ABSTRACT

Fatigue is the primary cause of failure of crankshafts in internal combustion engines. The cyclic loading conditions and the stress concentrations in the crank pin fillets are unavoidable, and can result in fatigue failure. The objectives of this study were to compare the fatigue behavior of forged steel and ductile iron crankshafts from a one-cylinder engine as well as to determine if the fatigue life of a crankshaft can be accurately estimated using fatigue life predictions. Monotonic tensile tests as well as strain-controlled fatigue tests were conducted using specimens machined from the crankshafts to obtain the monotonic and cyclic deformation behavior and fatigue properties of the two materials. The forged steel had higher tensile strength and better fatigue performance than the ductile cast iron. Charpy v-notch impact tests were also conducted using specimens machined from the crankshafts to obtain and compare the impact toughness of the materials. Forged steel in the L-T and T-L directions had a higher impact toughness than the ductile cast iron regardless of temperature. Load-controlled component fatigue tests were performed using the forged steel and ductile cast iron crankshafts. For a given bending moment amplitude, the forged steel crankshaft had a factor of six (6) longer life than the ductile cast iron crankshaft. A finite element analysis of the crankshafts was conducted using boundary conditions similar to the component test. The fatigue properties from the specimen tests were used in life predictions of the crankshafts. The lives based on the S-N predictions were close to the lives based on the component tests for both forged steel and cast iron crankshafts. The lives from the ε-N predictions were very close to the lives from the component tests for forged steel, but less accurate for the cast iron crankshafts.

INTRODUCTION

The crankshaft in an internal combustion engine converts the linear motion of the piston into a rotary motion. This rotary motion is used to drive the automobile or other device that the crankshaft is used in. A crankshaft has a very wide range of applications from small one cylinder lawnmower engines to very large multi-cylinder marine engines.

A crankshaft is a component that is intended to last the lifetime of the engine and/or vehicle. Being a high speed, rotating component, its service life contains many millions, or even billions of cycles of repetitive loading. Therefore, the crankshaft is typically designed for infinite life.

Jensen(1) showed in his study of a V-8 automotive crankshaft that the inertial and gas loads of the engine create a multiaxial stress situation in the form of bending and torsion. This was done through the application of strain gages to the crankshaft to measure bending and torsion. Only the maximum torsion and bending moment were considered and the test was reduced by using the maximum principal stress theory to a constant amplitude bending test. Resonant bending tests were conducted on sections of the crankshafts. The fatigue life of the crankshaft was determined using the S-N approach.

The presence of stress concentrations, or notches, in crankshafts is unavoidable. Anywhere on the crankshaft where there is a change in diameter, there exists a stress concentration which could lead to fatigue failure. Fillets are used in an attempt to reduce the severity of the stress concentration. Jensen identified the fillets of the crank pins as the most critical location on the crankshaft. The fillets in a crankshaft are often rolled in order to induce compressive residual stresses in the component, which can help offset the effects of the notch. The effects of residual stresses on crankshaft fatigue were analyzed by Chien et al.(2). The study also used resonant bending tests, where FEA revealed that the 4th mode shape induced bending in the section of the crankshaft. The crankshafts were tested until failure and the fatigue strength at 10^6 cycles was determined.

There is a constant demand for components that have less mass, are stronger, and cost less to produce. The automotive industry often seeks to improve gas mileage by using lighter components, including optimized geometry and materials, while reducing the cost of manufacturing. One way to reduce the cost of
manufacturing is by using different materials and or processes. There is a desire for crankshafts that are lighter weight and cheaper to produce while maintaining the desired fatigue performance. The most common processes used in crankshaft bulk manufacture are casting and forging. Typically, ductile iron is used in the casting whereas steel is used in the forging process. Microalloyed steels can be used to eliminate the need for a heat treatment process in some forged steel applications. Austempered ductile irons have higher strength than ordinary ductile iron.

Chatterley et al.\(^3\) compared the fatigue performance of crankshafts made from ductile iron, austempered ductile iron (ADI), and forged steel. The ductile iron and ADI crankshafts were manufactured to the same dimensions as the forged steel crankshaft. Each crankshaft was clamped at the two main bearings and a bending moment was applied by a moment arm attached to either end of the crankshaft. The crankshafts were tested to \(10^7\) cycles or failure. A fatigue limit was established at \(10^6\) cycles for the three materials. The results show that when standard fillet rolling forces are used, ADI had significantly lower fatigue strength than forged steel. Higher rolling forces improved the fatigue strength of ADI, but were still inferior to forged steel. However, the study did show that ADI had better fatigue strength than ductile iron.

Pichard et al.\(^4\) also compared the fatigue performance of several crankshaft materials: ductile iron, quenched and tempered (Q&T) forged steel, and control cooled 35 MV7 (microalloyed) steel. Constant amplitude bending tests were used to determine the fatigue strength for each material. The purpose of the study was to determine if microalloyed steel could replace traditional forged steel and eliminate the need for additional heat treatment. The study showed that Q&T forged steel had fatigue performance superior to that of fillet rolled ductile iron. The study also showed that ion nitrided or fillet rolled microalloyed steel had fatigue performance superior to that of ion nitrided Q&T forged steel.

This study compares the fatigue performance of forged steel and ductile cast iron crankshafts from a one-cylinder engine typical to that used in a riding lawnmower. The crankshafts analyzed in this study are shown in Figure 1. The forged steel crankshaft (Figure 1a) was designed to be used in a 460cc engine which produces approximately 9.3 kW. The cast iron crankshaft was from a similar engine size and type. The forged steel crankshaft had a mass of 3.9 kg, and the cast iron 3.7 kg.

First the procedures and results from specimen testing are presented and compared, including monotonic tension, constant amplitude uniaxial fatigue, and Charpy v-notch tests. A description of the finite element analysis (FEA) and results is also included. The procedure and results for component bending fatigue tests of the two crankshafts are then presented. Fatigue life predictions are made and compared with the results from component fatigue tests. Finally, conclusions are made comparing the two materials.

\[\text{Table 1: Chemical composition by percent weight}^{(5)}\]

<table>
<thead>
<tr>
<th></th>
<th>Forged Steel</th>
<th>Ductile Cast Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.45</td>
<td>3.44</td>
</tr>
<tr>
<td>Mn</td>
<td>0.81</td>
<td>0.48</td>
</tr>
<tr>
<td>P</td>
<td>0.016</td>
<td>0.019</td>
</tr>
<tr>
<td>S</td>
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<td>0.004</td>
</tr>
<tr>
<td>Si</td>
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<td>2.38</td>
</tr>
<tr>
<td>Al</td>
<td>0.033</td>
<td>0.01</td>
</tr>
<tr>
<td>Cr</td>
<td>0.1</td>
<td>0.09</td>
</tr>
<tr>
<td>Ni</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Cu</td>
<td>0.13</td>
<td>0.31</td>
</tr>
<tr>
<td>N</td>
<td>0.008</td>
<td>--</td>
</tr>
<tr>
<td>O</td>
<td>13 ppm</td>
<td>--</td>
</tr>
</tbody>
</table>
Round specimens were taken from the forged steel and ductile cast iron crankshafts which were in an unmachined state (as forged or cast). Two specimens were machined from each crankshaft. For forged steel, one specimen was removed from each of the far ends of the crankshaft. For the cast iron, both specimens were removed from the same end of the crankshaft, shown as the right side in Figure 1b. The longitudinal axis of the specimens coincided with the longitudinal axis of the crankshaft. The specimens were first rough cut from the crankshafts, and then the final geometry was machined with a CNC lathe. All specimens were checked for straightness and symmetry. Polishing was done after machining to ensure that all machining marks were removed from the specimens prior to testing. After polishing, the specimens were coated with an epoxy at the location of the extensometer knife edges in order to protect the specimen.

A 50 kN closed-loop servo-hydraulic test frame controlled by a digital servo-controller was used to perform the tests. An extensometer with a 6 mm gage length rated as ASTM Class B1 was used to control strain. The capable range of the extensometer was +10% and -6%. The extensometer was calibrated prior to use by using a micrometer head with the smallest increment of measure (0.0001 inch).

Tilt and eccentricity can cause misalignment in the load train. This misalignment causes bending stress in the specimens during testing when a uniaxial applied stress is desired. The load train, consisting of the load cell, actuator, grips, and specimen, were carefully aligned prior to testing. An alignment fixture along with a straight cylindrical bar with strain gages was used to align the load train. The maximum allowable bending strain should not exceed 5% of the minimum axial strain range imposed during any test program as stated by ASTM Standard E606\(^6\). The amount of bending strain was significantly less than the stated requirement.

Testing was conducted at room temperature which was monitored and maintained to ±2°C. The humidity was also monitored using a precision hydrometer. A monotonic tension test was performed on each of the two materials. One specimen was tested for each material. The testing was conducted according to ASTM Standard E8\(^7\).

Constant amplitude uniaxial fatigue tests were performed on the two materials. The tests were conducted according to ASTM Standard E606. Strain amplitudes ranging from 0.16% to 2% for forged steel were used while ductile cast iron specimens were tested with strain amplitudes from 0.135% to 2%. A minimum of two specimens were tested for each material at each strain amplitude with the exception of 2%, where only one specimen of each material was tested. A total of 13 specimens of forged steel and 15 specimens of ductile cast iron were tested.

The tests were conducted in strain control with the exception of some long life tests and run-out tests. For the longer life tests the control was switched from strain to load after the load had stabilized in strain control. In strain control the frequencies used varied from 0.1 Hz to 1 Hz depending on the strain amplitude and remained unchanged after switching to load control for longer life tests. For the run-out tests, the test was started in strain control and then switched to load control if the strain was all elastic and no plastic strain was building up. The frequency for run-out tests in load control was increased to 25 Hz. A triangular waveform was used for all tests. The computer software automatically recorded data for the test at intervals of \(2^n\) cycles.

RESULTS AND COMPARISONS OF MATERIAL PROPERTIES

The material properties obtained from the monotonic tension tests are summarized in Table 2. From the table it can be seen that the ultimate strength for ductile cast iron is 80% of that of forged steel, and the yield strength is only 66% of that of forged steel. Forged steel also exhibits far more ductility than ductile cast iron, with a percent reduction of area of 58% for forged steel and only 6% for ductile cast iron. Superimposed plots of monotonic engineering stress versus engineering strain are shown for the forged steel and ductile cast iron in Figure 2.

Figure 2: Superimposed monotonic stress-strain curves for forged steel and ductile cast iron.

Superimposed plots of monotonic and cyclic true stress versus true strain for both materials are shown in Figure 3. From the figure it can be seen that for forged steel the cyclic stress-strain curve is below the monotonic curve. This indicates that the forged steel cyclically softened. The ductile cast iron cyclic stress-strain curve is above the monotonic curve, which indicates that it cyclically hardened. The cyclic properties obtained from the constant amplitude completely reversed uniaxial fatigue tests are also summarized in Table 2.

Figure 4 shows the superimposed true stress amplitude versus reversals to failure for forged steel and ductile cast iron in log-log scale. The equation describing the S-N behavior of the materials is:
Equation (1) is used to determine the fatigue strength of the material which is defined as the limit at $10^6$ cycles. Steel has a fatigue limit at $10^6$ cycles below which fatigue failure does not typically occur under constant amplitude loading. The S-N curve for cast iron continues to decline after $10^6$ cycles. The fatigue strength at $10^6$ cycles for forged steel is 359 MPa and for ductile cast iron 263 MPa. This shows that the fatigue strength at $10^6$ cycles for ductile cast iron is 73% of the fatigue strength of forged steel. For a given stress amplitude, forged steel provides a factor of 30 times longer life than cast iron in the high cycle region.

The true plastic strain versus reversals to failure for the forged steel and ductile cast iron is shown in Figure 5. This plot would serve little purpose in the automotive application due to the presence of only elastic loading conditions which is necessary for the extremely high cycle fatigue that the crankshaft must endure. However, in the case of the lawn mower engine, there is a potential that the crankshaft could be subjected to impact loading conditions, such as a sudden stop, causing plastic strain at stress concentrations. Figure 5 shows that for a given plastic strain amplitude, forged steel has more than an order of magnitude longer life than the cast iron.

The total strain amplitude was obtained by adding the elastic strain amplitude and plastic strain amplitude curves. The strain-life equation is given by:
\[
\frac{\Delta \varepsilon}{2} = \frac{\Delta \varepsilon_{\epsilon}}{2} + \frac{\Delta \varepsilon_{\sigma}}{2} = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c \tag{2}
\]

Superimposed strain-life curves for the two materials are compared in Figure 6. It can be seen that for both low and high cycle fatigue the forged steel provides longer life for a given strain amplitude. At long life, forged steel provides approximately an order of magnitude longer life.

Fatigue behavior at notches is typically controlled by both stress and strain ranges operating at the notch root. A Neuber plot can often provide a better insight than the stress-life or strain-life curve since this parameter combines the stress amplitude, strain amplitude, and modulus of elasticity into one parameter. The Neuber curves for both materials are shown superimposed in Figure 7. The Neuber stress parameter is calculated by the equation:

\[
\sqrt{\frac{\Delta \sigma}{\Delta \varepsilon}E} = 2\varepsilon_f (2N_f)^b + \sigma_f E (2N_f)^c \tag{3}
\]

From Figure 7, it can be seen that forged steel provides more than a factor of fifty (50) times longer life at long lives.

Charpy v-notch specimens were machined from the forged steel and ductile iron crankshafts. The specimen geometry conforms to ASTM Standard E23\(^{(6)}\), which lists several options for geometry. The standard 10 mm x 10 mm x 55 mm (Type A) specimen geometry with the v-notch was chosen since it is the most common geometry used.

The forging process causes inclusions to become elongated in the direction of maximum grain flow, or the longitudinal direction of the component. The material properties can therefore depend on the orientation. Two different specimen orientations were used for the forged steel specimens, while only one orientation was used for cast iron. The two orientations used for the forged steel specimens were L-T and T-L as shown in Figure 8. The L-T specimens were oriented such that the longitudinal axis of the crankshaft was normal to the crack plane and the notch (direction of crack growth) was in the transverse direction. The L-T specimens were removed from the main bearing section of the crankshaft, while the T-L specimens were removed from the web section. The cast iron specimens were removed from the web section, perpendicular to the T-L specimen orientation for the forged steel shown in Figure 8. The specimens were rough cut from the crankshaft and then machined on a mill to dimensions larger than the final specifications. The final machining was performed on a grinding machine. The notch was cut with a horizontal milling machine with a 45 degree double angle milling cutter with the proper radius.
specimens were placed in the bath for at least 5 minutes prior to testing. For the tests at 100°C and 200°C an electric oven with digital controller was used to maintain the proper temperature. The specimens were placed in the oven at the proper temperature for at least an hour prior to testing. For all tests conducted at temperatures other than ambient, the test was performed within 5 seconds of removing the specimen from the temperature conditioning environment.

After testing, the specimens were examined and the percentage of shear fracture was determined. The percentage shear (ductile) fracture was obtained by comparing the fracture surface of each fractured specimen to the fracture surface chart supplied with ASTM Standard E23.

The averaged results from two tests at each temperature obtained from the Charpy impact test are presented in the form of a bar chart in Figure 9. From the figure it can be seen that forged steel in the L-T direction had the highest impact toughness over the entire temperature range. Impact toughness for the forged steel in the T-L direction was still significantly higher than the cast iron specimens. The absorbed energy versus temperature is plotted for all three specimen types in Figure 10. Due to the application of the components tested (lawnmower crankshafts), it was deemed necessary to only test within a temperature range that the engine might operate. Therefore, the curve does not show the lower shelf region.

The percentage shear fracture values obtained from post-test are summarized in Table 3. As mentioned before, two specimens were tested for each specimen type at a given temperature. The values presented for percentage shear fracture are an average of the two specimens tested. From the data it can be seen that the forged steel (L-T and T-L) behaved in a brittle manner at sub zero temperatures and both directions showed signs of ductile fracture at 0°C. At 100°C both orientations of forged steel were 100% ductile fracture. The ductile iron behaved in a completely brittle manner over the entire temperature range indicating that, although it is ductile iron, the amount of ductility is still small.

Table 3: Percent shear fracture for Charpy specimens at different test temperatures.

<table>
<thead>
<tr>
<th>Average % Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>-77</td>
</tr>
<tr>
<td>-40</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>26</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>200</td>
</tr>
</tbody>
</table>

FINITE ELEMENT ANALYSIS

FEA was performed on the forged steel and cast iron crankshafts to verify the component test setup, identify critical locations, and to determine the stress concentration factors for purposes of life prediction. Geometries of the two crankshafts were obtained using a digital caliper and a Coordinate Measuring Machine (CMM). Both crankshafts were modeled in IDEAS 12 and imported into ABAQUS which was used for the FEA. From a dynamic analysis of the engine, it was determined that the critical location was at location 1 as indicated in Figure 11. The details of the dynamic analysis and FEA performed on the crankshafts are provided in another paper by Montazersadgh and Fatemi (9).

Figure 11: A 3D Model of forged crankshaft showing locations of strain gages and critical location (9).
For the FE model a mesh of 122,441 quadratic tetrahedral elements were used with a global mesh length of 5.08 mm and a local mesh length of 0.762 mm at the fillet. The mesh is shown in Figure 12. Due to the linear elastic condition necessary to achieve a very long fatigue life of the crankshaft, linear elastic analysis was employed.

The boundary conditions were set according to the test set-up with the left side of the crankshaft being fully constrained. The load was applied either along axis 2 (as shown in Figure 12) resulting in stresses at locations a and b shown in Figure 11, or along axis 1 resulting in stresses at locations c and d.

A forged steel crankshaft was fitted with strain gages at locations a, b, c, and d as shown in Figure 11. The crankshaft was installed in the test fixture with the vertical load applied at the right side of the crankshaft in Figure 11 with a 44 cm moment arm. Loads of +890N and -890N were applied to the crankshaft. The crankshaft was also rotated 90 degrees and the load still applied vertically. The strain values at each load level were recorded. These values were compared to those from FEA and also analytical calculations (i.e. Mc/I). The comparison between strain gage readings, FEA, and analytical calculations are shown in Table 4. The percent difference shown is between the FEA and experimental values, with FEA as the base.

Table 4 shows that the percent differences between FEA results and experimental results are small. For locations a and b, the analytical results suggest that the magnitude of stresses at points a and b should be equal. Both FEA and experimental results show that there is a difference between the two due to the complex geometry. At locations c and d, the magnitude of the stresses are equal and also very similar to those obtained from analytical calculations.

The stress distribution from FEA is shown in Figure 13. The value of $K_t$ at the critical fillet was determined from the FEA analysis and found to be 3.94 for the forged steel and 3.32 for the cast iron.

**COMPONENT FATIGUE TESTS AND COMPARISONS**

In order to compare the fatigue life of the forged steel and ductile cast iron crankshafts, constant amplitude load-controlled fatigue tests were performed on both crankshafts.

Cantilever bending was used as the loading mechanism of the crankshafts. From previous studies and a dynamic analysis of this engine the effect of torsion on the crankshafts was found to be negligible, resulting in a bending condition. Cantilever bending was chosen to minimize the loads needed to create the appropriate nominal stress levels in the crankshaft.
The same test fixture was used for testing both the forged steel and cast iron crankshafts. A schematic representation of the test fixture is shown in Figure 14. The crankshaft was supported by a solid piece of bar steel with a hole bored to the precise size of the crankshaft main bearing section diameter. The moment was applied by a moment arm made of bar steel with a diameter the size of the nose of the crankshaft bored into it. The load was applied using a rod end bearing joint attached to the actuator to minimize any misalignment in the test set-up. This was attached to a rod fitted with needle roller bearings. The bearings were necessary to eliminate the horizontal friction force that would be present otherwise. This frictional force would have produced an undesired axial force on the crankshaft. The moment arm was slotted to fit the size of the roller bearings and allowed to roll horizontally. The bolts holding the crankshaft into place were equally tightened prior to testing to ensure adequate and uniform clamping force.

Tests were conducted using a 100 kN closed-loop servo-hydraulic test frame controlled by a digital servo-controller. The calibration of the system was verified prior to testing.

An applied R-ratio of -0.2 was used for all tests. From the dynamic analysis (9) it was shown that the in-service loading conditions for both crankshafts were approximately $R = -0.2$. Load levels were selected to produce lives in the range of $10^5$ cycles and $10^6$ cycles for the forged steel crankshafts.

Displacement amplitude versus cycles was recorded for each test and are shown superimposed in Figure 15. From the figure it can be seen that for all tests except cast iron at 630 N-m, the displacement amplitude was constant up to a point and then began to increase. The short life (630 N-m) cast iron crankshafts never reached stable displacement amplitude. The higher the applied moment, the more rapidly the displacement amplitude increased. It can also be seen that the displacement amplitude started to increase dramatically and then approach an asymptotic value. This asymptotic value was considered the final fracture point. Sample cross sections of the final fracture surface are shown in Figure 16. From the figures it can be seen that the forged steel fracture surface is smoother than the cast iron. Figure 16 (b) also shows the eccentricity of the hole in the cast iron crankshaft, the highest stress location was where the wall thickness was the greatest.

![Figure 14: Schematic drawing of component test set-up.](image)

![Figure 15: Displacement amplitude versus number of cycles from component tests.](image)

![Figure 16: Cross sections showing the final fatigue fracture surface from typical (a) forged steel and (b) cast iron crankshafts.](image)

It was found that crack growth life of the component was a significant portion of the life of the part. Due to the nature of the components being tested, the onset of a crack was defined as component failure. In order to detect the smallest crack possible, each test was stopped at a given interval corresponding to approximately 10% of the predicted life, at which point the crankshaft was inspected for the presence of a crack. Visible cracks were measured and their length was recorded at each interval. It was found that the cracks were on the order of 5 mm before being detected. Using the measured crack lengths, and displacement amplitude data, a relationship was developed between the change in displacement amplitude and the length of the crack for both materials. Displacement amplitude versus crack length is plotted in Figure 17 for the forged steel and cast iron crankshafts.
Moment amplitude versus cycles to failure is plotted for the two types of crankshafts in Figure 18. The cycles to failure used in this plot are defined as the cycles where a crack on the order of 2 mm was present from the change in displacement amplitude relationship. From the moment amplitude plot, it can be seen that the forged steel has approximately a factor of 6 longer life than the cast iron when tested at the same applied moment. Component test results are summarized in Table 5.

The presence of a crack can change the stiffness of a material. For this reason, a change in displacement amplitude corresponding to a change in stiffness, can indicate that a crack is present. A predefined change in displacement amplitude is often used as a criterion for failure in fatigue testing. A five (5) percent change in displacement amplitude was used as an alternate criterion for failure. The moment amplitude versus cycles to failure using the 5% change in displacement amplitude as the cycles to failure is shown in Figure 19.

**Table 5: Crankshaft test results and life prediction comparisons.**

<table>
<thead>
<tr>
<th>Applied Moment Amp. (N-m)</th>
<th>Cycles at First Observed Crack</th>
<th>Crack Initiation from Fitted Data</th>
<th>Cycles at 5% Change in Disp. Amp.</th>
<th>S-N Prediction</th>
<th>ε-N Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forged Steel Crankshaft</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>630</td>
<td>29,248</td>
<td>45,568</td>
<td>67,391</td>
<td>30,071</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45,302</td>
<td>69,670</td>
<td>67,391</td>
<td>30,071</td>
<td></td>
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<td>517</td>
<td>165,000</td>
<td>234,289</td>
<td>248,471</td>
<td>100,918</td>
<td></td>
</tr>
<tr>
<td>120,000</td>
<td>98,741</td>
<td>213,885</td>
<td>248,471</td>
<td>100,918</td>
<td></td>
</tr>
<tr>
<td>350 &gt;3,240,000</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cast Iron Crankshaft</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>630</td>
<td>11,504</td>
<td>17,353</td>
<td>2,162</td>
<td>517</td>
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</tr>
<tr>
<td>11,692</td>
<td>17,306</td>
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<td>42,750</td>
<td>54,966</td>
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<tr>
<td>431</td>
<td>132,877</td>
<td>32,988</td>
<td>3,716</td>
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<td></td>
</tr>
</tbody>
</table>

**COMPONENT FATIGUE BEHAVIOR AND LIFE PREDICTIONS**

Due to the long-life and elastic loading conditions on an engine crankshaft, the stress-life (S-N) approach to life estimation is commonly used. The S-N approach was one of the life estimation approaches used in this study. The fatigue notch factor $K_f$ was determined using Peterson’s equation (10):

$$K_f = 1 + \frac{K - 1}{1 + \epsilon}$$  \hspace{1cm} (4)
where $K_t$ is the stress concentration factor determined from FEA, $r$ is the radius at the fillet and $a$ is defined by (10):

$$a = 0.0254 \left( \frac{2070}{S_u} \right)^{1.8} \quad (5)$$

where $S_u$ is the ultimate tensile strength of the material. Using the stress amplitude versus number of cycles from the specimen testing (Figure 4), the S-N line for smooth, unnotched, and R = -1 loading condition was drawn. The S-N line for the notched condition was drawn using the same fatigue strength coefficient ($\sigma_f'$) value and reducing the fatigue strength at $2 \times 10^6$ reversals by $K_f$. The equation of the forged steel notched condition was determined to be:

$$S_{Nf} = 1124 \left( 2N_f \right)^{0.170} \quad (6)$$

where $S_{Nf}$ is the completely reversed stress amplitude and $N_f$ is the number of cycles to failure. The equation of the cast iron notched condition was determined to be:

$$S_{Nf} = 927 \left( 2N_f \right)^{0.166} \quad (7)$$

Since the loading was not completely reversed, the commonly used modified Goodman’s equation was used to account for the mean stress. From $R = -0.2$, the relationship between the applied mean stress, $S_m$, and the applied alternating stress, $S_a$, is obtained as:

$$S_m = 0.667 S_a \quad (8)$$

Modified Goodman’s equation is given by (10):

$$\frac{S_a}{S_{Nf}} + \frac{S_m}{S_u} = 1 \quad (9)$$

Predicted versus experimental cycles to failure are plotted in Figure 20 for S-N approach using the two failure criteria, with scatter bands of ±2 and ±3. From Figure 20 (a) it can be seen that when the crack length versus change in displacement data is used to determine crack initiation, the forged steel experimental data are within a factor of three (3) of the prediction and the cast iron data lie along the factor of three (3) scatter band. From Figure 20 (b) it can be seen that when the 5% change in displacement amplitude criterion is used, the forged steel experimental data are within a factor of two (2) of the prediction. Using the same criterion the cast iron experimental data lie outside the factor of three (3) scatter bands.

Figure 20: Predicted cycles to failure versus experimental cycles to failure for (a) crack initiation, and (b) 5% change in displacement amplitude criterion.

In the strain-life ($\varepsilon$-N) approach to life estimation local stress and strain at the notch is used to estimate the fatigue life of the component. The stress and strain range at the root of the notch ($\Delta S$, $\Delta \varepsilon$) were calculated using the commonly used Neuber’s rule (10):

$$\Delta \varepsilon \Delta \sigma = \frac{\left( K_f \Delta S \right)^{2}}{E} \quad (10)$$

and

$$\Delta \varepsilon = \frac{\Delta \sigma}{E} + 2 \left( \frac{\Delta \sigma}{2K'} \right)^{\frac{n'}{2}} \quad (11)$$

where $\Delta S$, $E$, $K'$, and $n'$ are the nominal stress range, modulus of elasticity, cyclic strength coefficient, and cyclic strain hardening exponent, respectively. Neuber’s rule assumes the geometric mean of stress concentration and strain concentration factors remain constant under plastic deformation.

The mean stress effect was accounted for by using the Smith-Watson-Topper (SWT) parameter (10):
\[ \varepsilon_a \sigma_{\text{max}} = \left( \sigma_f \right)^b \left( 2N_f \right)^{2b} + \varepsilon_f', \sigma_f' \left( 2N_f \right)^{c} \quad (12) \]

where \( \varepsilon_a \), \( \varepsilon_f' \), \( b \), and \( c \) are the strain amplitude at the notch, fatigue ductility coefficient, fatigue strength exponent, and fatigue ductility coefficient, respectively.

Predicted lives from the strain-life approach are included in Table 5. From this table it can be seen that the forged steel data are very close to the predicted results. The experimental results from the cast iron show longer lives than the predictions.

**CONCLUSIONS**

1. The ultimate strength and yield strength of ductile cast iron were 80% and 66% of forged steel, respectively. The forged steel has greater ductility than the ductile cast iron, with a percent reduction of area of 58% for forged steel and only 6% for ductile cast iron.

2. Constant amplitude specimen fatigue testing shows that the fatigue strength at \( 10^6 \) cycles was 359 MPa for forged steel and 263 MPa for ductile cast iron. The forged steel specimens had about 50 times longer life than the cast iron specimens in the long life region.

3. The forged steel L-T and T-L CVN specimens had significantly higher impact toughness than the ductile cast iron specimens at all temperatures.

4. The differences between the results from FEA and strain gage readings were close for the test set-up. The comparisons with analytic values were also reasonable for the complex geometry.

5. From component testing, the crack growth life was a significant part of the life to fracture of the part. The crack growth life was approximately three times the life to crack nucleation.

6. When the forged steel and cast iron crankshafts are tested at the same applied bending moment, the forged steel has a factor of six (6) times longer life.

7. For the forged steel crankshafts life predictions using S-N approach based on material fatigue test data provided reasonable, but non-conservative estimation of the component fatigue lives, as judged by comparison with crankshaft fatigue test data. For the cast iron the S-N approach was less accurate than for forged steel, but provided a conservative life estimate.

8. Life predictions using the \( \varepsilon - N \) approach provided reasonable estimation of the component fatigue lives for the forged steel, but were not as accurate for the cast iron crankshafts. For both the forged steel and cast iron crankshafts the \( \varepsilon - N \) approach provided conservative life estimates.

**REFERENCES**


