Finite Element Analysis of Metal Matrix Composite Connecting Rod and Comparison with Conventional AISI 4140 Alloy Steel Connecting Rod

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Abstract: Connecting rod is one of the important parts in automobile engines. In a reciprocating piston engine, the connecting rod (conrod) connects the piston to the crank or crankshaft. Together with the crank, they form a simple mechanism that converts reciprocating motion into rotating motion. They are usually made of steel, aluminium or titanium alloys. The connecting rod is under heavy stress due to the reciprocating load exerted by the piston. Failure of a connecting rod is one of the most common causes of catastrophic engine failure in automobiles, frequently putting the broken rod through the side of the crankcase and thereby rendering the engine irreparable. Through this work, it is tried to replace the conventional connecting rod material by AlSiC metal matrix composite (MMC) so that better physical and mechanical properties can be achieved. AlSiC is a metal matrix composite consisting of aluminium matrix with silicon carbide particles as reinforcement and they are stiff, lightweight, and strong. By changing the composition of reinforcement material that is SiC, the properties of the composite can be altered. In this study, Al/SiC composite with 5%, 10%, 15%, 20%, 25% and 30% volume of SiC is examined. The suitable composition is selected for modelling connecting rod. In this work a connecting rod is designed with the help of CATIA V5 R15 software using available design data. The bending stress experienced by a connecting rod is calculated numerically considering the typical forces acting on it. The connecting rod model is then imported to ANSYS 14.0 for finite element analysis. Various forces affected by the connecting rod and the boundary conditions are applied and stress analysis is carried out. Unit cell based modelling of metal matrix composite is also done. Axisymmetric and 3D cell are the two unit cell models considered. Results of finite element stress analysis is then compared with the numerical analysis.

Index Terms— IC engine connecting rod, Al/SiC Metal matrix composite, Finite element analysis.

1. Introduction

1.1. Metal matrix composites
A Metal Matrix Composite (MMC) is a composite material with at least two component parts, one being a metal fundamentally and the other material may be an alternate metal or another material, such as an organic compound or a ceramic. MMCs are made by scattering a strengthening material (reinforcement) into a metal matrix. The matrix is the monolithic and totally continuous material into which the reinforcement is installed. This implies not at all like two materials sandwiched together, there is a path through the matrix to any point in the material. The reinforcement material is implanted into the matrix phase. The reinforcement does not always serve a purely structural task (reinforcing the compound), but is also used to change physical properties of the composite such as wear resistance, friction coefficient or thermal conductivity. The reinforcement material can be either continuous, or discontinuous.

1.1.1. Al-SiC Metal Matrix Composites
Aluminum alloys strengthened with ceramic particulates have noteworthy potential for structural applications as a result of their high specific strength and stiffness as well as low density. These properties have made particle-reinforced metal matrix composites (MMCs) an excellent choice for the use in weight-sensitive and stiffness-critical components in transportation, aerospace and industrial sectors. Al-SiC is a metal matrix composite consisting of aluminium matrix with silicon carbide particles as the reinforcement. Studies shows that Al-SiC composites are the best replacements for copper-
molybdenum (CuMo) and copper-tungsten (CuW) alloys; they have about 1/3 the weight of copper, 1/5 of CuMo, and 1/6 of CuW, making them reasonable for weight-sensitive applications. Al-SiC metal matrix composites are stiff, lightweight, and strong.

1.2. IC engine connecting rods

![Conventional connecting rod](image)

In a reciprocating piston engine, the connecting rod or conrod is used to connect the piston to the crank or the crankshaft. Together with the crank, they make a simple mechanism which converts reciprocating motion into rotating motion. Connecting rods are generally made of steel, aluminium or titanium alloys. The connecting rod is under heavy stress from the reciprocating load caused by the piston, actually being stretched and compressed with every rotation, and the load increases with the square of the engine speed increase. Failure of a connecting rod, more often called throwing a rod, is one of the most common causes of catastrophic engine failure in automobiles, frequently putting the broken rod through the side of the crankcase and in this manner rendering the engine irreparable. At the point when building a high-performance engine, considerable attention is paid to the connecting rods, eliminating stress risers by such techniques as grinding the edges of the rod to a smooth radius, shot peening to induce compressive surface stresses (to prevent crack initiation), balancing all connecting rod/piston assemblies to the same weight and Magnafluxing to reveal otherwise invisible small cracks which would bring the connecting rod to fail under stress.

2. Design of connecting rod – analytical method

A Connecting rod is an essential engine part that transfers the motion from the piston to the crankshaft. Connecting rods are normally produced using forged steel and cast aluminium alloy. They are intended to withstand dynamic stresses from piston movement and combustion. The small end of the connecting rod is connected to the piston using a piston pin. The piston pint also called a wrist pin provides a pivot point between the piston and connecting rod. The big end of the connecting rod is connected to the crankpin journal in order to provide a pivot point on the crankshaft. Normally connecting rods are fabricated as one piece or two piece components. The rod cap is the removable segment of a two piece connecting rod that gives a bearing surface for the crankpin journal. The rod cap is joined to the connecting rod with two cap screws or bolts for easy installation and removal from the crankshaft.

D.Gopinatha [1] et al, considered following specifications of an automobile engine to calculate the bending stress on the connecting rod.

2.1 Configurations of the Engine

- Connecting rod length = 380 mm
- Piston diameter = 100 mm
- Mass of the reciprocating parts per cylinder = 2.25 kg
- Stroke length = 190 mm
- Speed of the engine = 1800 rpm.
- Compression ratio = 6:1
- Factor of safety = 6
- Length to diameter ratio of big end bearing = 1.3
- Length to diameter ratio of small end bearing = 2
- Maximum gas pressure = 3.15 N/mm²
- Bearing pressure at big end = 10 N/mm²
- Bearing pressure at small end = 15 N/mm²
- Allowable stresses in the bolts = 60 N/mm²
- Allowable stresses in the cap = 80 N/mm²
2.2 Standard Proportions of the I-Section

![Figure 2: Standard Proportions of the I-Section](image)

Width of the section, \( B = 4t \)
Depth of the section, \( H = 5t \)
Area of the section, \( A = 11t^2 \)
Depth of the section near the big end = 1.1H to 1.25H
Depth of the section near the small end = 0.75H to 0.9H
Moment of inertia about x axis \( I_{xx} = 34.91t^4 \)
Moment of inertia about y axis \( I_{yy} = 10.91t^4 \)
Therefore \( I_{xx}/I_{yy} = 3.2 \)
Radius of gyration of the section about X-axis = 1.78t
Length of the crank pin = 1.25d, to 1.5d
Length of the piston pin = 1.5d, to 2d

2.3. Dimensions of the I – Section

An I–section is considered for the connecting rod since it has much high value of section modulus when compared with a solid rectangular beam of same cross-sectional area and it gives higher moment of inertia.

Since the connecting rod is designed by taking the force on the connecting rod \( (F_C) \) equal to maximum force on the piston \( (F_L) \) due to gas pressure,

The maximum force acting on the piston due to gas pressure,

\[
F_C = F_L = \frac{p}{4}d^2 = 24740 \text{ N} \quad (1)
\]

Since factor of safety is considered, Buckling load \( W_B = 148440 \text{ N} \)
Radius of gyration of the section about X-axis,

\[
K_{xx} = \sqrt{\frac{5k}{A}} = 1.78t \quad (2)
\]

r = Stroke of piston/2 = 95 mm
Length of connecting rod, \( l = 380 \text{ mm} \)
From Rankine’s formula, we know buckling load \( (W_B) \),

\[
148440 = \frac{\frac{\sigma_t}{4}}{1 + \left( \frac{4k}{\sigma_t} \right)} \quad (3)
\]

Width of the section, \( B = 4t = 4 \times 7 = 28 \text{ mm} \)
Height of the section, \( H = 5t = 5 \times 7 = 35 \text{ mm} \)

2.4. Dimensions of crank pin and piston pin

\( d_c \) = Diameter of the crank pin
\( l_c \) = Length of the crank pin = 1.3 \( d_c \)
\( P_{bc} \) = Bearing pressure = 10 N/mm²

We know that load on the crank pin or big end bearing = Projected area \times \text{Bearing pressure}

\( d_c \times 1.3 \times d_c \times 10 = 13 (d_c)^2 \)

Since crank pin is designed for maximum gas force,

\( 13 (d_c)^2 = F_L = 24740 \text{ N} \)

\( d_c = 43.6 \text{ say 44 mm} \)

\( l_c = 1.3 \times 44 = 1.3 \times 44 = 57.2 \text{ say 58 mm} \)

Again let,

\( d_p \) = Diameter of the piston pin
\( l_p \) = Length of the piston pin = 2 \( d_p \)
\( P_{bp} \) = Bearing pressure = 15 N/mm²

We know that load on the crank pin or big end bearing = Projected area \times \text{Bearing pressure}

\( d_p \times 2 \times d_p \times 15 = 30 (d_p)^2 \)

Since piston pin is designed for maximum gas force, equating the load on the piston pin or the small end bearing to the maximum gas force,

\( 30 (d_p)^2 = F_L = 24740 \text{ N} \)

\( d_p = 28.7 \text{ say 29 mm} \)

\( l_p = 2 \times d_p = 2 \times 29 = 58 /mm \)

2.5. Size of bolts for securing the big end cap

Let \( d_{cb} \) = Core diameter of the bolts
\( \sigma_t \) = allowable tensile stress for the material of bolts = 60 N/mm²
\( n_b \) = number of bolts = 2

Inertia force on the reciprocating parts,

\[
F_I = m_r \omega^2 \left( \cos \frac{\theta}{2 \pi} + \frac{\sin \frac{\theta}{2 \pi}}{\frac{\theta}{2 \pi}} \right) \quad (4)
\]

At TDC, \( \theta = 0 \)
\( F_I = 9490 \text{ N} \)
Equating inertia force to the force on the bolts we have,

\( 9490 \text{ N} = 94.26 (d_{cb})^2 \)

\( d_{cb} = 11.94 \text{ say 12 mm} \)

2.6. Thickness of the big end cap

Let \( t_c \) = Thickness of the big end cap
\( b_c \) = Width of the big end cap = 58 mm
\( \sigma_b \) = Allowable bending stress for the material of the cap = 80 N/mm²

Maximum bending moment is given by,

\[
M_c = \frac{F_t x}{6} \quad (5)
\]

\( x = \text{Distance between the bolt centers} = 65 \text{ mm} \)
Maximum bending moment acting on the cap, \( M_c = 102810 \text{ N-mm} \)
Section modulus for the cap,
Zc = \frac{Z_{xx}^2}{6} = 9.7 (tc)^2 \quad (6)

We know that bending stress (\sigma_b),
\sigma_b = \frac{6 Zc}{t_c} = 10.50 \text{ MPa}

t_c = 11.5 \text{ mm}

Mass of the connecting rod per meter length, m_1 = Volume \times Density = Area \times Length \times Density
= 1.64 \text{ Kg}

Section modulus, Z_{xx} = \frac{Z_{xx}}{2} = 4792 \text{ mm}^3 \quad (7)

Maximum bending stress, \sigma_{b \text{ max}} = \frac{6 Zc}{t_c} = 10.7 \text{ N/mm}^2 \quad (8)

3. Modelling of Al-SiC metal matrix composite

3.1. Material Properties

Table 1: Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminium (Matrix)</th>
<th>SiC (Reinforcement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ( \rho ) (g/cc)</td>
<td>2.70</td>
<td>3.21</td>
</tr>
<tr>
<td>Young’s Modulus, E(GPa)</td>
<td>70</td>
<td>410</td>
</tr>
<tr>
<td>Shear Modulus, G(GPa)</td>
<td>26</td>
<td>180</td>
</tr>
<tr>
<td>Poisson’s ratio, ( \nu )</td>
<td>0.35</td>
<td>0.10</td>
</tr>
<tr>
<td>Co-efficient of thermal expansion (( \times ) 10^6)</td>
<td>21.5</td>
<td>4</td>
</tr>
<tr>
<td>Tensile strength, ( \sigma ) (MPa)</td>
<td>228</td>
<td>345</td>
</tr>
</tbody>
</table>

3.2. Formulae Used

Density of the composite, 
\rho_c = \rho_m V_m + \rho_f V_f \quad (9)

Tensile strength of the composite, 
\sigma_c = \sigma_m V_m + \sigma_f V_f \quad (10)

Co-efficient of thermal expansion,
\alpha_c = \frac{(\alpha_m E_m V_m + \alpha_f E_f V_f)}{(E_m V_m + E_f V_f)} \quad (11)

Where,
\rho_m = Density of the matrix material
\rho_f = Density of the reinforcement material
V_m = Matrix volume fraction
V_f = Reinforcement volume fraction
\sigma_m = Tensile strength of matrix material
\sigma_f = Tensile strength of reinforcement material
\alpha_m = Co-efficient of thermal expansion of matrix material

3.3. Material Properties for different Compositions of Reinforcement

3.3.1. Al with 5% of SiC Reinforcement
\rho_c = 2.7255 g/cc
\sigma_c = 233.85 MPa
\alpha_c = 17.376 \times 10^{-6} /\text{0C}

3.3.2. Al with 10% of SiC Reinforcement
\rho_c = 2.755 g/cc
\sigma_c = 239.7 MPa
\alpha_c = 14.60 \times 10^{-6} /\text{0C}

3.3.3. Al with 15% of SiC Reinforcement
\rho_c = 2.776 g/cc
\sigma_c = 245.55 MPa
\alpha_c = 12.60 \times 10^{-6} /\text{0C}

3.3.4. Al with 20% of SiC Reinforcement
\rho_c = 2.80 g/cc
\sigma_c = 251.40 MPa
\alpha_c = 11.10 \times 10^{-6} /\text{0C}

3.3.5. Al with 25% of SiC Reinforcement
\rho_c = 2.875 g/cc
\sigma_c = 257.25 MPa
\alpha_c = 9.927 \times 10^{-6} /\text{0C}

3.3.6. Al with 25% of SiC Reinforcement
\rho_c = 2.853 g/cc
\sigma_c = 261.30 MPa
\alpha_c = 8.985 \times 10^{-6} /\text{0C}

3.4. Unit Cell Model Approach

In real composites, particles have arbitrary shape and they are irregularly distributed. In this model, it is assumed that ceramic particles possess a spherical shape and they are uniformly distributed in the matrix. In that way, the unit cell model is used in the framework of the periodic micro field approach. The unit cells for three-dimensional and axisymmetric models are shown in Figure 5 and figure 6. A coordinate system was chosen with the origin at the particle’s centre and the z-axis coincides with the direction of particle alignment and tensile loading. The particles are represented as spheres with radius \( r \), which are spaced apart by a distance 2L_z in the loading direction (figure 3) and 2L_x (or 2L_y) for a cylindrical model (figure 4). The assumptions are made for the modelling of Metal matrix composite;
Particles possess spherical shape
- Particles are uniformly distributed
- The bonding between inclusions and matrix is perfect

Two types of unit cells are considered in this study,
- Axisymmetric Model
- 3D Cell Model

3.5. Effect of Aspect ratio

As proposed by Xu [4] et al. (1999), by changing the distances LR and LZ we can change the mechanical behaviour of the composite. Therefore, the aspect ratio of the unit cell is given by,

\[ r_a = \frac{L_R}{L_Z} \]  
(for Axisymmetric model) \hspace{1cm} (12)

or

\[ r_a = \frac{L_X}{L_Z} \]  
(for 3D Cell model) \hspace{1cm} (13)

Aspect ratio \( r_a \) is an important parameter which defines the degree of particle alignment in such an idealized composite. If \( L_R \) \( (L_X) \) is greater than \( r_a > 1 \) we can model the loading along the stripe direction (longitudinal loading) and when \( L_R \) \( (L_X) \) is less than \( L_Z \) \( (r_a < 1) \) we suppose that the loading is perpendicular to the stripe direction (transverse loading). It should be noted that, the sizes of axisymmetric and 3D unit cells do not coincide. The particle volume, the volume of unit cell and the cell aspect ratio are kept constant, but the sizes of the cells for 2D and 3D calculations differ from each other.

The volume fraction of the particles is related to the volume of the unit cell through particle volume fraction by,

\[ \frac{2}{3} \pi r^3 = \pi L_R^2 (2L_Z) f_p \]
(for axisymmetric model)

\[ \frac{2}{3} \pi r^3 = 4L_X^2 (2L_Z) f_p \]
(for 3D cell model)

Where \( r \) is the radius of the particles and \( f_p \) is the particle volume fraction.

Using the definition of cell aspect ratio, one can evaluate the minimal and the maximal values of cell aspect ratio for a given particle volume fraction. They are given below.

For Axisymmetric model

\[ \frac{2}{3} \pi r^3 = \pi L_R^2 (2L_Z) f_p \]

where \( f_p = \) Particle volume fraction

\[ r_{a_{\text{min}}} = \frac{\sqrt{2r^3}}{\sqrt{2L_Z^3} f_p} \]

\[ r_{a_{\text{max}}} = \frac{\sqrt{2r^3}}{r_{\text{min}} L_Z} \frac{1}{\sqrt{2L_Z^3} f_p} \]

\[ r_{a_{\text{max}}} = \frac{2}{\sqrt{3f_p}} \]  
(16)
\[ \pi = \pi (2) \]

Similarly for 3D Cell model

\[ r_{a}^{\text{max}} = \frac{\pi}{\sqrt{f_{v}}} \]

\[ r_{a}^{\text{min}} = \frac{3}{2} f_{v} \]

3.6. Axisymmetric Model

In this model we consider an elastic silicon carbide (SiC) inclusion and elastic-plastic aluminium (Al) matrix. The bonding between the inclusions and the matrix is assumed to be perfect, debonding on the inclusion-matrix interface is not studied. The flow stress can be calculated using the formula given below:

\[ \sigma_f = \sigma_0 + H (e_p^n) \]  

Where,

- \( \sigma_0 \) = Initial yield stress
- \( H \) = Co-efficient of hardening
- \( e_p \) = Strain value
- \( n \) = Power of hardening

Using the above equation 20, flow stress of composite for different volume fractions can be determined.

Up to a strain value of 0.001 the matrix is in elastic state. When the strain value becomes higher (about 0.02) the matrix will completely in plastic state. Figure 7 shows the strengthening effect of the composite for different composition.

It is clearly seen that the composite strengthens with increasing cell aspect ratio and softens with decreasing cell aspect ratio. In other words, the larger the distance between the stripes (or the more the degree of particle alignment) the more the composite strengthens in the stripe direction and the more it softens in the direction transverse to the stripe. The maximum and minimum values of the cell aspect ratios can be obtained from equations 16 to 19. The trend of the curve is obtained as per the study of D. Saradev and S. Schmauder [3].

3.7. 3D Cell Model

For this model, we consider the matrix material is in plastic state. To calculate the composite stress we use the formula;

\[ \sigma_z = f_r E_f e_z + (1 - f_r) [\sigma_0 + H (\varepsilon_{z p})^n] \]  

Where,

- \( f_r \) = Reinforcement volume fraction
- \( E_f \) = Young’s modulus of reinforcement material
- \( e_z \) = Composite strain value
- \( \sigma_0 \) = Initial yield stress
- \( H \) = Co-efficient of hardening
- \( \varepsilon_{z p} \) = Plastic strain value of matrix material
- \( n \) = Power of hardening

Figure 8 represents flow stress induced in the material for strain values ranging from 0.00 to 0.001. Since it is assumed that there is no residual stress in the material the first value of flow stress is taken as zero. Here as the composition of the reinforcement increases, the composite stress also increases.
The variation of composite stress with cell aspect ratio for 3D cell model is shown in figure 9. From the curve, we can see that when composition of reinforcement (percentage of SiC) is changed from 5% to 25%, the maximum value of composite stress is obtained for MMC with 5% of SiC. That is, as the material composition increases, the stress value is found to be decreasing. There is only a small change in composite stress is seen even if we increase the cell aspect ratio. This may be because of the change in matrix phase we considered for 3D cell model. For axisymmetric model, we considered the matrix material in elastic-plastic state, but in 3D cell model matrix material is assumed to be in plastic state. So the formula to find composite stress for 3D cell model is also changed accordingly.

4. Finite element stress analysis

4.1. Modelling the Connecting rod

Solid modelling software CATIA V5 R15 was used to create the model of connecting rod. Assembly design feature of CATIA V5 R15 was used for the modelling. The main body of the connecting rod, the big end cap and the bolts are modelled separately and assembled together. Figures 10, 11 and 12 represent three different parts modelled in CATIA V5 R15 software.

These parts are then assembled together using assembly design feature. Suitable constraints are used for assembling the three parts. The assembled view of the connecting rod is shown in figure 13.
14. Static structural stress analysis feature of ANSYS 14.0 is used for the study. Various properties of AISI 4140 steel and Al-SiC MMC used for analysis are enlisted in Table 2 shown below.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4140 Steel</td>
<td>2800 kg/m³</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>200</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>0.16667</td>
<td>GPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>76.923</td>
<td>GPa</td>
</tr>
<tr>
<td>Tensile Yield strength</td>
<td>250</td>
<td>MPa</td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>460</td>
<td>MPa</td>
</tr>
<tr>
<td>Compressive Yield Strength</td>
<td>250</td>
<td>MPa</td>
</tr>
<tr>
<td>Compressive Ultimate Strength</td>
<td>0</td>
<td>MPa</td>
</tr>
</tbody>
</table>

For the Finite element analysis, the connecting rod model created in CATIA V5 R15 software is converted into .igs format and then it imported into ANSYS 14.0 workbench. The imported model is meshed using automatic meshing method feature available in ANSYS 14.0. The meshed model is shown in Figure 15. Material properties are assigned as shown in Table 2. The forces acting on a connecting rod includes:

- Force on the piston due to gas pressure and inertia of reciprocating parts.
- Force due to inertia of the connecting rod (Inertia bending forces).
- Force due to piston pin bearing and crank pin bearing and
- Force due to friction of the piston rings and of the piston.

These forces found out analytically in section 2 are applied on the imported model of connecting rod.

Figure 14: Imported model of the connecting rod.

Figure 15: Meshed model of connecting rod

Force on the piston due to gas pressure and inertia of reciprocating parts is shown in Figure 16 and the force due to inertia of the connecting rod (Inertia bending forces) is shown in Figure 17.

Figure 16: Force due to gas pressure and inertia of reciprocating parts.

Figure 17: Inertia bending force.

Figure 18 represents force due to piston pin bearing and crank pin bearing.

Figure 18: Force due to piston pin bearing and crank pin bearing.
After applying forces, the boundary conditions are applied on the connecting rod model for stress analysis. Cylindrical support feature in ANSYS 14.0 workbench is used as boundary condition. It is shown in figure 19.

![Figure 19: Boundary conditions applied on the model.](image)

5. Results and discussions

The maximum Von Mises stress and deformation of the connecting rod under given forces is found out from finite element analysis. The total deformation obtained is $1.371 \times 10^{-6}$ mm and the maximum Von Mises stress is 8.189 N/mm$^2$. The value of maximum bending stress obtained by numerical analysis is 10.7 N/mm$^2$. We can see that the numerical result and finite element result are in good agreement. The small difference in both results may be due to the errors in applying boundary conditions or the modelling of the connecting rod itself. Total deformation and equivalent Von Mises stress of 4140 steel connecting rod are shown in figures 20 and 21.

![Figure 20: Total deformation of the connecting rod](image)

Various results such as Total Deformation, Equivalent Elastic Strain, Maximum Principal Elastic Strain, Maximum Shear Elastic Strain, Equivalent Von Mises Stress, Maximum Principal Stress, Shear Stress, Stress Intensity and Minimum Principal Stress are obtained from finite element analysis in ANSYS 14.0. These results are helpful in analyzing the compatibility of Al/SiC metal matrix composite as connecting rod material.

Results of finite element analysis of both AISI 4140 steel and Al-SiC MMC composite are shown in table 3.

<table>
<thead>
<tr>
<th>Result</th>
<th>4140 Alloy Steel</th>
<th>Al/SiC MMC</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Deformation</td>
<td>$1.371 \times 10^{-6}$</td>
<td>$1.987 \times 10^{-6}$</td>
<td>m</td>
</tr>
<tr>
<td>Equivalent Elastic Strain</td>
<td>$4.132 \times 10^{-2}$</td>
<td>$5.9612 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Max. Principal Elastic Strain</td>
<td>$2.0197 \times 10^{-2}$</td>
<td>$2.9271 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Max. Shear Elastic Strain</td>
<td>$5.5779 \times 10^{-3}$</td>
<td>$8.084 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Equivalent Von Mises Stress</td>
<td>8.1889</td>
<td>8.1889</td>
<td>MPa</td>
</tr>
</tbody>
</table>

![Figure 21: Equivalent Von Mises Stress](image)

Stress distribution and deformation of analysis with Al-SiC MMC is also shown here. Figure 22 represents total deformation and figure 23 represents equivalent Von Mises stress of the Al-SiC connecting rod.

<table>
<thead>
<tr>
<th>Figure 22: Total deformation Al/SiC MMC</th>
<th>Figure 23: Equivalent Von Mises stress Al/SiC MMC</th>
</tr>
</thead>
</table>

![Figure 22: Total deformation Al/SiC MMC](image)

![Figure 23: Equivalent Von Mises stress Al/SiC MMC](image)
Comparing the analysis on both Al-SiC MMC and AISI 4140 alloy steel, it is clear that when Al-SiC is used as the material the total deformation of connecting rod is very less. This shows the suitability of Al-SiC MMC for producing automobile connecting rods.

6. Conclusions

The value of bending stress calculated analytically in section 2 is 10.7 N/mm² and from finite element analysis, the equivalent stress value we obtained is 8.1889 N/mm². It means that the analytical value and the value obtained from finite element analysis are almost same. The small difference may be due to the errors in the model or errors in applied forces or boundary conditions. From table 3, it can be seen that for 4140 steel connecting rod the maximum value of total deformation is 1.371x10⁻⁵ m. But total deformation for Al-SiC connecting rod is only 1.987x10⁻⁶ m, which emphasize the suitability of Al-SiC MMC as the material that can be used to replace conventional connecting rod materials.

Comparing unit cell models, in the case of axisymmetric cell model, it can be inferred that as the composition of reinforcement increases the ultimate yield value of composite stress is also seen increased. But in the case of 3D cell model, the trend is opposite to that of axisymmetric model. This may be because we considered the matrix phase of 3D cell model in plastic state. Based on these results, it can conclude that Al-SiC metal matrix composites are suitable for replacing conventional AISI 4140 alloy steel used for producing automobile connecting rods.

7. Acknowledgements

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