Material optimization and structural analysis of internal combustion engine connecting rod and crank shaft

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Abstract- **In automobile industry most important part in internal combustion engine. The connecting rod and crank shaft are the main component. A connecting rod is a shaft which connects a pistons to crank is a mechanical part able to perform a conversion between reciprocating motion and rotational motion. crankshaft is to translate the linear reciprocating motion of a pistons into the rotational motion required by the automobile. optimization analysis of connecting rod and crankshaft is to study was to evaluate and compare the fatigue performance for automotive connecting rod and crankshafts, namely cast iron and aluminum. The design of the crankshaft and connecting rod mechanism of engine crank connecting rod mechanism. The paper comes up with the overall design of the crankshaft connecting rod mechanism through the analysis of force on the calculation and selection of the structure and size of the crankshaft. This project is taken for a Honda bike engine connecting rod and crank shaft. The scope of behalf is to material optimization and the design and analysis are carried in CREO software.**

1. INTRODUCTION

1.1 INTERNAL COMBUSTION ENGINE

In modern automotive internal combustion engines, the connecting rods are most usually made of steel for production engines, but can be made of T6-2024 and T651-7075 aluminum alloys (for lightness and the ability to absorb high impact at the expense of durability) or titanium (for a combination of lightness with strength, at higher cost) for high-performance engines, or of cast iron for applications such as motor scooters. They are not rigidly fixed at either end, so that the angle between the connecting rod and the piston can change as the rod moves up and down and rotates around the crankshaft. Connecting rods, especially in racing engines, may be called "billet" rods, if they are machined out of a solid billet of metal, rather than being cast or forged.

Large engines are usually multi cylinder to reduce pulsations from individual firing strokes, with more than one piston attached to a complex crankshaft. Many small engines, such as those found in mopeds or garden machinery, are single cylinder and use only a single piston, simplifying crankshaft design.

A crankshaft is subjected to enormous stresses, potentially equivalent of several tonnes of force. The crankshaft is connected to the fly-wheel (used to smooth out shock and convert energy to torque), the engine block, using bearings on the main journals, and to the pistons via their respective con-rods. An engine loses up to 75% of its generated energy in the form of friction, noise and vibration in the crankcase and piston area. The remaining losses occur in the valve train (timing chains, belts, pulleys, camshafts, lobes, valves, seals etc.) heat and blow.

The configuration, meaning the number of pistons and their placement in relation to each other leads to straight, V or flat engines. The same basic engine block can sometimes be used with different crankshafts, however, to alter the firing order. For instance, the 90° V6 engine configuration, in older day. sometimes derived by using six cylinders of a V8 engine with a 3 throw crankshaft, produces an engine with an inherent pulsation in the power flow due to the "gap" between the firing pulses alternates between short and long pauses because the 90 degree engine block does not correspond to the 120 degree spacing of the crankshaft. The same engine, however, can be made to provide evenly spaced power pulses by using a crankshaft with an individual crank throw for each cylinder, spaced.

1.2. CONNECTING ROD

A connecting rod is a shaft which connects a piston to a crank or crankshaft in a reciprocating engine. Together with the crank, it forms a simple mechanism that converts reciprocating motion into rotating motion.

A connecting rod may also convert rotating motion into reciprocating motion, its original use. Earlier mechanisms, such as the chain, could only impart pulling motion. Being rigid, a connecting rod may transmit either push or pull, allowing the rod to rotate the crank through both halves of a revolution. In a few two-stroke engines the connecting rod is only required to push.

Today, the connecting rod is best known through its use in internal combustion piston engines, such as automobile engines. These are of a distinctly different design from earlier forms of connecting rod used in steam engines and steam locomotives.

Small end and big end

The small end attaches to the piston pin, gudgeon pin or wrist pin, which is currently most often press fit into the connecting rod but can swivel in the piston, a "floating wrist pin" design.

The big end connects to the crankpin (bearing journal) on the crank throw, in most engines running on replaceable bearing shells accessible via the *connecting rod bolts* which hold the bearing "cap" onto the big end. Typically there is a pinhole bored through the bearing on the big end of the connecting rod so that pressurized lubricating motor oil squirts out onto the thrust side of the cylinder wall to lubricate the travel of the pistons and piston rings.

1.3 CRANK SHAFT

A crankshaft is a mechanical part able to perform a conversion between reciprocating motion and rotational motion. In a reciprocating engine, it translates reciprocating motion of the piston into rotational motion;

In a reciprocating compressor, it converts the rotational motion into reciprocating motion. In order to do the conversion between two motions, the crankshaft has "crank throws" or "crankpins", additional bearing surfaces whose axis is offset from that of the crank, to which the "big ends" of the connecting rods from each cylinder attach.

It is typically connected to a flywheel to reduce the pulsation characteristic of the four-stroke cycle, and sometimes a tensional or vibration damper at the opposite end, to reduce the tensional vibrations often caused along the length of the crankshaft by the cylinders farthest from the output end acting on the tensional elasticity of the metal.

The crankshaft has a linear axis about which it rotates, typically with several bearing journals riding on replaceable bearings (the main bearings) held in the engine block. As the crankshaft undergoes a great deal of sideways load from each cylinder in a multi cylinder engine, it must be supported by several such bearings, not just one at each end.

This was a factor in the rise of V8 engines, with their shorter crankshafts, in preference to straight-8 engines. The long crankshafts of the latter suffered from an unacceptable amount of flex when engine designers began using higher compression ratios and higher rotational speeds.

Despite the fact that most engineers and designers are aware of fatigue due to reversible cyclic loadings and a large amount of experimental data has been generated on the fatigue properties of various metallic and non-metallic materials, fatigue failures of engineering components are still common. The factors which influence the fatigue life of a component in service are

- complex stress cycles
- engineering design
- manufacturing and inspection
- service conditions and environment, and
- material of construction

The use of calculations and simulations is a key feature of the modern design process. Several properties such as stress, strength, stiffness, durability, handling, ride comfort and crash resistance, etc. can be numerically analyzed with varying levels of accuracy. Development time can be reduced by ensuring that some, or rather all, of these properties fulfil established requirements even before the first prototype is being built. Accordingly, calculations based on fatigue life and accurate loading histories permit structures and components to be optimized for durability without the need for expensive and time-consuming testing of series of prototypes. Thus, designs can be obtained that are less conservative (i.e., better optimized) than those based on traditional criteria, such as maximum load or stress for a series of standard load cases .

2. LITERACY SURVEY

Lu presented an approach to optimize the shape of a connecting rod subjected to a load cycle which consisted of the inertia load deducted from gas load as one extreme and peak inertia load exerted by the piston assembly mass as the other extreme. A FE routine is first used for calculating the displacements and stresses in the connecting rod, which are further used in another routine to calculate the total life.

Nana ware and Pable described a case study on the fatigue fracture of rear axle shafts of 575 DI tractors. The failure of rear axle shafts was due to inadequate spline root radius, which led to crack initiation and subsequent crack growth is by fatigue under the cyclic loading conditions of field operation. In general, the shafts in power plant systems run with a steady torsion combined with cyclic bending stress due to self-weight or weights of components or possible misalignment between journal bearings.

Ishida et al. measured the stress variation at the column centre and column bottom of the connecting rod, as well as the bending stress at the column centre. The plots, shown in Figure 1.4 indicate that at higher engine speeds, the peak tensile stress does not occur at 360o crank angle or at top dead centre. It is also observed that the R ratio varies with location as well as engine speed. The maximum bending stress magnitude over the entire cycle (0o to 720o crank angle) at 12000 rpm and at the column centre is found to be about 25% of the peak tensile stress over the same cycle.

M. Omid et al. performed FE analysis of U650 Tractor connecting rod on ANSYS software and concluded that under the reverse loading (tensile and compressive), the critical point is observed at node 46 (near the big end of the connecting rod). It is concluded that the fatigue life of connecting rod may be improved by reducing the stress concentration coefficient.

3. SOFTWARE USED

CREO

Creo is a family or suite of Computer-aided design (CAD) apps supporting product design for discrete manufacturers and is developed by PTC. The suite consists of apps, each delivering a distinct set of capabilities for a user role within product development.

Creo runs on Microsoft Windows and provides apps for 3D CAD parametric feature solid modeling, 3D direct modeling, 2D orthographic views, Finite Element Analysis and simulation, schematic design, technical illustrations, and viewing and visualization.

Creo Elements/Pro and Creo Parametric compete directly with CATIA, Siemens NX/Solid edge, and Solid Works. The Creo suite of apps replaces and supersedes PTC's products formerly known as Pro/ENGINEER, Co Create, and Product View.

4. PROPERTIES OF CONNECTING ROD

4.1 CONNECTING ROD MATERIALS

Commonly used as steel alloy, aluminum and titanium steel alloys like 42CrMo4, 43CrMo4, 44csr4, C-70,EN-8D, SAE1141, etc. It is steel that is alloyed with a variety of elements in total amounts between 1.0% and 50% by weight to improve its mechanical properties. Alloy steels are broken down arbitrarily Smith and Hashemi define the difference at 4.0%, while Degarmo, and define it at 8.0% .Most commonly, the phrase "alloy steel" refers to low-alloy steels.

Strictly speaking, every steel is an alloy, but not all steels are called "alloy steels". The simplest steels are iron (Fe) alloyed with carbon(C) (about 0.1% to 1%, depending on type). However, the term "alloy steel" is the standard term referring to steels with *other* alloying elements added deliberately *in addition to* the carbon. Common alloyants include manganese (the most common one), nickel, chromium, molybdenum, vanadium, sili con, and boron. Less common alloyants include aluminum, cobalt, copper, cerium, niobium, ti tanium, tungsten, tin, zinc, lead, and zirconium.

Aluminum alloys like T6-2024 and T651-7075 also light and has the ability to absorb high impact. It is alloys in which aluminium (Al) is the predominant metal. The typical alloying elements are copper, magnesium, manganese, silicon, tin and z inc. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable. About 85% of aluminium is used for wrought products, for example rolled plate, foils and extrusions. Cast aluminium alloys yield cost-effective products due to the low

melting point, although they generally have lower tensile strengths than wrought alloys. The most important cast aluminium alloy system is Al–Si, where the high levels of silicon (4.0–13%) contribute to give good casting characteristics. Aluminium alloys are widely used in engineering structures and components where light weight or corrosion resistance is required.

Titanium is used in high performance engines. It is light and strong, but comes at a higher cost. It is a chemical element with symbol Ti and atomic number 22. It is a lustrous transition metal with a silver color, low density, and high strength. Titanium is resistant to corrosion in sea water, aqua regia, and chlorine.

Cast Iron can be used for smaller applications like two wheelers. Cast iron is a group of iron-carbon alloys with a carbon content greater than 2% Its usefulness derives from its relatively low melting temperature. The alloy constituents affect its color when fractured: white cast iron has carbide impurities which allow cracks to pass straight through, grey cast iron has graphite flakes which deflect a passing crack and initiate countless new cracks as the material breaks, and ductile cast iron has spherical graphite "nodules" which stop the crack from further progressing.

Carbon (C) ranging from 1.8–4 wt%, and silicon (Si) 1–3 wt% are the main alloying elements of cast iron. Iron alloys with lower carbon content (~0.8%) are known as steel. While this technically makes the Fe–C–Si system ternary, the principle of cast iron solidification can be understood from the simpler binary iron–carbon phase diagram. Since the compositions of most cast irons are around the eutectic point (lowest liquid point) of the iron–carbon system, the melting temperatures usually range from 1,150 to 1,200 °C (2,100 to 2,190 °F), which is about 300 °C (540 °F) lower than the melting point of pure iron of 1,535 °C (2,795 °F).

- Galling, the process whereby cold-welding of material causes seizure, does not affect steel.
- Steel is no need to worry when inserting a bush, or when re-bushing con rods.
- The stiffness of steel is much higher than that of titanium.
- Its density of 7.85 g/cc, it is almost 80% more dense than a typical titanium.

4.2 PROPERTIES OF CRANK SHAFT
CRANK SHAFT MATERIALS

Manganese-molybdenum Steel is a relatively cheap forging steel and is used for moderate-duty petrol-engine crankshafts.

Chromium-molybdenum Steel is medium-to heavy-duty petrol- and diesel-engine crankshafts.

Nickel-chromium-molybdenum Steel is opted for heavy-duty diesel-engine applications.

Chromium-aluminium-molybdenum Steel is used for diesel-engine crankshafts suitable for bearing of hard high fatigue-strength materials.

Nodular Cast Irons is properties of grey cast iron(low melting point, excellent machinability ,wear resistance). Now-a-days crankshafts for both petrol and diesel engines are made nodular cast iron.

Medium-carbon steel alloys are composed of predominantly the element iron, and contain a small percentage of carbon (0.25% to 0.45%, described as "25 to 45 points" of carbon), along with combinations of several alloying elements, the mix of which has been carefully designed in order to produce specific qualities in the target alloy, including hardenability, nitridability, surface and core hardness, ultimate tensile strength, yield strength, endurance limit (fatigue strength), ductility, impact resistance, corrosion resistance, and temper-embrittlement resistance. The alloying elements typically used in these carbon steels are manganese, chromium, molybdenum, nickel, silicon, cobalt, vanadium, and sometimes aluminium and titanium. Each of those elements adds specific properties in a given material. The carbon content is the main determinant of the ultimate strength and hardness to which such an alloy can be heat treated.

MATERIAL "AL 2014" PROPERTIES

PROPERTY	VALUE
Structural type	Isotropic
Density	0.100924[ibm/(in^3)]
Young's modulus	4.09254e+09[ibm/(in sec^2)]
Poisson's ratio	0.33
Shear stiffness	1.53855e+09[ibm/(in sec^2)]
Failure criteria	None
Thermal expansion	1.28e+06[/F]
Thermal type	Isotropic
Conductivity	9266.13[in ibm/(sec^3 F)]
Specific heat	829900[in^2/(sec^2F)]

MATERIAL "FE60" PROPERTIES

PROPERTIES	VALUE
Structural type	Isotropic
Density	0.269799[ibm/in^3]
Young's modulus	7.33568e+09[ibm/(in sec^2)]
Poisson's ratio	0.25
Shear stiffness	2.93427e+09[ibm/(in sec^2)]
Failure criteria	None
Thermal expansion	6e*06[/F]
Thermal type	Isotropic
Conductivity	2508.8[in ibm/(sec^3 F)]
Specific heat	361900[in^2/(sec^2 F)]

5.DESIGN

1. Connecting rod

A connecting rod is a machine member which is subjected to alternating direct compressive and tensile forces. Since the compressive forces are much higher than the tensile force, therefore the cross-section of the connecting rod is designed as a strut and the rankine formula is used. A connecting rod subjected to an axial load W may buckle with x-axis as neutral axis in the plane of motion of the connecting rod,{or} y-axis is a neutral axis. The connecting rod is considered like both ends hinged for buckling about x-axis and both ends fixed for buckling about y-axis. A connecting rod should be equally strong in buckling about either axis. According to rankine formulae

Wcr about x-axis

$$= \frac{[\sigma c \times A]}{1 + a\left[\frac{L}{Kxx}\right]2} = \frac{[\sigma c \times A]}{1 + a\left[\frac{t}{Kxx}\right]2}$$

$[\because \text{ for bothends fixed } L = l/2]$

Wcr about y-axis

$$= \frac{[\sigma c \times A]}{1 + a\left[\frac{L}{Kyy}\right]2} = \frac{[\sigma c \times A]}{1 + a\left[\frac{t}{2Kyy}\right]2}$$

$[\because \text{ for both ends } L = l/2]$

In order to have a connecting rod equally strong in buckling about both the axis, buckling load must be equal .i.e,

$$= \frac{[\sigma c \times A]}{1 + a\left[\frac{L}{Kxx}\right]2} = \frac{[\sigma c \times A]}{1 + a\left[\frac{t}{2Kyy}\right]2}$$

$$\left[\frac{t}{Kxx}\right]2 = \left[\frac{t}{2Kyy}\right]2$$

K2xx = 4K2yy   [or] I xx = 4Iyy   [$\because I=A \times K2$]
This shows that the connecting rod is four times strong in buckling about y-axis than about-axis. If I xx > 4Iyy, Then buckling will occur about y-axis and if I xx < 4Iyy, then buckling will occur about x-axis .In Actual practice I xx is kept slightly less than 4Iyy. It is usually taken between 3 and 3.5 and the Connecting rod is designed for buckling about x-axis. The design will always be satisfactory for buckling about y-axis. The most suitable section for the connecting rod is I-section with the proportions shown mfg.

Area of the cross section = 2[4t x t] + 3t x t=11t2
Moment of inertia about x-axis = 2[4txt]+3txt=11t2
Moment of inertia about x-axis

$$Ixx = \frac{1}{12}[4t\{5t\}^3 - 3t\{3t\}^3] = \frac{419}{12}[t^4]$$

Moment of inertia about y-axis

$$Iyy = \frac{2 \times 1}{12} \times t \times \{4t\}^3 + \frac{1}{12}\{3t\}t^3 = \frac{131}{12}[t^4]$$

Ixx/Iyy=[419/12]×[12/131]=3.2
Since the value of I xx/I yy lies between 3 and 3.5 m therefore I-section chosen is quite satisfactory.
Pressure Calculation for 150cc Engine
Engine type air cooled 4-stroke
Bore x Stroke (mm) = 57×58.6
Displacement = 149.5 CC
Maximum Power = 13.8 bhp @ 8500 rpm
Maximum Torque = 13.4 Nm @ 6000 rpm
Compression Ratio = 9.35/1
Density of Petrol C8H18 = 737.22 kg/m3
= 737.22E-9 kg/mm3
Temperature = 60* F   = 288.855* K
Mass = Density × Volume
= 737.22E-9 x149.5E3
= 0.11kg
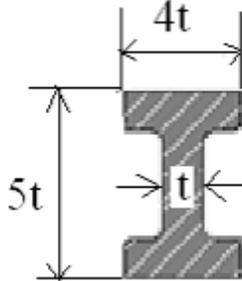Molecular Weight of Petrol 114.228 g/mole
From Gas Equation,
PV = Mrt R

$$= \frac{Rx}{Mw}$$

= 8.3143/114228 =72.76

$$P = \frac{(0.11 \times 72.786 \times 288.85)}{149.5E^3}$$

P=15.5Mpa

Design calculation for existing connecting rod

Thickness of flange & web of the section = t

Width of section B= 4t

The standard dimension of I - SECTION.

Height of section H = 5t

Area of section A= 2(4t×t) +3t×t

A = 11t²

M.O.I of section about x axis:

$$Ixx = \frac{1}{12}[4t\{5t\}^3 - 3t\{3t\}^3]$$

$$= \frac{419}{12}[t^4]$$

MI of section about y axis:

$$Iyy = \frac{2 \times 1}{12} \times t \times \{4t\}^3 + \frac{1}{12}\{3t\} 3t^3$$

$$= \frac{131}{12}[t]^4$$

$$\frac{Ixx}{Iyy} = 3.2$$

Length of connecting rod (L) = 2 times the stroke

L = 117.2 mm

Buckling load WB = maximum gas force × F.O.S

$$Wb = \frac{(\sigma c \times A)}{(1 + a(L/Kxx)2)}$$

=37663N

σc= compressive yield stress = 415MPa

$$Kxx = \frac{Ixx}{A}$$

Kxx=1.78t

$$a = \frac{\sigma c}{\pi^2 E}$$

a=0.0002

By substituting σc, A, a, L, Kxx on WB then

= 4565t4-37663t2-81639.46 = 0

t2 = 10.03

t = 3.167mm

t = 3.2mm

Width of section B = 4t

= 4×3.2

= 12.8mm

Height of section H = 5t

= 5×3.

= 16mm

Area A = 11t2

=11×3.2×3.2

= 112.64mm2

Height at the big end (crank end) = H2

= 1.1H to 1.25H

= 1.1×16

H2 =17.6mm

Height at the small end (piston end) = 0.9H to 0.75H

= 0.9×16

H1 =12mm

Stroke length (l) =117.2mm

Diameter of piston (D) =57mm

P=15.5N/mm2

Radius of crank(r) =stroke length/2

=58.6/2

=29.3

Maximum force on the piston due to pressure

Fl = π4xD2xp

=π/4 x (57)2x15.469

=39473.16N

Maximum angular speed Wmax= $\frac{[2\pi Nmax]}{60}$

$$= \frac{[2\pi \times 8500]}{60} A = \pi r^2$$

=768 rad/sec

Ratio of the length of connecting rod to the radius of crank

N=1/r=112/(29.8)=3.8

Maximum inertia force of reciprocating parts

$$F_{in} = Mr(Wmax)^2 r \left(\cos\theta + \frac{\cos 2\theta}{n}\right) (or)$$

$$F_{in} = Mr(Wmax)^2 r \left(1 + \frac{1}{n}\right)$$

=0.11=

$$0.1 \times (768)^2 \times (0.0293) \times (1 + \left(\frac{1}{3.8}\right))$$

F_{in} =2376.26N

Inner diameter of the small end d1= $\frac{F_g}{pb1 \times l1}$

$$\frac{6277.167}{12.5 \times 1.5 d1}$$

=17.94mm

Where,

Design bearing pressure for small end pb1=12.5 to 15.4N/mm2

Length of the piston pin l1= (1.5to 2) d1

Outer diameter of the small end = d1+2tb+2tm

= 17.94 + [2×2] + [2×5]

= 31.94mm

Where,

Thickness of the bush (tb) = 2 to 5 mm

Marginal thickness (tm) = 5 to 15 mm

Inner diameter of the big end $d2 = \frac{F_g}{pb2 \times l2}$

$$= \frac{6277.167}{10.8 \times 1.0 d2}$$

=23.88mm

Where, Design bearing pressure for big end pb2 = 10.8 to 12.6N/mm2

Length of the crank pin l2=(1.0 to 1.25) d2

Root diameter of the bolt $= \left(\frac{(2f_{in})}{(\pi xst)}\right) 1/2$

$$= \left(\frac{2 \times 6277.167}{\pi \times 56.667}\right) 1/2$$

=4mm

Outer diameter of the big end = d2 + 2tb + 2db +2tm

= 23.88+2×2+2×4+2×5 = 47.72mm

Where,

Thickness of the bush [tb] = 2 to 5 mm

Marginal thickness [tm] = 5 to 15 mm

Nominal diameter of bolt [db] = 1.2 x root diameter of the bolt

=1.2×4=4.8mm

Connecting rod parameters

| Parameters	Diameter(mm)
Thickness of the connecting rod	3.2
Width of the section (B=4t)	12.8
Height of the section (H=5t)	16
Height of the section (H=5t)	16
Height of the big end	1.1 to 1.125=17.6
Height of the small end	0.9-0.75H=14.4
Inner diameter of the small end	17.94
Outer diameter of the small end	31.94
Inner diameter of the big end	23.88
Outer diameter of the big end	47.72

Connecting rod in 2-D
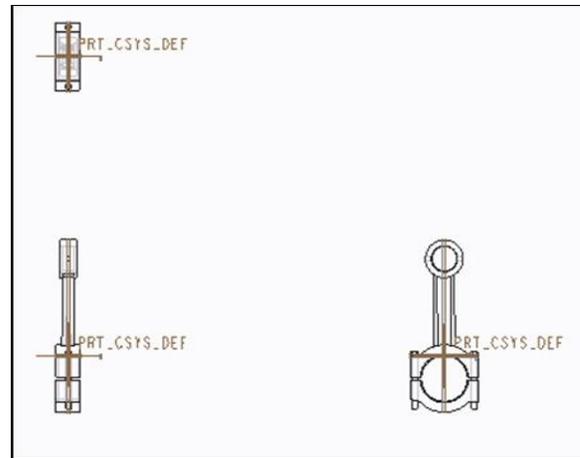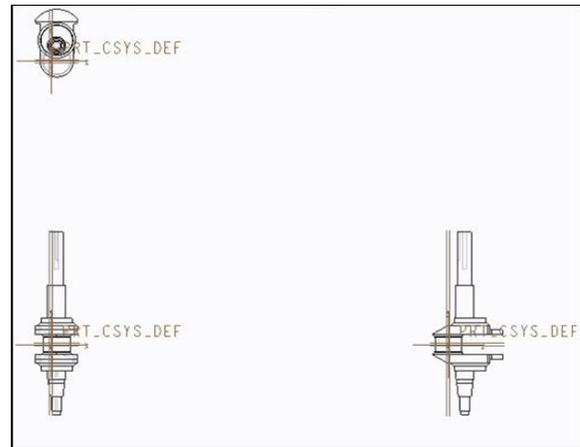
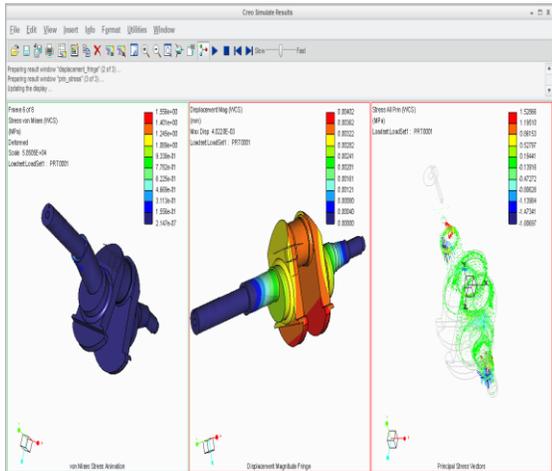
Crank shaft in 2-D

6. FINITE ELEMENT ANALYSIS

6.1 connecting rod fatigue test-
Aluminum
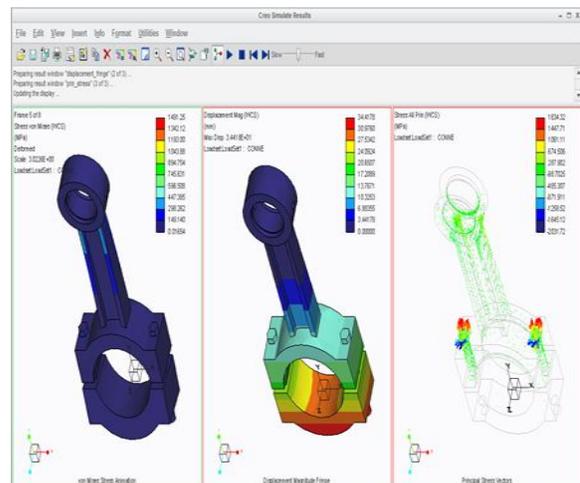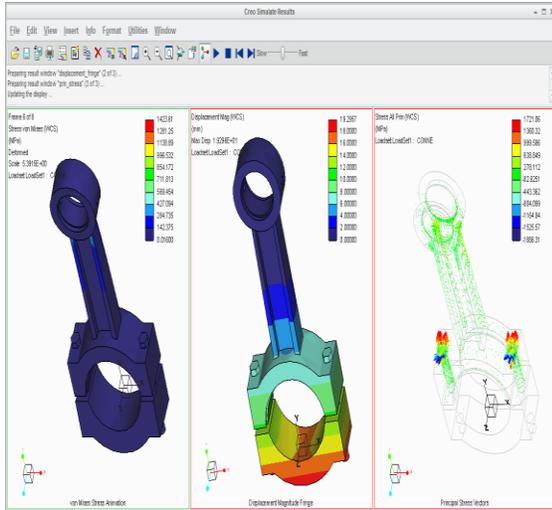
Cast iron

6.2 crank shaft fatigue test
Aluminum
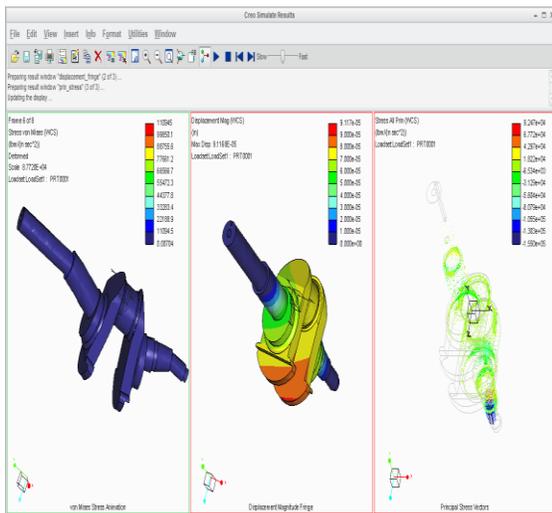
Cast iron

6.3 Thermo mechanical test
Aluminum
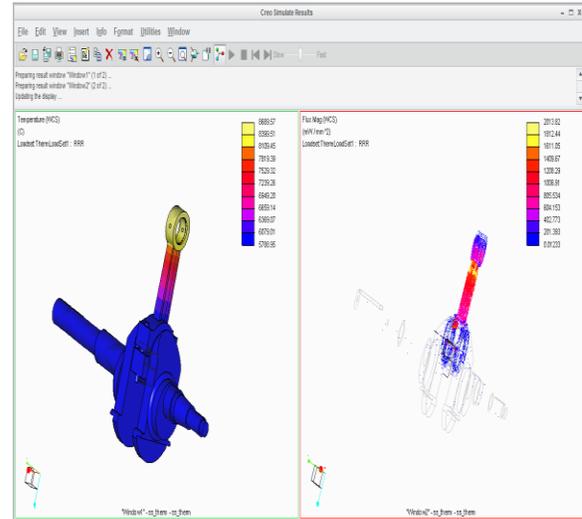
Cast iron

7. CONCLUSION

In this paper, the connecting rod and crankshaft model is created by CREO software. The maximum deformation appears at the centre of crankshaft and connecting rod surface. By checking and comparing the results of materials in finalizing the results are shown in below.

By checking and comparing the results of materials in finalizing the results are shown in below.

Considering the parameters,

1. Equivalent stress for the both the materials are same.

2. For the forged steel material factor of safety (from Soderberg's) and stiffness is increased compared to existing carbon steel.

3. The weight of the aluminum is less than the cast iron.

4. From the fatigue analysis life time of the connecting rod can be determined.

5. And also no. of cycles for aluminum (8500×103) is more than the existing cast iron (6255×103).

6. When compared to both of the materials, aluminum is cheaper than cast iron.

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