CHAPTER 5

MODELING AND ANALYSIS

5.1 INTRODUCTION TO FEA

In recent years, Finite element analysis (FEA) is a common place to solve very complicated stress problems for obtaining numerical solutions. The introductory treatments of mechanics of materials are an important FEA method and their modules outline its principal features. While using the similar methods, the disadvantage of system solutions is to be kept in mind. The stresses influenced by process variables such as geometrical features, material properties and their errors in input data may produce incorrect results, which are not reviewed necessarily and they are resolved by analysis. Sharpening the designer perception is the important function of theoretical modeling and the experimental analysis is closed related with computer simulation by making strategy plan with finite element codes.

5.1.1 Pre-Processing

Develop a model of the part whose geometry is divided into a number of discrete elements, sub regions, connected at discrete points called nodes. Nodes have prescribed loads and certain of these nodes may also have fixed displacements. Preparing the models is extremely consuming time and the commercial codes strive with one another to have the most accessible graphical pre-processor to contribute in this rather tedious task. In existing CAD, file meshing of elements is to be done for finite element analysis as conveniently as part of the computer drafting -and- design process.
5.1.2 Analysis

Linear or nonlinear algebraic equation of the given system is solved by assuming ‘u’ as displacement and ‘f’ as frequency applied at the nodal points and also enter the finite element code prepared by the pre-processor. Based on the type of problem, ‘K’ matrix is formed and the module of the system may outline the truss approach and linear elastic stress analysis. Nowadays, a wide range of problems with typical elements are solved by using commercial codes with very large number of element libraries. The most important advantages of FEA method is different types of problem can be solved using same code and simply identifying the appropriate type of element from the library.

5.1.3 Post Processing

Nowadays, the visualizing result in graphical display using modern codes is to avoid the important trends and hot spots. Whereas in last decades, the users give more concentration on code generation and identifying the displacements, stresses at distinct positions in the model. A distinctive postprocessor exhibit overlay contours demonstrating stress levels on the model, displaying a full-field picture similar to photo elastic experimental results. The operation of a precise code is usually comprehensive in the documentation associated with the software, and vendors’ needs workshops or training sessions are used to learn the complexities of code operation.

5.2 METHODOLOGY

- Open the ANSYS
- Describe the element type
- Select the material properties
5.3 RULE OF MIXTURES

For analyzing the samples, the properties of materials are calculated to each and every sample, by using rule of mixture. Composite rigidity can be anticipated using a micro-mechanics method termed as rule of mixtures.

5.3.1 Assumptions

1. Dispersed material phase are uniformly distributed over the matrix.
2. Perfect bonding strength between matrix and the dispersed phase
3. Matrix and its composites are free of void.
4. Applied loads are either parallel or normal to the direction of dispersed material phase.
5. Lamina is primarily in stress-free state i.e., no residual stresses.
6. Matrix and its dispersed material phases behave as linearly elastic materials.
7. Composite material has equal strain as $\varepsilon_c = \varepsilon_1 = \varepsilon_2$. 
Convert dispersed phase weight fraction of composite to dispersed phase volume fraction by using the relation as

\[ V_2 = \frac{W_2}{\rho_2} = \frac{W_2}{\rho_2} \times \frac{W_1}{\rho_1} \]

The properties of the samples were calculated and tabulated in Table 5.1 as

- **Volume fraction**  \( V_1 = 1 - V_2 \)
- **Density**  \( \rho = \rho_1 v_1 + \rho_2 v_2 \)
- **Poisson’s ratio**  \( \mu = \mu_1 v_1 + \mu_2 v_2 \)
- **Young’s modulus**  \( E = E_1 v_1 + E_2 v_2 \)

Where,

- \( V_1 \) - volume fraction for matrix
- \( V_2 \) - volume fraction for dispersed phase
- \( E_1 \) - young’s modulus for matrix
- \( E_2 \) - young’s modulus for dispersed phase
- \( \rho_1 \) - density for matrix
- \( \rho_2 \) - density for dispersed phase
Table 5.1 Properties of modeling samples on FEA

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density in Kg/mm$^3$</td>
<td>1246</td>
<td>1296.5</td>
<td>1373.7</td>
<td>1250</td>
<td>1305</td>
<td>1385</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.498</td>
<td>0.495</td>
<td>0.492</td>
<td>0.497</td>
<td>0.494</td>
<td>0.49</td>
</tr>
<tr>
<td>Young’s modulus in N/mm$^2$</td>
<td>4300</td>
<td>6680</td>
<td>14200</td>
<td>4700</td>
<td>7500</td>
<td>15255</td>
</tr>
<tr>
<td>Coefficient of thermal expansion in 10$^{-6}$/°C</td>
<td>28.9</td>
<td>24.63</td>
<td>15.98</td>
<td>27.47</td>
<td>21.89</td>
<td>15.6</td>
</tr>
</tbody>
</table>

5.4 PU / MoS$_2$ COMPOSITES

5.4.1 Tensile Analysis (MPa)

The tensile strength of the samples was calculated by using ANSYS software, in which the selected element type was solid 8node 185 and entered the material properties as already calculated using the rule of mixture. Then created a model of specified specimen size applying the mesh and selected the boundary condition.

Figure 5.1 Tensile stress of PU/MoS$_2$ (93/7)
The load was applied on the specified nodes and the solution was plotted. The tensile property of the sample 1 was observed as maximum tensile stress was 18.0 MPa and minimum tensile stress was 4.56 MPa, as shown in Figure 5.1.

Figure 5.2 Tensile strain of PU/MoS$_2$ (93/7)

Figure 5.3 Tensile stress of PU/MoS$_2$ (90/10)
Figure 5.4 Tensile strain of PU/MoS$_2$ (90/10)

For sample 2, the maximum tensile stress was 18.3 MPa and minimum tensile stress was 5.26 MPa as shown in Figure 5.3. Whereas, for sample 3, the maximum tensile stress was 19.3 MPa and minimum tensile stress was 5.52 MPa as also shown in Figure 5.5.

Figure 5.5 Tensile stress of PU/MoS$_2$ (80/20)
Similarly, the tensile strain values were also plotted and shown in Figures 5.2, 5.4 and 5.6 for the samples 1, 2 and 3 respectively.

![Figure 5.6 Tensile strain of PU/MoS\textsubscript{2} (80/20)]

Table 5.2 Tensile stress analysis of samples 1, 2 and 3.

<table>
<thead>
<tr>
<th>Stress in MPa</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Tensile Stress</td>
<td>18.00</td>
<td>18.30</td>
<td>19.30</td>
</tr>
<tr>
<td>Minimum Tensile Stress</td>
<td>4.56</td>
<td>5.26</td>
<td>5.52</td>
</tr>
</tbody>
</table>

For samples 1, 2 and 3 maximum and minimum tensile strength were calculated and tabulated in Table 5.2. From Table 5.2, it was found that, the tensile strength for sample 1 was lesser than the other sample 2 and 3. The sample 3 had higher tensile strength than the samples 1 and 2, whereas, in general, it was observed that the tensile stress of the sample increased with the increase in composition of molybdenum disulphide particles with
polyurethane matrix. Thus, sample 3 having 20% molybdenum disulphide in the matrix had maximum tensile strength.

5.4.2 Compressive Analysis (MPa)

The compressive strength of the sample was calculated by using ANSYS software, in which the selected element type was solid 8node 185 and entered the properties of material as already calculated by using the rule of mixture. Then created a model of specified specimen size for the samples, applied the mesh and selected the degrees of freedom. The loads were applied on the specified nodes and the solution was plotted. The compressive property of the sample 1 was observed as maximum compressive stress was 47.50 MPa and minimum tensile stress was 19.30 MPa as shown in Figure 5.7.

Figure 5.7 Compressive stress of PU/MoS$_2$ (93/7)

For sample 2, the maximum compressive stress was 50.1 MPa and minimum compressive stress was 20.30 MPa as shown in Figure 5.9.
Whereas, for sample 3, the maximum compressive stress was 51.90 MPa and minimum compressive stress was 21 MPa as shown in Figure 5.11.

Figure 5.8 Compressive strain of PU/MoS$_2$ (93/7)

Figure 5.9 Compressive stress of PU/MoS$_2$ (90/10)
Similarly, the compressive strain images were also shown in Figures 5.8, 5.10 and 5.12 for the samples 1, 2 and 3 respectively and strain values were observed for the samples.

Figure 5.10 Compressive strain of PU/MoS$_2$ (90/10)

Figure 5.11 Compressive stress of PU/MoS$_2$ (80/20)
Figure 5.12 Compressive strain of PU/MoS$_2$ (80/20)

Table 5.3 Compressive stress analysis of samples 1, 2 and 3

<table>
<thead>
<tr>
<th>Stress in M Pa</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Compressive Stress</td>
<td>47.50</td>
<td>50.10</td>
<td>51.90</td>
</tr>
<tr>
<td>Minimum Compressive Stress</td>
<td>19.30</td>
<td>20.30</td>
<td>21.00</td>
</tr>
</tbody>
</table>

For samples 1, 2 and 3 maximum and minimum compressive stress was calculated and tabulated in Table 5.3. From the Table 5.3, it was found that the compressive stress for sample 2 was lesser than the sample 3 and greater than the sample 1. In general, it was observed that the compressive stress of the sample increased with the increase in composition of
molybdenum disulphide particles with polyurethane matrix. Thus, sample 3 having 20% molybdenum disulphide in the matrix had maximum compressive stress.

5.4.3 Impact Analysis (MPa)

In ANSYS software, the impact properties of the samples 1, 2 and 3 were calculated by selecting the element as structural beam - 2D- elastic and the material properties of the samples were entered which were calculated by using rule of mixtures. Model of the sample of specified size by identifying the nodes on the element and selecting the transient analysis with damping effect was created. By known degrees of freedom, applied the load on nodes of the element and plotted the results. The impact stress, impact strain and their deformation of various samples 1, 2 and 3 were plot in figures.

In Figure 5.13, the impact stress for sample 1 was shown having the maximum impact stress as 196.05 MPa and minimum impact stress as 18.49 MPa.

Figure 5.13 Impact stress of PU/MoS$_2$ (93/7)
Similarly the impact strain values were shown in Figure 5.14, the maximum impact strain was 0.48 and the minimum strain was 0.11. The deformation for sample 1 was 4.09mm as shown in Figure 5.15. The impact stress for sample 1 was lesser than the sample 2 and 3, due to agglomeration of MoS$_2$ in matrix.

Figure 5.14 Impact strain of PU/MoS$_2$ (93/7)

Figure 5.15 Deformed shape of PU/MoS$_2$ (93/7)
Figure 5.16 Impact stress of PU/MoS$_2$ (90/10)

Figure 5.17 Impact strain of PU/MoS$_2$ (90/10)
Figure 5.18 Deformed shape of PU/MoS$_2$ (90/10)

Figure 5.19 Impact stress of PU/MoS$_2$ (80/20)
Figure 5.20 Impact strain of PU/MoS$_2$ (80/20)

Figure 5.21 Deformed shape of PU/MoS$_2$ (80/20)
Table 5.4 Impact analysis of samples 1, 2 and 3.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum stress in MPa</td>
<td>196.05</td>
<td>203.00</td>
<td>204.20</td>
</tr>
<tr>
<td>Minimum stress in MPa</td>
<td>18.49</td>
<td>25.57</td>
<td>23.30</td>
</tr>
<tr>
<td>Maximum strain</td>
<td>0.048</td>
<td>0.031</td>
<td>0.015</td>
</tr>
<tr>
<td>Minimum strain</td>
<td>0.011</td>
<td>0.007</td>
<td>0.003</td>
</tr>
<tr>
<td>Deflection (mm)</td>
<td>4.091</td>
<td>2.941</td>
<td>1.445</td>
</tr>
</tbody>
</table>

Properties such as maximum stress, strain, minimum stress, strain and its deflection for all the three samples were observed from ANSYS output as shown in Figures from 5.13 to 5.21 and it was tabulated in Table 5.4. From Table 5.4, it was suggested that the sample 3 had maximum impact stress than other samples 1 and 2. Thus, the increase in composition of molybdenum disulphide particles with the polyurethane matrix increased the impact stress values. But the minimum stress values were higher for sample 2 than other samples 1 and 3.

Similarly, the impact strain was maximum to sample 1 and minimum to sample 3, which indicated that less content of molybdenum disulphide was not able to resist the impact load which acted on it. Whereas, with the increase in the molybdenum disulphide content in the polyurethane matrix, decreased the strain values of both maximum and minimum strain for the samples 1, 2 and 3. Thus, it was understood that the addition of molybdenum disulphide with polymer matrix reduced the strain values. The deflection for samples had also reduced with the increases of composition of additives in the matrix. Hence, the sample 3 had lesser deflection than the others.
other samples 1 and 2 as indicated in the Table 5.4 and their values were observed from Figures 5.21, 5.15 and 5.18 respectively.

5.4.4 Fracture Analysis (KJ/m²)

The fracture toughness was calculated for varying crack length such as 10, 21, 23, 25 and 30 mm of different specimens on each sample by using ANSYS software, in which the selected element type was solid 8node 185. The material properties were calculated by using the rule of mixture and then entered value of their properties. A model of specified specimen size having definite crack length was designed and then applied the mesh, by selecting the degrees of freedom. The load was applied on the specified nodes and the solution was plotted. From the nodal solution, the maximum yield stress was equal to the fracture stress of the specimen and its value was identified and tabulated.

Figure 5.22 10mm Crack length of PU/MoS₂ (93/7)
The maximum and minimum stress value was $1.187$ and $-1.543 \text{KJ/m}^2$ for the crack length of 10mm as shown in Figure 5.22. Similarly, the maximum and minimum strain values were $0.628 \times 10^{-4}$ and $-0.428 \times 10^{-5}$, whose maximum deflection was $0.002481 \text{mm}$.

![Figure 5.23 21mm Crack length of PU/MoS$_2$ (93/7)](image1)

![Figure 5.24 23mm Crack length of PU/MoS$_2$ (93/7)](image2)
Figure 5.23 shows the maximum and minimum stress value as 3.513 and -2.367 KJ/m$^2$ for the crack length of 21mm to sample1 specimen and its maximum deflection was observed as 0.003652 mm.

For the crack length of 23mm to sample 1 specimen, the maximum and minimum stress values were 2.778 and -2.346 KJ/m$^2$ as shown in Figure 5.24. The maximum and minimum strain values were observed as .894E-04 and -.116E-04, whereas, a maximum deflection of the specimen was .004314 mm.

Figure 5.25 25mm Crack length of PU/MoS$_2$ (93/7)

Figure 5.25 shows the maximum and minimum stress values as 3.927 and -2.389 KJ/m$^2$ for the crack length of 25mm specimen and its maximum deflection as .004524 mm. Their maximum and minimum strain values were .915E-04 and -.810E-05.

For 30mm crack length of the sample 1, the maximum and minimum stress values were 3.777 and -3.482 KJ/m$^2$ as shown in Figure 5.26.
The maximum and minimum strain values were $0.978 \times 10^{-4}$ and $-0.674 \times 10^{-5}$, whose maximum deflection was $0.005971$ mm.

Figure 5.26 30mm Crack length of PU/MoS$_2$ (93/7)

Figure 5.27 10mm Crack length of PU/MoS$_2$ (90/10)
The maximum and minimum stress values of sample 2 were 1.156 and -1.158 KJ/m² for the crack length of 10mm as shown in Figure 5.27. Similarly, the maximum and minimum strain values were 0.454E-04 and -0.645E-05 respectively, whose maximum deflection was 0.001696 mm.

Figure 5.28 21mm Crack length of PU/MoS₂ (90/10)

Figure 5.29 23mm Crack length of PU/MoS₂ (90/10)
Figure 5.28 showed the maximum and minimum stress values as 2.743 and -1.614 KJ/m\(^2\) for the crack length of 21mm sample 2 specimens and its maximum deflection was .002824 mm. The maximum and minimum strain values were observed as .675E-04 and -.100E-04.

For the crack length of 23mm to sample 2 specimens, the maximum and minimum stress values were 2.31 and -1.377 KJ/m\(^2\) as shown in Figure 5.29. The maximum and minimum strain values were observed as .629E-04 and -.834E-05, whereas, a maximum deflection of the specimen was .003243 mm.

Figure 5.30 25mm Crack length of PU/MoS\(_2\) (90/10)

Figure 5.30 showed the maximum and minimum stress values as 2.981 and -1.659 KJ/m\(^2\) for the crack length of 25mm specimen and its maximum deflection was .003439 mm. Their maximum and minimum strain values were .788E-04 and -.782E-05.
For 30mm crack length of the sample 2, the maximum and minimum stress values were 3.085 and -2.48 KJ/m$^2$ as shown in Figure 5.31. The maximum and minimum strain values were .827E-04 and -.748E-05, whose maximum deflection was .004814 mm.

The maximum and minimum stress values of sample 3 having 20% molybdenum disulphide with polyurethane were 1.702 and -1.074 KJ/m$^2$ for the crack length of 10mm as shown in Figure 5.32. Similarly, the maximum and minimum strain values were .308E-04 and -.750E-05, whose maximum deflection was .717E-03 mm.

Figure 5.33 showed the maximum and minimum stress values as 3.042 and -1.39KJ/m$^2$ for the crack length of 21mm sample 3 specimens and its maximum deflection was .001399 mm. The maximum and minimum strain values were observed as .449E-04 and -.560E-05.
Figure 5.32 10mm Crack length of PU/MoS$_2$ (80/20)

Figure 5.33 21mm Crack length of PU/MoS$_2$ (80/20)
For the crack length of 23mm to sample 3 specimens, the maximum and minimum stress values were 1.728 and -1.371 KJ/m² as shown in Figure 5.34.

Figure 5.34 23mm Crack length of PU/MoS₂ (80/20)

Figure 5.35 25mm Crack length of PU/MoS₂ (80/20)
The maximum and minimum strain values were observed as .388E-04 and -.890E-04, whereas, a maximum deflection of the specimen was .001663 mm. Figure 5.35 showed the maximum and minimum stress values as 2.512 and -1.659 KJ/m$^2$ for the crack length of 25mm sample 3 specimens and its maximum deflection was .001958 mm. Their maximum and minimum strain value was .433E-04 and -.580E-05.

Figure 5.36 30mm Crack length of PU/MoS$_2$ (80/20)

For 30mm crack length of the sample 3 specimens, the maximum and minimum stress values were observed as 2.744 and -1.878KJ/m$^2$ respectively as shown in Figure 5.36. The maximum and minimum strain values were 0.500E-04 and -0.607E-05, whose maximum deflection was .002491mm.
Table 5.5 Fracture analysis of samples 1, 2 and 3

<table>
<thead>
<tr>
<th>Initial crack length</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.187</td>
<td>1.156</td>
<td>1.702</td>
</tr>
<tr>
<td>21</td>
<td>3.513</td>
<td>2.743</td>
<td>3.042</td>
</tr>
<tr>
<td>23</td>
<td>2.778</td>
<td>2.31</td>
<td>1.728</td>
</tr>
<tr>
<td>25</td>
<td>3.927</td>
<td>2.981</td>
<td>2.512</td>
</tr>
<tr>
<td>30</td>
<td>3.77</td>
<td>3.085</td>
<td>2.744</td>
</tr>
<tr>
<td>Average</td>
<td>3.035</td>
<td>2.455</td>
<td>2.3456</td>
</tr>
</tbody>
</table>

The fracture toughness of varying crack length of each specimen was analyzed using ANSYS software and its average values were calculated and tabulated in the Table 5.5. From the average fracture toughness, as shown in table, it was observed that the fracture toughness decreased with the increased volume percentage of molybdenum disulphide particles in the polyurethane matrix.

5.4.5 Wear Rate Analysis (mm³/N-Km)

In Finite element analysis, the wear rate for different samples was calculated by using ANSYS software. In ANSYS, selected solid 8node 185 as the element type and entered the value of their material properties, which were calculated by using the rule of mixture. A model of specified specimen size that had been used on Pin on disk test was designed and then applied the mesh, by selecting the degrees of freedom. The load was applied on the specified nodes and the solution was plotted. From the nodal solution, the maximum stress and maximum strain on each sample were observed and applied using the formula as given below and then calculated the rate of wear using the formula as;

\[
\text{Wear Rate, } K = \frac{(e \times h)}{\sigma \times L}
\]
Where,

\[ e \quad - \quad \text{Maximum strain} \]
\[ h \quad - \quad \text{Height of the sample}, \]
\[ \sigma \quad - \quad \text{Maximum stress on each sample}, \]
\[ L \quad - \quad \text{Sliding Distance}. \]

Figure 5.37 showed the modeling of 50mm diameter disk and a pin of 4.76mm slides around the disk with a force on it. The maximum stress induced on the contact surface of pin on disk for the sample 1 was observed as 26.134 MPa. The maximum strain identified from the Figure 5.38 for the sample 1 was 0.000925. By applying the values in the above formula, the wear rate was calculated for the sample 1 as 1.606 mm\(^3\)/N-Km.

**Figure 5.37 Wear stress of PU/MoS\(_2\) (93/7)**
Figure 5.38 Wear strain of PU/MoS$_2$ (93/7)

Figure 5.39 Wear stress of PU/MoS$_2$ (90/10)
Figure 5.40 Wear strain of PU/MoS₂ (90/10)

For the sample 2, the maximum stress value from the plotted solution as shown in Figure 5.39 was observed as 27.145 MPa and the maximum strain value was taken as 0.000972 from Figure 5.40. Applying the values of maximum stress and strain in the given formula $K = (e \times h) / (\sigma \times L)$, height of the sample was taken from the geometry of modeling and its sliding distance $L$. Then the wear rate for the sample was calculated as 1.6250 mm³/N-Km.

The maximum stress value from the plotted solution for the sample 3 as shown in Figure 5.41 was observed as 32.534 MPa and the maximum strain value for the same sample was taken as 0.001417 from Figure 5.42. Applying the values of maximum stress and strain in the given formula $K = (e \times h) / (\sigma \times L)$, height of the sample was taken from the geometry of modeling.
and its sliding distance $L$ then the wear rate for the sample was calculated as

$$1.9765 \text{mm}^3/\text{N-Km}.$$
Table 5.6 Wear rate analysis of samples 1, 2 and 3

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Stress</td>
<td>26.134</td>
<td>27.145</td>
<td>32.534</td>
</tr>
<tr>
<td>Maximum Strain</td>
<td>0.000925</td>
<td>0.000972</td>
<td>0.001417</td>
</tr>
<tr>
<td>Calculated Wear Rate in mm³/N-Km</td>
<td>1.6062</td>
<td>1.6250</td>
<td>1.9765</td>
</tr>
</tbody>
</table>

The wear rate of sample 1, 2 and 3 was calculated from their maximum stress and strain values, which was observed from FEA solution using ANSYS Software. The calculated wear rate was tabulated as shown in Table 5.6. From the Table 5.6, it was understood that the rate of wear was increasing with the increase in the additive particles such as molybdenum disulphide particle in the polyurethane matrix. The wear rate was higher for the sample 3 having 20% molybdenum disulphide in polyurethane matrix than other samples 1 and 2. Whereas, the sample 2 had more wear rate than the sample 1 due to the addition of molybdenum disulphide alone and then further addition of molybdenum disulphide with polyurethane matrix increased the rate of wear.

5.5 POLYURETHANE MATRIX HYBRID NANO COMPOSITES

5.5.1 Tensile Analysis (MPa)

The tensile strength of the samples was calculated by using ANSYS software, in which the selected element type was solid 8node 185 and entered the material properties as already calculated using the rule of mixture and then created a model of specified specimen size, applying the mesh on the selected degrees of freedom. The load was applied on the specified nodes and the solution was plotted. The tensile property of the sample 4 was observed as maximum tensile stress as 20.60MPa and minimum tensile stress as 5.69 MPa.
as shown in Figure 5.43. The tensile strain value for the sample 1 was observed from Figure 5.44 as the maximum strain value was 31.9 and their minimum strain value was 9.2.

Figure 5.43 Tensile stress of PU/MoS₂/TiO₂ (92.5/7/0.5)

Figure 5.44 Tensile strain of PU/MoS₂/TiO₂ (92.5/7/0.5)
The properties of the sample 5 having 10% molybdenum disulphide and 1% titanium dioxide with polyurethane matrix were calculated by rule of mixture and provided for analyzing the tensile property of the modeling element.
The maximum tensile stress as 21.0 MPa and minimum tensile stress as 6.54 MPa were observed for the given sample as shown in Figure 5.45. The tensile strain value for the sample 5 had also been examined and observed from the Figure 5.46, as 31.25.

Figure 5.47 Tensile stress of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)

Figure 5.48 Tensile strain of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)
Similarly, sample 6 having 20% molybdenum disulphide and 1.5% titanium dioxide in polyurethane matrix had been analyzed for finding the tensile property of the modeling element. The maximum tensile stress as 16.70 MPa and minimum tensile stress as 4.27 MPa were observed for the given sample 6 as shown in Figure 5.47. The tensile strain for the sample 6 had also been examined and observed from the Figure 5.48, as 25.87.

**Table 5.7 Tensile stress analysis of samples 4, 5 and 6.**

<table>
<thead>
<tr>
<th>Stress in MPa</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Tensile Stress</td>
<td>20.60</td>
<td>21.00</td>
<td>16.70</td>
</tr>
<tr>
<td>Minimum Tensile Stress</td>
<td>5.98</td>
<td>6.54</td>
<td>4.27</td>
</tr>
</tbody>
</table>

For samples 4, 5 and 6 maximum and minimum tensile strength were observed from analysis using ANSYS software and tabulated in Table 5.7. From Table 5.7, it showed the tensile strength for sample 4 having 7% molybdenum disulphide and 0.5% titanium dioxide was lesser than the sample 5 having 10% molybdenum disulphide and 1% titanium dioxide with polyurethane matrix. The tensile strength increased with the increase in addition of additive particles in the matrix, but there was a sudden decrease in the tensile property for the further addition of additive particles with the polyurethane matrix.

Thus, the sample 5 had optimum tensile strength than the other samples 4 and 6. In general, it was observed that the tensile stress of the sample increased with the increase in composition of molybdenum disulphide particles up to 10% and the titanium dioxide up to 1% with polyurethane matrix.
5.5.2 Compressive Analysis (MPa)

The compressive strength of the sample was calculated by using ANSYS software, in which the selected element type was solid 8node 185 and entered the properties of material as already calculated by using the rule of mixture. A model was created on the specified specimen size for the samples, applying the mesh on the selected degrees of freedom. The loads were applied on the specified nodes and the solution was plotted. The compressive property of the sample 4 was observed to have the maximum compressive stress as 52.70 MPa and a minimum compressive stress as 21.40 MPa, as shown in Figure 5.49. The compressive strain value for the sample 4 had also been observed from the Figure 5.50 and their maximum compressive strain as 18.99.

Figure 5.49 Compressive stress of PU/MoS$_2$/TiO$_2$ (92.5/7/0.5)
Figure 5.50 Compressive strain of PU/MoS$_2$/TiO$_2$ (92.5/7/0.5)

The sample 5 having 10% molybdenum disulphide and 1% titanium dioxide with polyurethane matrix, whose properties were calculated by rule of mixture and provided for analyzing the compressive property of the modeling element. The maximum compressive stress as 53.60 MPa and minimum compressive stress as 21.70 MPa were observed for the given sample as shown in Figure 5.51. The compressive strain values for the sample 5 had also been examined and observed from the Figure 5.52 and their maximum compressive strain as 19.30.
Figure 5.51 Compressive stress of PU/MoS$_2$/TiO$_2$ (89/10/1)

Figure 5.52 Compressive strain of PU/MoS$_2$/TiO$_2$ (89/10/1)
Figure 5.53 Compressive stress of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)

Figure 5.54 Compressive strain of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)
Similarly, sample 6 having 20% molybdenum disulphide and 1.5% Titanium dioxide in polyurethane matrix had been analyzed for finding the tensile property of the modeling element. The maximum compressive stress as 52.30 MPa and minimum compressive stress as 21.20 MPa were observed for the given sample 6 as shown in Figure 5.53. The compressive strain for the sample 6 had also been examined and observed from the Figure 5.54 and their maximum compressive strain as 18.99.

**Table 5.8 Compressive stress analysis of samples 4, 5 and 6.**

<table>
<thead>
<tr>
<th>Stress in MPa</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Compressive Stress</td>
<td>52.70</td>
<td>53.60</td>
<td>52.30</td>
</tr>
<tr>
<td>Minimum Compressive Stress</td>
<td>21.40</td>
<td>21.70</td>
<td>21.20</td>
</tr>
</tbody>
</table>

For samples 4, 5 and 6 the maximum and minimum compressive strength was calculated and tabulated in Table 5.8. From the Table 5.8, it was found that the compressive strength for sample 5 was greater than the sample 4 and 6. In general, it was observed that the compressive stress increased with the increase in composition of molybdenum disulphide and titanium dioxide particles up to 10% and 1% respectively with polyurethane matrix and a further addition of particles decreased the compressive strength of the composites.

**5.5.3 Impact Analysis (MPa)**

The impact properties of the samples 4, 5 and 6 were calculated by selecting the element as structural beam - 2D- elastic elements in ANSYS software and the material properties of the samples were entered which were
calculated earlier by using rule of mixtures. A model of specified size, by identifying the nodes on the element and selecting the transient analysis with damping effect was created. By known degrees of freedom, loads were applied on the nodes of the element and the results were plotted. The impact stress, impact strain and their deformation of various samples 4, 5 and 6 were plotted in the figures.

In Figure 5.55, the impact stress for sample 4 having 7% molybdenum disulphide and 0.5% titanium dioxide had the maximum impact stress as 199.43 MPa and minimum impact stress as 20.82 MPa.

Figure 5.55 Impact stress of PU/MoS$_2$/TiO$_2$ (92.5/7/0.5)

Similarly, the impact strain values of the sample 4 were shown in Figure 5.56, whose maximum and the minimum impact strains were 0.46 and 0.11 respectively. The deformation for sample 4 was 3.99 mm as observed from the deflection diagram as shown in Figure 5.57.
Figure 5.56 Impact strain of PU/MoS$_2$/TiO$_2$ (92.5/7/0.5)

Figure 5.57 Deformed shape of PU/MoS$_2$/TiO$_2$ (92.5/7/0.5)
Figure 5.58 Impact stress of PU/MoS$_2$/TiO$_2$ (89/10/1)

Figure 5.59 Impact strain of PU/MoS$_2$/TiO$_2$ (89/10/1)
Figure 5.60 Deformed shape of PU/MoS$_2$/TiO$_2$ (89/10/1)

Sample 5 having 10% molybdenum disulphide and 1% titanium dioxide with maximum and minimum impact stress as 204.177 and 27.460 MPa respectively were observed from Figure 5.58. The maximum and minimum strain values were also analyzed in ANSYS and their values were 0.027 and 0.006 respectively, which had been shown in Figure 5.59. The deflection of the sample 5 was identified as 2.675 mm, which was lesser than the sample 4 as shown in Figure 5.60.

In similar, the sample 6 having 20% molybdenum disulphide and 1.5% titanium dioxide with maximum and minimum impact stress as 207.192 and 32.192 MPa respectively were observed from Figure 5.61. The maximum and minimum strain values were also analyzed in ANSYS and their values were 0.014 and 0.003 respectively, which had been shown in Figure 5.62. The deflection of the sample 6 was identified as 1.388 mm, which was lesser than
the sample 4 and 5 as shown in Figure 5.63, the deflection of the sample decreased with the increase in the composition of the additive particles with polyurethane matrix.

Figure 5.61 Impact stress of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)

Figure 5.62 Impact strain of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)
Figure 5.63 Deformed shape of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)

Table 5.9 Impact analysis of samples 4, 5 and 6.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum stress in MPa</td>
<td>191.433</td>
<td>204.177</td>
<td>207.192</td>
</tr>
<tr>
<td>Minimum stress in MPa</td>
<td>20.817</td>
<td>27.460</td>
<td>32.192</td>
</tr>
<tr>
<td>Maximum strain</td>
<td>0.046</td>
<td>0.027</td>
<td>0.014</td>
</tr>
<tr>
<td>Minimum strain</td>
<td>0.011</td>
<td>0.006</td>
<td>0.003</td>
</tr>
<tr>
<td>Deflection (mm)</td>
<td>3.939</td>
<td>2.675</td>
<td>1.388</td>
</tr>
</tbody>
</table>

Properties of all the three samples were observed from ANSYS and it was tabulated in Table 5.9. From Table 5.9, it was suggested that the sample 5 had maximum impact stress than other samples 4 and 6. Thus, the increase in composition of molybdenum disulphide and titanium dioxide particles up to 10% and 1% respectively in the polyurethane matrix increased
the impact stress values and further addition of particles in the matrix decreased the impact stress. Hence, the sample 5 having 10% molybdenum disulphide and 1% titanium dioxide in the polyurethane matrix was the optimum composition of particles in the polyurethane matrix.

5.5.4 Fracture Analysis (KJ/m²)

The fracture toughness for different specimens on samples 4, 5 and 6 were calculated for varying crack length such as 10, 21, 23, 25 and 30 mm by using ANSYS software. A model of specified specimen size having definite crack length was designed and meshing the element by selecting the degrees of freedom. The load was increased on the specified nodes for finding the fracture stress and the solution was plotted. From the nodal solution on ANSYS output, the maximum yield stress was equal to the fracture stress of the specimen which was identified and tabulated.

Figure 5.64 10mm Crack length of PU/MoS₂/TiO₂ (92.5/7/0.5)
Figure 5.65 21mm Crack length of PU/MoS$_2$/TiO$_2$ (92.5/7/0.5)

Figure 5.64 showed sample 4 having 7% molybdenum disulphide and 0.5% titanium dioxide with polyurethane matrix for the crack length of 10mm. The fracture stress observed from the Figure 5.64 as the maximum and minimum stress value was 1.206 and -1.573 KJ/m$^2$ respectively. Similarly, the maximum and minimum strain values were observed as 0.632E-04 and -0.597E-05, whose maximum deflection was .002313mm.

For crack length of 21mm of the sample 4 specimen, the fracture stress was observed from the output of ANSYS solution plotted in the Figure 5.65. The maximum and minimum fracture stress values were observed as 3.833 and -1.93KJ/m$^2$ respectively, which were equal to the maximum yield stress of the sample. For the same crack length, the maximum and minimum strain values were also observed from the analysis output as 0.915E-04 and -0.119E-04 respectively, whereas, their maximum deflection was calculated as 0.004129mm.
For the crack length of 23mm to sample 4 specimens, the maximum and minimum stress values were 2.451 and -2.133 KJ/m² as shown in Figure 5.66. The maximum and minimum strain values were observed as...
0.981E-04 and -0.106E-04, whereas, a maximum deflection of the specimen was 0.004045mm.

Figure 5.67 showed the maximum and minimum stress values as 3.858 and -2.331 KJ/m² for the crack length of 25mm specimen to the sample 4 having 7% molybdenum disulphide and 0.5% titanium dioxide with polyurethane matrix and its maximum deflection was 0.004583 mm. Their maximum and minimum strain values were 0.840E-04 and -0.689E-05.

![Figure 5.67](image)

**Figure 5.68 30mm Crack length of PU/MoS₂/TiO₂ (92.5/7/0.5)**

For 30mm crack length of the sample 4, the maximum and minimum stress values were 3.732 and -3.499 KJ/m² as shown in Figure 5.68. The maximum and minimum strain values were 0.998E-04 and -0.650E-05, whose maximum deflection was 0.006213mm.
Figure 5.69 10mm Crack length of PU/MoS$_2$/TiO$_2$ (89/10/1)

The maximum and minimum stress values of sample 5 were 1.138 and -1.209 KJ/m$^2$ for the crack length of 10mm as shown in Figure 5.69. Similarly, the maximum and minimum strain values were 0.456E-04 and -0.777E-05 respectively, whose maximum deflection was 0.00197mm.

Figure 5.70 showed the maximum and minimum stress values as 3.064 and -1.358KJ/m$^2$ for the crack length of 21mm sample 5 having 10% molybdenum disulphide and 1% titanium dioxide with polyurethane matrix specimens and its maximum deflection was observed as 0.00271mm. The maximum and minimum strain values were observed as 0.788E-04 and -0.104E-04 respectively.

For the crack length of 23mm to sample 5 specimens, the maximum and minimum stress values were 1.87 and -1.382 KJ/m$^2$ as shown in Figure 5.71. The maximum and minimum strain values were observed as
0.783E-04 and -0.984E-05, whereas, the maximum deflection of the specimen was 0.003476 mm.

Figure 5.70 21mm Crack length of PU/MoS₂/TiO₂ (89/10/1)

Figure 5.71 23mm Crack length of PU/MoS₂/TiO₂ (89/10/1)
Figure 5.72 25mm Crack length of PU/MoS$_2$/TiO$_2$ (89/10/1)

Figure 5.73 30mm Crack length of PU/MoS$_2$/TiO$_2$ (89/10/1)
For 25mm crack length of the sample 5, the maximum and minimum stress values were 3.321 and -1.554 KJ/m$^2$ respectively as shown in Figure 5.72. The maximum and minimum strain values were observed as 0.907E-04 and -0.660E-05, whose maximum deflection was 0.003485mm.

Figure 5.73 showed the maximum and minimum stress value as 3.077 and -2.501 KJ/m$^2$ for the crack length of 30 mm to sample 5 specimens and its maximum deflection was observed as 0.004955mm. Their maximum and minimum strain values were identified as 0.815E-04 and -0.725E-05 respectively.

![Image](image.png)

**Figure 5.74 10mm Crack length of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)**

The maximum and minimum stress values of sample 6 having 20 % molybdenum disulphide and 1.5 % titanium dioxide with polyurethane matrix were observed as 1.204 and -1.013KJ/m$^2$ respectively for the crack length of 10mm as shown in Figure 5.74. Similarly, the maximum and minimum strain
values were $0.245 \times 10^{-4}$ and $-0.451 \times 10^{-5}$, whose maximum deflection was identified as $0.943 \times 10^{-3}$ mm.

Figure 5.75 21mm Crack length of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)

Figure 5.76 23mm Crack length of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)
Figure 5.75 showed the maximum and minimum stress values as 2.661 and -1.307 KJ/m$^2$ for the crack length of 21mm to sample 6 specimens and its maximum deflection was 0.00143 mm. The maximum and minimum strain values were observed as 0.412E-04 and -0.717E-05 respectively.

![Figure 5.75](image1)

**Figure 5.77 25mm Crack length of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)**

For the crack length of 23mm to sample 6 specimens, the maximum and minimum stress values were 1.986 and -1.108 KJ/m$^2$ as shown in Figure 5.76. The maximum and minimum strain values were observed as 0.339E-04 and -0.355E-05 respectively, whereas, the maximum deflection of the specimen was 0.001707 mm.

Figure 5.77 showed the maximum and minimum stress values as 2.518 and -1.47 KJ/m$^2$ for the crack length of 25mm to sample 3 specimens and its maximum deflection was observed as 0.001877 mm. The maximum and minimum strain values were identified for the sample 6 as 0.407E-04 and -0.548E-05 respectively.
For 30mm crack length of the sample 6 specimens, the maximum and minimum stress values were observed as 2.768 and -1.994 KJ/m² respectively as shown in Figure 5.78. The maximum and minimum strain values were 0.452E-04 and -0.403E-05, whose maximum deflection was 0.002574 mm.

Figure 5.78 30mm Crack length of PU/MoS₂/TiO₂ (78.5/20/1.5)

Table 5.10 Fracture analyses of samples 4, 5 and 6

<table>
<thead>
<tr>
<th>Initial crack length</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.206</td>
<td>1.138</td>
<td>1.024</td>
</tr>
<tr>
<td>21</td>
<td>3.833</td>
<td>3.064</td>
<td>2.661</td>
</tr>
<tr>
<td>23</td>
<td>2.451</td>
<td>1.87</td>
<td>1.986</td>
</tr>
<tr>
<td>25</td>
<td>3.858</td>
<td>3.321</td>
<td>2.518</td>
</tr>
<tr>
<td>30</td>
<td>3.732</td>
<td>3.077</td>
<td>2.768</td>
</tr>
<tr>
<td>Average</td>
<td>3.016</td>
<td>2.494</td>
<td>2.1914</td>
</tr>
</tbody>
</table>
The fracture toughness of varying crack length of each specimen was analyzed using ANSYS software and its average values were calculated and tabulated in the Table 5.10. From the average fracture toughness as shown in Table 5.10, it was observed that the fracture toughness decreased with the increased volume percentage of molybdenum disulphide and titanium dioxide particles in the polyurethane matrix. The fracture toughness was higher for pure polyurethane matrix, whereas, when the matrix was mixed with the additive particles, the fracture toughness decreased.

5.5.5 Wear Rate Analysis (mm$^3$/N-Km)

The wear rate for different samples was calculated by using ANSYS Software. A model was designed as per the specified specimen size that had been used on Pin on disk test by applying the mesh on the selected degrees of freedom. The load was applied on the specified nodes and the solution was plotted. From the nodal solution, the maximum stress and maximum strain on each sample were observed and applied using the formula as given below. The rate of wear was

Wear Rate, $K = \frac{(e \times h)}{(\sigma \times L)}$

Where,

- $e$ - Maximum Strain,
- $h$ - Height of the sample,
- $\sigma$ - Maximum Stress on each sample,
- $L$ - Sliding Distance.

Figure 5.79 showed the modeling of 50mm diameter disk and a pin of 4.76 mm slides around the disk with a force on it. The maximum stress induced on the contact surface of pin on disk for the sample 4 having 7% molybdenum disulphide and 0.5% titanium dioxide with polyurethane matrix was observed as 36.172 MPa. The maximum strain identified from the Figure
5.80 for the sample 4 was 0.00061635. By applying the values in the above formula, the wear rate was calculated for the sample 4 as 2.2690 mm³/ N-Km.

![Figure 5.79 Wear stress of PU/MoS₂/TiO₂ (92.5/7/0.5)](image1)

![Figure 5.80 Wear strain of PU/MoS₂/TiO₂ (92.5/7/0.5)](image2)
For the sample 5, the maximum stress values from the plotted solution as shown in Figure 5.81 was observed as 28.937 MPa and the maximum strain value was taken as 0.000847 from Figure 5.82.

**Figure 5.81 Wear stress of PU/MoS$_2$/TiO$_2$ (89/10/1)**

**Figure 5.82 Wear strain of PU/MoS$_2$/TiO$_2$ (89/10/1)**
Applying the values of maximum stress and strain in the given formula $K = (e \times h) / (\sigma \times L)$, height of the sample was taken from the geometry of modeling and its sliding distance $L$. Then the wear rate for the sample 5 was calculated as $1.3283 \text{ mm}^3/\text{N-Km}$.

Figure 5.83 Wear stress of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)

Figure 5.84 Wear strain of PU/MoS$_2$/TiO$_2$ (78.5/20/1.5)
The maximum stress values from the plotted solution for the sample 6 having 20% molybdenum disulphide and 1.5% titanium dioxide with polyurethane matrix as shown in Figure 5.83 was observed as 27.880 MPa and the maximum strain value for the same sample was taken as 0.000893 from Figure 5.84. Applying the values of maximum stress and strain in the given formula \( K = (e \times h) / (\sigma \times L) \), height of the sample was taken from the geometry of modeling and its sliding distance \( L \) then the wear rate for the sample 6 was calculated as 1.4536 \( \text{mm}^3/\text{N-Km} \).

Table 5.11 Wear rate analysis of samples 4, 5 and 6

<table>
<thead>
<tr>
<th>Properties</th>
<th>Sample 4</th>
<th>Sample 5</th>
<th>Sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Stress</td>
<td>36.172</td>
<td>28.937</td>
<td>27.880</td>
</tr>
<tr>
<td>Maximum Strain</td>
<td>0.000616</td>
<td>0.000847</td>
<td>0.000893</td>
</tr>
<tr>
<td>Calculated Wear Rate in</td>
<td>2.269</td>
<td>1.328</td>
<td>1.453</td>
</tr>
<tr>
<td>( \text{mm}^3/\text{N-Km} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The wear rate of sample 4, 5 and 6 was calculated from their maximum stress and strain values, which were observed from finite element analysis solution using ANSYS software. The calculated wear rate was tabulated as shown in Table 5.11. From the Table 5.11, it was understood that the rate of wear increased with the increase in the additive particles such as molybdenum disulphide and titanium dioxide particles in the polyurethane matrix. The wear rate was higher for the sample 4 having 7% molybdenum disulphide and 0.5% titanium dioxide in polyurethane matrix than other samples 5 and 6, whereas, the sample 5 had lesser wear rate than the sample 6 due to 10% of molybdenum disulphide and 1% titanium dioxide in the polyurethane matrix and then further addition of molybdenum disulphide and titanium dioxide particles with polyurethane matrix increased the rate of wear.