# Fatigue Performance Evaluation of Forged Steel versus Ductile Cast Iron Crankshaft: A Comparative Study

## (EXECUTIVE SUMMARY)

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# EXECUTIVE SUMMARY

The overall objective of this study was to evaluate and compare the fatigue performance of two competing manufacturing technologies for automotive crankshafts, namely forged steel and ductile cast iron. In addition, weight and cost reduction opportunities for optimization of the forged steel crankshaft were also investigated. Details of the literature review conducted, experimental program and results, and analyses preformed on the crankshaft study are presented in two extensive reports and several other publications. The list of these reports and publications is provided in ***Appendix I***. This executive summary provides a brief background and motivation for the study, as well as a brief discussion of the objectives and the scope of the study. This is followed by a summary of the conclusions obtained from the study.

## Background and Motivation for the Study

The increased demand for improved performance and reduced cost in engines has lead to significant competition in engine component materials and manufacturing process technologies. High strength, ductility, and fatigue resistance are critical properties required from the crankshaft material and manufacturing process. In spite of its generally lower fatigue resistance, ductile cast iron is a major competition to forged steel crankshafts.

To realize the goal of increased usage of forged ferrous components, comparative and comprehensive fatigue performance data of forged steel and cast iron crankshafts were generated. Since a crankshaft experiences a large number of load cycles during its service life, fatigue performance and durability of this component is a key consideration in its design and performance evaluation.

Crankshafts are high volume production engine components and their most common application is in an automobile engine. In an internal combustion engine, the reciprocating motion of the piston is linear and is converted into rotary motion through the crankshaft. There are many other applications of a crankshaft which range from small one cylinder engines to very large multi cylinder marine crankshafts.

Design developments have always been an important issue in the crankshaft production industry, in order to manufacture a less expensive component with the minimum weight possible and proper fatigue strength and other functional requirements. These improvements result in lighter and smaller engines with better fuel efficiency and higher power output.

This project was an extension of a completed project on competing manufacturing technologies using steering knuckles. It supports the initiatives detailed in both the Forging Industry Technology Roadmap as well the Steel Industry Technology Roadmap.

## Objectives of the Study

The overall objective of this research project was to evaluate and compare mechanical properties of forged steel crankshaft and the competing component, commonly produced by casting. Fatigue is the primary cause of failure of crankshafts due to the cyclic loading and presence of stress concentrations at the fillets. In addition, weight and cost reduction opportunities for optimization of the forged steel crankshaft were also investigated.

The crankshafts used in this study were forged steel and ductile cast iron crankshafts from a one-cylinder four stroke engine typical to that used in a riding lawnmower. These single throw crankshafts consisted of two web sections and a crankpin. The forged steel crankshaft was designed to be used in a 460cc engine which produces approximately 9.3 kW. The ductile cast iron crankshaft was from a similar engine size and type. The masses of both crankshafts were similar with the forged steel at 3.9 kg and the ductile cast iron at 3.7 kg (see ***Figure 1***). The overall dimensions were also similar.

Typically in automotive crankshaft analysis a single throw is analyzed regardless of the size of the crankshaft. Therefore, the analyzed section in automotive crankshafts closely resembles the analyzed section in this study, allowing the procedures and information to be easily applied to automotive applications. Also, the failure location of the crankshafts used in this study was in the crank-pin fillet, which agrees with the typical failure location for an automotive crankshaft.

## Scope of the Study

The work consisted of a literature review, experimental evaluation of mechanical properties and performance of the two materials and components, as well as analytical studies of durability and optimization. The literature review included the material and manufacturing processes used for crankshafts, as well as design requirements and optimization studies for this engine component. The experimental work consisted of two types of experiments. One type of experiments characterized material monotonic deformation, impact resistance, and fatigue performance by using standard small laboratory specimens. Another type of experiments used actual crankshafts.

For specimen testing, strain-controlled monotonic and fatigue tests of specimens made of the forged steel and cast iron crankshafts were conducted. From these experiments, both static as well as baseline cyclic deformation and fatigue properties of both materials were obtained. Such data provide a direct comparison between deformation, fatigue performance, and failure mechanisms of the base materials, without introducing the effects and interaction of complex design parameters such as surface finish, component size, residual stress, stress concentration, etc. ASTM standard test methods and recommended practices were followed in all tests. Charpy V-notch specimen tests were also conducted due to the occasional impact loads applied to the crankshaft.

A number of load-controlled fatigue tests of crankshafts made of forged steel and ductile cast iron were also conducted. Such data provide a direct comparison between fatigue performance of the components made of each base material and manufacturing process. Such comparison inherently includes design effects such as surface finish, component size, residual stress, and stress concentration.

Finite element analyses of the crankshafts were conducted to obtain stress distributions, determine the critical location of the crankshafts and to determine the stress concentration factors. Based on the finite element analysis performed for the two crankshafts, life predictions were performed using the properties obtained from the strain-controlled specimen fatigue tests. Both the S-N and the strain-life approaches were used, results of which were then compared with the component test data.

Dynamic load and stress analysis of the forged steel and ductile cast iron crankshafts were also performed. The analysis was done for different engine speeds and as a result, critical engine speed and critical region on the crankshafts were obtained. Stress variation over the engine cycle and the effect of torsional load in the analysis were investigated.

Based on the results of the finite element analyses and the testing performed, an analytical optimization study of the forged steel crankshaft was then performed. This optimization seeks to minimize stress, maximize fatigue life, and minimize manufacturing cost and weight. Geometry, material, and manufacturing processes were optimized considering different constraints, manufacturing feasibility, and cost. The optimization process included geometry changes compatible with the current engine, fillet rolling, and the use of microalloyed steel.

## Conclusions of the Study

### Material Behavior and Comparisons

1. Based on the monotonic tensile test results, the forged steel has significantly higher strength than the ductile cast iron. The yield strength of the forged steel is 52% higher than that of the cast iron, while the ultimate strength is 26% higher for the forged steel than the ductile cast iron (see ***Table 1*** and ***Figure 2***).
2. The forged steel material also has more ductility than the ductile cast iron as shown by the percent reduction in area, which was 58% for the forged steel and 6% for the ductile cast iron (see ***Table 1***).

3. The forged steel Charpy V-notch impact results show that the forged steel in both the L-T and T-L directions have higher impact toughness than the ductile cast iron at all temperature levels investigated (see ***Figure 3***). This is important for this application due to the possibility of impact loading condition in the engine if subjected to a sudden stop.

4. The S-N curves for the two materials show that the forged steel has better fatigue resistance than the ductile cast iron. The fatigue strength at $10^6$ cycles was 359 MPa for the forged steel and 263 MPa for the ductile cast iron, which results in a factor of 30 longer life for the forged steel in the long life region. The forged steel fatigue strength at $10^6$ cycles is 36% higher than the ductile cast iron (see ***Table 1*** and ***Figure 4***).

5. The forged steel also shows longer life when subjected to plastic deformation, based on the true plastic strain amplitude versus reversals to failure plot. For a given plastic strain amplitude, the forged steel has a factor of 40 longer life than the ductile cast iron (see ***Figure 5***).

6. The Neuber curves for the two materials also show better fatigue performance for the forged steel material, compared to the ductile cast iron. The Neuber curves show that in the long life region the forged steel has a factor of 50 longer life than the ductile cast iron (see ***Figure 6***).

## Crankshaft Fatigue Behaviors and Comparisons

7. The crack growth life for both crankshafts was a significant portion of the fatigue life during the crankshaft testing (see ***Figure 7***). The crack growth rate of the forged steel crankshaft was slower than the ductile cast iron crankshaft.

8. Failure criterion based on crack initiation is more reasonable in crankshaft applications since an engine would not tolerate the increased deflection caused by the presence of a crack. A 5% change in displacement criterion resulted in a crack that was 10 mm or longer.
9. Based on the crack initiation failure criterion the forged steel crankshaft had a factor of 6 longer life than the ductile cast iron crankshaft at long lives (see ***Figure 8***). The 5% change in displacement amplitude also showed better fatigue performance for the forged steel crankshaft, resulting in an order of magnitude longer life than the ductile cast iron crankshaft at long lives.
10. At $10^6$ cycles the fatigue strength of forged steel crankshaft was 36% higher than the fatigue strength of the ductile cast iron crankshaft (see ***Figure 8***). Specimen fatigue test results also show that the fatigue strength of the forged steel material was 36% higher than the fatigue strength of the ductile cast iron material at $10^6$ cycles (***Figure 4***).
11. During crankshaft fatigue tests, circumferential cracks developed in the rear crankpin fillet of both forged steel and ductile cast iron crankshafts which was identified as the critical location from FEA (see ***Figure 9***). These cracks grew and were the ultimate cause of failure for the crankshafts, despite secondary cracks which developed in the opposite crankpin fillet in some crankshafts.

## Fatigue Life Predictions

12. Using the rainflow cycle counting method on the critical stress history plot shows that in an entire cycle only one peak is important and can cause fatigue damage in the component.

13. The life predictions were more accurate for the forged steel crankshafts than the ductile cast iron crankshafts. The S-N predictions proved to be a more accurate life prediction method, providing reasonable results for both the forged steel and cast iron crankshafts (see ***Figure 10***). The strain-life predictions also provided reasonably accurate estimations for the fatigue life of the forged steel crankshafts and less accurate, however conservative, estimations for the ductile cast iron crankshafts (see ***Figure 11***).
14. The accuracy of fatigue life predictions using the S-N or the strain-life approach is strongly influenced by an accurate estimation of notch sensitivity of a material. Using a low notch sensitivity for the ductile cast iron crankshaft ($q$ = 0.2) as suggested in the literature resulted in life predictions that did not agree with the experimental data. When low notch sensitivity was assumed the predictions overestimated the results while high notch sensitivity underestimated the results (see ***Figure 10b***).

## Dynamic Load and Finite Element Analyses

15. Dynamic loading analysis of the crankshaft results in more realistic stresses whereas static analysis provides overestimated results. Accurate stresses are critical input to fatigue analysis and optimization of the crankshaft.
16. There are two different load sources in an engine; inertia and combustion. These two load source cause both bending and torsional load on the crankshaft. The maximum load occurs at the crank angle of 355 degrees for this specific engine. At this angle only bending load is applied to the crankshaft (see ***Figure 12***).

17. Considering torsional load in the overall dynamic loading conditions has no effect on von Mises stress at the critically stressed location (see ***Figure 13***). The effect of torsion on the stress range is also relatively small at other locations undergoing torsional load. Therefore, the crankshaft analysis could be simplified to applying only bending load.
18. Finite element analysis is necessary to obtain the stresses in the crankshafts due to the relatively complex geometry (see ***Figure 14***). The geometry led to a lack of symmetry at the top and bottom of the crankpin in the forged steel crankshaft in spite of cross-section symmetry, which could not be accounted for in the analytical stress calculations (see ***Figure 15***). The lack of symmetry at the top and bottom of the crankpin in the forged steel crankshaft was confirmed with experimental strain gage results. Experimental stress and FEA results showed close agreement, within 7% difference.
19. Critical (i.e. failure) locations on the crankshaft geometry are all located on the fillet areas because of high stress gradients in these locations, which result in high stress concentration factors (see ***Figure 15***).
20. Superposition of FEM analysis results from two perpendicular loads is an efficient and simple method of achieving stresses for different loading conditions according to forces applied to the crankshaft from the dynamic analysis.

## Optimization

21. Geometry optimization resulted in 18% weight reduction of the forged steel crankshaft, which was achieved by changing the dimensions and geometry of the crank webs while maintaining dynamic balance of the crankshaft. This stage of

optimization did not require any changes in the engine block or connecting rod (see ***Figure 16***).

22. As a result of geometry optimization from Stage II, the weight of the crankshaft was reduced by 26%. Crankshaft geometry changes in this optimization stage required changing the main bearings in the engine according to the optimized diameters and using thrust bearings to reduce the increase of axial displacement of the crankshaft (see ***Figure 17***).
23. Adding fillet rolling was considered in the manufacturing process. Fillet rolling induces compressive residual stress in the fillet areas, which results in 165% increase in fatigue strength of the crankshaft and increases the life of the component significantly.
24. Using microalloyed steel as an alternative material to the current forged steel results in the elimination of the heat treatment process. In addition, considering better machinability of the microalloyed steel along with the reduced material cost due to the weight reduction result in significant reduction in overall cost of the forged steel crankshaft.

# ACKNOWLEDGEMENTS

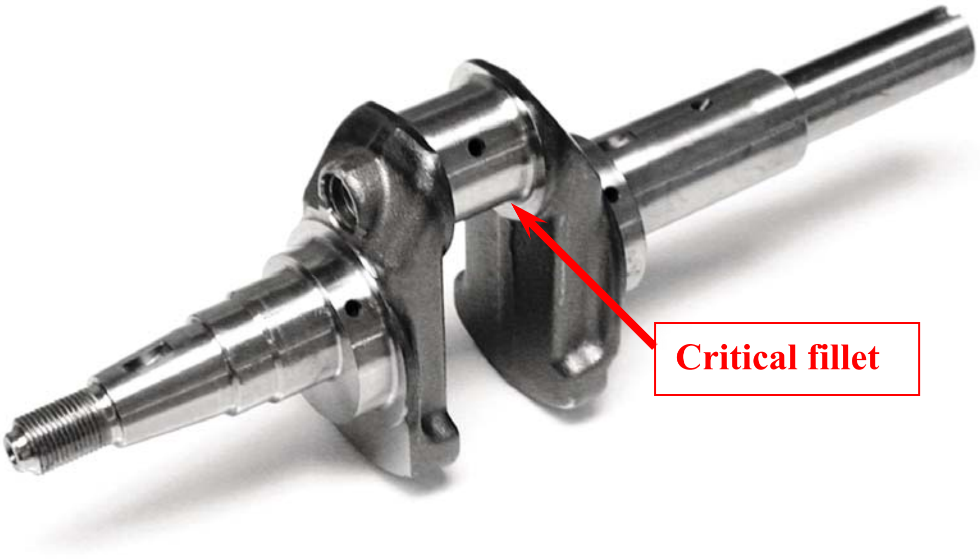
Financial support for this research project was provided by the Forging Industry Educational Research Foundation (FIERF) and the American Iron and Steel Institute (AISI). We would like to thank Karen Lewis (Executive Director of FIERF), David Anderson (Director of Bar and Rod Products at AISI), Michael Wicklund (President of FIERF) for providing technical support and information, and George Mochnal from the Forging Industry Association.

**Table 1** Summary of monotonic and cyclic properties for the two materials.

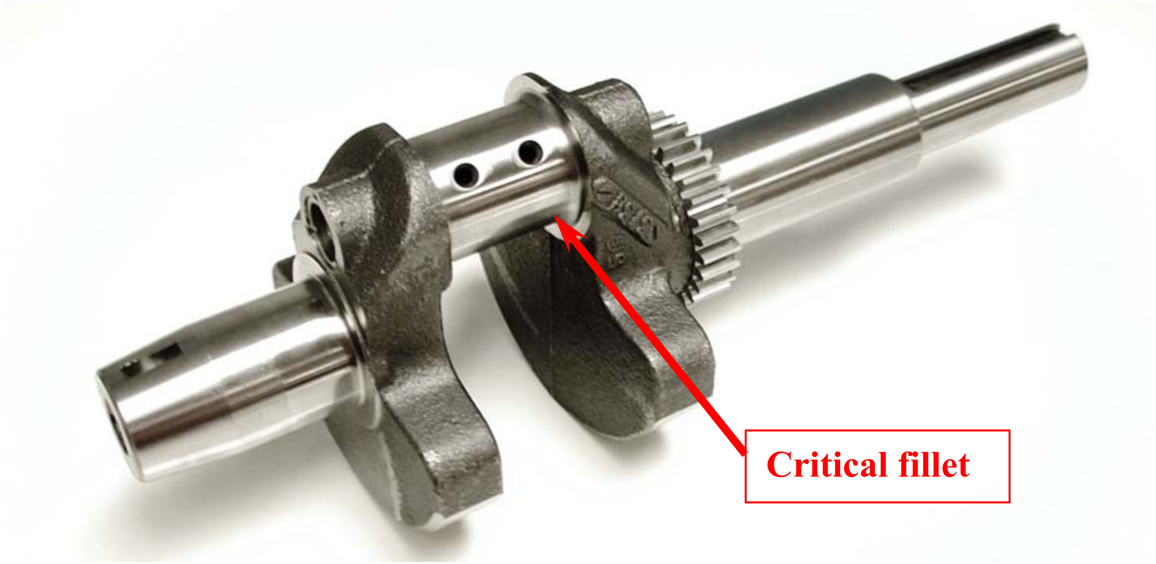
| Monotonic Properties | Forged Steel | | Cast Iron | | Ratio |
|---|---|---|---|---|---|
| Average Hardness, HRC | 23 | | 18 | | 0.8 |
| Average Hardness, HRB | 101 | | 97 | | 0.96 |
| Modulus of elasticity, E, Gpa (ksi) | 221 | (32,088) | 178 | (25,838) | 0.81 |
| Yield Strength (0.2%offset), YS, MPa (ksi) | 625 | (91) | 412 | (60) | 0.66 |
| Ultimate strength, $S_u$, MPa (ksi) | 827 | (120) | 658 | (95) | 0.80 |
| Percent elongation, %EL | 54% | | 10% | | 0.19 |
| Percent reduction in area, %RA | 58% | | 6% | | 0.10 |
| Strength coefficient, K, MPa (ksi) | 1316 | (191) | 1199 | (174) | 0.91 |
| Strain hardening exponent, n | 0.152 | | 0.183 | | 1.20 |
| True fracture strength, $\sigma_f$, MPa (ksi) | 980 | (142) | 658 | (95) | 0.67 |
| True fracture ductility, $\varepsilon_f$ | 87% | | 6% | | 0.07 |

| Cyclic Properties | Forged Steel | | Cast Iron | | Ratio |
|---|---|---|---|---|---|
| Fatigue strength coefficient, $\sigma_f'$, MPa (ksi) | 1124 | 163 | 927 | (134) | 0.82 |
| Fatigue strength exponent, b | -0.079 | | -0.087 | | 1.10 |
| Fatigue ductility coefficient, $\varepsilon_f'$ | 0.671 | | 0.202 | | 0.30 |
| Fatigue ductility exponent, c | -0.597 | | -0.696 | | 1.17 |
| Cyclic yield strength, YS', MPa (ksi) | 505 | 73 | 519 | (75) | 1.03 |
| Cyclic strength coefficient, K', MPa (ksi) | 1159 | 168 | 1061 | (154) | 0.91 |
| Cyclic strain hardening exponent, n' | 0.128 | | 0.114 | | 0.89 |
| $S_f = \sigma_f'(2N_f)^b$ at $N_f = 10^6$, MPa (ksi) | 359 | (52) | 263 | (38) | 0.73 |
| Average E' Gpa (ksi) | 204 | (31,437) | 174 | (25,229) | 0.85 |

Note: Forged steel taken as the base for all ratio calculations



(a) Forged steel crankshaft



(b) Ductile cast iron crankshaft

**Figure 1** Forged steel and ductile cast iron crankshafts in their final machined condition.

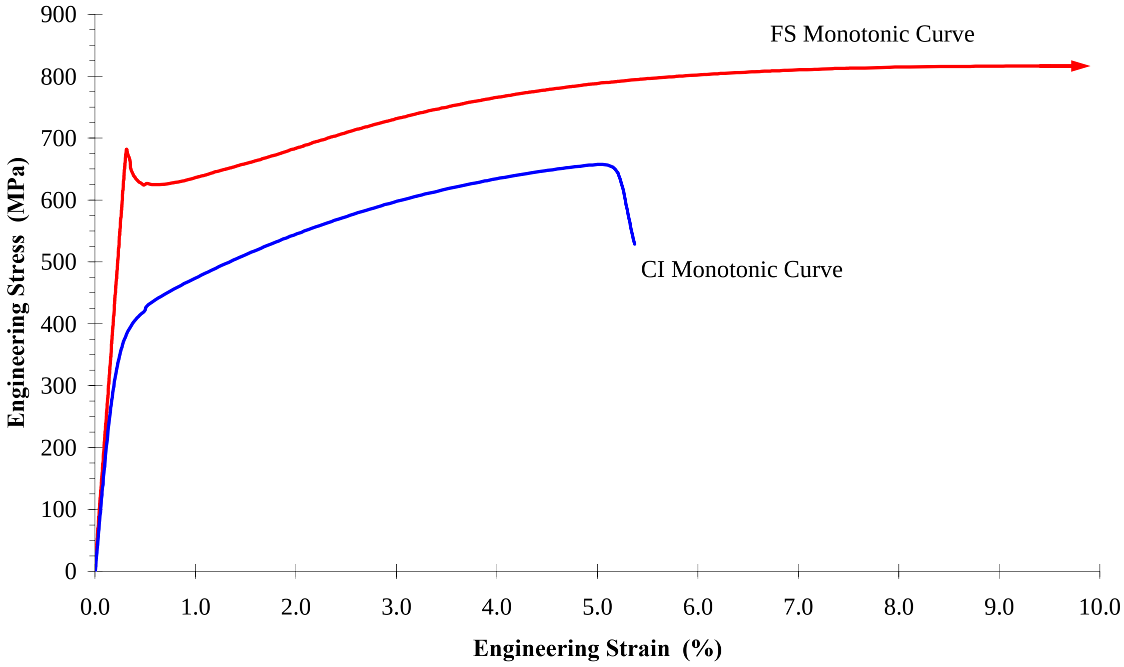


**Figure 2** Superimposed monotonic engineering stress versus strain curves for forged steel and ductile cast iron.

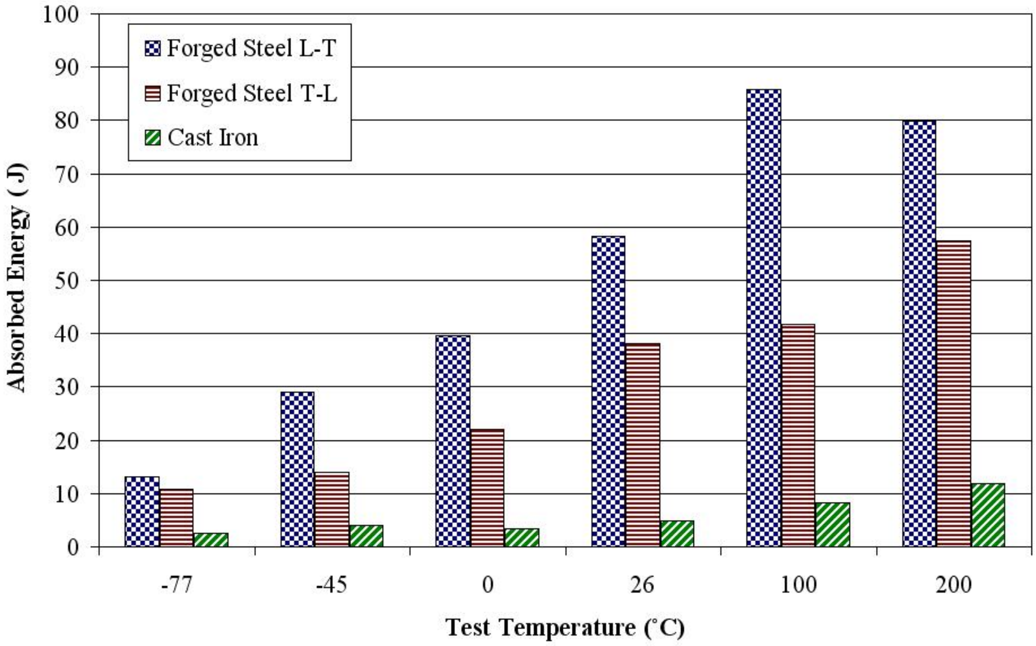


**Figure 3** Average absorbed energy values at the different test temperatures for forged steel (L-T, T-L) and ductile cast iron.

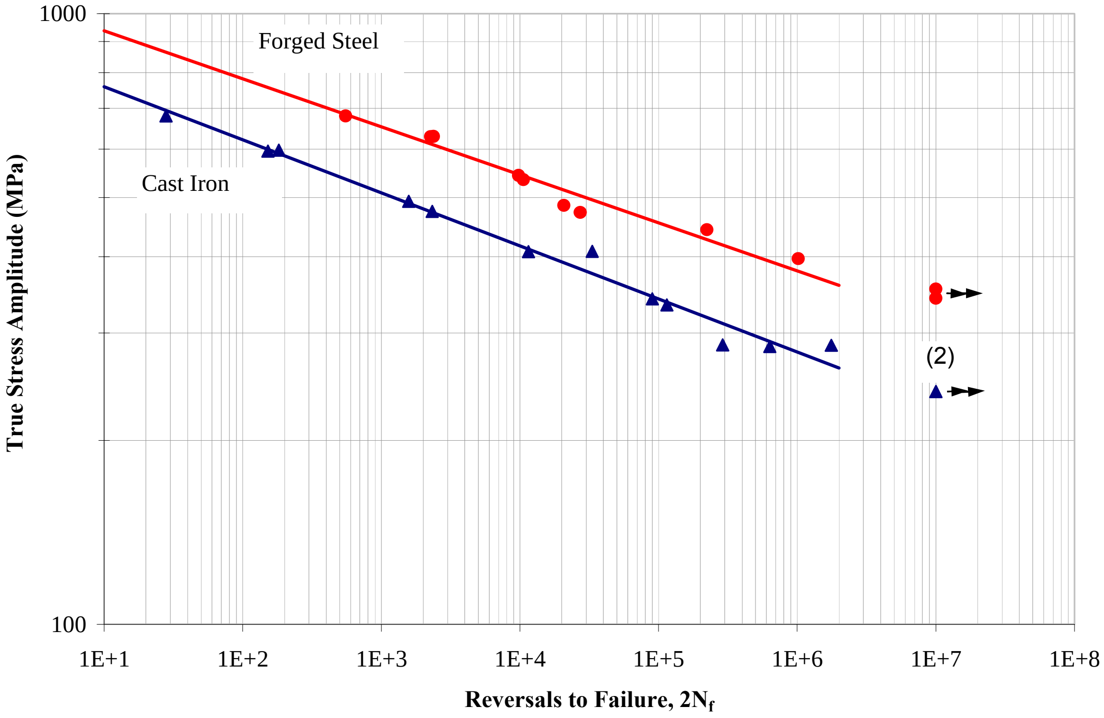


**Figure 4** Superimposed plots of true stress amplitude versus reversals to failure for forged steel and ductile cast iron.

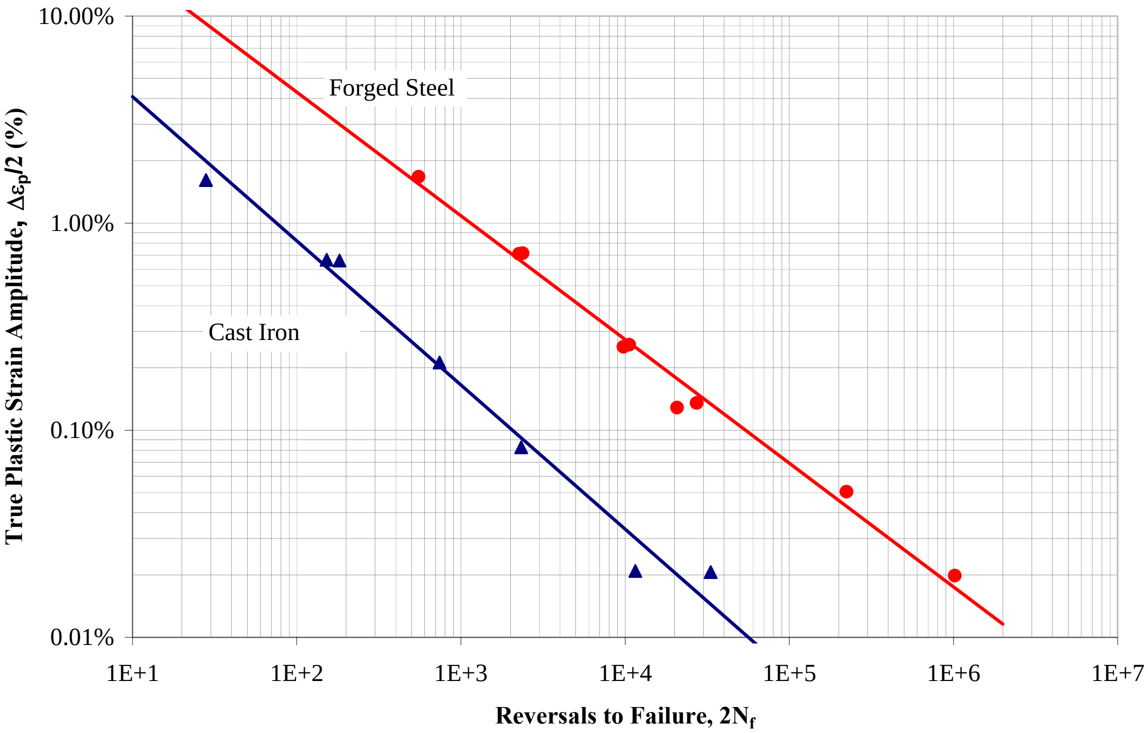


**Figure 5** Superimposed plots of true plastic strain versus reversals to failure for forged steel and ductile cast iron.

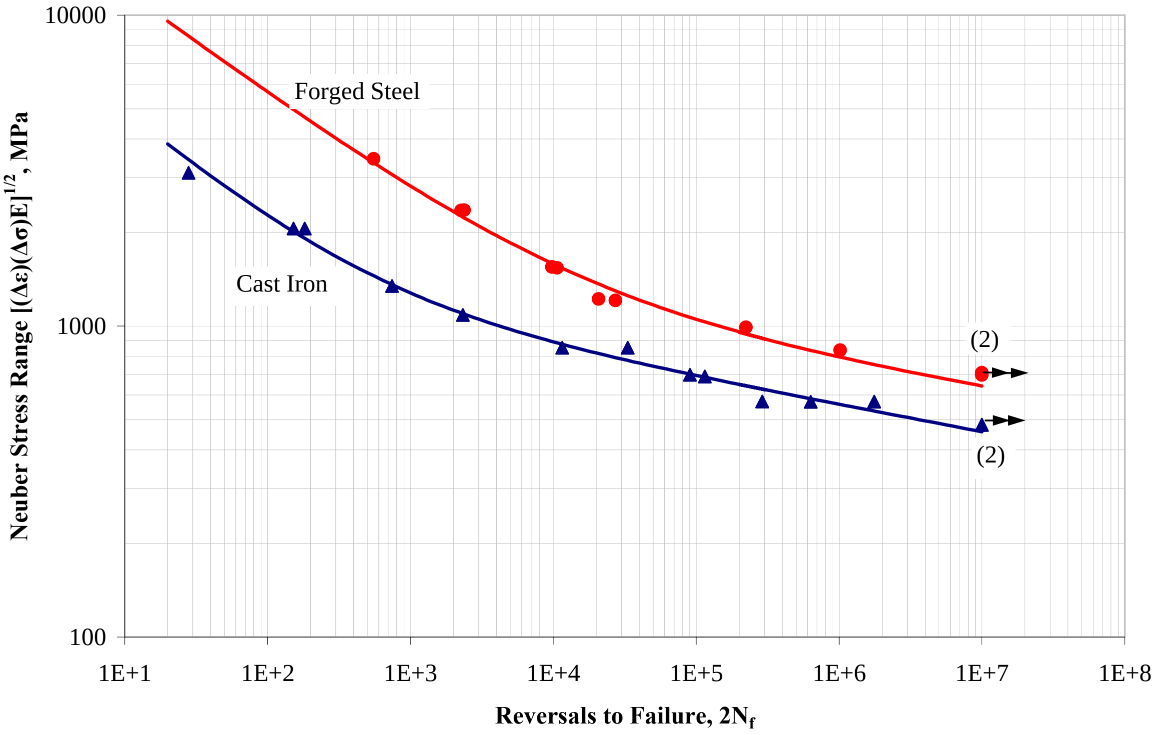
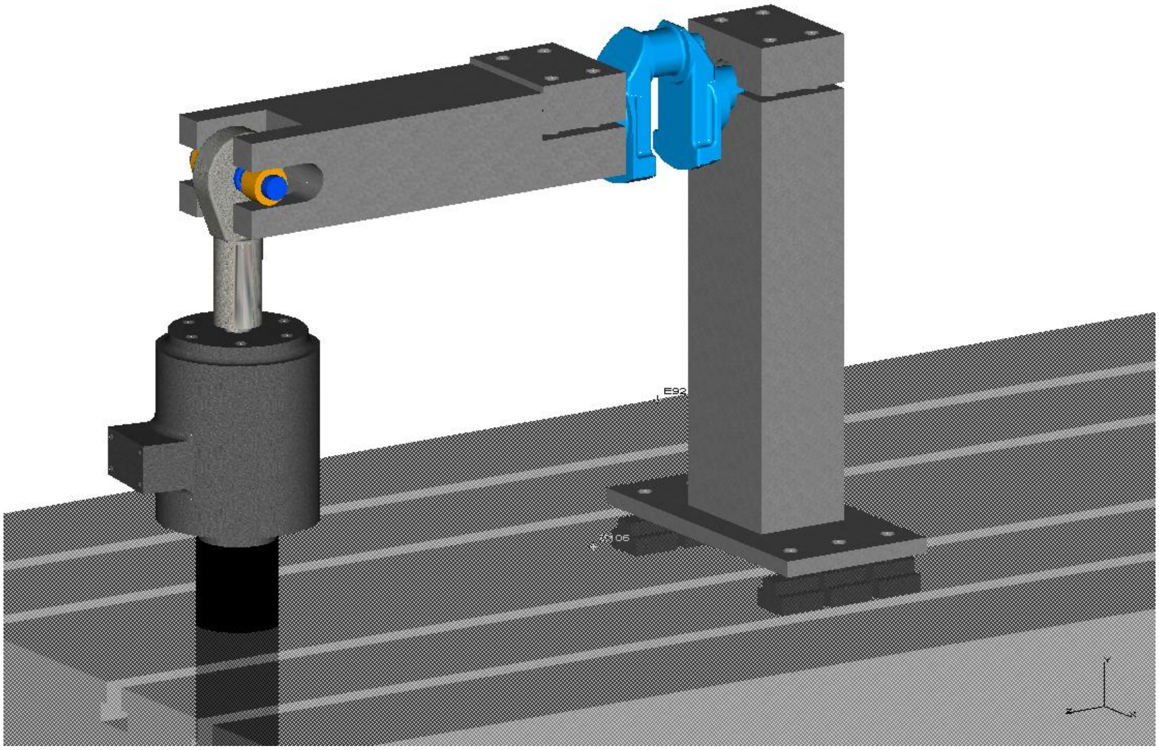


**Figure 6** Superimposed Neuber stress range versus reversals to failure for forged steel and ductile cast iron.



(a) Schematic of test set-up.

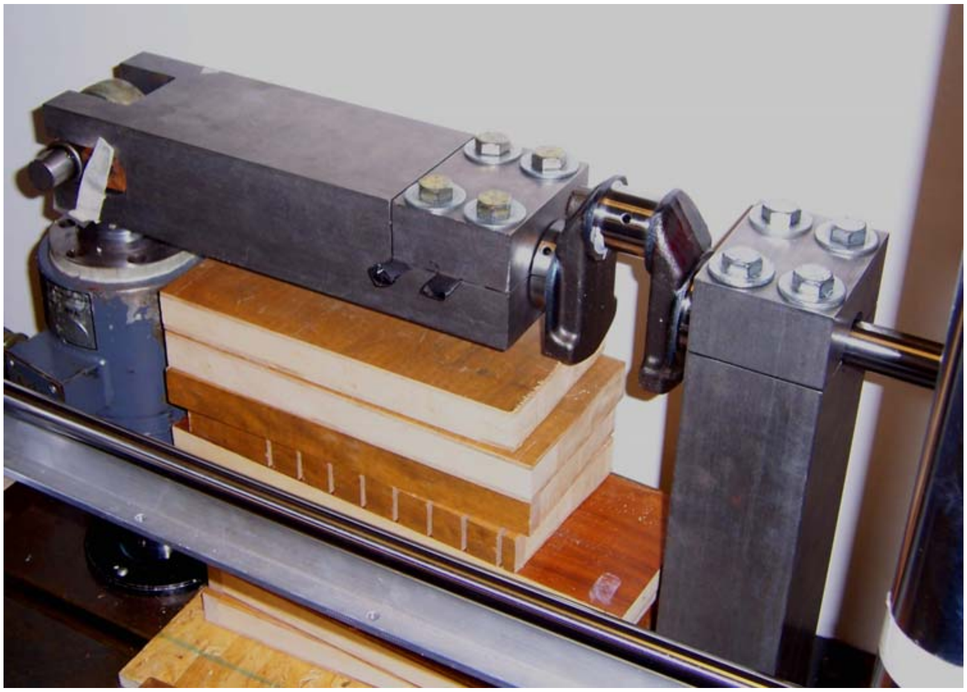


**Figure 7** Test set-up for the crankshaft. (a) Schematic, and (b) Forged steel crankshaft

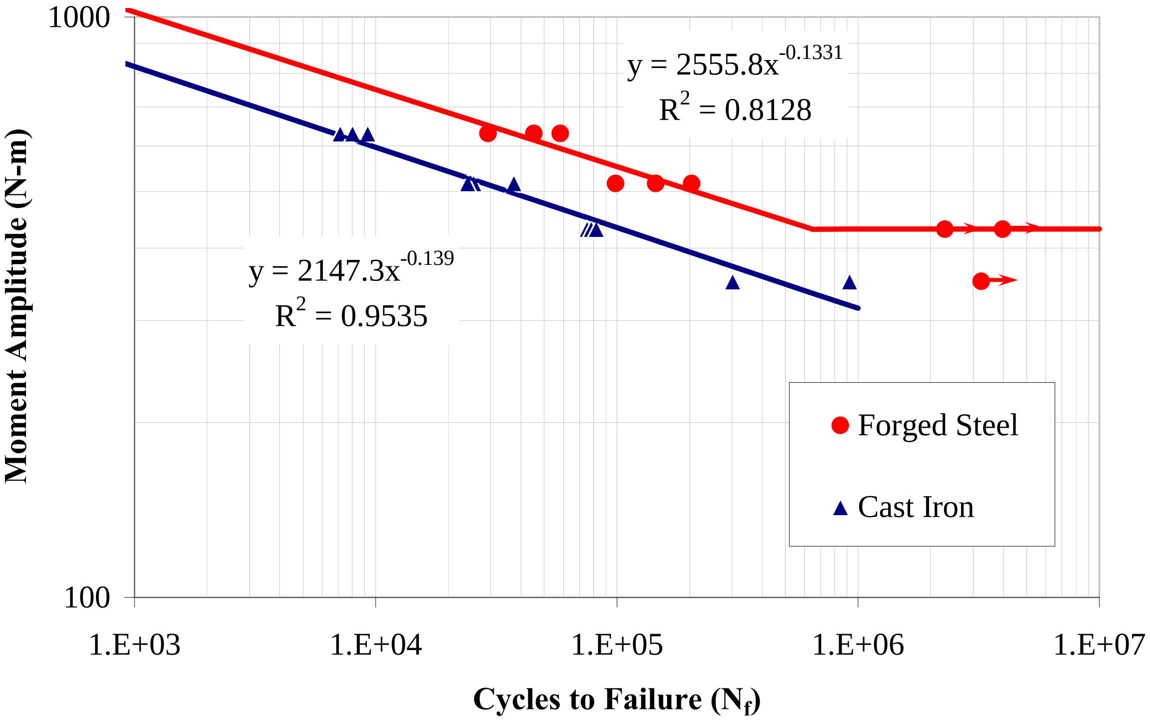
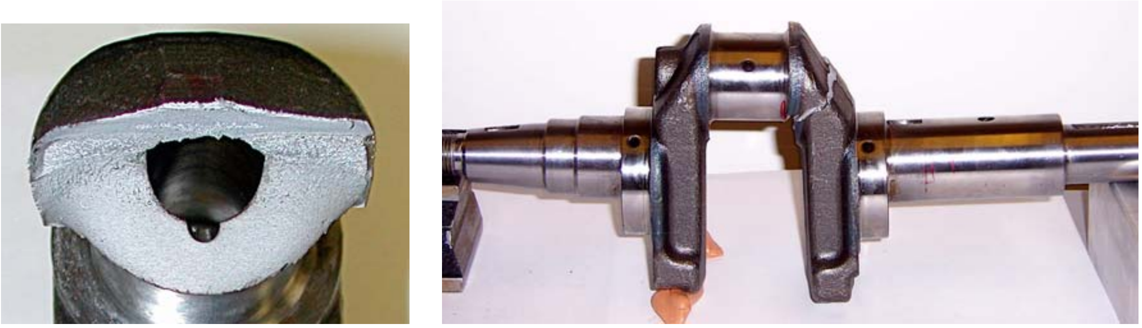
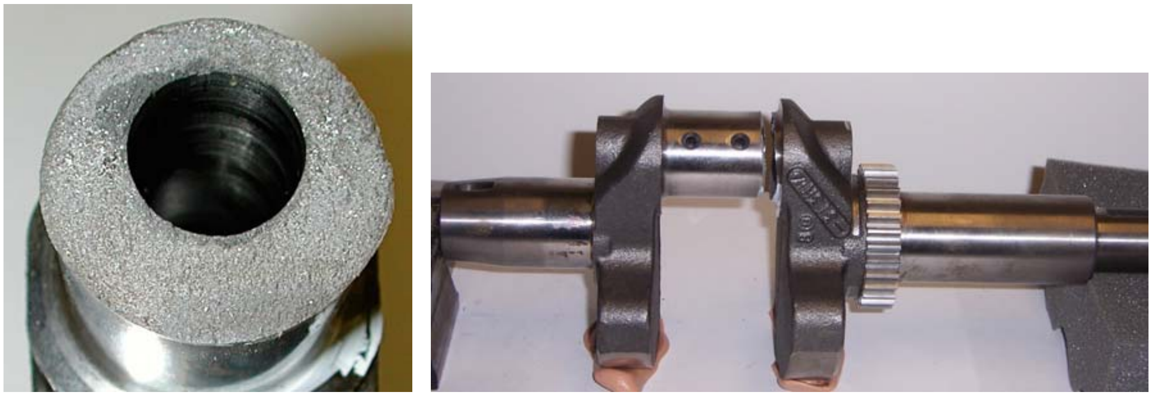


***Figure 8*** Moment amplitude versus cycles to failure using the crack initiation failure criterion.

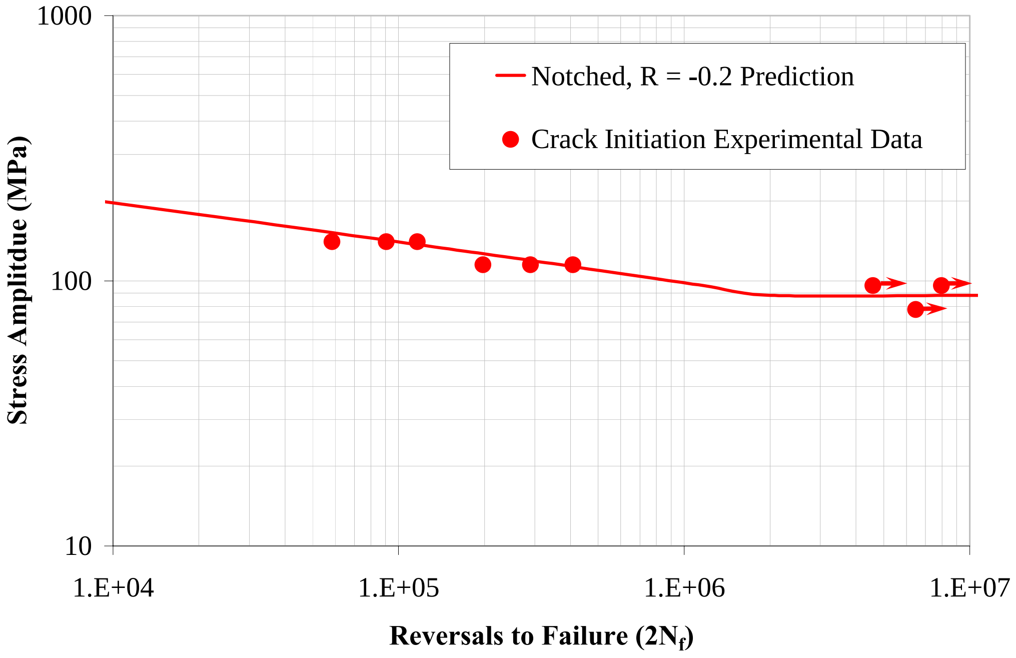


(a) Forged steel crankshaft

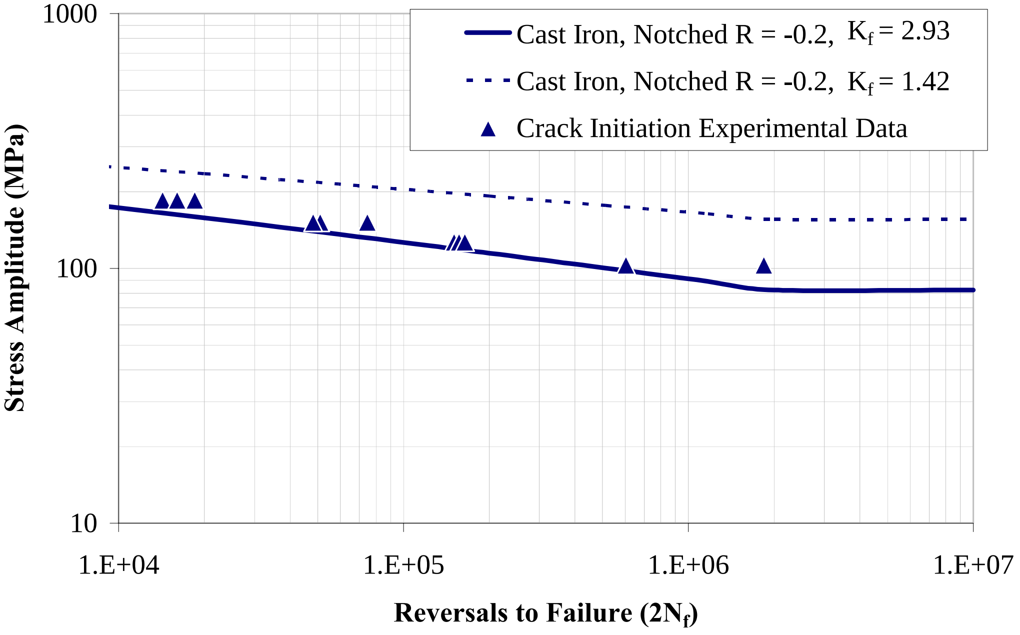


(b) Cast iron crankshaft

**Figure 9** Typical fatigue fractures of the crankshafts.

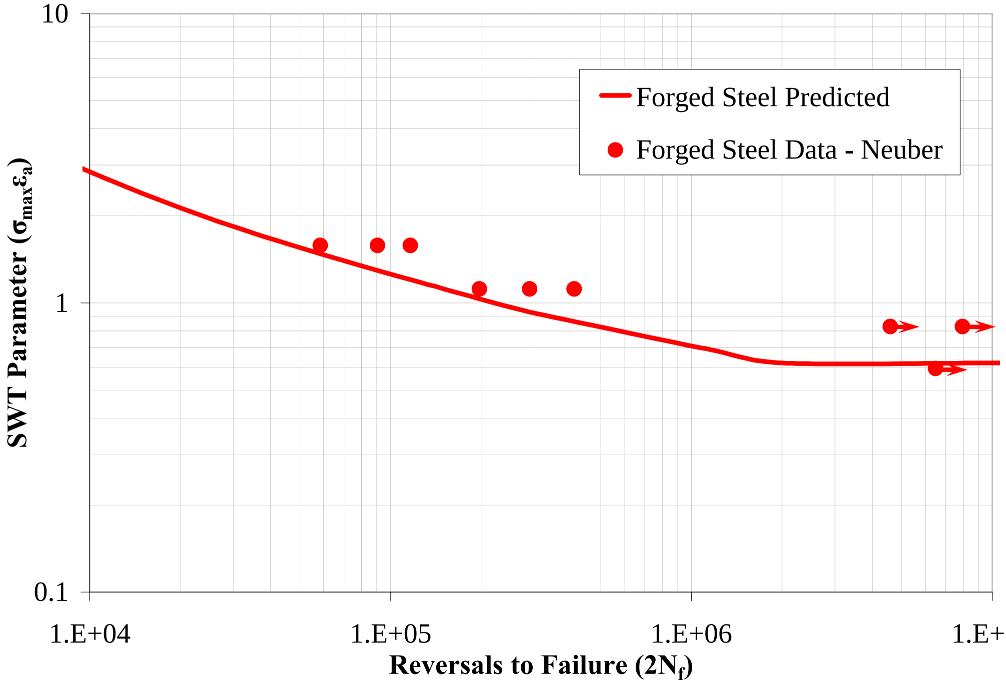


(a) Forged steel crankshaft

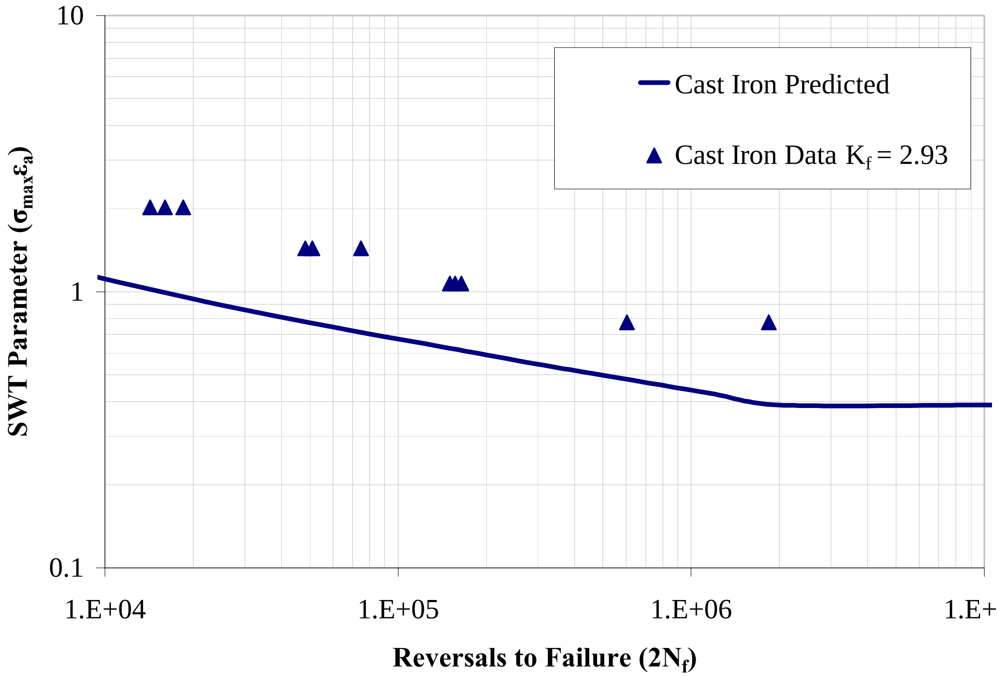


(b) Cast iron crankshaft

**Figure 10** Crankshaft S-N lines superimposed with the crack initiation experimental data.



(a) Forged steel crankshaft



(b) Cast iron crankshaft

**Figure 11** SWT parameter versus reversals to failure based on crack initiation with superimposed strain-life prediction data.

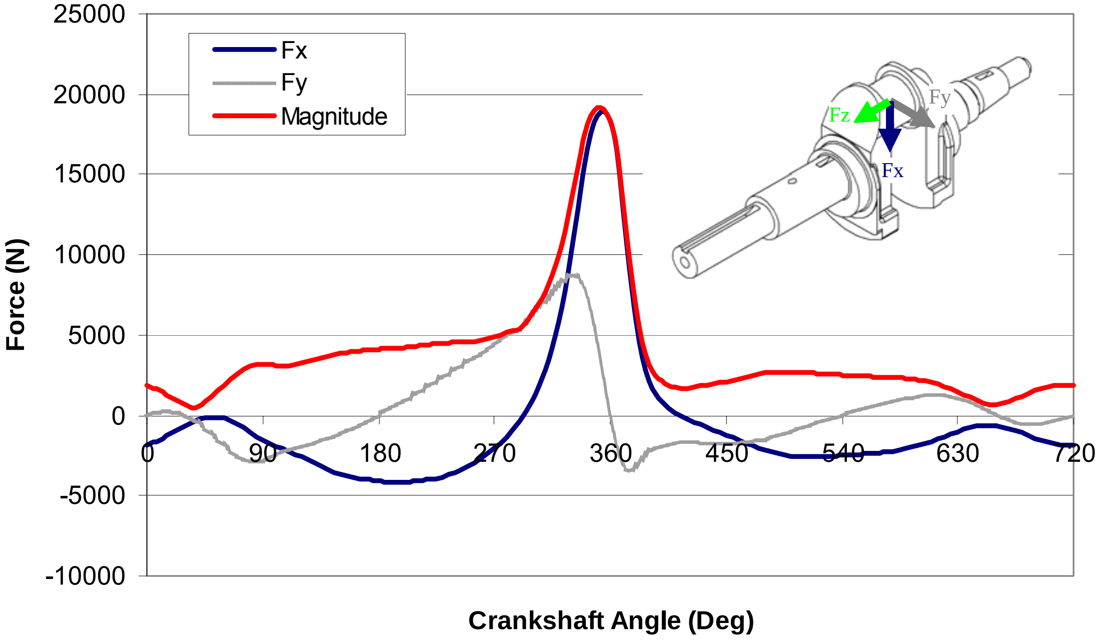
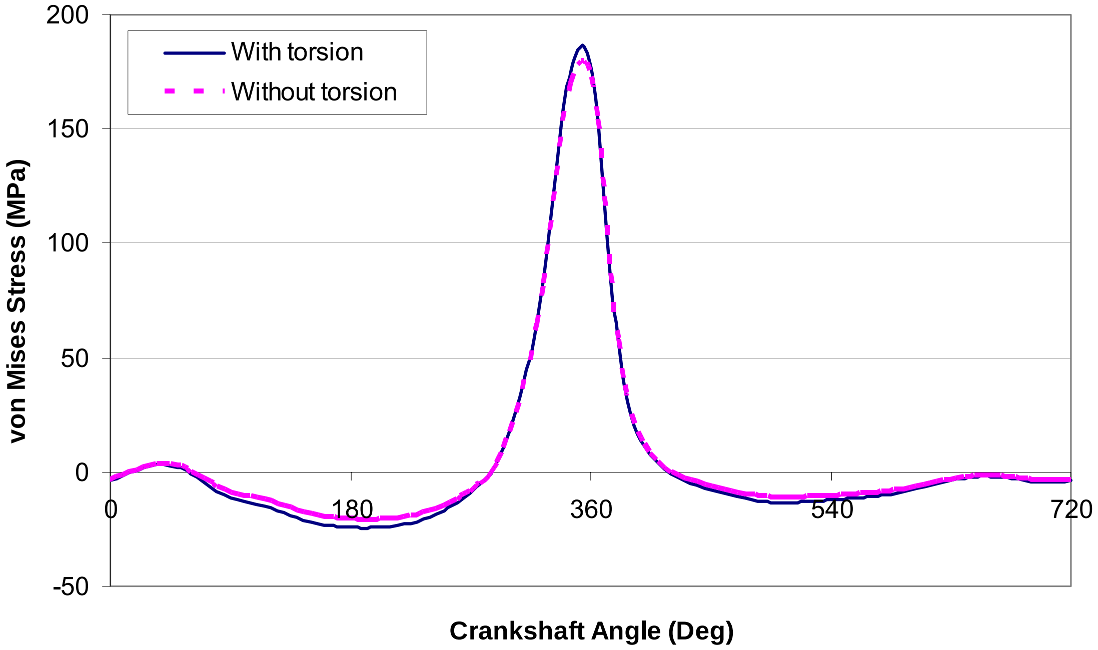
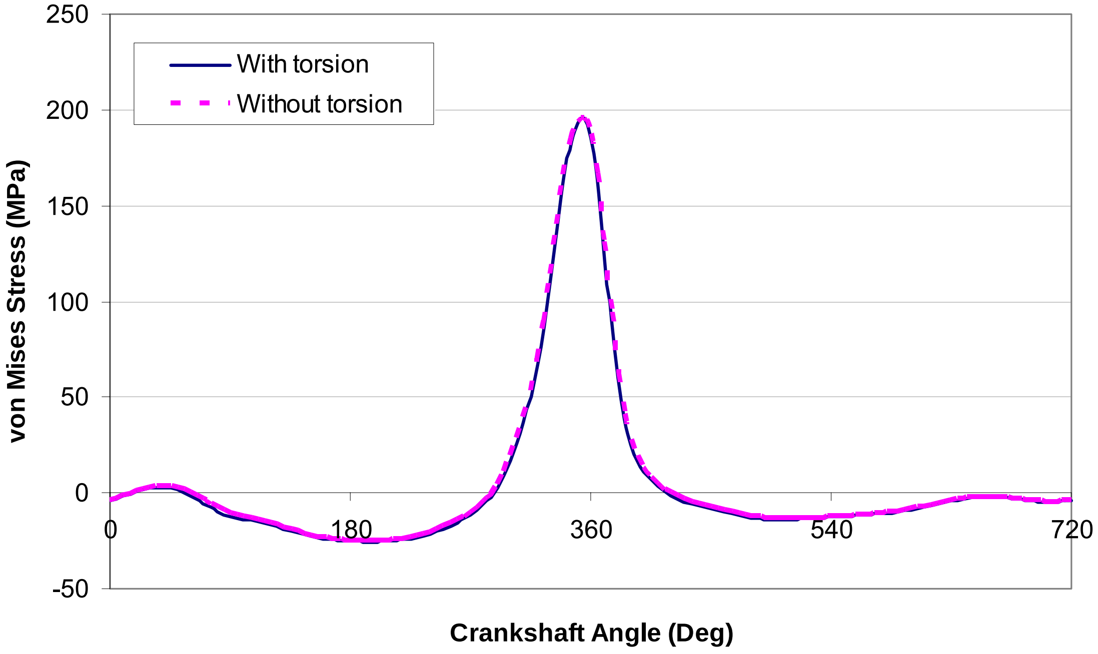


**Figure 12** Variation of the force components over one complete cycle at the crank end of the connecting rod defined in the local/rotating coordinate system at crankshaft speed of 2000 rpm.

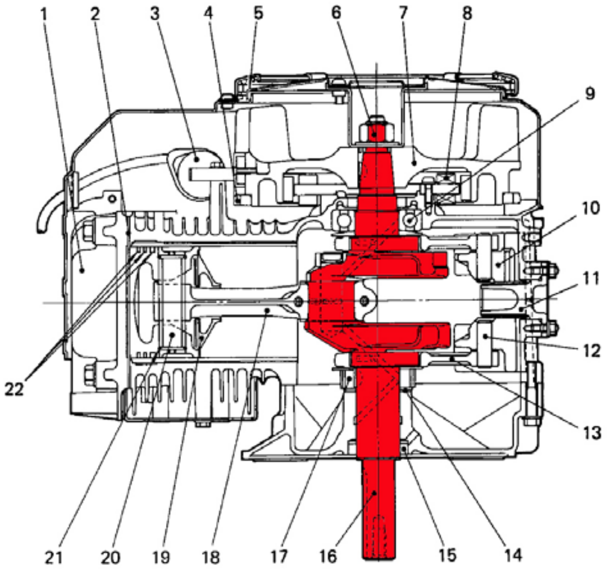


(a) Forged steel crankshaft

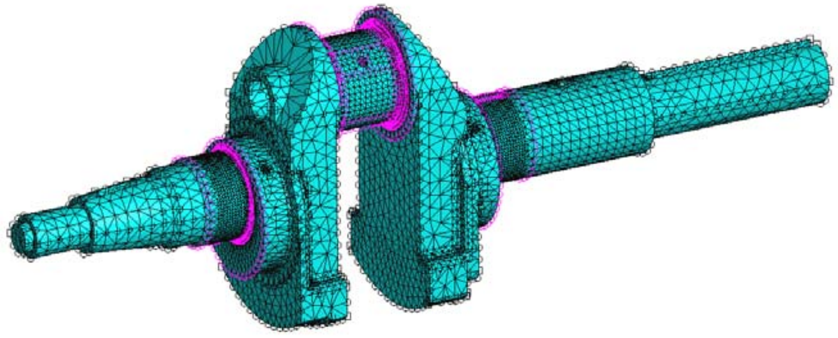


(b) Cast iron crankshaft

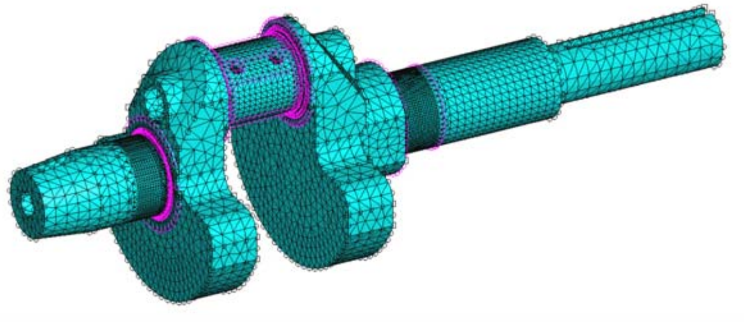
**Figure 13** Effect of torsion on von Mises stress at the critical location at the engine speed of 2000 rpm.



(a) Crankshaft in the engine block



(b) Forged steel crankshaft



© Cast iron crankshaft

**Figure 14** Crankshaft in the engine block and element size at different locations on the crankshaft geometries.

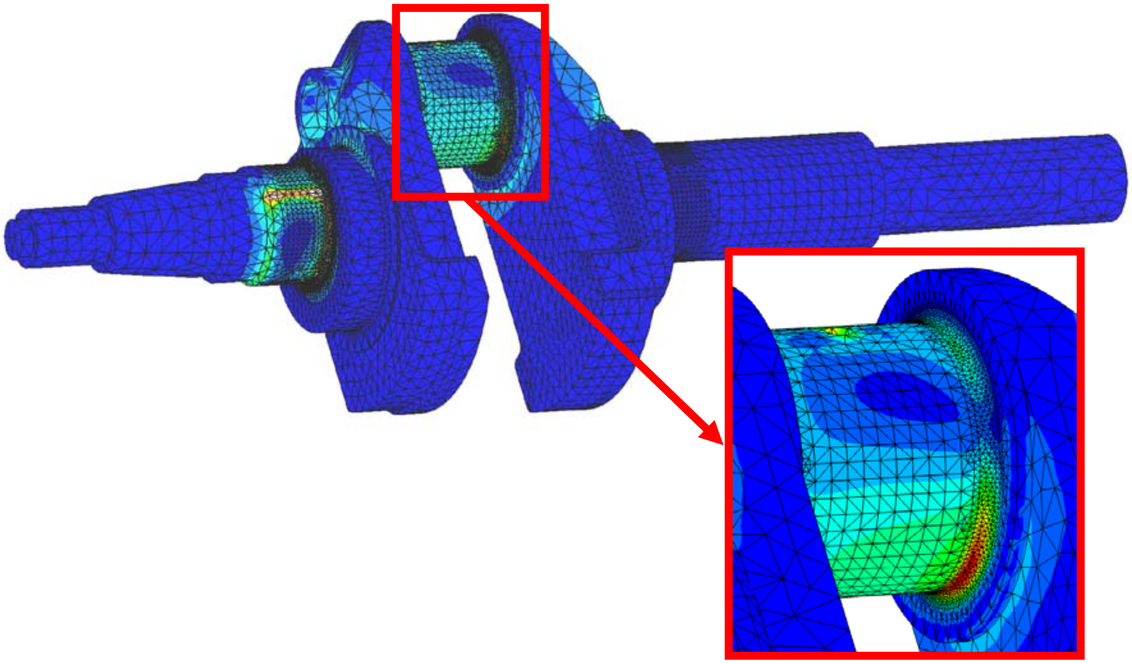


**Figure 15** Forged steel crankshaft showing FEA stress contour with the crankpin fillet magnified.

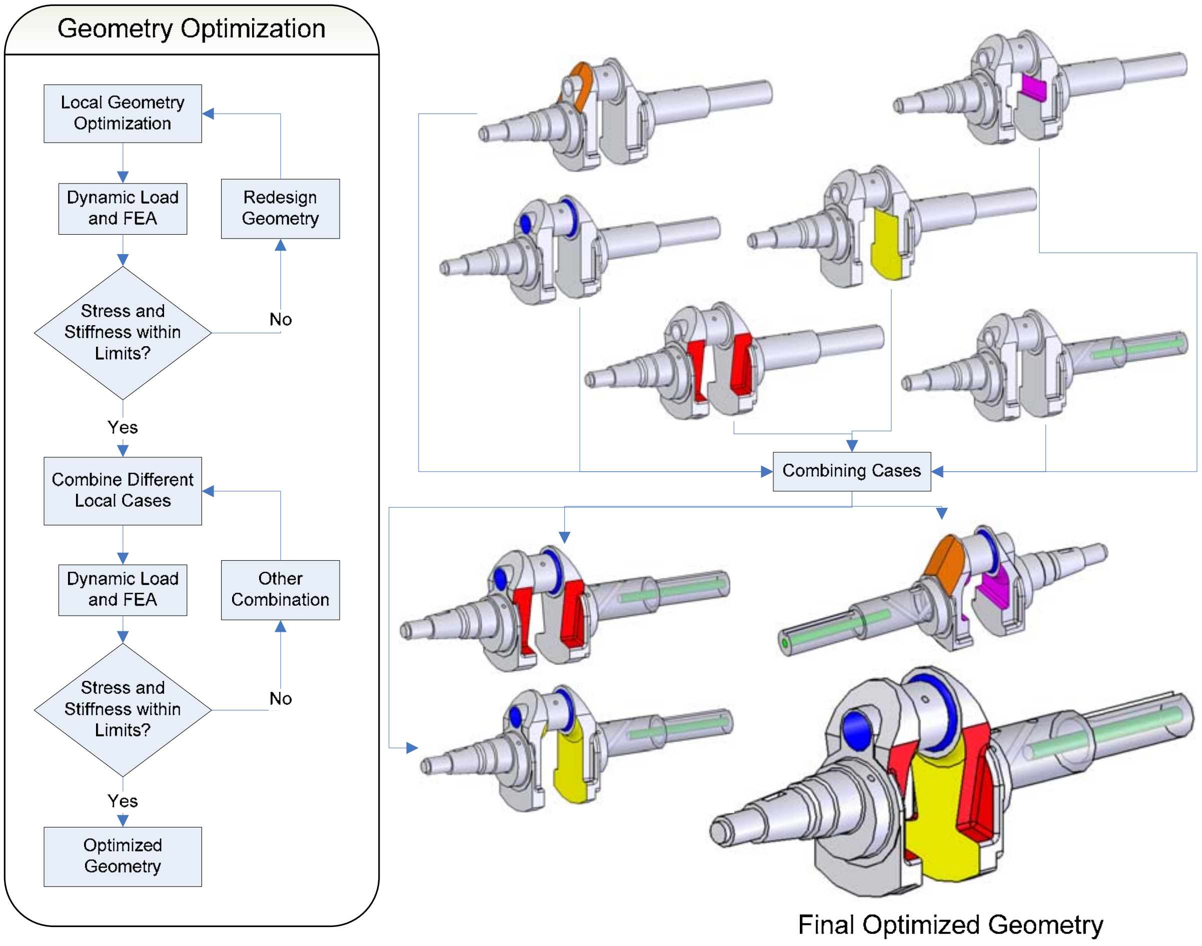


**Figure 16** Geometry optimization flowchart and optimized geometry of the forged steel crankshaft from Stage I.

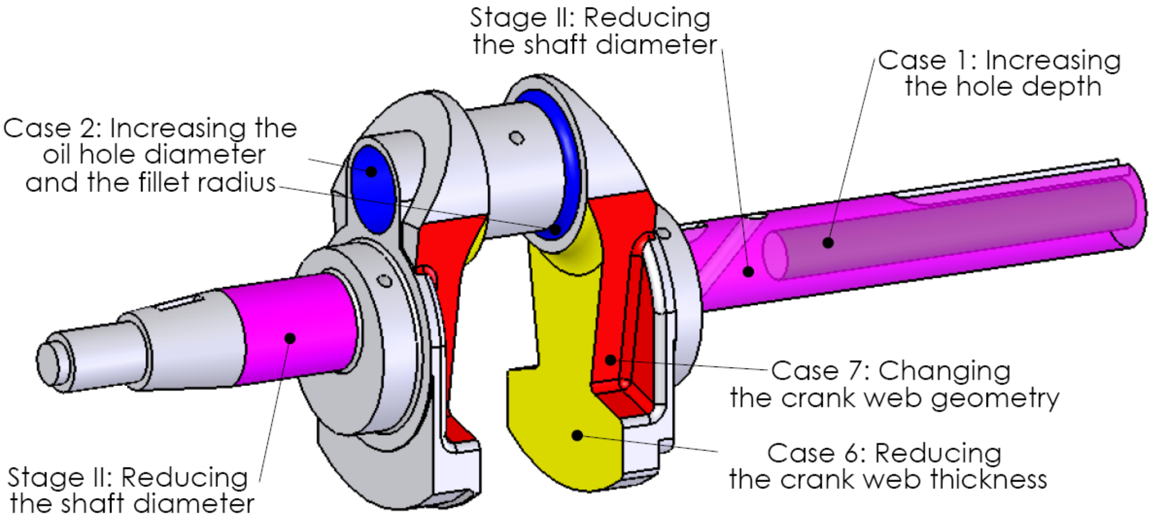


**Figure 17** Optimized forged steel crankshaft from Stage II of the optimization process.

## APPENDIX I: List of Publications and Presentations on the Study

1. *A Literature Review on Durability Evaluation of Crankshafts Including Comparisons of Competing Manufacturing Processes and Cost Analysis*, Mehrdad Zoroufi and Ali Fatemi, ***26th Forging Industry Technical Conference***, Chicago, IL, November 2005.

2. *Durability Comparison and Optimization of Forged Steel and Ductile Cast Iron Crankshafts,* Jonathan Williams, Farzin Montazersadgh and Ali Fatemi, ***Great Designs in Steel***, Livonia, Michigan, March 7, 2007.

3. *Fatigue Performance Comparison and Life Prediction of Forged Steel and Ductile Cast Iron Crankshafts*, Jonathan Williams, Farzin Montazersadgh and Ali Fatemi, **27th *Forging Industry Technical Conference***, Ft. Worth, Texas, March 27, 2007.

4. *Fatigue Performance of Forged Steel and Ductile Cast Iron Crankshafts,* Jonathan Williams and Ali Fatemi, ***SAE Technical Paper 2007-01-1001***, SAE World Congress 2007, Innovations in Steel Bar Products and Processing, April 17, 2007, Detroit, Michigan.

5. *Dynamic Load and Stress Analysis of a Crankshaft,* Farzin Montazersadgh and Ali Fatemi, ***SAE Technical Paper 2007-01-0258***, *SAE World Congress 2007,* New SI Engine and Component Design, April 17, 2007, Detroit, Michigan.

6. *Fatigue Performance Comparison and Optimization of Forged Steel and Ductile Cast Iron Crankshafts,* Ali Fatemi, ***Executive Summary***, August 2007.

7. *Fatigue Performance Comparison and Life Predictions of Forged Steel and Ductile Cast Iron Crankshafts,* Jonathan Williams and Ali Fatemi**, *Final Project Report***, August 2007.

8. *Stress Analysis and Optimization of Crankshafts Subject to Dynamic Loading,* Farzin Montazersadgh and Ali Fatemi**, *Final Project Report***, August 2007.

9. *Optimization of a Forged Steel Crankshaft Subject to Dynamic Loading,* Farzin Montazersadgh and Ali Fatemi, ***SAE Technical Paper 2008-XX-XXXX***, *SAE World Congress 2008,* Innovations in Steel Bar Products and Processing, 2008, Detroit, Michigan.