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A review on fatigue behaviour of connecting rod made of Austempered Ductile Iron

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Abstract – *This article is a review of the fatigue behavior of connecting rod made of Austempered ductile iron (grade 1050) . It is estimated that 50-90% of structural failure is due to fatigue . Due to cyclic loading and presence of stress concentrations at the critical areas, fatigue becomes the primary cause of failure of connecting rods. A literature review on several relevant aspects of this work is also provided. The parametric model of connecting rod was modeled using CATIA V5 R20 which was then later imported to ANSYS 15.0, a Finite Element Analysis tool. Also this project includes a comparison of fatigue behavior of ADI with AISI 4340 steel ,a medium carbon low alloy steel. Stress Life (SxN) theory was used to carry out the fatigue analysis. The focus of fatigue in ANSYS is to provide useful information to the design engineer when fatigue failure may be a concern.*

Key Words: **Fatigue, Stress, Austempered ductile Iron, Catia V5 R20, Ansys 15.0, Finite Element Analysis , Stress Life theory**

1. INTRODUCTION

1.1 Connecting Rod

The connecting rod connects the piston to the crankshaft, and consists of the crank(big end),pin (small end),and shank. The connecting rod small end, which is connected to the piston via the piston pin, transmits the combustion pressure of the cylinder to a force on the crank pin. The crank pin is eccentric to the rotational axis of the crankshaft, resulting in a moment force that induces a rotary motion(Fig.).The connecting end is thus a mechanical element that transforms the axial motion of the piston into the rotation of the crankshaft.

A connecting rod consists of a pin-end, a shank section, and a crank-end as shown in Fig 1.1.To permit accurate fitting of bearings the pin-end and crank-end pinholes at the upper and lower ends are machined.

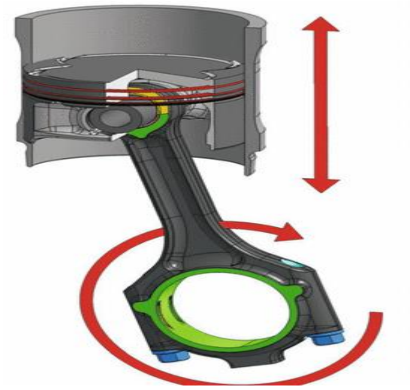

Fig -1: Main motions of piston-connecting rod system

These holes must be parallel. The upper end of the connecting rod is connected to the piston by the piston pin. The upper end is forced to turn back and forth on the piston pin as the lower end of the connecting rod revolves with the crankshaft. Although this movement is slight, the bushing is necessary because of the high pressure and temperatures.

For the connecting rod to be clamped around the crankshaft,the lower hole is splitted. The bottom part, or cap, is made of the same material as the rod and is attached by two bolts. A bearing material in the form of a separate split shell is the surface that bears on the crankshaft. The two parts of the bearing are positioned in the rod and cap by dowel pins, projections, or short brass screws. Split bearings may be of the precision or semi precision type.

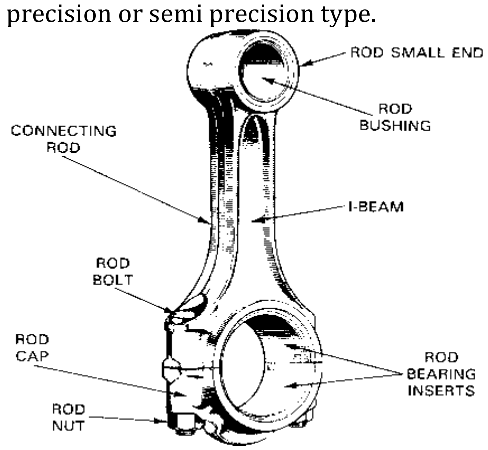

Fig-2: Schematic of a typical connecting rod (Schreier, 1999).

The precision type bearing is accurately finished to fit the crankpin and does not require further fitting during installation. The projections prevent the bearings from moving sideways and prevent rotary motion in the rod and cap.

Service loads and failures experienced by connecting rods:

The function of connecting rod is to translate the transverse motion to rotational motion. It is a part of the engine, which is subjected to millions of repetitive cyclic loadings. It should be strong enough to remain rigid under loading, and also be light enough to reduce the inertia forces which are produced when the rod and piston stop, change directions and start again at the end of each stroke.

The connecting rod should be designed with high reliability. It must be capable of transmitting axial tension, axial compression, and bending stresses caused by the thrust and pull on the piston, and by centrifugal force without bending or twisting.

An explanation of the axial forces acting on connecting rod is provided by Tilbury (1982). The top-dead-center (TDC) position of the induction stroke is denoted by 0 ° in Fig 1.3. From 0°to approximately 75° of the crank angle the connecting rod is in compression as the piston is accelerated down the cylinder bore. The connecting rod begins to decelerate from 75° to approximately 285° of the crank angle. The connecting rod is in tension from 285° to 360° as it reduces the rate of acceleration of the piston up the cylinder bore. Between 0° and 180° the pressure is slightly below atmospheric, as air is drawn into the engine through the spark plug hole, causing compression in the connecting rod. Between 180° and 360° the pressure is above atmospheric as the air is expelled from the engine.

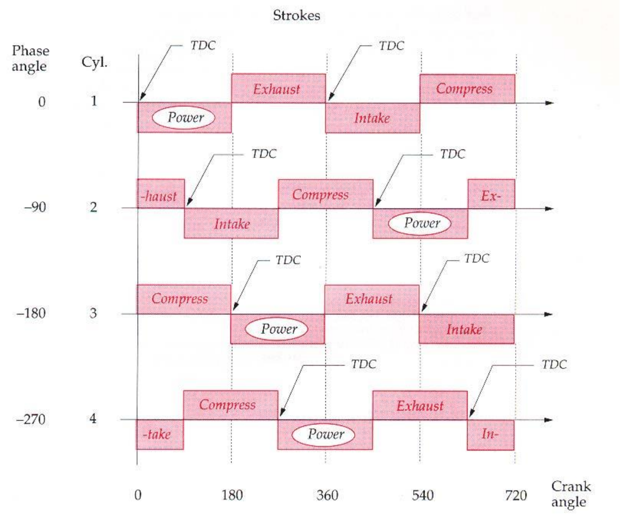

Fig -3: Even firing four strokes, four-cylinder engine (Nortan, 1994).

Connecting rod is submitted to mass and gas forces. The superposition of these two forces results in the axial force, which acts on the connecting rod. The gas force is determined by the speed of rotation, the masses of the piston, gudgeon pin and oscillating part of the connecting rod consisting of the small end and the shank. Fig 1.4 shows axial loading (Fay) due to gas pressure and rotational mass forces. Bending moments ($M_{b,xy}$, $M_{b,zy}$) originate due to eccentricities, crankshaft, case wall deformation, and rotational mass force, which can be determined only by strain analyses in engine (Sonsino, 1996). The connecting rod experiences inertia forces plus direct forces that produce bending in a plane perpendicular to the crankshaft longitudinal axis as shown in Fig 1.5, where part (a) shows bending perpendicular and part (b) shows bending parallel to the crankshaft axis (Wright, 1993).

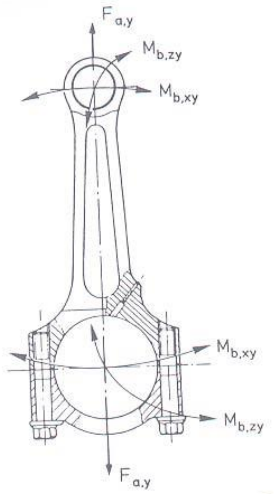

Fig-4: The origin of stresses on a connecting rod (Sonsino, 1996).

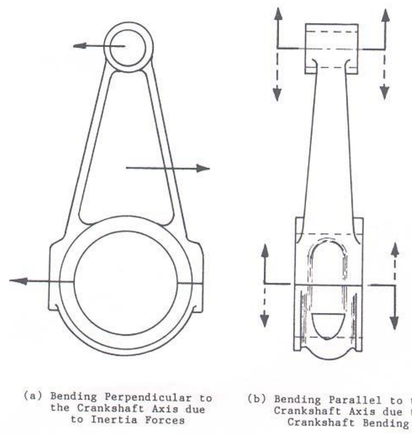

Fig -5: Two modes of bending that occur in connecting rods (Wright, 1993).

Connecting rod is designed for infinite-life and the endurance limit is the design criterion. It experiences axial tension/compression with constant amplitude loading and multi-directional bending with variable amplitude, as inertia force, torque and moment are all functions of engine speed (rpm). The ratio of σa (axial stresses) to σb (bending stresses) is 1: 1 to 1: 0.1 (Sonsino, 1996).

Failures of connecting rods are often caused by bending loads, as shown in Fig 1.5 acting perpendicular to the axes of the two bearings. As a result of these bending loads Failure in the shank section occurs in any part of the shank between piston-pin end and the crank-pin end. At the crank end fracture can occur at the threaded holes or notches for the location of headed bolts. Pin-end failures can occur from fretting in the bore against a fitted bushing (Wright, 1993).

During suction stroke, the engine has to do work. So as the crankshaft rotates, the connecting rod tends to pull the piston down. This will lead to a tensile force on the connecting rod.

At the end of the compression stroke, the compressed fluid will tend to oppose the compression from the piston. Hence the piston experiences a downward force, which will lead to a compressive force on the connecting rod. This is because, the connecting rod will experience two forces at this instant. One is the upward force due to inertia and another is downward force due to compressed gases. This will tend to compress the CR. At the beginning of the power stroke, the combusted gases will exert a downward force, on the CR which is yet to gain momentum. So force will again be compressive.

During the exhaust stroke, the gases will naturally escape as soon as the exhaust valve opens, due to the pressure difference. So not much work is done by the CR. But at the end of the stroke, CR will undergo a tensile stress.

1.2 Austempered Ductile Iron

The first commercial applications of Austempered Ductile Iron (ADI) occurred in 1972.Pioneering heat treatment work with steel (1930's) and the discovery of ductile cast iron (1940's) are included among the important events which lead to the development of ADI.

What material offers the design engineer the best combination of low cost, design flexibility, good machinability, high strength-to-weight ratio and good toughness, wear resistance and fatigue strength? The answer to that question may be Austempered Ductile Iron. Subsequently it is subjected to the Austempering process to produce mechanical properties that are superior to conventional ductile iron, cast and forged aluminum and many cast and forged steels.

Austempering is an isothermal heat treatment process that, when applied to ferrous materials, produces a structure that is stronger and more ductile than comparable structures produced with conventional heat treatments.

The main change in foundry practice when producing castings for austempering is to ensure that the ductile iron is correctly alloyed to allow the required microstructure to be developed during the austempering heat treatment. The critical stage is the quench from the austenitizing temperature to the isothermal transformation (austempering) temperature.

A continuous communication between founder and heat treater is crucial for process safety. Appropriate fully-automatic and computer-controlled heat-treatment facilities are also required for the setting of the desired ADI-structure. These can be operated with precision and give reproducible results for the austemper heat- treatment process.

Kristin Brandenberg highlighted that due to the high hardness and strength of ADI, it has often been mistaken as an un-machinable material. By taking into account the unique characteristics of this material and modifying the machining practices to suit the material, ADI can be successfully machined. Difficulties can arise from the formation of carbides from the segregation of different alloying elements during the heat treat process. These can be addressed in the casting process. The strain-induced transition to Martensite can also create obstacles in the machining process. However, with the appropriate tool material, feed rate, tool speed and depth of cut, ADI can be successfully machined.

Engineers are continually investigating designs that require less energy to operate or propel. Lost in that assessment is the fact that massive amounts of energy are consumed in the extraction and processing of the materials that make up the components assembled in the operating unit or system. The architectural community has for some years extensively used the concept of "embodied energy" to define the energy that is intrinsic to a kg of mass of that material (MJ/kg).

The density of ADI is approximately !0% less dethan steel ,also it has strength equal to that of steel. ADI is approximately three times stronger than aluminum at only 2.5 times the mass. Therefore, we already know that ADI can be, in fact, a lightweight material.Many examples of ADI replacing aluminum have been presented by the authors, but most neglect to consider the embodiement energy in extracting the materials from the earth and turning them into functional products.

1.3 Fatigue analysis

When a material is subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than the static yield strength of the material the progressive, localized, and permanent structural change that occurs in tha material is known as fatigue. Fatigue might later progress into cracks and cause fracture after a sufficient number of fluctuations.

The simultaneous action of cyclic stress, tensile stress, and plastic strain causes fatigue damage. If any one of these three is not present, a fatigue crack will not initiate and propagate. The continuous cyclic stress produces the plastic strain which is responsible for initiating the crack; the crack growth (propagation) is promoted by tensile stress. Where the strain might otherwise appear to be totally elastic, microscopic plastic strains can also can be present at low levels of stress.

Finite Element Analysis belongs to numerical method category. Finite element modelling of any solid component consists of geometry generation, applying material properties, meshing the component, defining the boundary constraints, and applying the proper load type.

Making calculations at only limited (Finite) number of points and then interpolate the results for the entire domain (surface or volume) is the basic idea of FEA.Any continuous object has infinite degrees of freedom and it's just not possible to solve the problem in this format.

With the help of discretization or meshing(nodes and elements), finite element method reduces the degrees of freedom from infinite to finite .The Finite Element Method only makes calculations at a limited number of points and then interpolates the results for the entire domain.The objective of FEA is to investigate stresses,displacements and hotspots experienced by the connecting rod.The fatigue life and the expected failure regions can then be predicted by using the obtained stress resuts.

As discussed, by experimental studies, the compressive load was found to be distributed over 120° of the contact surface area and the tensile load distributed over 180° of the contact surface area. There are totally 4 load cases considered for the *static analysis:*

a) Constraining the crank pin end for all degrees of freedom and applying a compressive force distributed over 120º at piston pin end.
b) Constraining the piston pin end for all degrees of freedom and applying a compressive load distributed over 120º at crank pin end.
c) Constraining the crank end for all degrees of freedom and applying a tensile load distributed over 180º at piston pin end.
d) Constraining the piston pin end for all degrees of freedom and applying a tensile load distributed over 180º at crank pin end.

2. LITERATURE REVIEW

The loading experienced by connecting rods analyzed by Sonsino (1996) [7]. Connecting rods are submitted to mass and gas forces. The superposition of mass and gas forces produce the axial force, which acts on the connecting rod. Axial loading can be calculated by the knowledge of engine pressure and rotational speed. Connecting rods also experience bending moments due to eccentricities, crankshaft and rotational mass forces, which can be determined by strain analysis in an engine.He studied the fatigue aspect by operating a connecting rod for about $2x10^9$ cycles.Test loads being higher than the calculated load,resulted in failures occurring mainly from fretting corrosion between gudgeon pin and small end.

Majidpour et al. (2002) [5] discussed to develop dynamic stress analysis using FE techniques and stress-time history generations. Inertia forces are composed of two parts. The inertia of reciprocating masses that acts on the pin end and its direction changes with respect to the piston acceleration is the firt part. The second part includes centrifugal forces, which act on the connecting rod in a distributed manner. The maximum moment occurs when the crank is perpendicular to the rod. At the top dead center point of every cycle, maximum tension and compression forces occur. It was observed that inertia load is proportional to the engine speed.

Webster et al. (1983) [8] explained the loading of connecting rod in an engine. In this study the tension and compression were obtained from experimental results. For tension loading the crank ends and piston ends were found to have a sinusoidal distribution on the contact surface with pins and connecting rod whereas,in compression, a uniform distribution over the contact area.The stresses found in the shaft and cap exhibited the beam and axial loading distribution.It was concluded that the highest stress levels occurred in four locations: the upper area of the cap end on the axis of symmetry, the transition region of the bolt section and the lower rib, the transition region of the lower rib and the shaft, and the connecting rod's bolt head.

Adila Afzal (2004) [1] carried out the fatigue behavior analysis of forged steel and powder metal connecting rods.Strain-controlled fatigue properties as well as monotonic and cyclic deformation behaviors of the two materials were evaluated and compared.Also,connecting rods made of C-70 steel were tested and the results were compared with forged steel and powder metal connecting rods.The SN curves of the two connecting rods were also evaluated from the bench tests which were obtained under R=-1.25 constant amplitude axial loading conditions.Thereafter using the SN approach the life predictions of the connecting rods were evaluated.To account for the mean stress effects Goodman equation was used.Fractography of the connecting rod fracture surfaces were also conducted.

Mirehei, M. Hedayati Zadeh, A. Jafari, M. Omid (2008) [6] carried out the analysis of fatigue strength of a connecting rod.The fatigue analysis of the connecting rod of universal tractor was carried out by ANSYS ,a FEA software application and also its life prediction was carried out. The fatigue phenomenon occurring due to the cyclic loadings affects the connecting rod behavior and also to consider the more saving in time and costs were the reason for performing this research as the two are very significant parameters relevant to manufacturing. The results of the research showed that with fully reverse loading the life cycle of a connecting rod can be estimated and also the critical points can be found from where more possibly the crack growth initiates from.

Endurance limit is a primary design criterion for the connecting rod.The factors, which effect the fatigue strength in PF connecting rod are metallurgical structure, hardness of the material, density, depth of decarbuized layer and surface roughness, such was reported by Imahashi et al. (1984) [3]. They conducted constant amplitude, load-controlled component axial fatigue tests on PF connecting rods. The fatigue behaviour were compared to SAE 1055 steel. They concluded that fatigue strength or fatigue behavior of a connecting rod is largely affected by its hardness.

M. Ravichandran (2013) [4] discussed the design of connecting rod of internal combustion engine using the topology optimization. The mesh convergence analysis was performed to select the best mesh for the analysis. To achieve the objectives of optimization the topology optimization technique is used which is to reduce the weight of the connecting rod. The optimized connecting rod is 11.7% lighter and predicted low maximum stress compare to initial design. For future research, the optimization should cover on material optimization to increase the strength of the connecting rod.

Finite element analysis was used to optimize the connecting rod model in a study by Balasubramanian et al. (1991) [2]. The connecting rod load was broken down into various individual loads for the simulation and the actual stress was obtained by superposition. The individual loads were the inertia load, firing load, press fit of the bearing shell, and bolt forces. These individual load cases were analyzed based on alternating load, lateral acceleration, buckling, and free-free vibrations. With 3-D model it is possible to take account of bolt geometry.

3. CONCLUSIONS

From the fatigue analysis it shows that ADI 1050 gives much better results as compared to AISI 4340 Steel. ADI 1050 has a superior performance in all the fatigue results for all the four loading conditions except for tension at piston pin side where the fatigue life is same i.e zero cycles.
The yield strength of ADI 1050 is 33.28% higher than that for AISI 4340 steel.Ultimate tensile strength of ADI 1050 is 21.42% higher than that for AISI 4340 steel.
The ADI material has a better fatigue resistance as compared to AISI 4340 steel.
The density of ADI connecting rod is less by 8.55 kg/m^3 as compared to AISI 4340 steel connecting rod i.e. around 10% lighter than the steel counterpart.
On the piston pin side the stresses are maximum during the tensile load condition.While during the compressive load the stresses are concentrated at the transition regions to the crank and pin end.
Fatigue strength is the most significant factor (design driving factor) in the optimization of connecting rods.
Considering the performance advantages of ADI , AISI 4340 steel connecting rod presented in this research can be considered to be replaced by ADI 1050. It is easy to see the engineering and design advantages inherent in Austempered Ductile Iron.
Manufacturing connecting rods through standard casting method might create blowhole defects.Using counter pressure during the entire process helps prevent the introduction of gases and porosity.Therefore counter pressure die casting methods can be used to produce ADI connecting rods.
As design engineers become more familiar with ADI's strength, wear resistance,toughness, and noise damping properties reported in successful ADI conversions from steel castings, weldments and forgings and aluminum castings and forgings, ADI will continue its remarkable growth.

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