

Fabrication, Material and Design Modification based Analysis of Connecting Rod Using FEA

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Abstract- Connecting rod is a critical element in an automotive power transmission system, being the kinematic link between the piston and the crankshaft. It is used to convert the reciprocating motion of the piston to the rotary motion of the crankshaft. In the present study, the stress and deformation analysis of the connecting rod has been carried out, and viable changes in three domains, namely the manufacturing processes, material and design of the connecting rod, have been proposed. Under the head of manufacturing processes, different processes including forging and sintering have been discussed. Effect of shot peening on fatigue strength and heat treatment on the overall performance of the connecting rod have been taken into account. Newer and more efficient materials, namely C-70 steel, Micro-alloyed steels and aluminium based composites with particle and fiber reinforcements have been tested. Lastly, the design of the connecting rod has been modified to get the best combination of overall stress, stress concentration and deformation. In this process, areas of high stress concentrations are identified and attempts have been made to relieve stresses in these sections. Modifications in each of the above mentioned stages have led to stress and weight reduction and increase in the stiffness, thus enhancing the overall performance of the connecting rod.

Static and fatigue analysis has been carried out in ANSYS 15.0 Workbench. Output parameters including Von Mises stress, total deformation, factor of safety, fatigue life and fatigue factor of safety have been used for comparative study of the modified models and their existing counterparts.

Index Terms- Connecting rod, FEA, Forging, Sintering, Peening, MMCs, Fatigue

1. INTRODUCTION

Connecting rod is one of the most critical element of the engine assembly acting as a link between the piston and the crankshaft. One end of the connecting rod, known as the small end is connected to the piston by means of a gudgeon pin, while the big end is connected to the crankshaft by means of a crank pin. Connecting rod is subjected to tensile and compressive loading which are cyclic in nature. Hence, the connecting rod is generally subjected to fatigue failure. However, a static structural analysis may be used for comparison purposes. In this paper, both static and fatigue analysis has been carried out as per requirement.

Connecting rods are generally manufactured through steel forging, which is both efficient and cost-effective. However due to high expenditure of subsequent machining and crackability problems, powder metallurgy is slowly gaining wide acceptance. Casting may also be used as the manufacturing process, but the formation of blowholes during casting greatly reduce the fatigue strength of the final product. The materials used for connecting rod include steel (strength and low cost), aluminium (lightness and ability to absorb impact

loads) and titanium (used in high performance engines where the high costs are justified). The cross-section of the connecting rod is generally of I section or H-section.

There is a scope of modification at various stages in the production of the connecting rod. Effective implementation of these modifications serve the purpose of effective reduction in weight, increase in durability, reduction in fuel consumption and less emission. Since connecting rods are manufactured in the industry on a large scale, a small reduction in weight has a massive impact on the reduction in overall costs.

2. LITERATURE REVIEW

Kadiam Bhargav [1] et al, carried out a comparative structural and thermal analysis of connecting rods manufactured by forging and sintering. The conclusion drawn from the project was that the maximum stress produced in sintered connecting rod is much higher than the connecting rod manufactured by forging. Kuldeep B [2] et al, carried out analysis and optimization of connecting

rod made of AlFASiC composites and concluded that the composite connecting rod has higher strength and stiffness and is comparatively lighter than its counterpart made of Al-360. Mr. Vivek T. Fegade [3] et al, in his paper concluded that insertion of titanium strips on both sides of shank in steel connecting rod increases the strength and stiffness. Mithilesh K Lade [5] et al, carried out static load analysis of a carbon fiber connecting rod. An increase in strength and stiffness and reduction in weight (about 50%) was observed for carbon fiber as compared to the Aluminium alloy 7075 connecting rod. Hitesh Kumar [6] et al, in his paper tested AISI 1045 Carbon Steel and AISI 4340 Alloy steel as the constituent material of the connecting rod and observed that value of Von-Mises stress is less for AISI 4340 steel than AISI 1045 carbon steel. Shenoy P.S. and Fatemi A [7], in their research, ventured to optimize the connecting rod for weight and cost reduction towards the end of large scale savings. Adila Afzal [8], in her master's thesis, investigated the fatigue behaviour of forged steel and powder metal connecting rods and elucidated the pros and cons of each process based on

strength, stiffness, crackability, durability, manufacturing costs amongst other parameters. Tarun Kumar Reddy [9] et al, performed the optimization of connecting rod for reduced weight and demonstrated that the weight of connecting rod for forged steel is considerably less than carbon steel. Vikram A Shedge [10] et al, modified the design of connecting rod by means of topological optimization on the basis of static and fatigue analysis. Shahrukh Shamim [11], employed E-glass epoxy resin and Aluminium-Carbon nano-tube composites as material for connecting rod. Parameters namely Von-Mises stress, total deformation, elastic strain, etc were tested for both the materials.

3. OBJECTIVE

The main objective of this paper is to modify and optimize the connecting rod in terms of manufacturing process, constituent material and design for enhancing performance and reducing weight. To achieve the final objective, the scope of the paper is as follows:-

- (1) To develop a geometric model of the connecting rod based on standard dimensions in modelling software CATIA V5R20.
- (2) To substantiate the advantages of crackable C-70 steel and micro-alloyed steel over conventional manufacturing processes.

- (3) To demonstrate the effect of shot peening on fatigue strength and subsequent heat treatment on overall performance and weight of connecting rod
- (4) To analyse metal matrix composites with particle and fiber reinforcements in the light of lower weight and increased stiffness.
- (5) To identify sections of high stress concentration and make provisions in design to relieve these stresses.

Effects of each of the above modifications have been shown through a comparative static and fatigue structural analysis carried out in the FEM software ANSYS. The output parameters include Von Mises stress, total deformation, factor of safety, fatigue life and fatigue factor of safety.

4. DESIGN OF CONNECTING ROD

The design of the connecting rod has been done on the basis of dimensions calculated analytically from the forces acting in a standard single cylinder petrol engine. The forces acting on the connecting rod include:-

- (1) Force due to combustion pressure on piston
- (2) Inertia of the reciprocating parts
- (3) Friction of the piston rings and the piston
- (4) Friction at the piston pin bearing and crank pin bearing

4. INPUT PARAMETERS FOR DESIGN:

Table 1. Input parameters

Diameter of piston	57 mm
Length of connecting rod	200 mm
Mass of the reciprocating parts	1.6 Kg
Stroke	58.6 mm
Speed	8500 rpm
Compression ratio	9.35
Combustion pressure	16 MPa

The output parameters required for designing the model of connecting rod are calculated from the following formula:-

$$\text{Force acting on piston due to combustion pressure } (F_g) = \pi d^2 / 4 \times (\text{Combustion pressure}) \quad (1)$$

$$\text{Inertia load on the piston } (F_i) = m\omega^2 r (1 + 1/n) \quad (n = l/r) \quad (2)$$

$$\text{Buckling load } (F) = F_g - F_i \quad (3)$$

$$\text{Rankine's formula : } F = (C \times A) / [1 + a(L/K_{xx})^2] \quad (4)$$

where C = compressive yield stress

$$A = \text{Area of cross section} = 11(t^2) \quad (5)$$

$$K_{xx} = \text{Radius of gyration about x-axis} = 1.78 t \quad (6)$$

$a= 0.002(7)$

5. OUTPUT PARAMETERS

Table 2. Output parameters

Thickness of the connecting rod(t)	4.5 mm
Width of the section	18 mm
Height of the section	22.5 mm
Height at the crank end	34 mm
Height at the piston end	32 mm
Inner diameter of the piston end	24 mm
Outer diameter of the piston end	38 mm
Inner diameter of the crank end	58 mm
Outer diameter of the crank end	78 mm

6. MODELLING OF CONNECTING ROD

The model of the connecting rod was designed in the modelling software CATIA V5R20 in accordance with the dimensions obtained in the preceding discussion. The 3D model of the connecting rod is as shown in Fig.1.

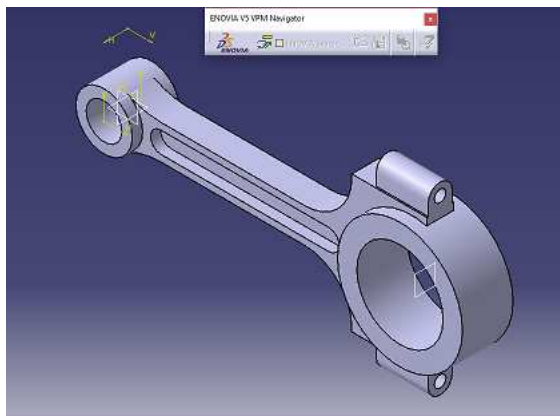


Fig.1. Model of connecting rod

7. MESHING OF CONNECTING ROD

A finite element tetrahedral mesh was generated with a global element size of 2 mm. The meshed model of the connecting rod is as shown in Fig.2.

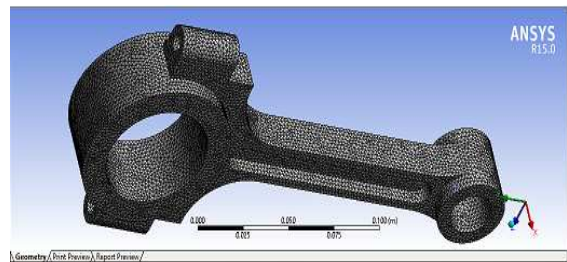


Fig. 2. Meshed model of connecting rod

8. LOADS AND CONSTRAINTS

- (1) All degrees of freedom were constrained at the crank end.
- (2) For static structural analysis, an axial compressive load of 30188 N was applied at the piston end .This force was calculated as the resultant of force due to combustion pressure(corresponding to a combustion pressure of 16MPa) and force due to inertia of the reciprocating masses.
- (3) For fatigue structural analysis, the piston end was subjected to a fully reversed load of 30188 N with crank end fixed.

The application of fixed support on crank end and force on piston end is shown in Fig.3 and Fig.4 respectively.

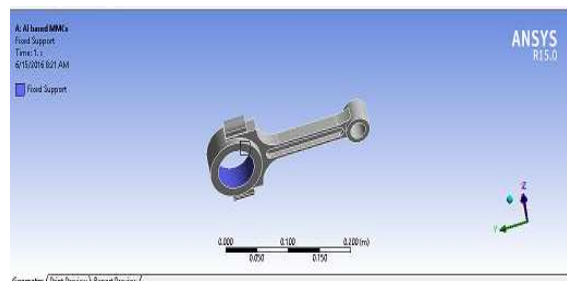


Fig. 3. Fixed support on crank end

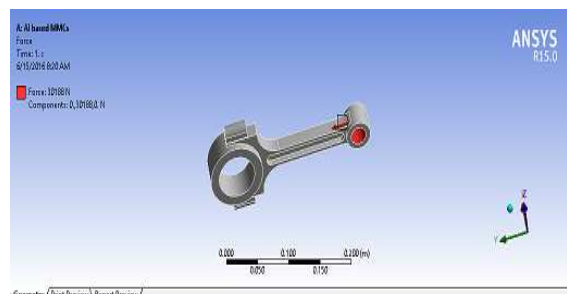


Fig. 4. Force on piston end

9. MANUFACTURING PROCESS

9.1. Primary manufacturing process

Forging and sintering are the conventional processes for manufacture of the connecting rod.

(1) **Forging** is a plastic deformation process in which the final part is made by the application of pressure to a metal billet at room temperature (cold forging) or elevated temperatures (hot forging). The connecting rod made of forged steel has high stiffness, good toughness, resistance to impact and fatigue. The factor of safety and total deformation may be calculated using FEA as shown in Fig.5 and Fig.6.

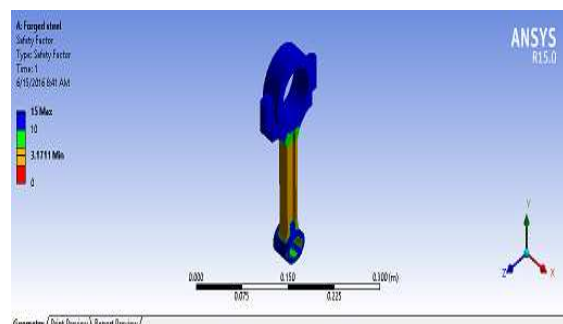


Fig. 5. Safety factor (Forged con rod)

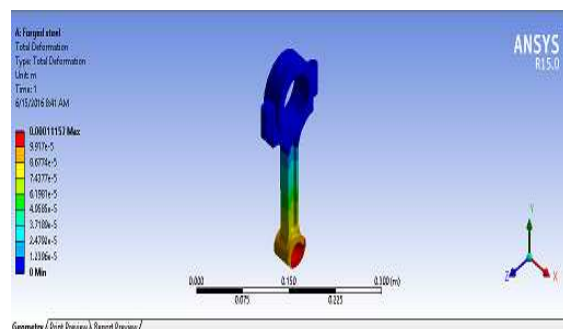


Fig. 6. Total deformation (Forged con rod)

Problem Specification: The cap of the connecting rod must be separated from the rod to incorporate the rod in the piston assembly. This may be accomplished by means of fracture splitting. The major problem is that extensive machining is required after fracture splitting leading to higher production costs.

(2) **Powder metallurgy** is the process in which the metal powder is compacted under ambient temperature and very high pressure to achieve the final shape. Advantages include near net shape manufacturing and easy crackability (that accounts for easy separation of the cap from the rod).

Problem Specification: The cost of manufacturing is very high due to a large number of secondary processes involved. Moreover, the strength and stiffness of the rod is less than that of forged rod, as may be validated from the FEA diagrams below (Fig.7 and Fig.8).

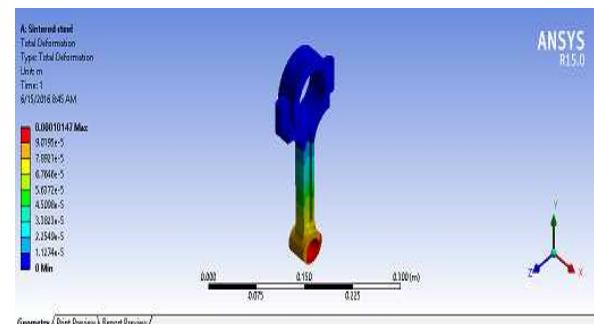


Fig. 7. Total deformation (Sintered con rod)

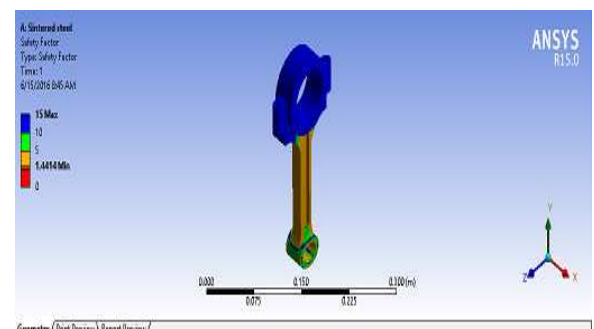


Fig. 8. Safety factor (Sintered con rod)

The two problems associated with the conventional manufacturing processes are addressed by the introduction of two new materials, namely :-

a) C-70(Crackable Steel)

C-70 crackable steel is a form of high carbon micro-alloyed steel, main alloying elements being silicon, phosphorus, sulphur, manganese and vanadium shots. These steels provide for easy fracture splitting, besides incurring low manufacturing costs and high strength and stiffness compared to steel forged and powder forged connecting rod.

b) A-656(Micro-alloyed Steel)

A-656 steel is a series of high strength, low alloy, hot-rolled steels with an excellent combination of strength and formability and is suitable for applications where high strength to weight ratios are required. A small quantity of vanadium is added to obtain a refined grain size. Higher weldability and formability of these

steels is a veritable factor in cutting down the machining costs.

Table 3. Material properties

Material properties	C-70 Steel	Micro-alloyed steel
Density(Kg/m ³)	7850	7850
Modulus of elasticity(GPa)	212	206
Poisson's ratio	0.33	0.29
Yield strength(MPa)	574	550
Ultimate tensile strength(MPa)	966	655

The FEA diagrams of total deformation and safety factor for C-70 Steel (Fig.9 and Fig.10) and Micro-alloyed steel (Fig.11 and Fig.12) are shown below:

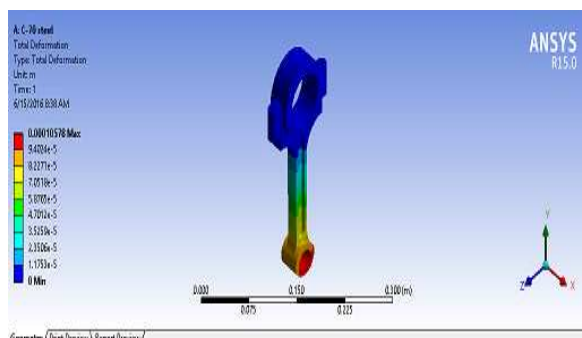


Fig. 9. Total deformation(C-70 Steel)

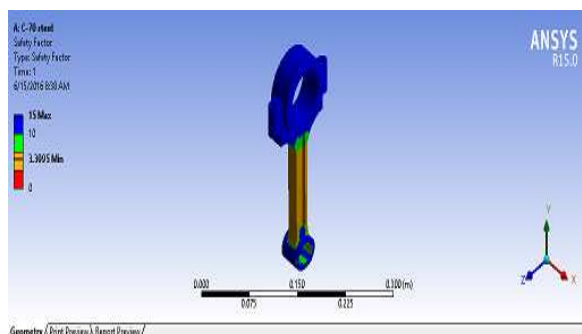


Fig. 10. Safety factor(C-70 Steel)

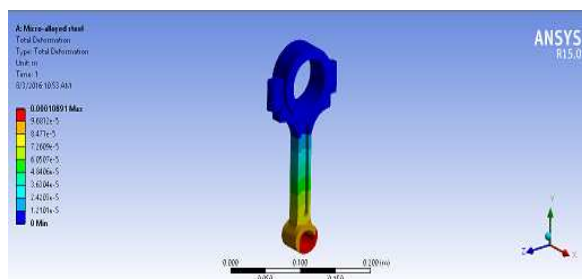


Fig. 11. Total deformation (Micro-alloyed steel)

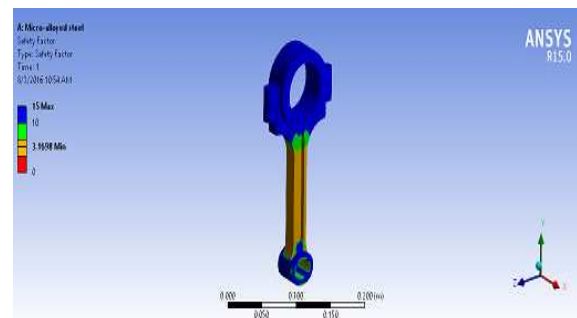


Fig. 12. Safety factor (Micro-alloyed steel)

Table 4:A comparative study of the strength and stiffness of the connecting rod manufactured by the above mentioned processes was made in the tabular form:

Materials	Strength (N)	Stiffness(N/mm)	Optimized model weight(kg)
Forged steel	95729.166	134.686	1.4353
Sintered steel	43512	139.768	1.4457
C-70 steel	99907.186	141.882	1.4084
Micro alloyed steel	95689.922	137.804	1.4084

In the conventional manufacturing processes, forged connecting rod has higher strength and lower weight than sintered connecting rod but incur higher machining costs due to crackability problems. Advanced materials, C-70 (Crackable) steel and Micro-alloyed steel, besides addressing the problem of crackability, exhibit a desirable edge over conventional processes in terms of strength, stiffness and weight.

9.2 Shot peening and Subsequent heat treatment

9.2.1 Shot peening

Shot peening is the process by which the surface of the structural material is impacted by small particles, called shots. As a result of this process, residual stresses are produced on the surface. These residual stresses arrest the propagation of micro-cracks and consequently enhance the fatigue strength of the material.

The increase in fatigue strength of the connecting rod has been demonstrated by the following analysis. Steel shots have been used for peening the surface of the connecting rod.

FATIGUE DATA :

AISI 4340-[Infinite life=1E6 cycles]	
Cycles	Alternating stress(MPa)
6000	1378
88000	1000
98000	937
740000	874
980000	858
1000000	852

AISI 4340(Shot peened)-[Infinite Life=1E7 cycles]	
Cycles	Alternating stress(MPa)
8000	1382
62000	1138
300000	1030
8000000	866
10000000	859

The fatigue life and fatigue factor of safety for steel(before shot peening) i.e.Fig.13 and Fig.14, and steel(after shot peening) i.e.Fig.15 and Fig.16 have been shown below.

Before shot peening:

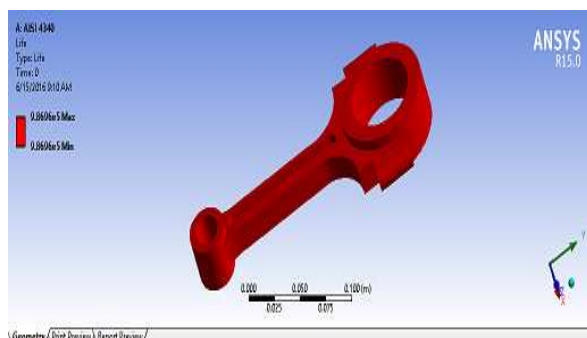


Fig.13. Fatigue life

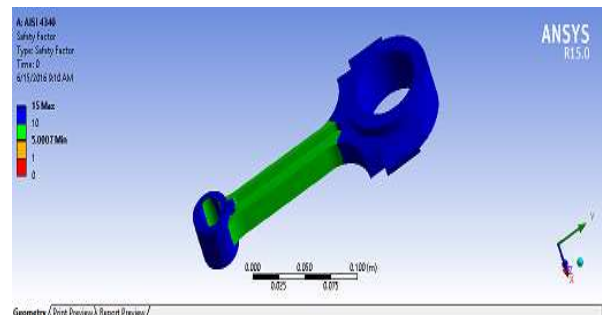


Fig.14. Fatigue safety factor

After shot peening:

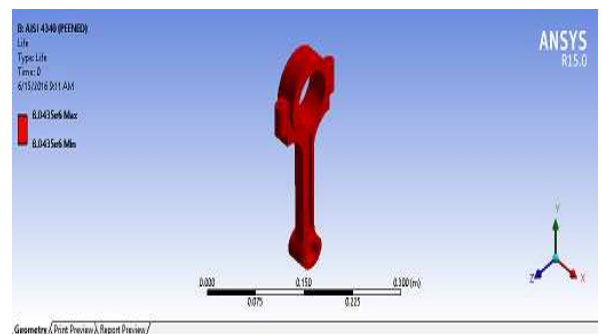


Fig.15. Fatigue life

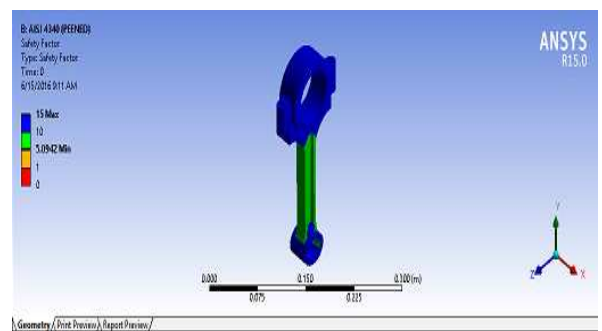


Fig.16. Fatigue safety factor

Results :

Shot peening has a desirable effect of enhancing the fatigue life and fatigue factor of safety of connecting rod. A 7.15% increase in fatigue life as a result of shot peening may be observed from the table.

Table 5. Effect of shot peening

Materials	Fatigue life(cycles)	Factor of safety
Steel(without shot peening)	9.869e5	5.007
Steel(Shot peened)	8.043e6	5.0942

9.2.2 Heat treatment

Shot peening results in residual compressive stresses on the surface of the connecting rod. These stresses are relieved by heating the material to a temperature below the critical temperature and then cooling uniformly. The aforesaid heat relieving technique serves to enhance the strength and stiffness of the connecting rod.

The FEA diagrams before and after the process have been shown below, output parameters involving total deformation (Fig.17 and Fig.19) and factor of safety (Fig.18 and Fig.20).

Before heat treatment :

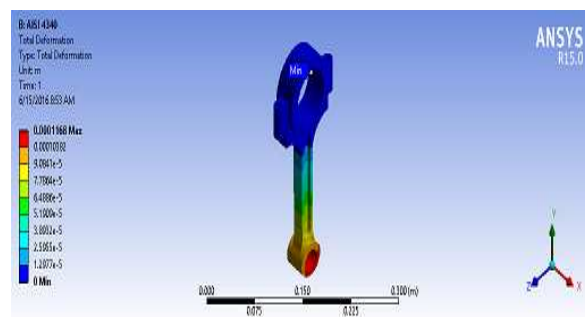


Fig.17. Total deformation

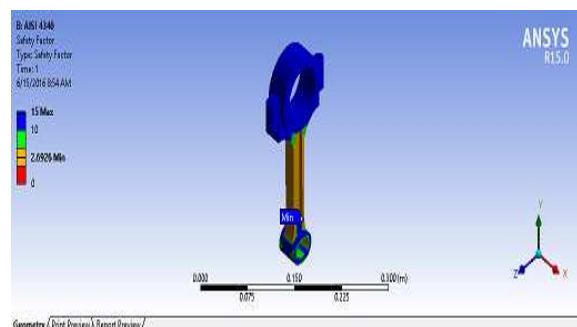


Fig.18. Factor of safety

After heat treatment :

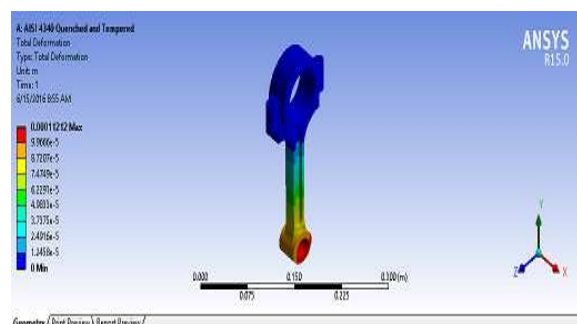


Fig.19. Total deformation

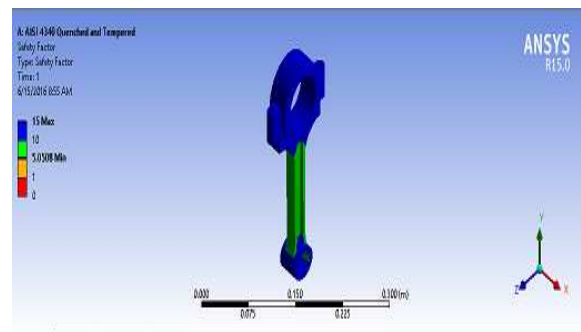


Fig.20. Factor of safety

Results :

An increase in strength and stiffness has been observed as a result of the elimination of residual stresses from the surface of connecting rod by heat treatment process.

Table 6. Effect of heat treatment

Heat treatment	Strength(N)	Stiffness(N/mm)
Before	81.2845	128.495
After	152.473	133.859

10. MATERIALS

Structural steel and aluminium are the conventional materials used for the manufacture of the connecting rod. In recent times, metal matrix composites(MMCs) have opened up new possibilities for achieving enhanced mechanical properties at a lower cost. In this paper, the materials tested constitute the following:-

- (1) **Al-6061** -Aluminum alloy 6061 is a precipitation hardened aluminium alloy, containing magnesium and silicon as its major alloying elements.
- (2) **Al-15% Al₂O₃**- MMC with aluminium as the metal matrix with alumina reinforcements in form of continuous fibres.
- (3) **Al-10%SiC** - Aluminium metal matrix with silicon carbide reinforcements in the form of whiskers.

Table 7. Material properties

Materials	Al-6061	Al-15%Al ₂ O ₃	Al-10%SiC
Density(kg/m ³)	2700	2890	2730
Young's Modulus(Gpa)	68.9	119.63	93.7
Poisson's ratio	0.33	0.33	0.33
Tensile strength(MPa)	276	173	233
Behaviour	Isotropic	Isotropic	Isotropic

The Von-Mises stress and total deformation for each of the test materials discussed in the previous section, may be validated from the FEA diagrams below.

Al-6061:

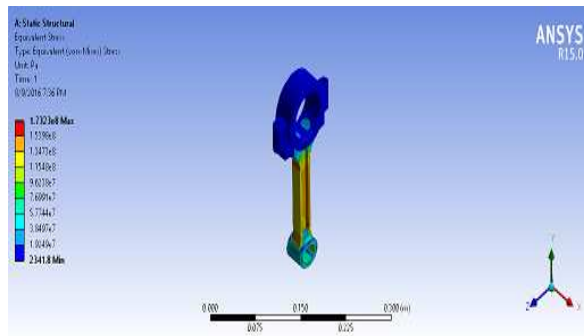


Fig.21. Von-Mises stress

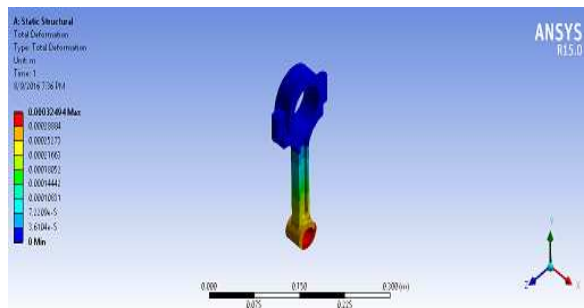


Fig.22. Total deformation

Al-15%Al₂O₃:

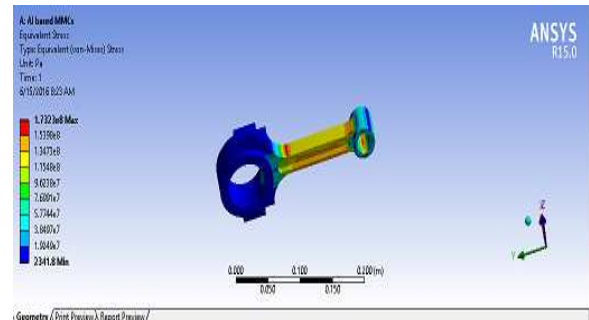


Fig.23. Von-Mises stress

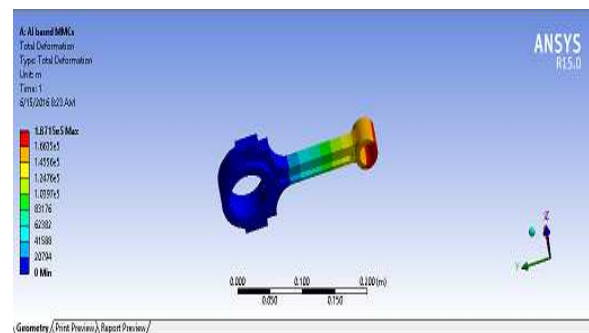


Fig.24. Total deformation

Al-10%SiC:

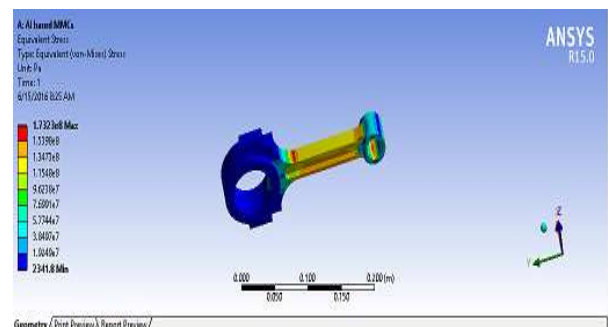


Fig.25. Von-Mises stress

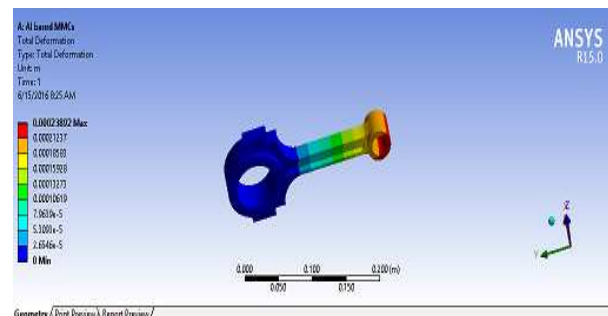


Fig.26. Total deformation

Results:

The replacement of conventional Al-6061 by aluminium based composites has led to a patent increment in the stiffness and reduction in weight of the connecting rod. Moreover, introduction of MMCs as the constituent material for the connecting rod will open up new and infinite number of possibilities for the manufacture of high performance connecting rods at lower costs.

Table 8. Stiffness and weight for different materials

Materials	Stiffness (N/mm)	Weight(kg)
Aluminum alloy-6061	15.885	0.52619
Al-15% Al ₂ O ₃	21.964	0.56322
Al-10% SiC	21.845	0.53204

11. DESIGN MODIFICATION

The forces in the connecting rod produce very high stresses in the shank region at the two ends. The non-uniform distribution of the stresses in this region also alleviate the chances of failure of the shank of the connecting rod. This condition may be demonstrated by the following stress analysis diagram of structural steel connecting rod (Fig.27)

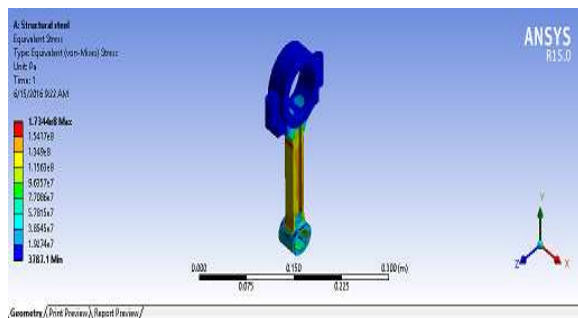


Fig.27. Von-mises stress (structural steel)

The stresses may be released by cutting small holes at appropriate locations. The holes are coated with titanium to provide extra strength as these holes become the centers of stress concentration. The diagram below shows the condition of stresses in the modified design:

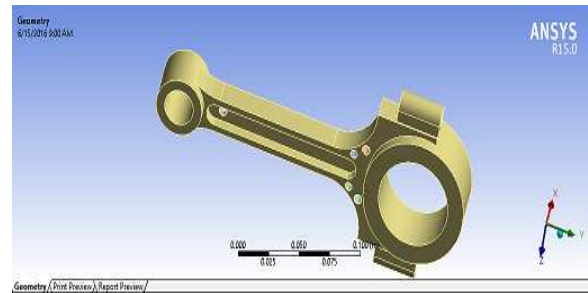


Fig.28. Modified design of connecting rod

FEA diagrams of the modified model:

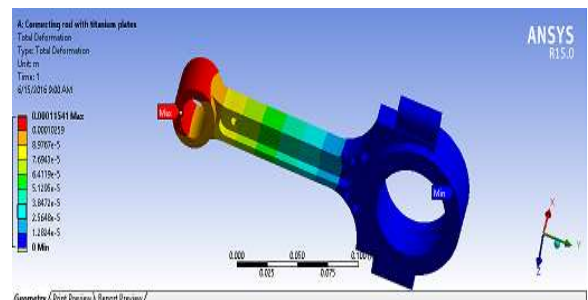


Fig.29. Total deformation

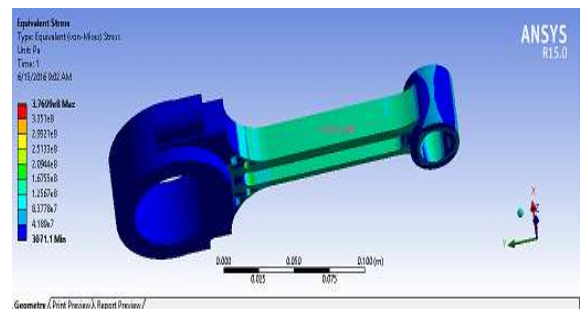


Fig.30. Von-Mises stress

The FEAdiagram shown in Fig.30 demonstrate that the stresses in the shank region for the modified model is less than that for the original model. The titanium coating provided on the holes ensure that crack initiation does not occur at the holes (due to stress concentration). The results may be shown in a tabular form as shown below:

Table 9. Effect of design modification

Design	Maximum stress in shank region(Pa)
Conventional model	1.7344E08
Modified model	1.6755E08

The stresses in the shank region for the modified model is less than that of the original values. There has been a 3.4 % reduction in the magnitude of stresses as may be calculated from the values listed in the table.

12. CONCLUSION

In this paper, modifications in the connecting rod in three areas namely, manufacturing process, material and design have been proposed. The results and validity of the discussed changes may be summarised as follows:

(1) Besides addressing the problem of crackability of connecting rod, advanced materials namely, C-70 (Crackable) steel and Micro-alloyed steel exhibit better combination of strength and stiffness than steel manufactured by forging and sintering. Weight reduction in the latter two cases compared to forged and sintered steel is also quite evident.

(2) Shot peening serves to increase the fatigue life and improves the fatigue strength of the model. The residual stresses produced on the surface as a result of shot peening may be relieved by subsequent heat treatment.

(3) The connecting rods made of metal matrix composites (namely, Al-15%Al₂O₃ and Al-10%SiC) have lower weight and higher stiffness than that manufactured by the conventional material (i.e. Al-6061).

(4) The stresses in the shank section may be reduced by machining small holes at appropriate locations in the connecting rod. There is 3.395% reduction in Maximum Von-Mises stress in the modified model.

(5) The stress distribution is more uniform in case of the modified model.

13. ACKNOWLEDGEMENT

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