A COMPARATIVE STUDY ON TRIBOLOGICAL BEHAVIOUR OF BIOMATERIALS USED IN MEDICAL IMPLANTATION

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Abstract - One of the major health issues that people will be facing in the coming years is osteoarthritis. This affects mainly the knee joint and hip joint which requires replacement surgeries with an artificial bio-implant material. The focus of this study is on the comparison of tribological behaviour of knee implant materials using pin on plate testing. The materials selected are Ti-6Al-4V, Cobalt Chromium Molybdenum (CoCrMo) alloy, Zirconia Toughened Alumina (ZTA) and Ultra High Molecular Weight Poly Ethylene (UHMWPE). An analytical approach is also carried out using Ansys on a knee implant design.

Keywords: Osteoarthritis, Tribological, Bio-implant, CoCrMo, UHMWPE, Ti-6Al-4V, ZTA

1. INTRODUCTION

Knee replacement, which is also called knee arthroplasty, is a surgical procedure that is carried out to replace the damaged parts of the knee. The replacement of different parts of the knee is done by using a biomaterial, which can be a metallic or plastic part. A biomaterial is a material that can interact with human tissue and body fluids to treat, improve, or replace damaged tissues or biological functions of the human body. Biomaterials are classified into four based on material: Metals and metallic alloys, ceramics, polymers and natural materials. It should possess some important properties which include:

- Biocompatibility
- Resistance to Implant Wear and Aseptic Loosening
- Corrosion Resistance
- Long fatigue life
- Adequate Strength
- Modulus equivalent to that of bone
- Osseointegration

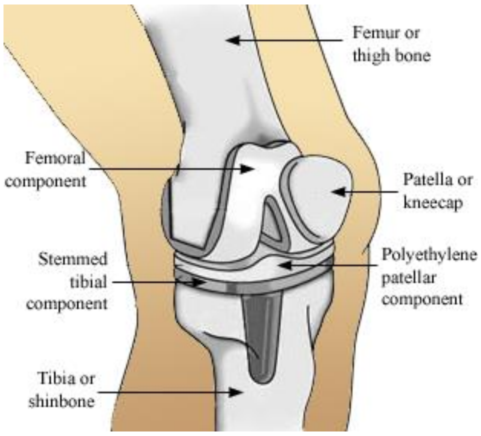

Fig 1: A knee implant attached in a human knee

There are basically four different parts that constitute a knee implant:

- Tibial component: Attached to the tibia bone and is made of softer metals.
- Femoral component: Attached to the femoral bone and is made of more durable metals.
- Patellar component: Used to replicate the kneecap and is mostly made of polyethylene.
- Plastic spacer: Used to provide smooth rubbing surface between tibial and femoral components. It is mainly made of polyethylene.

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2. EXPERIMENTATION AND RESULTS

2.1. Tribometer Test

The tribological behaviour are carried out for the following material combinations: CoCrMo on UHMWPE, ZTA on UHMWPE, Ti6Al4V on UHMWPE, ZTA on Ti6Al4V, CoCrMo on Ti6Al4V, Ti6Al4V on Ti6Al4V, CoCrMo on ZTA, ZTA on ZTA, Ti6Al4V on ZTA.

The Pin diameter is 6mm and length is 15mm

The Plate dimension is 40mm length x 40mm width x 5 mm thickness

Fig 2: ZTA plate

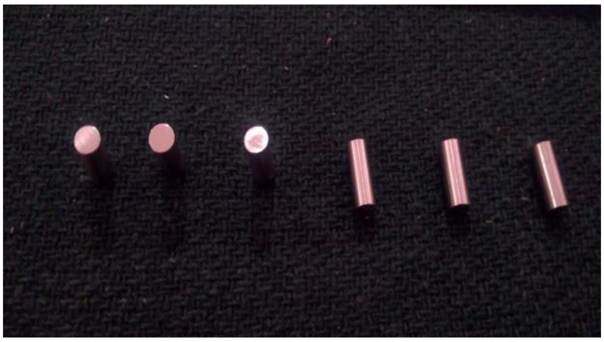

Fig 3: CoCrMo pin

Parameters for experimentation:

Load: 20 N
Temperature: 37°c
Stroke: 5mm
Frequency: 7 Hz
Number of Cycles: 50000 cycles
Test Time (sec) = Number of cycles / Frequency

= 50000/7
= 7142.85 ≈ 7200 seconds
= 120 minutes = 2 hours

2.2. Ansys Analysis

A design of a knee implant is made using Ansys workbench 2021 (Fig 4). In the engineering data of static structural, the materials that are selected for the experiment are either selected from the library or entered into it.

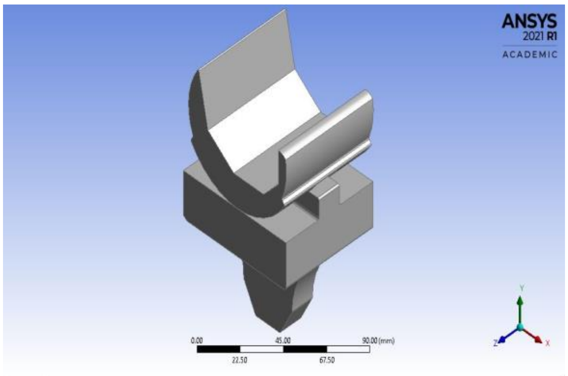

Fig 4: Knee implant model

Certain constraints are applied on the implant so as to simulate some real life conditions (Fig 5). The femoral component is subjected to a downward force of 4500 N while keeping the base of the tibial component as a fixed support. A rotational velocity of 2 radians/second or 114 degrees/second is given to the femoral component which represents the bending of the knee during any activity. In addition to these forces, the implant is also subjected to standard earth gravity of 9.8 m/s^2.

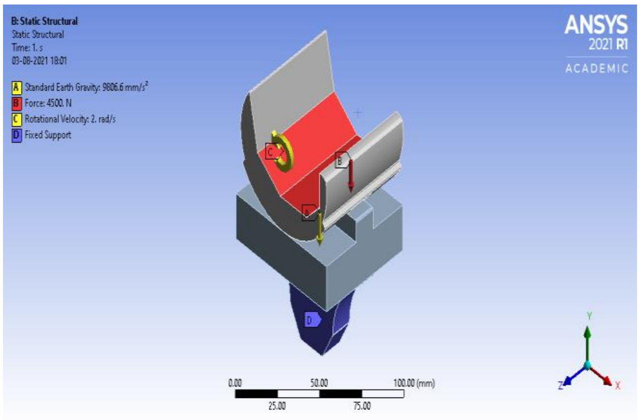

Fig 5: Constraints applied on knee implant in Ansys

The knee implant model is analysed using static structural. The method of meshing used is tetrahedron meshing. It divided the model into 56472 elements and there were 94095 nodes. The constraints that were mentioned earlier are applied onto the model at this stage and a contact region is defined between the bottom face of the femoral component and the top face of the tibial component. The analysis is carried out to find the values of total deformation, shear stress and maximum shear elastic strain, which are major factors in deciding the durability of the implant.

2.3. Ansys results

By using Ansys, the 16 different material combinations are analysed to determine the maximum deformation, maximum shear stress and the maximum shear elastic strain in the presence of the applied constraints. In the material combinations listed in table 1, the first material in each case represents the femoral component and the second material represents the tibial component, i.e. taking the example of the 2^{nd} combination of CoCrMo on Ti-6Al-4V, the femoral component is CoCrMo and the tibial component is Ti-6Al-4V.

From table 1, it can be observed that minimum deformation of 0.0050765 mm occurs in the case of ZTA on ZTA. This low deformation can be justified due to the properties of high fracture toughness, high flexural strength and great wear resistance. ZTA also possesses very high hardness which can reach values near 1900 HV. CoCrMo, which has the highest wear resistance among metals, shows low values of deformation as well. UHMWPE shows the highest deformation because this material has lower hardness, compressive strength and certain other mechanical properties as compared to the other materials used in this study. However, UHMWPE is not commonly used to make an entire femoral or tibial component. Instead, it is used as an excellent implant bearing surface material to reduce the wear.

On comparing the values of maximum shear stress, the lowest value of 5.9436 MPa corresponds to ZTA on ZTA which highlights the superior mechanical properties of ZTA in comparison to the other materials. Higher values of stress are observed whenever UHMWPE is subjected to forces from the other materials like CoCrMo and ZTA.

From the values of maximum shear elastic strain, we can observe that ZTA on ZTA shows the lowest value of 0.000093108 among all the combinations and UHMWPE shows the higher values of shear elastic strain.

Table 1: Values obtained through Ansys analysis

Material Combination	Maximum Deformation (mm)	Maximum shear stress (MPa)	Maximum shear elastic strain
CoCrMo on CoCrMo	0.0077111	6.0305	0.00014383
CoCrMo on Ti-6Al-4V	0.01072	6.0836	0.00014638
CoCrMo on ZTA	0.007026	6.007	0.0001418
CoCrMo on UHMWPE	0.3691	15.663	0.017865
Ti-6Al-4V on CoCrMo	0.01467	6.0872	0.00023994
Ti-6Al-4V on Ti-6Al-4V	0.017001	6.1234	0.00024388
Ti-6Al-4V on ZTA	0.013955	6.0733	0.00023917
Ti-6Al-4V on UHMWPE	0.48666	6.7754	0.017744
ZTA on CoCrMo	0.0057323	5.9742	0.000094601
ZTA on Ti-6Al-4V	0.0085971	6.0415	0.00014821

ZTA on ZTA	0.0050765	5.9436	0.000093108
ZTA on UHMWPE	0.36687	16.151	0.017835
UHMWPE on CoCrMo	1.2741	6.292	0.036695
UHMWPE on Ti-6Al-4V	1.3652	6.2874	0.031012
UHMWPE on ZTA	1.2733	6.2918	0.036721
UHMWPE on UHMWPE	1.7337	6.398	0.035106

2.4. Tribometer test results

During the tribometer test, for each material combination, the experiment was carried out for a duration of 2 hours. The weight readings of the pin and plate specimens in grams are taken before and after the experiment. The wear rate of the specimens in m^3/ min can be then calculated using the formula

$$\text{Wear rate} = \frac{(Final\ Weight - Initial\ Weight) \times 1.17 \times 10^{-6}}{120}$$

$$(1\ g = 1.17\ \times 10^{-6}\ m^3)$$

2.4.1. CoCrMo alloy on Ti-6Al-4V alloy

Table 3: Wear rate of CoCrMo pin on Ti-6Al-4V plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
CoCrMo pin	3.4632	3.4626	5.85×10^{-12}	1.0235×10^{-11}
Ti-6Al-4V plate	27.1947	27.1932	1.462×10^{-11}	

The wear rates of the CoCrMo pin and the Ti-6Al-4V plate are 5.85×10^{-12} m^3/ min and $1.462 \times 10^{-11} m^3$/ min respectively. The wear rate of the plate is higher than that of the pin.

2.4.2. CoCrMo alloy on Zirconia Toughened Alumina

Table 4: Wear rate of CoCrMo pin on ZTA plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
CoCrMo pin	3.4646	3.4636	9.78×10^{-12}	5.868×10^{-12}
ZTA plate	31.9298	31.9296	1.956×10^{-12}	

The wear rates of the CoCrMo pin and the ZTA plate are $9.78 \times 10^{-12} m^3$/ min and $1.956 \times 10^{-12} m^3$/ min respectively. The wear rate of the pin is higher than that of the plate.

2.4.3. CoCrMo alloy on Ultra High Molecular Weight Polyethylene

Table 5: Wear rate of CoCrMo pin on UHMWPE plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
CoCrMo pin	3.4552	3.4548	3.9×10^{-12}	3.4125×10^{-12}
UHMWPE plate	7.7391	7.7381	2.925×10^{-12}	

The wear rates of the CoCrMo pin and the UHMWE plate are 3.9×10^{-12} m^3/ min and 2.925×10^{-12} m^3/ min respectively. The wear rate of the pin is higher than that of the plate.

2.4.4. Ti-6Al-4V alloy on Ti-6Al-4V alloy

Table 6: Wear rate of Ti-6Al-4V pin on Ti-6Al-4V plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
Ti-6Al-4V pin	2.1252	2.124	1.17×10^{-11}	9.75×10^{-12}
Ti-6Al-4V plate	26.9793	26.9785	7.8×10^{-12}	

The wear rates of the Ti-6Al-4V pin and the Ti-6Al-4V plate are 1.17×10^{-11} m^3/ min and 7.8×10^{-12} m^3/ min respectively. The wear rate of the pin is higher than that of the plate.

2.4.5. Ti-6Al-4V alloy on Zirconia Toughened Alumina

Table 7: Wear rate of Ti-6Al-4V pin on ZTA plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
Ti-6Al-4V pin	2.159	2.148	1.0725×10^{-10}	5.46×10^{-11}
ZTA plate	31.9187	31.9185	1.95×10^{-12}	

The wear rates of the Ti-6Al-4V pin and the ZTA plate are 1.0725×10^{-10} m^3/ min and 1.95×10^{-12} m^3/ min respectively. The wear rate of the pin is higher than that of the plate.

2.4.6. Ti-6Al-4V alloy on Ultra High Molecular Weight Polyethylene

Table 8: Wear rate of Ti-6Al-4V pin on UHMWPE plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
Ti-6Al-4V pin	2.1025	2.1021	3.9×10^{-12}	3.4125×10^{-12}
UHMWPE plate	7.8443	7.844	2.925×10^{-12}	

The wear rates of the Ti-6Al-4V pin and the UHMWPE plate are 3.9×10^{-12} m^3/ min and 2.925×10^{-12} m^3/ min respectively. The wear rate of the pin is higher than that of the plate.

2.4.7. Zirconia Toughened Alumina on Zirconia Toughened Alumina

Table 9: Wear rate of ZTA pin on ZTA plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
ZTA pin	1.778	1.7777	2.925×10^{-12}	2.4375×10^{-12}
ZTA plate	31.9098	31.9096	1.95×10^{-12}	

The wear rates of the ZTA pin and the ZTA plate are 2.925 × 10^{-12} m^3/ min and 1.95× 10^{-12} m^3/ min respectively. The wear rate of the pin is higher than that of the plate.

2.4.8. Zirconia Toughened Alumina on Ti-6Al-4V alloy

Table 10: Wear rate of ZTA pin on Ti-6Al-4V plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
ZTA pin	1.7785	1.7781	3.9 × 10^{-12}	1.0725 × 10^{-11}
Ti-6Al-4V plate	27.1928	27.191	1.755 × 10^{-11}	

The wear rates of the ZTA pin and the Ti-6Al-4V plate are 3.9 × $10^{-12}$$m^3$/ min and 1.755 × $10^{-11}$$m^3$/ min respectively. The wear rate of the plate is higher than that of the pin.

2.4.9. Zirconia Toughened Alumina on Ultra High Molecular Weight Polyethylene

Table 11: Wear rate of ZTA pin on UHMWPE plate

Sample Specimen	Initial Weight (g)	Final Weight (g)	Wear Rate (m^3/ min)	Average Wear Rate (m^3/ min)
ZTA pin	1.791	1.7908	1.95 × 10^{-12}	5.85 × 10^{-12}
UHMWPE plate	7.7391	7.7381	9.75 × 10^{-12}	

The wear rates of the ZTA pin and the UHMWPE plate are 1.95 × 10^{-12} m^3/ min and 9.75 × 10^{-12} m^3/ min respectively. The wear rate of the plate is higher than that of the pin.

2.4.10. Graphical representation of frictional force and coefficient of friction

In addition to the wear rates, we also obtain the graphs of frictional force and the coefficient of friction for each material combination. The consolidated graph for each material combination is shown below.

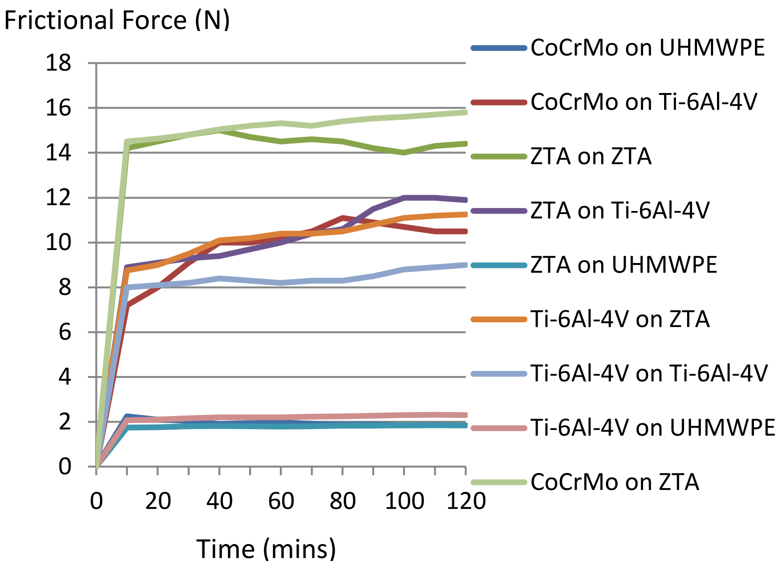

Fig 9: Plots of Frictional Force

From the consolidated graph shown above, we can observe that the highest frictional force occurs in the case of CoCrMo pin on ZTA plate. The highest value of frictional force obtained for this combination was 15.8 N at the end of the experiment.

The lowest value of frictional force was obtained for the combination of ZTA pin on UHMWPE plate. The highest value obtained for this combination was 1.85 N.

The highest value of frictional force obtained for all the material combinations during the experiment is listed below:

- CoCrMo pin on UHMWPE plate – 2.24 N
- CoCrMo pin on Ti-6Al-4V plate – 11.1 N

- ZTA pin on ZTA plate – 15 N
- ZTA pin on Ti-6Al-4V plate – 12 N
- ZTA pin on UHMWPE plate – 1.85 N
- Ti-6Al-4V pin on ZTA plate – 11.25 N
- Ti-6Al-4V pin on Ti-6Al-4V plate – 9 N
- Ti-6Al-4V pin on UHMWPE plate – 2.32 N
- CoCrMo pin on ZTA plate – 15.8 N

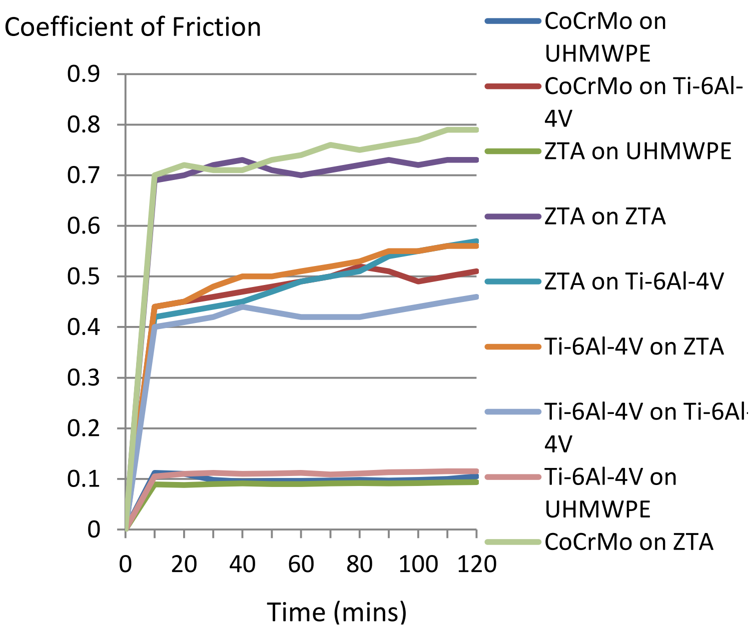

Fig 10: Plots of Coefficient of Friction

From the consolidated graph of coefficient of friction shown above, we can observe that the highest coefficient of friction occurs in the case of CoCrMo pin on ZTA plate. The highest value of coefficient of friction obtained for this combination was 0.79 at the end of the experiment.

The lowest value of coefficient of friction was obtained for the combination of ZTA pin on UHMWPE plate. The highest value obtained for this combination was 0.094.

The highest value of coefficient of friction obtained for all the material combinations during the experiment is listed below:

- CoCrMo pin on UHMWPE plate – 0.112
- CoCrMo pin on Ti-6Al-4V plate – 0.52
- ZTA pin on ZTA plate – 0.73
- ZTA pin on Ti-6Al-4V plate – 0.57
- ZTA pin on UHMWPE plate – 0.094
- Ti-6Al-4V pin on ZTA plate – 0.56
- Ti-6Al-4V pin on Ti-6Al-4V plate – 0.46
- Ti-6Al-4V pin on UHMWPE plate – 0.115
- CoCrMo pin on ZTA plate – 0.79

3. CONCLUSIONS

- From the table obtained from Ansys results, it can be observed that the cobination of ZTA on ZTA shows the lowest values of maximum deformation, maximum shear stress and maximum shear elastic strain as compared to the other material combinations.
- Upon comparing the results obtained from the tribometer test, it was observed that ZTA pin on ZTA plate material combination showed the lowest wear rate whereas Ti-6Al-4V pin on ZTA plate showed the highest wear rate.
- The highest values for frictional force and coefficient of friction were shown by the combination of CoCrMo pin on ZTA plate.
- The lowest values for frictional force and coefficient of friction were shown by the combination of ZTA pin on UHMWPE plate.
- On analysing all the results obtained, it is evident that ZTA pin on ZTA plate combination exhibits excellent wear and deformation characteristics. Therefore, it can be concluded that the ZTA pin on ZTA plate combination offers better tribological

properties than the other material combinations analysed in this study.

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