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Comparison of tensile properties of Ti-Ta alloys and Ti-6Al-4V for biomedical implant application.

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Abstract

In medical field, the metallic materials have proven their significance to additive manufacturing allowing the production of complex geometries of implants accurately. The requirement of such implants is increased due to increase in accident and also increase in population of aged people. The wide range of materials are being used or are under development and there is a great scope of improvement. The implant material should have better wear resistance, corrosion resistance, Young's Modulus nearer to the bones. The most widely used material for the implants is pure Titanium and Titanium based alloys. Among them the Ti-6Al-4V has been in the market since long. Recent research has proven that the biocompatibility of Tantalum is superior than that of Titanium and its other alloys. Addition of Ta, as an alloying element with Ti improves the mechanical properties and biocompatibility of the implant. So, this study is intended to check the possibility of Ti-Ta alloy to be the implant material by comparing the tensile properties to check if Ti-Ta alloys can overcome the limitations of currently used materials.

Keywords: Ti-Ta alloy; Implant; Ti-6Al-4V; Tensile properties.

1. Introduction

Ti and its alloys are used widely to serve the purpose of implant. But to fulfill all the characteristic of human body implant with the adjacent tissues and bones, further research is required as there is a huge scope of improvement in properties of Ti by adding various alloying elements.

Since 1940s the Ti alloys are in use for orthopedics, are gaining a lot of attention of researchers due to their distinctive mechanical properties and biocompatibility. Their compatibility with the human bone tissue provides longer life cycle for the implants.

The studies of Song Y. et al. [15] states that the various alloying elements likewise Zr, Mo, Nb, Ta etc. can be added to lower the Young's modulus without reducing the strength of the given Ti alloy. Currently the metallic materials used for the implants are Stainless steel of specific grades, Co-Cr alloys, Ti based alloys etc. But the release of

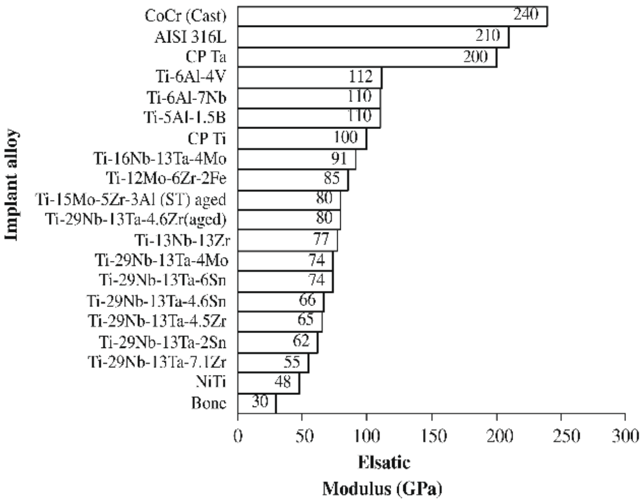

Figure 1: Elastic Modulus of different materials (GPa) [6]

elements like Ni, Cr, Co etc. from Stainless steel and Co-Cr alloy are dangerous for the human body due to corrosive environment in the body. [15] When compared with 316 L SS the Ti based alloy possesses similar strength and 55% less density which makes the implant light weight. The much higher Young's modulus of 316L SS and Cr-Co alloys mismatches with that of human bone and it leads to the Stress shielding of the implant. Stress Shielding is the phenomenon which leads to lesser stress transfer to the human bone and as a result the implant gets loosen in few years which leads to revision surgery. Due to cyclic loading the hip implant failure is also reported. [18] Dermatitis - a skin related diseases have been found because of the presence of Ni and the carcinogenic effects have been reported due to presence of Co. [12]

The comparison of modulus of elasticity of various biomedical alloys is shown if the figure 1. The properties like higher strength, lower modulus of elasticity, corrosion resistance, inertness, better biocompatibility and ability to join with bone tissues etc. possessed by the Ti based alloys makes them the ultimate choice for the implant material. [14]

Human bones have much lower modulus (3-30 GPa) as mentioned in table 1. So that the artificial implant must possess lower modulus of elasticity. 316L SS and Cr-Co alloys possesses the young's modulus of 210 GPa and 240 GPa respectively. Whereas the Ti based alloys possesses much lower modulus of elasticity varying from110 GPa to 55 GPa. The most commonly used Ti based alloys are pure Ti and Ti–6Al–4V(also known as Ti64) for the purpose of implant material.

Table 1 : Properties of bone[24]

Bone type	Tensile Strength (MPa)	Compressive Strength (MPa)	Young's Modulus (GPa)
Cortical	60-160	130-180	3-30
Cancellous	N/a	4-12	0.02-0.5

There is a huge scope of Ti and its alloys to be used in medical field. Currently, pure Ti (CP) and some other Ti alloys like Ti6Al4V are in use in the medical field. These applications include various implants like hip, knee, elbow, dental, wrist, spine implant and other orthopedic surgeries. The housing device for the pacemaker is also made of these Ti alloys. [9] [2] [7] For the required strength the pure Ti is not capable to fulfill the requirements. Thus the alloys of Ti are preferred to serve the purpose. Due to its higher strength and low modulus with compared to Co-

Cr alloys and stainless steel alloys Ti-Ta alloy are more suitable porous material. And the porosity helps the implant to be of lower weight and brings the young's modulus down. [13] It is the fact that Ti-6Al-4V was developed for aerospace applications. But its excellent corrosion resistance and biocompatibility brought it to the medical field. Other than the implants the Ti and its alloys are in use for making wheel chairs, artificial limbs etc.

2. Ti-Ta alloys

The formation of Ta_2O_5 film in Ti-Ta alloy adds the strength to the Tio_2 film inside, and thus it results in the improvement of the corrosion resistance. [22] TaO_2 coating on Ti-6Al-4V (Ti64) alloy for hip joint has been described by Rahmati B. et al. [16] in which pure Ta was deposited on Ti-6Al-4V. Corrosion test using Fetal Bovine Serum (FBS) showed that the corrosion resistance of TaO_2 coated Ti64 is considerably improved and wear testing revealed the fact that there is more wear in uncoated one than coated. But, Ti-6Al-4V that is already in use for biomedical applications. The study of Elias C. N. et al. [5] shows that Ti-6Al-4V has higher young's modulus and leads to mismatch with the human bone. Ti-6Al-4V implant (103-120 GPa) and human bone (10-30 GPa) having mismatch in young's modulus leads to implant failure. So, there is a huge requirement of research to obtain the material having lower young's modulus without compromising its strength.

Ti-Ta alloy have the potential for dental applications due to their excellent bio-mechanical properties. In the study of Mareci D. et al. [10] Two-way ANOVA method was used to find the behavior of different Ti alloys for testing the corrosion behavior. All the Ti alloys showed reduction in corrosion resistance and less stable oxide layer in fluoridated acidified saliva. The Ti-Ta alloys have superior corrosion resistance than that of Ti-6Al-7Nb. So it is necessary to research better Ti-Ta alloy composition which can be used for medical application.

Ti-Ta alloys are non-toxic. The wear resistance of Ti-Ta alloy is superior to pure Ti and Ti-6Al-4V alloy. Ti-30% Ta and Ti-70% Ta had much lower modulus and high strength. So, Ti-Ta alloys have great potential to be the implant material. [22]

Human body contains large number of fluids causing chemical reactions and hence it is important to study the reaction of implant material towards those solutions. Implant material must behave normally in all corrosive media as the bones do. Experiments of De Souza K. A. et al. [4] had derived that the micro hardness of Ti-Ta alloys is higher than the pure Ti or Pure Ta. The experiments have also derived that the Ti-20%Ta was active in 80%wt H_2SO_4 solutions at room temperature, where Ti-60%Ta and Ti-80%Ta were passive. Thus, it concludes that the increase in Ta content leads to increase in corrosion resistance

The corrosion test of Ti-30Ta, Ti-40Ta, Ti-50Ta, Ti-60Ta was carried out and compared with commercially used Ti–6Al–7Nb alloy for dental applications. All alloys were tested in artificial saliva with different pH, acid lactic and fluoride contents. [10]

Elastic modulus of Ti-Ta alloy

The elastic modulus of the Ti-Ta alloy is shown in figure 2 which varies as the amount of Ta content varies. It can be seen that the elastic modulus first decreases with increasing Ta content, and reaches a minimum value of 69 GPa at 30% Ta. Then it gradually increases to 88 GPa at 50% Ta, and drops again to another minimum value of 67 GPa at 70% Ta as shown in figure 2. Now the increase in Ta will increase the Young's modulus, closer to that of pure Ta. Thus, elastic modulus varies with Ta content.

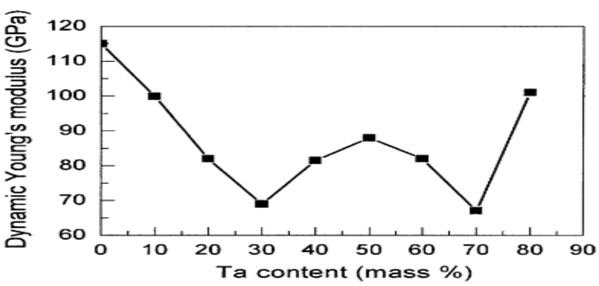

Figure 2 : Elastic Modulus of Ti-Ta alloys [23]

The figure 3 shows the tensile strength, yield strength and elongation at fracture at various compositions of Ti-Ta alloy. [27] Both the tensile strength and yield strength of all Ti-Ta alloys are much higher than those of pure Ti, the tensile strength at 10% Ta is 510 Mpa, and increases as the amount of Ta is increased. The maximum value of tensile strength of 690 MPa is achieved at 60% Ta. Then increase of Ta more than 60% reduces the tensile strength.

This variation in the tensile strength due to change in amount of Ta is a function of its microstructure. As the Ta content varies the microstructure varies and it changes the tensile strength. Highest value can be achieved at 60% of Ta as discussed earlier. As the Ta content increases the elongation at fracture of the Ti-Ta alloy decreases, when the yield strength increases, the ductility accordingly decreases. [27]

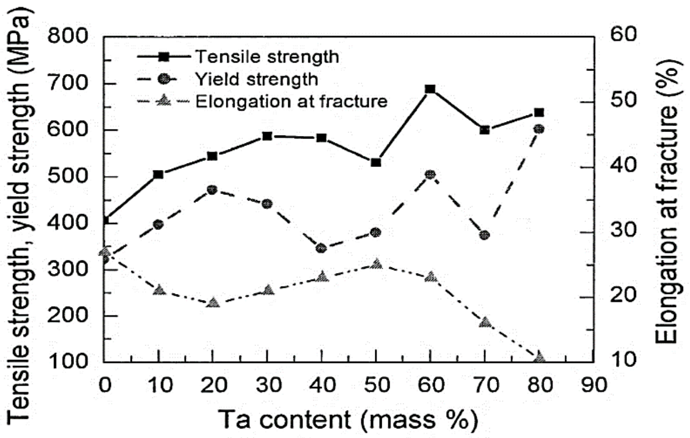

Figure 3 : Variation of tensile properties of pure Ti and Ti-Ta alloys [23]

Superiority of Ta for Ti as an alloying element

That is why the the most preferred alloying element for Ti alloy is Ta. The addition of Ta improves the corrosion resistance and bio compatibility of the implant. It also brings the Young's Modulus of the implant closer to the human bone which makes it acceptable by human body tissues.

Tantalum has a great potential to be an implant material whose mechanical properties closely matches with human bone [19] Mechanical properties of tantalum closely match with the human bones and allowed bone ingrowth. Ti-Ta alloy can produce porous implants which have high resistance to cyclic loading which increase the life of the implant and helps to avoid revision surgery. It also provides better ductility and biocompatibility.

The study of Zhou Y. L. et al. [21] has strengthened the position of Ta as a better alloying element with Ti to enhance the properties which is suitable biomedical implant. In the study of Zhou Y. L. et al. [21] various composition of Ti-Ta had been tested for evaluating Elastic modulus, Tensile strength, Cyto-toxicity and corrosion resistance. They had experimented different tests by varying Ta content in Ti and obtained the composition which suits best for a particular property and concluded that the Ta has great potential to be the alloying element which can improve the property of implant than pure Ti.

Ta is highly resistant to chemical attack. It gives very little adverse biological response. (X medics, http://previous.xmedics.com/tantalum_biocompatibility.htm) [27] Ta remains inert in various body fluids. So Ta can be suggested as fracture repair, dental applications, in repair of cranial defects, as permanent bone implant etc. [3]

Ta content has a strong effect on Young's modulus and tensile properties of binary Ti–Ta alloys as discussed earlier. Ti–30% Ta alloy with martensite α'' phase and Ti–70% Ta alloy with metastable phase have much lower modulus, and a good combination of low modulus and high strength among all the studied Ti–Ta alloys under the given solution treatment. They have the great potential to become new candidates for biomedical applications.

3. Use of Tantalum

Due to inertness in body environment the Tantalum is used for surgical and biomedical applications. The passive oxide layer helps to achieve better corrosion resistance. Furthermore, in the bodily fluids Ta remains inert and has good mechanical properties. Example applications are surgical clips, bone grafts, plates for cranioplasty, mesh for abdominal wall reconstruction and dental implants [3] [8]. Tantalum has been la rgely replaced in prosthetics by titanium, which is sufficiently bio inert and has better mechanical properties for this application. [1]

Among metallic biomaterials, tantalum is gaining more attention as a new biomaterial. Widespread research has been performed on the mechanical properties of porous tantalum demonstrating that this material, despite a low modulus of elasticity and highly porous structure, can withstand physiologic load and support bone ingrowth under this stress. There is speculative benefit of decreased stress shielding, the potential for immediate postoperative weight bearing and a more normal pattern of bone remodeling adjacent to the component. In addition, tantalum is more resistant to corrosion than titanium but it presents high costs of production. [13] .

Due to these excellent properties of high biocompatibility, corrosion resistance and good mechanical properties Tantalum is a valid biomaterial to be added with Ti and its alloys to implant inside the human body. [16]

4. Implant

Materials used for implants must be highly non-toxic and must not cause any inflammatory or allergic reactions in the human body. The success of the biomaterials is mainly depending upon the reaction of the human body to the implant, and this measures the biocompatibility of a material. [20] Two main factors that influence the biocompatibility of a material are the host response induced by the material and the materials degradation in the body environment. Classification of biomaterials based on the response by the human body is given in Table 2. [6]

Classification	Response	Examples	Effect
Biotolerant materials	Formation of thin connective tissue capsules (0.1–10 lm) and the capsule does not adhere to the implant surface	Polymer-poly tetra fluorethylene (PTFE), polymethyl metha acralyte (PMMA), Ti, Co–Cr, etc.	Rejection of the implant leading to failure of the implant
Bioactive materials	Formation of bony tissue around the implant material and strongly integrates with the implant surface	Bioglass, synthetic calcium phosphate including hydroxyl apatite (HAP)	Acceptance of the implant leading to success of implantation
Bioreabsorbable materials	Replaced by the autologous tissue	Polylactic acid and polyglycolic polymers and processed bone grafts, composites of all tissue extracts or proteins and structural support system	Acceptance of the implant leading to success of implantation

Table 2 : Classification of Biomaterials and its effects [6]

Population of aged people are increasing greatly and hence the demand of human body implants are increasing as shown in figure 4. [13] Thus there is a requirement of development of material that can fulfill the demand along with all required characteristics has to be researched and developed

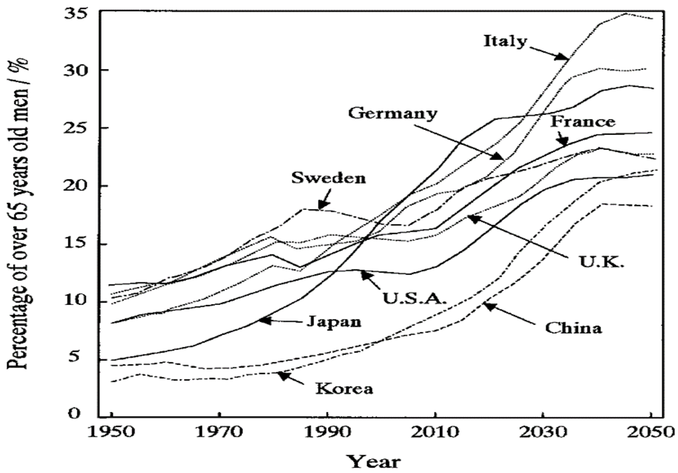

Figure 4 : Change in population of old people in each country. [14]

.5. Materials and Methodology:

The studies have indicated that, among Ti based alloys the Ti-6Al-4V serves the purpose of implant currently. Due to mismatch of Young's modulus with bone the Ti-6Al-4V implants can't provide longer life cycle. In other hand Ti-Ta alloys are providing strong competition to be the first choice for the same as their Young's Modulus is much lower than that of Ti-6Al-4V. Hence, they are not used commercially but they can be compare in terms of the mechanical properties they possess. For the study low modulus Ti-30Ta and Ti-70Ta are selected.

Table 3 Properties of materials

Ti-30Ta [23]			
Sr. No.	**Properties**	**Unit**	**Value**
1.	Young's Modulus	GPa	69
2.	Tensile Strength	MPa	587
3.	Density	g/cm^3	5.71
4.	Possion's Ratio	-	0.35

Ti-70Ta[23]			
Sr. No.	**Properties**	**Unit**	**Value**
1.	Young's Modulus	GPa	67
2.	Tensile Strength	MPa	600
3.	Density	g/cm^3	9.17
4.	Possion's Ratio	-	0.35

Ti-6Al-4V[25]			
Sr. No.	**Properties**	**Unit**	**Value**
1.	Young's Modulus	GPa	114
2.	Tensile Strength	MPa	993
3.	Density	g/cm^3	4.42
4.	Possion's Ratio	-	0.342

6. Tensile Specimen

General tensile specimen of is selected according to ASTM standard E8/E8M is shown in figure. The dimensions are applied according to ASTM standards for subsize specimen. [26]

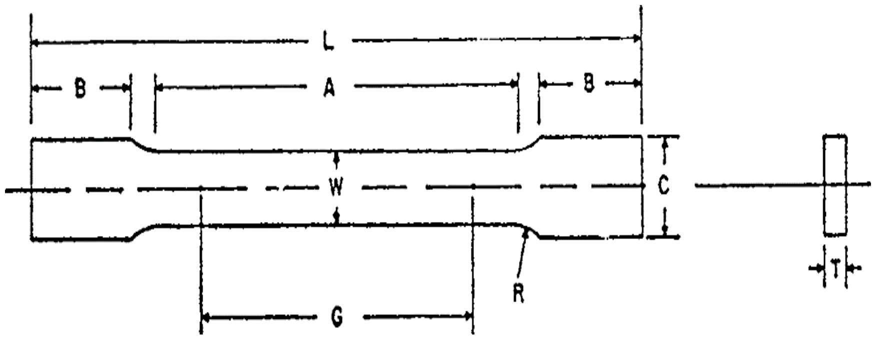

Figure 5 : Standard Tensile Specimen [26]

Table 4: Dimensions of the tensile specimen[26]

Symbol	Dimension (mm)
G- Gage Length	25
W- Width	6
T- Thickness	8
R- Radius of fillet, min	6
L- Overall length, min	100
A- Length of Reduced Section, min	32
B- Length of Grip Section	30
C-Width of Grip Section, Approximate	10

7. Design and Analysis:

The design of the tensile specimen was prepared in Solidworks 16.0. SolidWorks is a solid modelling software which also helps to create assemblies. Solid works is midrange parametric modeling software.

Design is intended according to designer's approach. For example, if a geometry is required to be added on any surface of a cube, regardless of the height the geometry can be drawn in 2D on that particular surface and then could be converted into a 3D object on that surface. The dimensions can be changed later.

The feature based modelling is the beneficial thing for the designer. As the features are the shapes that are the building blocks of the part. They can be used to bulid holes, chamfer, slots etc. The 2-D shape can be extruded, swiped or lofted in order to create the desired 3-D part. See figure 6.

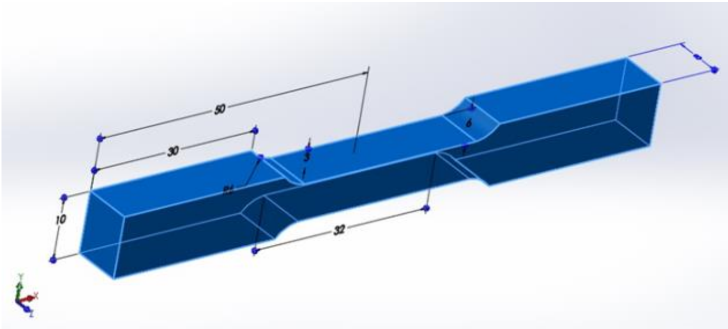

Figure 6 : A 3D tensile specimen model created in Solidworks 16.0

The Finite Element Analysis was performed in Ansys16.0.

Procedure for static analysis in ANSYS

- First of all, open ANSYS 14 work bench and select static structural analysis.
- After opening window of work bench from Engineering data give material Properties, update project, and return project.
- Import geometry in STEP/IGES file format so another window of model will open.
- For analysis we have to mesh the model. Select mesh and then give specification like mesh size, smoothing, method etc. parameters. See figure 7.

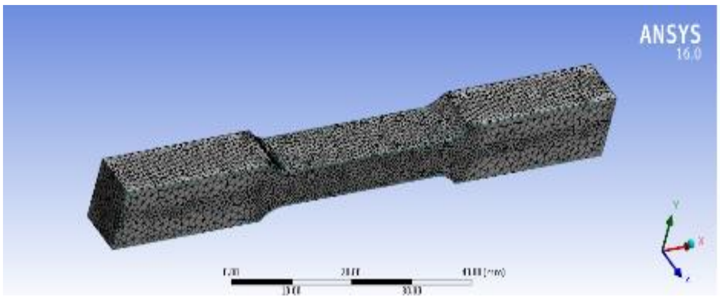

Figure 7 : A 3D meshed model of tensile specimen

- Generate mesh after some time mesh model will be generated. Here the prism type mesh was created as shown in figure 7.

- Give the pressure, force, displacement etc. parameters from Analysis menu give information of force and displacement in x, y, and z direction.
- For final Solution information from left side menu bar give solution information like Von Misses Stress, Von Misses Strain, and Total Deformation etc.
- Run the solver. After some time, Result will be obtained in the form of figure which will give the result.

8.Results and Discussion:

The one side of the specimen was fixed and the load of different potential was applied to the other side in the FEA model in ANSYS. The deformation at the free end can be seen and the values of the stress is obatined. The results of tensile stress and deformation of Ti-6Al-4V, Ti-30Ta and Ti-70Ta were analyzed and the results are given below. The figure 8,9,10,11,12,13 shows the deformation and stress generated at the application of 100kg of load.

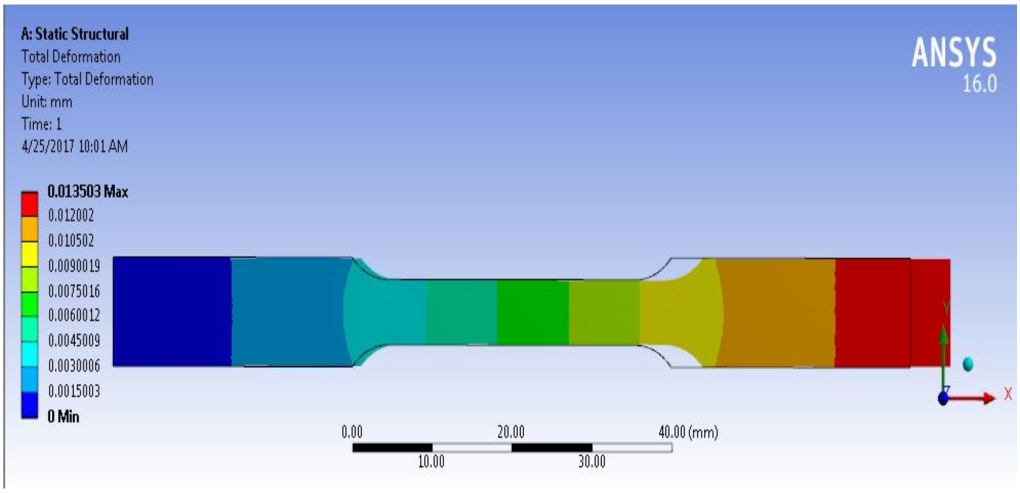

Figure 8 : Deformation at 100kg load in Ti-6Al-4V

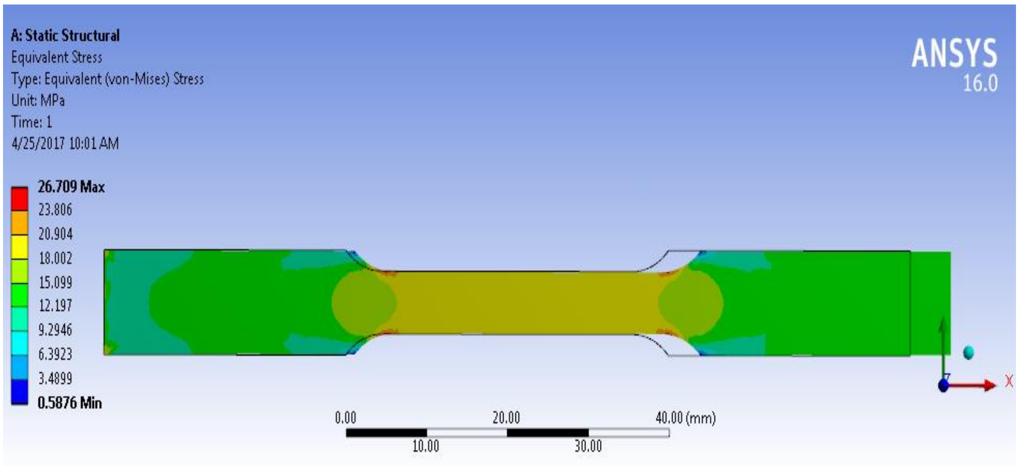

Figure 9 : Stress at 100kg load in Ti-6Al-4V

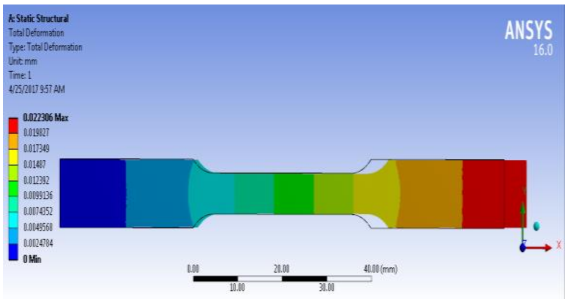

Figure 10 : Deformation at 100kg load in Ti-30Ta

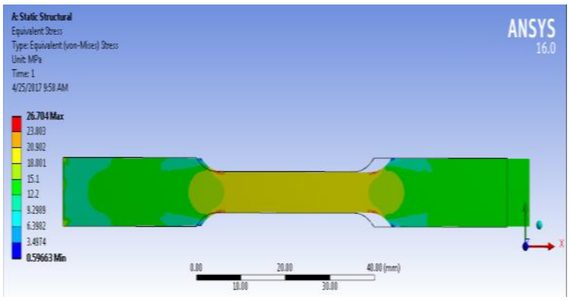

Figure 11 : Stress at 100 kg load in Ti-30Ta

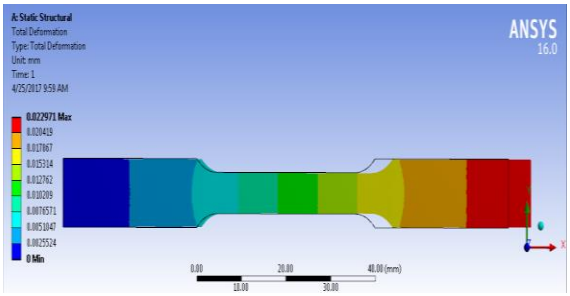

Figure 12 Deformation at 100kg load in Ti-70Ta

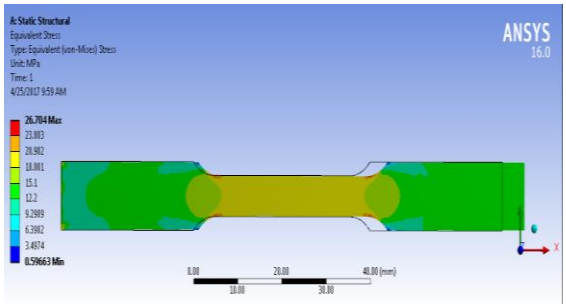

Figure 13 : Stress at 100kg load in Ti-70Ta

The results are shown in the table 5,6 and 7.

Table 5 : Results of Ti-6Al-4V

Paitent weight (kg)	Load (N)	Deformation (µm) Max	Von Mises Stress (MPa) Max
60	588.6	8.09	16.009
70	686.7	9.45	18.75
80	784.8	10.802	21.429
90	882.9	12.15	24.038
100	981	13.50	26.709

Table 6 : Results of Ti-30Ta

Paitent weight (kg)	Load (N)	Deformation (µm) Max	Von Mises Stress (MPa) Max
60	588.6	13.37	16.006
70	686.7	15.614	18.88
80	784.8	17.844	21.597
90	882.9	20.07	24.296
100	981	22.30	26.704

Table 7 : Results of Ti-70Ta

Paitent weight (kg)	Load (N)	Deformation (μm) Max	Von Mises Stress (MPa) Max
60	588.6	13.76	16.006
70	686.7	16.08	18.897
80	784.8	18.37	19.304
90	882.9	20.67	27.717
100	981	22.97	26.704

From the results it can be clearly seen that there is a very less difference in stress generated in all of these 3 materials. The results show that the Ti-6Al-4V performs slightly better in terms of deformation. But the stress produced in all the three material is nearly same. Hence due to its lower young's modulus the Ti-30Ta and Ti-70Ta will be more effective implant material in terms of stress shielding and the life of implant.

Due to the inertness in the bodily fluid, the better wear and corrosion resistance have been the highlights of the Ti based alloys. But the Ti-Ta alloys offer lower Young's modulus which was the limitation of the currently used Ti-6Al-4V. So, this study will strengthen the position of Ti-Ta alloys to be the choice for the implant material.

9. Conclusion

The human body implants are vital to one who has lost it in an accident or due to natural defect. Artificial implants have to bear the loads applied on it as the natural ones do. Implants must be biocompatible and must not react with body fluids. They must possess properties like corrosion resistance, wear resistance, modulus of elasticity, tensile strength, non-cytotoxicity etc. The past studies indicate that Titanium and its alloys are mostly used metallic materials for implants due to its compatibility to human bones. But still few properties can improve and make the implant more suitable to human body tissues. The mechanical properties and biocompatibility can be improved by adding Tantalum into pure Titanium. Ti-Ta alloy offer overall better performance than pure Ti, pure Ta or its alloy.

This study has shown how the tensile properties of Ti-Ta alloys closely matches with that of Ti-6Al-4V. The big advantage of Ti-Ta alloy is its low Young's modulus which can help to reduce the stress shielding resulting in good implant joining with the human bone and improved life of the implant.

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