Durability Comparison and Optimization of Forged Steel and Ductile Cast Iron Crankshafts

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Outline

- Overview and Overall Goal

- Forged Steel & Cast Iron Crankshafts and Comparisons
  - Experimental Work
    - Specimen tests
    - Component tests
  - Analytical Work
    - Life predictions
    - Dynamic load analysis and FEA
    - Optimization
  - Conclusions
Overview and Overall Goal

- Evaluate and compare fatigue performance of forged steel components with competing manufacturing process technologies.
  - Steering Knuckle
    * Forged steel * Cast aluminum * Cast iron
  - Connecting Rod
    * Forged steel * Powder metal
  - Crankshaft
    * Forged steel * Ductile cast iron

- Evaluate life prediction techniques as compared with experimental results and perform optimization.
**Overview and Overall Goal**

**Steering Knuckle**
- Forged Steel: 2.5 kg, 11V37 Steel
- Cast Aluminum: 2.4 kg, A356-T6
- Cast Iron: 4.7 kg, 65-45-12

**Connecting Rod**
- Forged steel: 0.93 lb
- Powder metal: 1.2 lb

**Crankshaft**
- Forged steel: 3.9 kg
- Ductile cast iron: 3.7 kg
Publications of Results
(Steering Knuckle and Connecting Rod)

**Steering Knuckle**


**Connecting Rod**


Crankshaft Study
Overall Objectives

• Evaluate and compare fatigue performance of forged steel and ductile cast iron crankshafts.

• Perform life predictions and compare with component test data.

• Perform dynamic load analysis and optimization.
Outline

• **Literature Survey on Crankshafts**
  – Design and manufacturing considerations including cost analysis
  – Comparison of Competing manufacturing techniques
  – Durability assessment and optimization
  – Experimental techniques and bench testing

• **Experimental Work**
  – Specimen Testing (Forged steel and ductile cast iron)
  – Component Testing (Forged steel and ductile cast iron)

• **Analytical Evaluations**
  – Dynamic Load Analysis
  – Stress Analysis Using FEA
  – Durability Analysis and Life Predictions
  – Optimization
Crankshaft Publication of Results


Crankshaft Nomenclature

Loading: Bending and Torsion

Crankshafts

Forged Steel Crankshaft
- Outdoor power equipment engine
- 460 cc, 12.5 HP
- 3.9 kg

Ductile Cast Iron Crankshaft
- Similar engine type and size
- 3.7 kg
Specimen Testing

- **Specimen Tests**
  - Strain-controlled tensile tests
  - Strain-controlled fatigue tests
  - Procedures and practices as outlined by ASTM
  - Round specimens machined from unmachined crankshafts

Closed-loop servo-hydraulic axial load frame
Specimen Geometry
Material Stress-Strain Curves

- Forged Steel Monotonic
- Forged Steel Cyclic
- Cast Iron Cyclic
- Cast Iron Monotonic
Forged steel has better S-N fatigue performance than the ductile cast iron.

At long lives, for a given stress, forged steel has a factor of 30 longer life.
Material Comparison

- Fatigue life is often controlled by stress and strain ranges at root of the fillet.
- At long lives, the forged steel has a factor of 50 longer life.
Charpy V-Notch Results

Specimen Orientation

Results

Absorbed Energy (J)

Test Temperature (°C)

Forged steel L-T
Forged steel T-L
Cast Iron

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## Mechanical Properties

<table>
<thead>
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<th>Property</th>
<th>Forged Steel</th>
<th>Cast Iron</th>
<th>Ratio*</th>
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<tr>
<td>YS (MPa)</td>
<td>625</td>
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<td>UTS (MPa)</td>
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<td>%RA</td>
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<td>CVN (Room Temp) (J)</td>
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<td>$S_f$ (at $N_f=10^6$) (MPa)</td>
<td>359</td>
<td>263</td>
<td>0.73</td>
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* base of comparison is the forged steel
Component Fatigue Tests

Schematic of test set-up

- Load-controlled, constant amplitude fatigue tests
- R-Ratio: -0.2
- Test frequency: 1.4 – 3 Hz
- Life range: $7 \times 10^3 – 4 \times 10^6$
- Both crankshafts tested at the same load (moment) amplitudes
Component Fatigue Test Results

- Lives based on crack initiation (small crack on the order of a few mm).
- For a given bending moment, forged steel crankshaft has a factor of 6 longer life.
Component Fatigue Test Results Based on 5% Change

- Lives based on 5% change in displacement amplitude (large crack).
- For a given bending moment, the forged steel crankshaft has an order of magnitude longer life.
Fractured Components

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\[
\frac{S_a}{S_{Nf}} + \frac{S_m}{S_u} = 1 \\
S_{Nf} = \sigma_f^' \left(2N_f\right)^b
\]
Dynamic Load Analysis

Pressure vs. Crankshaft Angle

Slider-Crank Mechanism (ADAMS Simulation)

Resultant
Bending
Torsional

Critical Speed

Max Bending
Max Torsion
Range of Bending
Range of Torsion

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Digitized Models

Forged Steel

Cast Iron

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Boundary Conditions for FEA

Service Life
(1 of 4 steps)

Fixed surface in all degrees of freedom over 180°

Fixed edge in directions 1 & 2 over 180°

Applied load; constant pressure over 120°
Mesh Generation

Forged Steel

Cast Iron
FEA and Critical Location

Stress Magnitude (MPa)

Crankshaft Angle (Deg)

Critical Location

Location Number

Critical Location

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Comparison Between FEA and Experimental

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Optimization Flowchart

- Objective Function
  - Weight Reduction
  - Improve Performance
  - Reduce Cost

- Design Variables
  - Material Properties
  - Geometry Variables
  - Manufacturing Process

- Constraints
  - Material Limits and Cost
  - Geometry Restrictions
  - Manufacturing Feasibility and cost

- Initial Design Model (Geometry, Material, Process)

- Optimization
  - Geometry Optimization
  - Alternative Materials

- Redesigned Model
  - Redesign

- Original Model

- Replaceable with the original crankshaft
- 18% weight reduction
- Reduced finished cost
- Significantly higher fatigue strength
Geometry Optimization Process

Final Optimized Geometry
Material and Manufacturing Optimization

- Manufacturing
  - Adding fillet rolling
- Material
  - Using Micro-Alloyed Steel

Specimen Rig Test (Park et al. 2001)
Conclusions

• Yield strength of the forged steel is 50% higher than that of the cast iron, while the ultimate strength is 26% higher. Ductility and impact toughness of the forged steel is also significantly higher.

• Material fatigue strength at $10^6$ cycles for the forged steel is 37% higher than that of the cast iron, resulting in 30 times longer life.

• Component fatigue tests show fatigue strength based on crack initiation for the forged steel crankshaft to be 27% higher than that of the cast iron. This results in a factor of 6 longer life.

• Fatigue crack growth was a significant portion of the life for both crankshafts. The crack growth rate for the forged steel was slower than that of the cast iron.
Conclusions

- Life predictions using the S-N approach provided very reasonable estimations for the forged steel crankshafts. Predictions for the cast iron crankshafts were less accurate but were conservative.

- Dynamic load analysis results in more realistic stresses, whereas static analysis overestimates the results.

- Considering the torsional load in the overall dynamics analysis has no effect on von Mises stress at the critically stressed location.

- Geometry optimization resulted in 18% weight reduction of the forged steel crankshaft. Fillet rolling results in significant increase of the crankshaft fatigue strength.