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Fatigue Behavior and Life Predictions of Forged Steel and Powder Metal Connecting Rods

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ABSTRACT: This study investigates and compares fatigue behavior of forged steel and powder metal connecting rods. A literature review on several aspects of connecting rods in the areas of load and stress analysis, durability, manufacturing, and optimization is also provided. The experiments included strain-controlled specimen testing, with specimens obtained from the connecting rods, as well as load-controlled connecting rod bench testing. Monotonic and cyclic deformation behaviors, as well as strain-controlled fatigue properties of the two materials are evaluated and compared. Experimental S-N curves of the two connecting rods from the bench tests obtained under R = -1.25 constant amplitude axial loading conditions are also evaluated and compared. Fatigue properties obtained from specimen testing are then used in life predictions of the connecting rods, using the S-N approach. The predicted lives are compared with bench test results and include the effects of stress concentrations, surface finish, and mean stress. The stress concentrations factors were obtained from FEA, and the modified Goodman equation was used to account for mean stress effect.

Keywords: Fatigue life, forging, steel, powdered metal

I. INTRODUCTION

A. Background

Connecting rods are widely used in variety of engines such as, in-line engines, opposed cylinder engines, radial engines and oppose-piston engines. A connecting rod consists of a pin-end, a shank section, and a crank-end as shown in Fig.1. Pin-end and crank-end pinholes at the upper and lower ends are machined to permit accurate fitting of bearings. These holes must be parallel. The upper end of the connecting rod is connected to the piston by the piston pin. If the piston pin is locked in the piston pin bosses or if it floats in the piston and the connecting rod, the upper hole of the connecting rod will have a solid bearing (bushing) of bronze or a similar material. As the lower end of the connecting rod revolves with the crankshaft, the upper end is forced to turn back and forth on the piston pin. Although this movement is slight, the bushing is necessary because of the high pressure and temperatures.

The lower hole in the connecting rod is split to permit it to be clamped around the crankshaft. The bottom part, or cap, is made of the same material as the rod and is attached by two bolts. The surface that bears on the crankshaft is generally a bearing material in the form of a separate split shell. 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.

B. 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. 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. 2 shows axial loading (Fay) due to gas pressure and rotational mass forces. Bending moments (Mb, xy, Mb, zy) originate due to eccentricities, crankshaft, case wall deformation, and rotational mass force, which can be determined only by strain analyses in engine. Failure in the shank section as a result of these bending loads 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. Connecting rod is typically designed for infinite-life and the design criterion is endurance limit. 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).

II. MATERIALS AND MANUFACTURING PROCESSES

A. Drop-Forged

A forged steel connecting rod is a production of drop-forged closed die process. The round steel stock as being forged to a connecting rod. Hot working proportions the metal for forming the connecting rods. Fullering, which is the portion of the die, is used in hammer forging primarily to reduce the cross section and lengthen a portion of the forging stock. The fullering impression is often used in conjunction with an edger or edging impression. Bustering converts square section bar into a preform to reduce the cross-section and lengthen it. Blocking operation forms the connecting rod into its first definite shape. This involves hot working of the metal in several successive blows of the hammer, compelling the work piece to flow into and fill the blocking impression in the dies. Flash is produced, which is the unformed metal around the edge of the connecting rod that was forced away from blocking die impressions by the successive blows of the forging hammer. Flash is removed by different ways with trim dies in mechanical press or in special circumstances by sawing and grinding. The trimmed connecting rod is ready for heat-treating and machining.

Heat treating: After final forging and before machining, proper heat treatment methods are used to acquire optimum grain size, microstructure and mechanical properties.

B. Powder Forging

Powder forging is a process in which powders such as iron and copper are compacted, heated and forged so that their density increases up to that of wrought steel. The technology involves the following steps:

Stage I: A controlled amount of mixed powder used for connecting rods is automatically gravity-fed into a precision die and is compacted usually at room temperature and at high pressure up to 200 to 400 MPa. The resulting mass of powder is a green compact and has very little cohesive strength requiring further operations.

Stage II: The green component is ejected out of the die–tool system and placed on wide endless mesh belt, which moves slowly through a controlled atmosphere-heating furnace. This is called sintering and it develops the metallurgical bonds between the green compacted grains. The green compacts are heated below the melting temperature of the base metal and held at the sintering temperature for an appropriate time and then cooled.

Stage III: Shot peening: is implemented after forging. Before shot peening, some connecting rods receive primary milling/rework. Bad connecting rods are thrown to scrap baskets.

Stage IV: Inspection: During this process presence of any cracks and flaws are inspected. Inspection of any flaw on the surface can be observed by white light. Magnetic particle inspection is done randomly to check for hidden cracks, fillet or inner contour machining, jamming or forging marks. Finally, the rods are inspected for weight and length, and any overweight connecting rods are rejected.

C. Die-Casting

Die-casting is accomplished by forcing molten metal under high pressure into reusable metal dies. Cast connecting rods were introduced in 1962. Riser is designed to achieve directional solidification by tapering the central web so that solidification begins at a point remote from the risers, in this case the center of the thin arm. After trimming and machining, all connecting rods pass through conveyorized sonic, ultrasonic, and magnaglow inspection stations, where defective castings are removed Die casting machines, large or small, vary fundamentally only in the method used to inject molten metal into the die. The rapidity of operation depends upon the speed with which the metal can be forced into the die, cooled and ejected, the casting removal, and the die prepared for the next shot.

D. Comparison of Forged Steel and Powder Metal Connecting Rods

The two most competitive high volume manufacturing processes of connecting rods are forged steel and powder metal processes. There has been a significant increase in the production of powder metal connecting rods in North America in the last decade. The main driving force for this trend has been cost effectiveness of PM connecting rods resulting from near net shape manufacturing as well as fracture splitting of the cap from the rod, introduced in 1990. Near-net shape achieved in powder metal forged connecting rods results in substantial reduction in the material used to make them. In spite of the substantially lower weight of the material used, however, the cost of the powder forged rough stock could be higher than that for the conventional hot drop-forged rough stock, because of additional operations of powder formation, perform formation, presintering, and sintering. The manufacturing steps for the powder metal connecting rod. By comparing the steps in manufacturing processes it can be seen that the fracture splitting step is the main difference between conventional forged steel and powder metal connecting rod manufacturing processes.

III. STRESS ANALYSIS AND FEA

A. Finite Element Modeling

The objective of FEA is to investigate stresses, displacements and hotspots experienced by the connecting rod. The stresses obtained can then be used to predict the fatigue life, and determine the expected failure regions. Forged steel rod was used for the finite element analysis, since this connecting rod was also optimized. Linear elastic analysis was used since the connecting rod is designed for long life where stresses are mainly elastic.

Therefore, only Young's modulus (E = 207 GPa or 30,000 Ksi) and Poisson's ratio (ν = 0.3) were needed as material properties. Axial loading was considered for all the analyses, since this is the primary service loading.

Generation of the geometry and FEA mesh of the component. Modeling incorporated three-dimensional geometry, tension and compression loading, symmetry conditions and other aspects of designing. A 3-D model geometry was developed in IDEAS-8. Dimensions of the forged steel connecting rod were taken from three different connecting rods, and the average of these dimensions were used to generate the model. The dimensions were obtained by a coordinate measurement machine, as well as a micrometer, digital calipers, dial calipers, compass and depth probe.

Loading and boundary conditions. Tension and compression loads were applied as pressure on the bearing surfaces of the connecting rod. The research found that under actual service condition the pin end experiences tension by the piston pin causing distribution of pressure along the upper half of the inner diameter, which is approximated by the cosine function (Fig. 1). In compression, the piston pin compresses the bearings against the pin end inner diameter, causing uniform distribution of pressure.

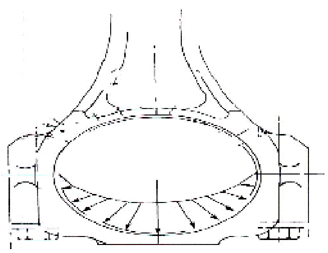

Fig. 1. Distribution of compression loading of connecting rods.

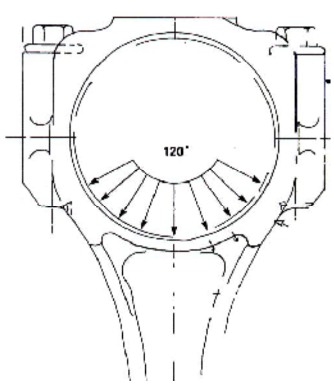

Fig. 2. Distribution of tension loading of connecting rod.

IV. LIFE PREDICTIONS AND COMPARISONS WITH EXPERIMENTAL RESULTS

A. Test methods and procedures

Monotonic tension tests. All monotonic tests in this study were performed using test methods specified by ASTM Standard E8. One specimen was used from each material to obtain the monotonic properties. Due to the limitations of the extensometer, strain control was used only up to 10% strain. After this point, displacement control was used until fracture. A stress versus strain plot was obtained automatically for each test. After the extensometer was removed, a displacement rate of 0.00846 in/min was used. This displacement rate provided approximately the same strain rate as that used prior to switching control modes. After the tension tests were concluded, the broken specimens were carefully reassembled. The final gage lengths of the fractured specimens were measured with a Vernier caliper having divisions of 0.001 in. Using an optical comparator with 10X magnification and divisions of 0.001 in, the final cross-section dimensions were measured. It should be noted that prior to the test, the initial cross section was measured with this same instrument.

Constant amplitude fatigue tests. All constant amplitude fatigue tests in this study were performed according to ASTM Standard E606. It is recommended by this standard that at least 10 specimens be used to generate the fatigue properties. For this study, only four forged steel specimens at four different strain amplitudes ranging from 0.2% to 0.5% were utilized, due to the limited number of available forged steel connecting rods. Twelve powder metal specimens were used at six different strain amplitudes ranging from 0.175% to 0.7%. Thirteen C-70 steel specimens at eight different strain amplitudes ranging from 0.174% to 0.7% were used. A strain amplitude larger than 0.7% was not possible due to specimen buckling limitation. Instron LCF software was used in all tests, except for some long life tests in which Instron SAX software was used after changing to load control mode. During each test, the total strain was recorded using the extensometer output. Test data were automatically recorded throughout each test.

B. Experimental results and comparisons

Monotonic deformation behavior. The properties determined from monotonic tests were the following: yield strength (YS), ultimate tensile strength (Su), percent elongation (%EL), percent reduction in area (%RA), true fracture strength (σf), true fracture ductility (εf), strength coefficient (K), strain hardening exponent (n) and modulus of elasticity (E).

True stress (σ), true strain (ε), and true plastic strain (εp) were calculated from engineering stress (S) and engineering strain (e), according to the following relationships, which are based on constant volume assumption:

$\sigma = S(1 + e)$ (1)

$\varepsilon = \ln(1 + e)$ (2)

ε ε ε ε
σ
p e E
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A summary of the monotonic properties for three materials are provided in Table 1.

Table 1: Summary of mechanical properties for three materials.

Monotonic properties	Forged steels	Powder metals	C-70 steel
Modulus of Elasticity(E) in Gpa	201	199	212
yield strength(YS) in Mpa	700	588	574
Ultimate strength(Su) in Mpa	938	866	966
Percent elongation, %EL (%):	24%	23%	27%
Percent reduction in area, %RA (%):	42%	23%	25%
True fracture strength, sf, Mpa	1266	994	1141
True fracture ductility, ef (%):	54%	26%	28%

The monotonic stress-strain curves for all three materials are shown in Fig. 3.

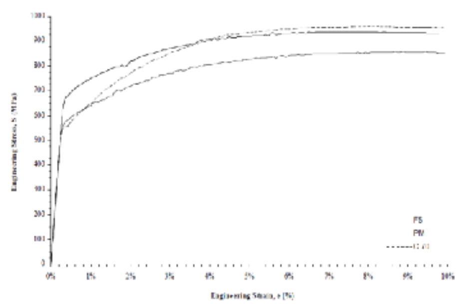

Fig. 3. Superimposed monotonic stress-strain curves of the three materials.

Constant amplitude fatigue behavior. Constant amplitude strain-controlled fatigue tests were performed to determine the strain-life curves. The following equation relates the true strain amplitude to the fatigue life: Δε/2 Δε/2 Δε/2= $\sigma f/E\,(2Nf)^{b} + ef(2Nf)^{c}$.

Life Prediction Based on S-N Approach.

(i) Surface factor, Ks (Ks = 0.30 for forged surface finish) $b' = b + 0.159 \log K_s$

(ii) Stress concentration factor, Kt (Kt = 1.18 from FEA)

(iii) Surface compressive residual stress (does not affect life prediction due to subsurface failure)

(iv) Modified Goodman equation was used to consider the mean stress.

$R = P_{min}/P_{max} = -1.25$

$S_a/S_f/K_f = S_m/S_u = 1$

Component experimental fatigue behavior and comparisons.

(i) Load-controlled axial tests

(ii) Load ratio Pmin/ Pmax = - 1.25

(iii) Test frequency 2-5 Hz

(iv) Life range 4 X 104 – 4 X106 Cycles

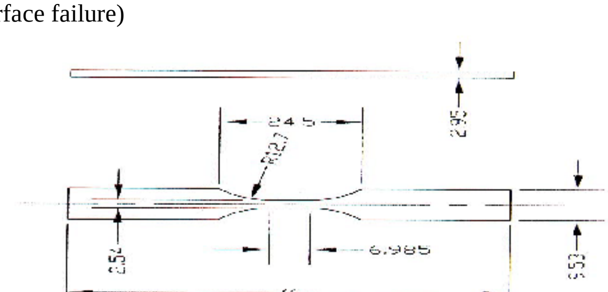

Fig. 4. The Location of two specimens obtained from one connecting rod for specimen testing.

V. CONCLUSIONS

In this study, first a literature review on several aspects of connecting rods in the areas of load and stress analysis, durability, manufacturing, economic and cost analysis, and optimization was carried out. Forged steel, C-70 steel and powder metal connecting rods were then used to obtain nd compare the fatigue properties and behaviors. The experiments conducted used both specimen testing of the three materials, as well as component testing of forged steel and powder metal connecting rods. Tensile tests of specimens were conducted to obtain and compare the monotonic properties. Strain controlled fatigue tests were performed to obtain and compare the S-N, strain life, and cyclic stress-strain curves and properties. Component fatigue tests for forged steel and powder metal connecting rods were performed under axial load-controlled condition with a load ratio of R = -1.25. The analysis conducted included FEA to obtain stresses, as well as life prediction analysis to compare with the experimental component test results. Based on the literature review conducted, experimental results and observations, and analyses performed, the following conclusions can be drawn:

(i) The literature review indicates that a major driving force for the increased use of PM connecting rods has been its cost effectiveness resulting from the fracture splitting of the cap from the rod. With recent introduction of new materials such as C-70 and MA splittable steels, this key advantage of powder metal connecting rods no longer exists. Some automotive manufacturers are starting to switch back from PM to forged steel connecting rods, due to their higher strength and lower manufacturing cost.

(ii) From tensile tests and monotonic curves it is concluded that forged steel is considerably stronger than the powder metal. Yield strength of forged steel is 19% higher than that for the powder metal. Ultimate tensile strength of forged steel is 8% higher than that for the powder metal. The Yield strength of C-70 steel is slightly lower than the powder metal (by 2%) and its ultimate tensile strength is higher than the powder metal (by 12%).

(iii) Based on strain-life fatigue behaviour, the forged steel provides about a factor of 7 longer life than the powder metal in the high cycle regime. At short life regime the difference is smaller. The C-70 steel exhibits the same strain-life resistance, as compared to powder metal in the high cycle regime.

(iv) Forged steel and PM connecting rod component testing indicate the forged steel connecting rod exhibits 37% higher fatigue strength, as compared with the powder metal connecting rod. This increased strength results in about two orders of magnitude longer life for the forged steel connecting rod. The difference in fatigue performance between the two connecting rods increases with longer lives.

(v) The dominant fracture location of the powder metal connecting rods was near the transition region to the pin end. The forged steel connecting rods mainly failed in the transition to the crank end region. For the PM connecting rods the crack origins appeared to be from either the surface or subsurface, while for the forged steel connecting rods cracks started subsurface.

(vi) The S-N approach predictions are very reasonable, if the predictions are based on smooth surface finish, rather than forged surface finish. The beneficial compressive residual stresses on the surface from the shot peening process nullify the detrimental effect of forged surface finish.

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