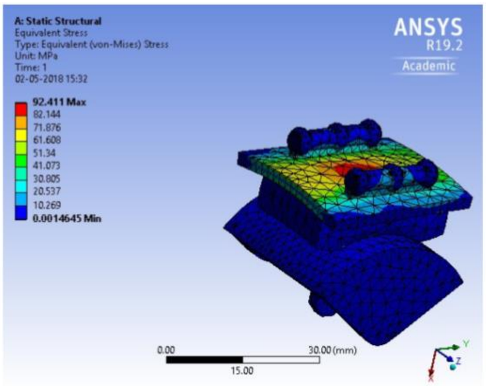


Fig.13 Von-mises stress of Ti-13Nb-13Zr Material

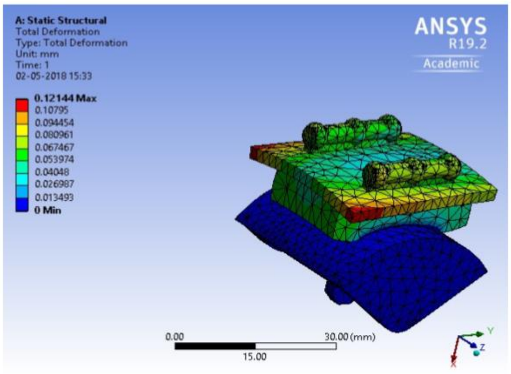


Fig.14 Total deformation ofTi-13Nb-13Zr Material

6.4.1 Von mises stress (MPa) at different loading conditions and different materials

Load	Co-Cr-Mo Material	Ti-6Al-4V Material	Ti-13Nb-13Zr Material
2000N	66.287	57.952	52.807
2500N	82.859	72.439	66.008
3000N	99.431	86.927	79.21
3500N	116.1	101.42	92.411

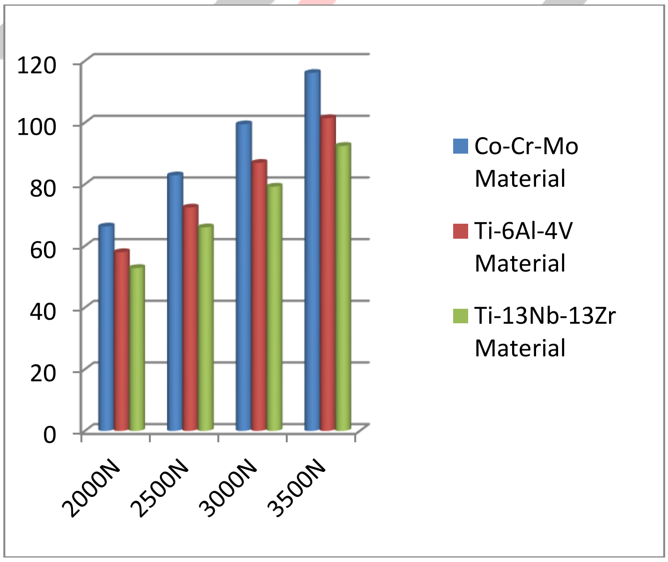
Table.2 Von-mises stress (MPa)

6.4.2 Total Deformation (mm) at different loading conditions and different materials

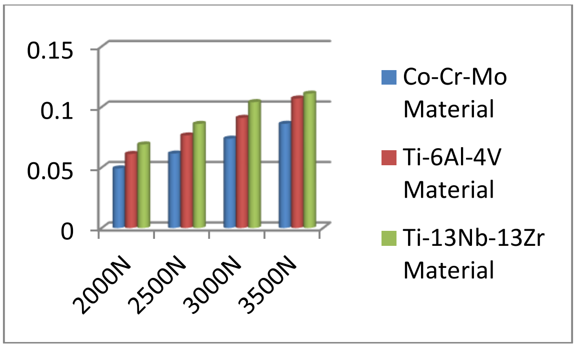
Load	Co-Cr-Mo Material	Ti-6Al-4V Material	Ti-13Nb-13Zr Material
2000N	0.0492	0.06115	0.069
2500N	0.0615	0.07644	0.086
3000N	0.0738	0.091	0.104
3500N	0.0861	0.107	0.121

Table.3 Total Deformation (mm)

6.4.3 Von-mises stress and Total deformation Graphs



Graph.1 Von-mises stress (Mpa)



Graph.2 Total Deformation (mm)

6.5 Modal analysis Results and Discussion

Modal analysis is the study of the dynamic properties of structures under vibrational excitation. In Ankle joint assembly fixed at the one side . In addition, a dynamic interaction between a component and its supporting structure is very important because the component could cause structural damage or failure if its operating frequency is close to one of the natural frequencies of the structure. So we proceed further and analyze the structure for different frequency modes. The mesh parameters and the boundary conditions for the problem would be same as of above. The analysis was performed to find the total deformation under 6 modes.

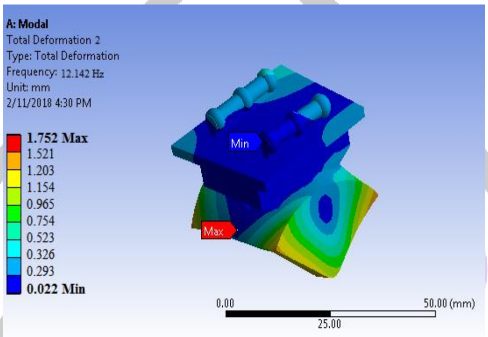


Fig.15 Modal analysis of Co-Cr-Mo Material

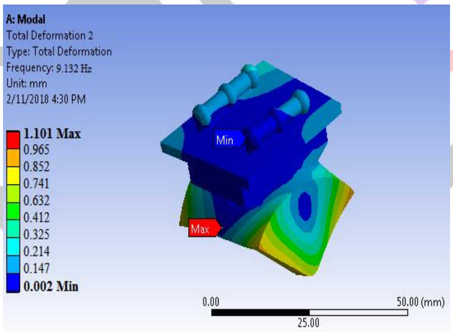


Fig.16 Modal analysis of Ti-6Al-4V Material

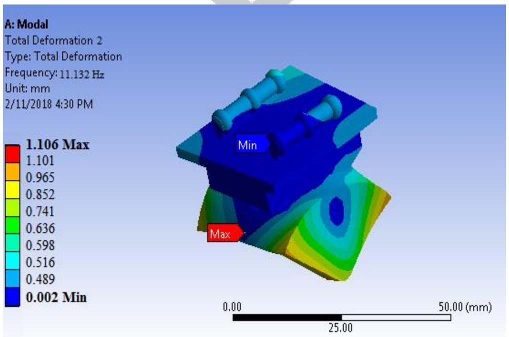


Fig.17 Modal analysis of Ti-13Nb-13Zr Material

6.5.1 Mode shapes of different materials

Mode	Frequency [Hz]	Total Deformation (mm)
1	1.913	0.0013
2	9.132	1.101
3	25.31	2.155
4	53.76	4.661
5	111.33	12.136
6	159.83	17.25

Table.4 Mode shapes & Total deformation of Co-Cr-Mo Material

Mode	Frequency [Hz]	Total Deformation (mm)
1	1.231	0.0025
2	12.142	1.752
3	28.314	3.216
4	56.12	6.823
5	110.14	9.242
6	171.22	17.14

Table.5 Mode shapes & Total deformation of Ti-6Al-4V Material

Mode	Frequency [Hz]	Total Deformation (mm)
1	2.12	0.0010
2	11.132	1.106
3	30.183	2.131
4	57.262	5.231
5	113.307	9.732
6	180.262	15.73

Table.6 Mode shapes & Total deformation of Ti-13Nb-13Zr Material

7. CONCLUSIONS

The static structural analysis of the ankle joint has a great significance, In this project, the design approach for a 3-component mobile bearing artificial ankle joint using CATIA V5 R20 software, Analysis work was supported by ANSYS 19.2

- Both Static structural and Modal analysis are to be performed
- Among the Static structural analysis, considered on materials, Co-Cr-Mo Material exhibited the maximum stress of 116.1 Mpa and maximum deformation of 0.0861mm at maximum load 3500N applied.
- Ti-6Al-4V Material exhibited the maximum stress of 101.42 Mpa and maximum deformation of 0.107 mm at maximum load 3500N applied.
- Ti-13Nb-13Zr Material exhibited the maximum stress of 92.41 Mpa and maximum deformation of 0.121 mm at maximum load 3500N applied.
- From the Modal analysis we obtained Frequencies and corresponding mode shapes.

From the Static and modal analysis results Ti-13Nb-13Zr produces less stress compare to other two materials, Because of low young's modulus and the use of Ti-13Nb-13Zr material we avoid both toxic and stress shielding effect. Finally we conclude that Ti-13Nb-13Zr is better material suitable for artificial ankle joint implant.

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