

**Fatigue Performance Evaluation of Forged versus Competing  
Manufacturing Process Technologies:  
A Comparative Analytical and Experimental Study**

***(EXECUTIVE SUMMARY)***

**Ali Fatemi and Mehrdad Zoroufi  
Professor and Research Assistant, Respectively  
Department of Mechanical, Industrial, and Manufacturing Engineering  
The University of Toledo  
Toledo, OH 43606**

**Prepared for:  
Forging Industry Educational and Research Foundation (FIERF)  
and  
American Iron and Steel Institute (AISI)**



**September 2004**

## EXECUTIVE SUMMARY

This study was concerned with fatigue performance evaluation of forged versus competing manufacturing process technologies using experimental, numerical and analytical tools. A detailed report including the literature review, experimental data and analytical results is available as a separate document. Most of the results have also been presented at several conferences and published in conference proceedings and journals (*see Appendix I*). In the following sections, a brief background and motivation for the study is presented, followed by a brief description of the study objectives and scope. Conclusions from the study are then presented, including some key figures.

### Background and Motivation for the Study

Manufacturing processes face major competitions in automotive industry to produce lighter, cheaper and more efficient components that exhibit more precise dimensions, need less machining and require less part processing. Material mechanical properties and manufacturing parameters play decisive roles and the weaknesses and strengths of each manufacturing process need to be available to designers in these respects, to enable them to choose the optimum choice for the specific component and application.

Mechanical properties of the manufactured component are influenced by its manufacturing process. For example, the process parameters that affect mechanical properties and material behavior of a forged component are identified in a chart in *Figure 1*. The chart lists the forging process influential parameters, as well as the mechanical and

metallurgical parameters that play a bridge role between the process and mechanical properties.

In the automotive industry, designers have a wide range of materials and processes to select from. Steel and aluminum forgings and castings, cast irons, and powder forgings have found broad applications in automotive safety-critical systems. The competition is particularly acute in the chassis, and it is not unusual to find a range of different materials and manufacturing technologies employed within modern chassis components.

Many safety-critical components in the vehicle experience time-varying loadings during a major portion of their service life. However, material selection for these components made by various manufacturing techniques is often based on monotonic rather than cyclic properties. The stress-strain behavior obtained from a monotonic tension or compression test can be quite different from that obtained under cyclic loading. In addition, fatigue is the major cause of most mechanical failures in components. Fatigue behavior is, therefore, a key consideration in design and performance evaluation of automotive components, and to address the issue effectively and economically, engineers need to model and design for mechanical fatigue early in the product design stage. Overlooking fatigue behavior often results in inefficient design and/or over-designed parts from large safety factors.

In automotive design, durability evaluation of components based on exclusively experimental assessments is time-consuming and expensive, so analytical approaches that include limited number of component verification tests have gained more attention. In addition, the significant increase of the demand for lighter, more fuel efficient vehicles,

reduced design-testing iterations, and satisfactory reliability level requires the adoption of optimum materials and components. The analytical approach combined with a limited number of component testing reduces design cycle time due to reduced testing, allows inexpensive evaluation of changes in geometry, material, loading and manufacturing process through performance simulation, and provides evaluation techniques for product optimization and failure analysis.

Accordingly, this research was motivated by a practical need to assess and compare fatigue performance of components produced by competing manufacturing processes, to develop a general durability assessment methodology for automotive chassis (and similar) components, and to implement an optimization methodology that incorporates structural durability performance, material properties, manufacturing and cost considerations for such components.

### **Objectives and Scope of the Study**

The overall objectives of this research program were: To assess fatigue life and compare fatigue performance of competing manufacturing processes; to develop a general durability assessment methodology for safety-critical automotive components; and to develop a method for efficient and reliable optimization of such components that satisfies performance criteria and considers geometry, material, manufacturing parameters and costs.

The study consisted of several main topics: 1) a background study on forging and its competing manufacturing processes, and vehicle engine and chassis components that are produced by these competing processes, 2) a literature review that focuses on

comparison of competing manufacturing processes, and durability assessment and optimization of automotive components, 3) experimental work including specimen and component testing, and 4) analytical work including durability assessment and optimization analysis.

Vehicle steering knuckles of three materials/processes were selected as the example parts for this study. These included forged steel SAE Grade 11V37 steering knuckle of the rear suspension of a 4-cylinder sedan weighing 2.4 kg, cast aluminum ASTM A356-T6 steering knuckle of front suspension of a 6-cylinder minivan weighing 2.4 kg, and cast iron ASTM A536 Grade 65-45-12 steering knuckle of the front suspension of a 4-cylinder sedan weighing 4.7 kg. *Figure 2* shows the three components

For specimen testing, strain-controlled monotonic and fatigue tests of specimens made of forged steel, cast aluminum and cast iron steering knuckles based on ASTM standard test methods and recommended practices were conducted. The data obtained made it possible to compare deformation response, fatigue performance, and failure mechanisms of the base materials and manufacturing processes, without introducing the effects and interaction of complex design parameters. In addition, these data provide the required baseline data for life prediction analysis to predict component fatigue life. Load-control component tests for the forged steel and cast aluminum steering knuckles were also conducted. Such data provides a direct comparison between fatigue performances of the components made of competing manufacturing processes. In addition, the component test results make it possible to verify the analytical durability assessment.

The analytical work consisted of finite element analysis (FEA), durability assessment and optimization analysis. Linear and nonlinear finite element analyses of the

steering knuckles were conducted to obtain critical locations of, and stress and strain distributions of each component. A general life prediction methodology for the subject components was developed, where material monotonic and cyclic data and results of the FEA were used in life prediction methods applicable to safety-critical automotive components. The strengths and shortages of each method were evaluated. An analytical optimization study of the forged steel steering knuckle was also performed. Such optimization sought to minimize weight and manufacturing costs while maintaining or improving fatigue strength of the component by targeting geometry, material and manufacturing parameters.

### **Summary and Conclusions of the Study**

The effects of manufacturing process on fatigue design and optimization of automotive components using experimental, numerical and analytical tools were investigated. Even though the methodologies developed apply to a wide range of automotive and other components, vehicle steering knuckles made of forged steel, cast aluminum, and cast iron were selected as example parts for this study. The findings of this study are summarized below.

#### **Material Fatigue Behavior and Comparisons**

1. From tensile tests and monotonic deformation curves it is concluded that forged steel is considerably stronger and more ductile than cast aluminum and cast iron. Cast aluminum and cast iron reached 37% and 57% of forged steel ultimate tensile strength, respectively. The yield strength of cast aluminum and cast iron is also lower, 42% and 54% of the forged steel, respectively. The percent elongation, as a

measure of ductility, of cast aluminum and cast iron were found to be 24% and 48% of the forged steel, respectively. See *Table 1* and *Figure 3*.

2. From strain-controlled cyclic tests it is concluded that the cyclic deformation curve of the forged steel is independent of the geometrical direction (i.e. isotropic behavior). For the fatigue behavior, however, some degree of anisotropy was observed. Both the long-life as well as the short-life fatigue of forged steel were observed to be longer (by about a factor of two) in the direction coinciding with the primary stressing direction of the forged steering knuckle.
3. The cyclic yield strength of cast aluminum and cast iron were found to be 54% and 75% of forged steel, respectively. The cyclic strain hardening exponent of cast aluminum and cast iron was 46% and 55% of the forged steel, respectively. These indicate the higher cyclic strength of forged steel against yielding, and its higher resistance to plastic deformation. See *Table 1* and *Figure 3*.
4. Significantly better S-N fatigue resistance of the forged steel was observed, as compared with the two cast materials (see *Figure 4*). Comparison of long-life fatigue strength (defined as the fatigue strength at  $10^6$  cycles) shows that the fatigue limit of cast aluminum and cast iron are only 35% and 72% of the forged steel, respectively. In addition, while the fatigue strength of forged steel at  $10^6$  cycles is expected to remain about constant at longer lives, fatigue strength of the two cast materials is expected to continuously drop with longer lives.
5. Forged steel was found to be superior to cast aluminum and cast iron with respect to low cyclic fatigue (i.e. cyclic ductility, see *Figure 5*). In automotive design, cyclic ductility can be a major concern when designing components subjected to occasional

overloads, particularly for notched components, where significant local plastic deformation can occur.

6. Comparisons of strain-life fatigue behavior of the three materials demonstrate the superiority of the forged steel over cast aluminum and cast iron (see *Figure 6*). The forged steel provides about a factor of 5 longer lives in the short-life regime, compared to the cast aluminum and cast iron. In the high-cycle regime, forged steel results in about an order of magnitude longer life than the cast iron, and about a factor of 3 longer life, compared to the cast aluminum.
7. Neuber stress versus life plot, which considers the combined effects of both stress and strain amplitudes, shows forged steel to have about two orders of magnitude longer life than cast iron and about four orders of magnitude longer life than cast aluminum (see *Figure 7*).

### **Finite Element Analysis**

8. In order to avoid a complex meshed model that increases the FEA run-time, a relatively coarse global mesh size, and a finer mesh at the vicinity of the critical points using free local meshing feature was selected for each component. This procedure increased the computational efficiency of the model significantly, particularly for nonlinear models where material deformation was elastic-plastic.
9. Even at the lower loading level, which can be considered as an indication of long-life service of the components, the material undergoes local plastic deformation. This is evidence that mere use of linear elastic FEA is not sufficient for reliable fatigue life predictions.



10. The spindle 1<sup>st</sup> step fillet area for the forged steel and hub bolt hole for the cast aluminum and cast iron steering knuckles were found to be high-stressed locations with high stress gradient (see *Figure 8*). Both stress concentration as well as stress gradient due to the mode of loading applied (i.e. bending in this case) are major factors in making an area fatigue-critical location.
11. Although the primary loading on the components is unidirectional, it is shown that the stress and strain at the critical locations are multiaxial. The type of primary loading that the components undergo generates proportional stresses throughout the components. For proportional stressing, von Mises stress and strain have been found effective in calculating the equivalent values as a result of multiaxiality, and were used for fatigue life analyses.
12. At the critical location the state of plane strain prevails for the forged steel steering knuckle, while the state of stress at the critical location of the cast aluminum and cast iron steering knuckles is closer to plane stress. Knowledge of the state of stress and strain at the critical location of the components helps in choosing the appropriate deformation model, leading to more accurate fatigue life predictions.
13. FEA simulation for cyclic loading is important for fatigue analysis since cyclic deformation material response can be vastly different from monotonic deformation response. In addition, the local and nominal behaviors are generally different under various loading conditions. For example, as the nominal stress R-ratio remains almost constant (close to zero), significant negative local stress R-ratio is observed for most of the simulations as a result of the residual stress generated at the stress concentrations due to local plastic deformation.

### **Component Fatigue Behavior and Comparisons**

14. Strain gages were used to validate the stresses in the component tests (see *Figure 9*) with those from analytical calculations. The differences between experimentally measured and FEA-predicted strains obtained for the forged steel and cast aluminum steering knuckles were found to be reasonable for the complex geometries considered.
15. Based on the component testing observations, crack growth life was found to be a significant portion of the cast aluminum steering knuckle fatigue life (on the average, about 50% of the cast aluminum steering knuckle life is spent on macro-crack growth), while crack growth life was an insignificant portion of the forged steel steering knuckle fatigue life.
16. Component testing results showed the forged steel steering knuckle to have about two orders of magnitude longer life than the cast aluminum steering knuckle, for the same stress amplitude level (see *Figure 10*). This occurred at both short as well as long lives. Comparison of the strain-life prediction curves of the components demonstrated that the forged steel steering knuckle offers more than an order of magnitude longer life than the cast iron steering knuckle (see *Figure 11*).
17. The failed forged steel steering knuckle had a typical ductile material fatigue failure surface including crack initiation, smooth crack growth and rough fracture sections (see *Figure 12*). The failed cast aluminum had a relatively longer crack growth portion as compared to the crack growth portion of the forged steel steering knuckle. The failure locations in the component tests agreed with FEA predictions.

### **Fatigue Life Predictions**

18. The nominal stress approach cannot be used for complex component geometries, such as the cast aluminum steering knuckle in this study due to the fact that for complex geometries, nominal stress can not be defined explicitly. For the forged steel steering knuckle, the predictions of the nominal S-N approach were conservative, by about a factor of seven on fatigue life, as compared to the experimental results.
19. The local stress or strain approaches in conjunction with the FEA results were found to provide better life predictions, as compared with the commonly used nominal S-N approach (see *Figure 13*). This is partly due to the fact that the local approaches directly account for the residual stresses from local plastic deformation.
20. The local strain approach using nominal stresses for the forged steel knuckle in conjunction with Neuber's rule predicted conservative lives, by about an order of magnitude, as compared with experimental results. This confirms the suggestion that Neuber's rule is more applicable to plane stress states, since plane strain state existed at the fatigue-critical location of the forged steel knuckle.
21. Life predictions based on local approaches using linear elastic FEA results in conjunction with Neuber-corrected stresses were found to be close to those obtained based on nonlinear elastic-plastic FEA results. Therefore, the simpler and less time consuming linear elastic FEA, when modified to correct for plastic deformation, is an effective and capable approach for life prediction of components with complex geometries and/or loadings.

22. For the local stress approach, Gerber's mean stress parameter provides better predicted fatigue lives, as compared with the experimental lives, than the commonly used modified Goodman equation. For the local strain approach, Morrow's mean stress parameter provides better predicted fatigue lives than the Smith-Watson-Topper mean stress parameter (see *Figure 13*).

### **Optimization**

23. Manufacturing process considerations, material and cost parameters are major constituents of a general optimization procedure with durability constraints for automotive component. A geometrical optimization without these considerations is not a practical approach for such high volume components.
24. The proposed material alternatives provide higher fatigue strength for the component. Manufacturability and cost are two other main issues that are critical to the final selection of the replacing material(s). Limited weight saving is achieved by replacing the potential alternative materials, mainly due to geometrical constraints. If comprehensive changes to the geometry are allowed or for other components with fewer constraints, the weight saving will be more significant.
25. Additional manufacturing operations such as surface hardening and surface rolling to induce compressive residual stress can be considered to improve fatigue strength of the forged steel steering knuckle at the spindle fillet area.
26. Overall weight and cost reductions of at least 12% and 5%, respectively, are estimated for the example part following the optimization task (see *Figure 14*). The cost of the saved material is additional reduction, though not very considerable due to small portion of material cost within the total production cost. Due to the small

size of the forged steel steering knuckle and many attachment compatibility constraints, limited changes could be implemented during the optimization process. More comprehensive changes require a more detailed design of the component and the suspension system.

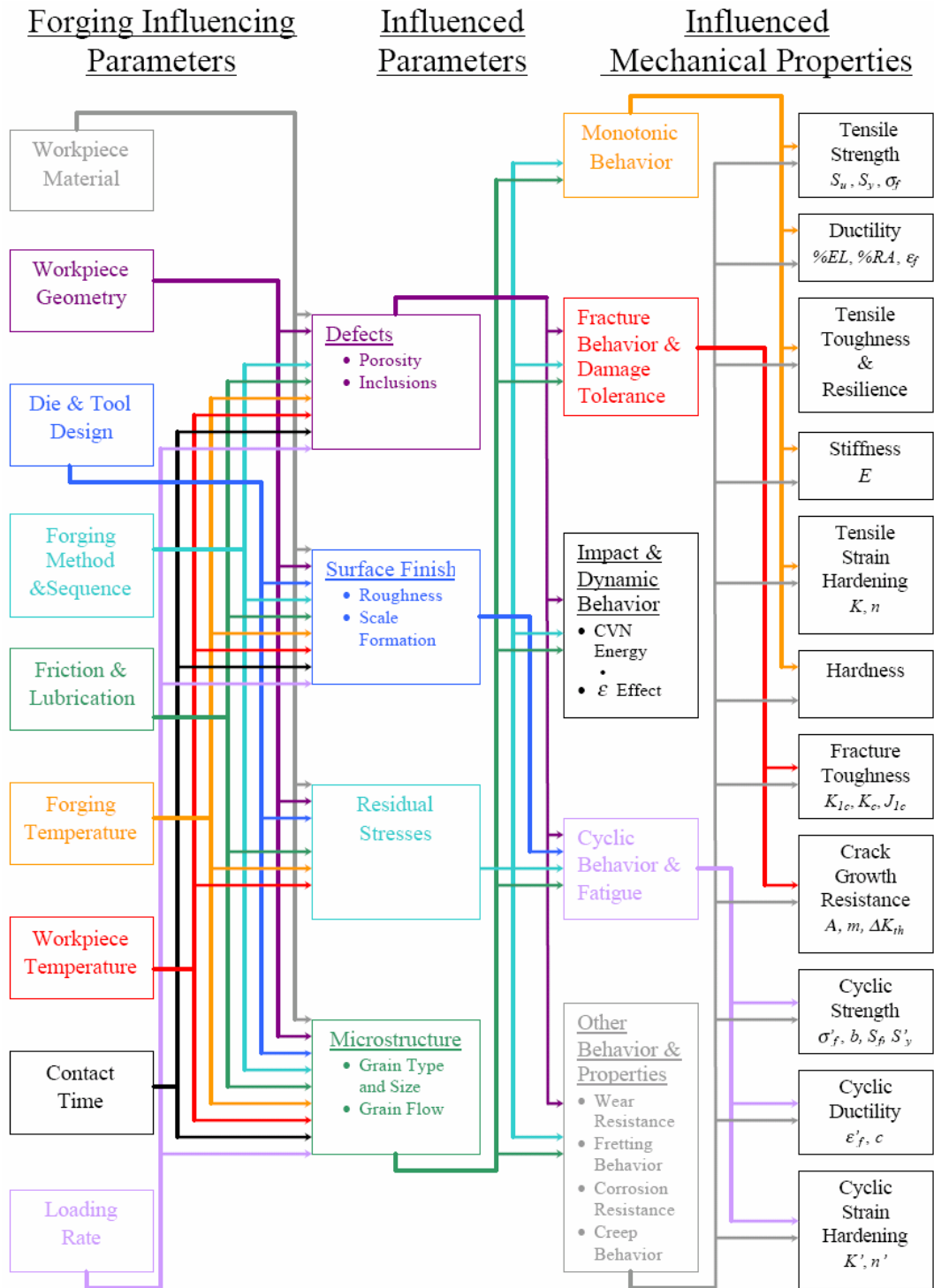
27. The approach that was followed is applicable to other forged components. Components with fewer geometrical restrictions than the steering knuckle considered have much higher potential for weight reduction and cost savings.

## **Acknowledgements**

Financial support for this study was provided by the Forging Industry Educational and Research Foundation (FIERF), the American Iron and Steel Institute (AISI), and the University of Toledo. George Mochnal (Director of Research and Education) and Karen Lewis (Executive Director) at FIERF, and David Anderson (Director of Bar and Rod Programs) at AISI facilitated this research program. Helpful suggestions related to various aspects of this work were provided by Peter Bauerle (Senior Specialist) at Daimler-Chrysler, Michael Crews, Jay Hedges, Mohammad Saeed, Andrew Snow, and Gary Studt at Metaldyne, Tom Oakwood (formerly of Inland Steel), Chinchuan Chu at Ford, and Joseph Grosso (Program Manager) at Citation.

**Table 1** Summary of mechanical properties and their comparative ratios (forged steel is taken as the base for ratio calculations).

	<b>Forged Steel</b>	<b>Cast Aluminum</b>	<b>Cast Iron</b>
	<b>11V37</b>	<b>A356-T6</b>	<b>65-45-12</b>
<b>Monotonic Properties</b>			
Modulus of elasticity, $E$ , GPa (ksi)	201.5 (29,231)	78.1 (11,327)	193.0 (27,991)
<i>Ratio</i>	1	0.39	0.96
Yield strength (0.2% offset), $S_y$ , MPa (ksi)	556.2 (80.7)	232.4 (33.7)	300.0 (43.5)
<i>Ratio</i>	1	0.42	0.54
Ultimate tensile strength, $S_u$ , MPa (ksi)	821.2 (119.1)	302.7 (43.9)	471.2 (68.3)
<i>Ratio</i>	1	0.37	0.57
Percent elongation, %EL (%)	21	5	10
<i>Ratio</i>	1	0.24	0.48
Percent reduction in area, %RA (%)	37	10	25
<i>Ratio</i>	1	0.27	0.68
Strength coefficient, $K$ , MPa (ksi)	1,347.3 (195.4)	417.8 (60.6)	796.5 (115.5)
<i>Ratio</i>	1	0.31	0.59
Strain hardening exponent, $n$	0.157	0.095	0.187
<i>Ratio</i>	1	0.6	1.19
True fracture strength, $\sigma_f$ , MPa (ksi)	496 (71.9)	301 (43.7)	219.2 (31.8)
<i>Ratio</i>	1	0.6	0.44
True fracture ductility, $\epsilon_f$ (%)	47	10	28
<i>Ratio</i>	1	0.23	0.59
<b>Cyclic and Fatigue Properties</b>			
Cyclic modulus of elasticity, $E'$ , GPa (ksi)	194.9 (28,267)	73.3 (10,636)	169.4 (24,568)
<i>Ratio</i>	1	0.38	0.87
Fatigue strength coefficient, $\sigma_f'$ , MPa (ksi)	1,156.8 (167.8)	665.9 (96.6)	760.8 (110.3)
<i>Ratio</i>	1	0.58	0.66
Fatigue strength exponent, $b$	-0.082	-0.117	-0.076
<i>Ratio</i>	1	1.42	0.92
Fatigue ductility coefficient, $\epsilon_f'$	3.032	0.094	0.864
<i>Ratio</i>	1	0.03	0.28
Fatigue ductility exponent, $c$	-0.791	-0.610	-0.771
<i>Ratio</i>	1	0.77	0.97
Fatigue strength, $S_r$ @ $10^6$ cycles, MPa (ksi)	352 (51.0)	122 (17.6)	253 (36.6)
<i>Ratio</i>	1	0.35	0.72
Cyclic yield strength, $S_y'$ , MPa (ksi)	541.2 (78.5)	290.7 (42.2)	407.3 (59.1)
<i>Ratio</i>	1	0.54	0.75
Cyclic strength coefficient, $K'$ , MPa (ksi)	1,269.5 (184.1)	430.3 (62.4)	649.1 (94.1)
<i>Ratio</i>	1	0.34	0.51
Cyclic strain hardening exponent, $n'$	0.137	0.063	0.075
<i>Ratio</i>	1	0.46	0.55



**Figure 1** Forging process parameters, the manufacturing influenced parameters and the effect on mechanical properties. Each parameter and its connector lines are coded with the same color.





**Forged steel  
SAE Grade 11V37  
steering knuckle of  
rear suspension of  
a 4-cylinder sedan  
weighing 2.4 kg**

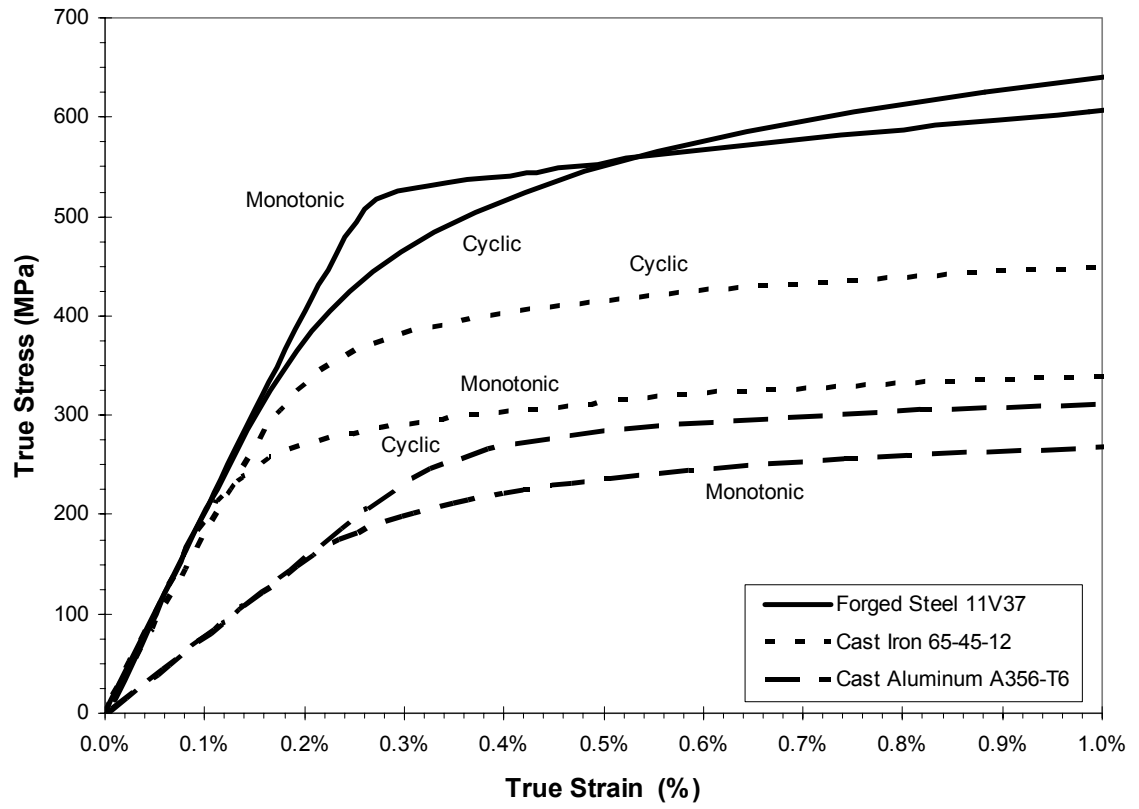


**Cast aluminum  
ASTM A356-T6  
steering knuckle of  
front suspension of a  
6-cylinder minivan  
weighing 2.4 kg**

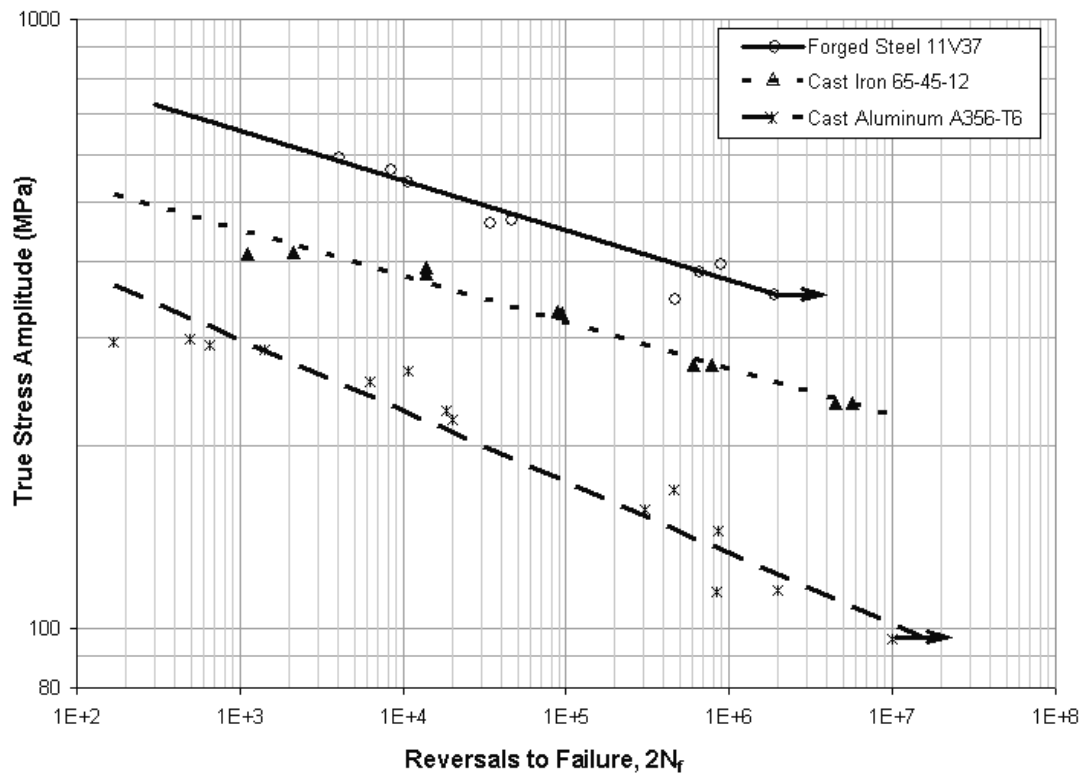


**Cast iron  
ASTM A536  
Grade 65-45-12  
steering knuckle of  
front suspension of a  
4-cylinder sedan  
weighing 4.7 kg**

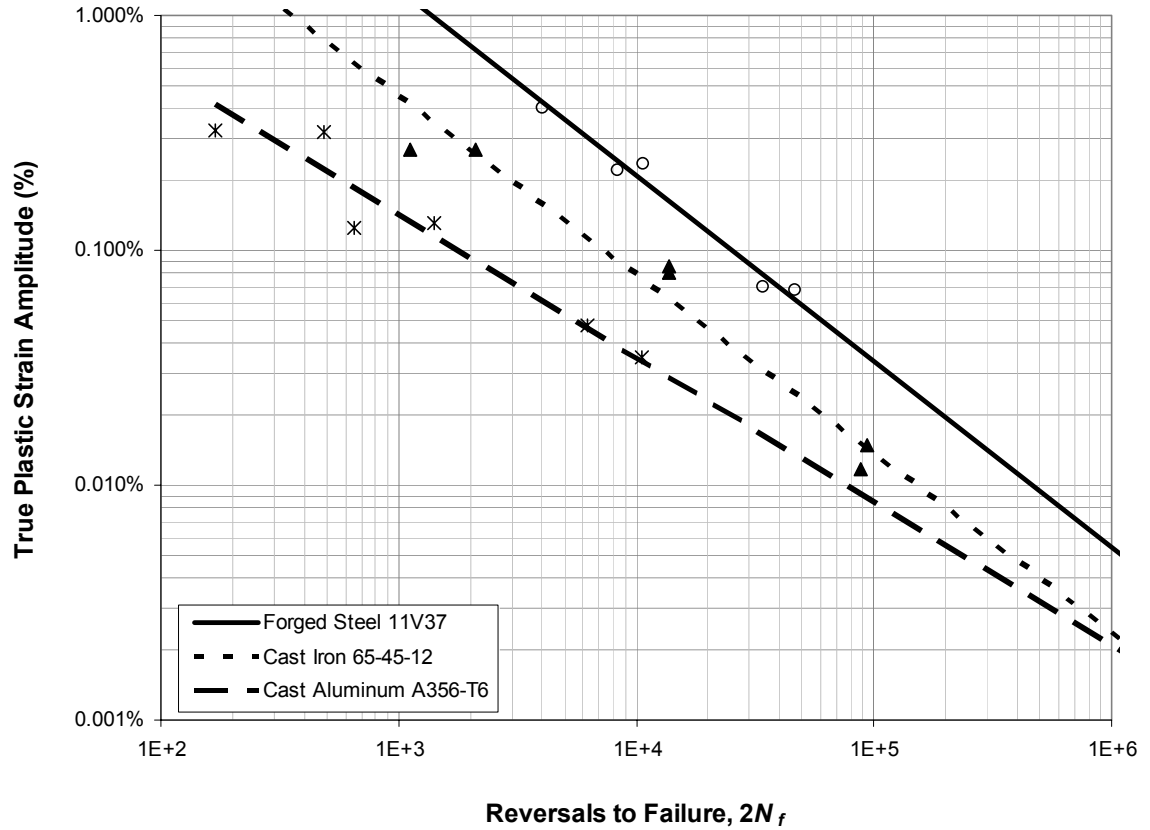
**Figure 2** From left forged steel, cast aluminum and cast iron steering knuckles selected as example parts for this study.



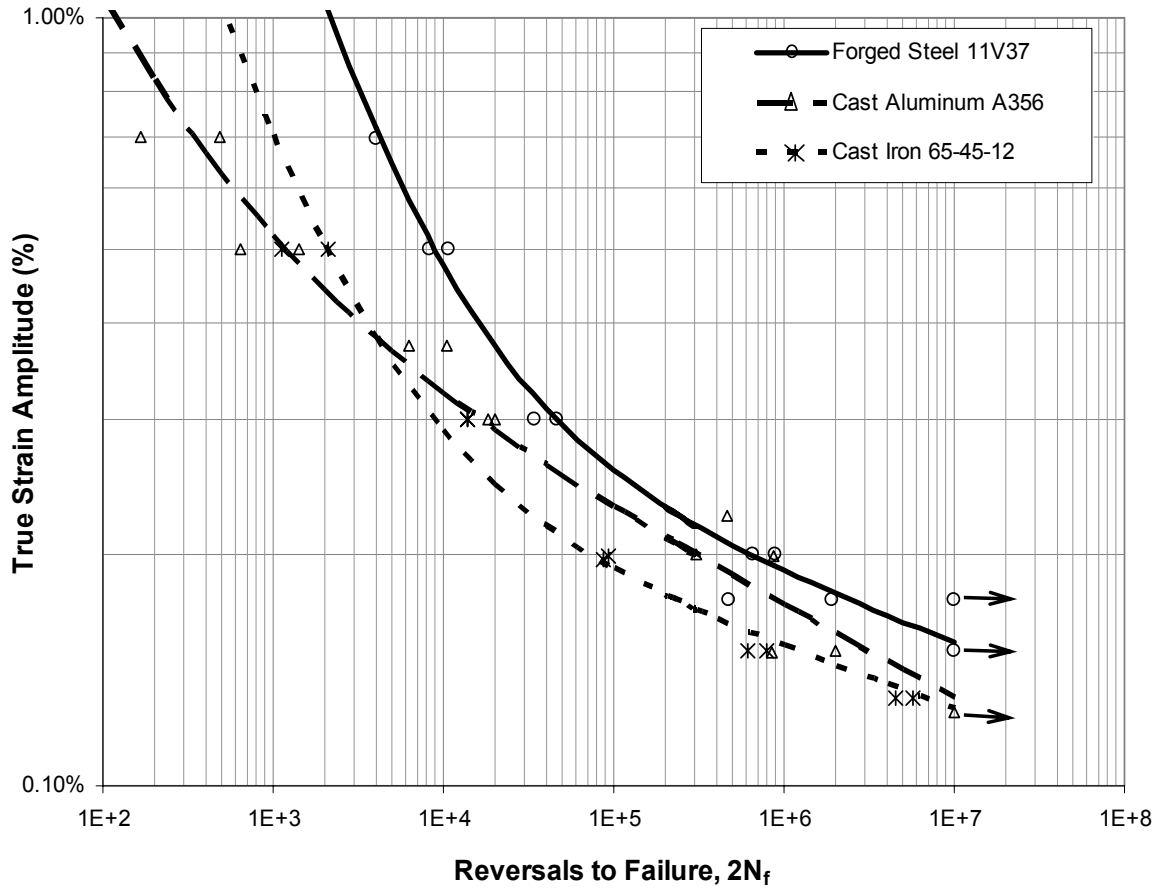
**Figure 3** Superimposed plot of cyclic and monotonic stress-strain curves for the three materials; forged steel 11V37 in direction A, cast aluminum A356-T6, and cast iron 65-45-12.



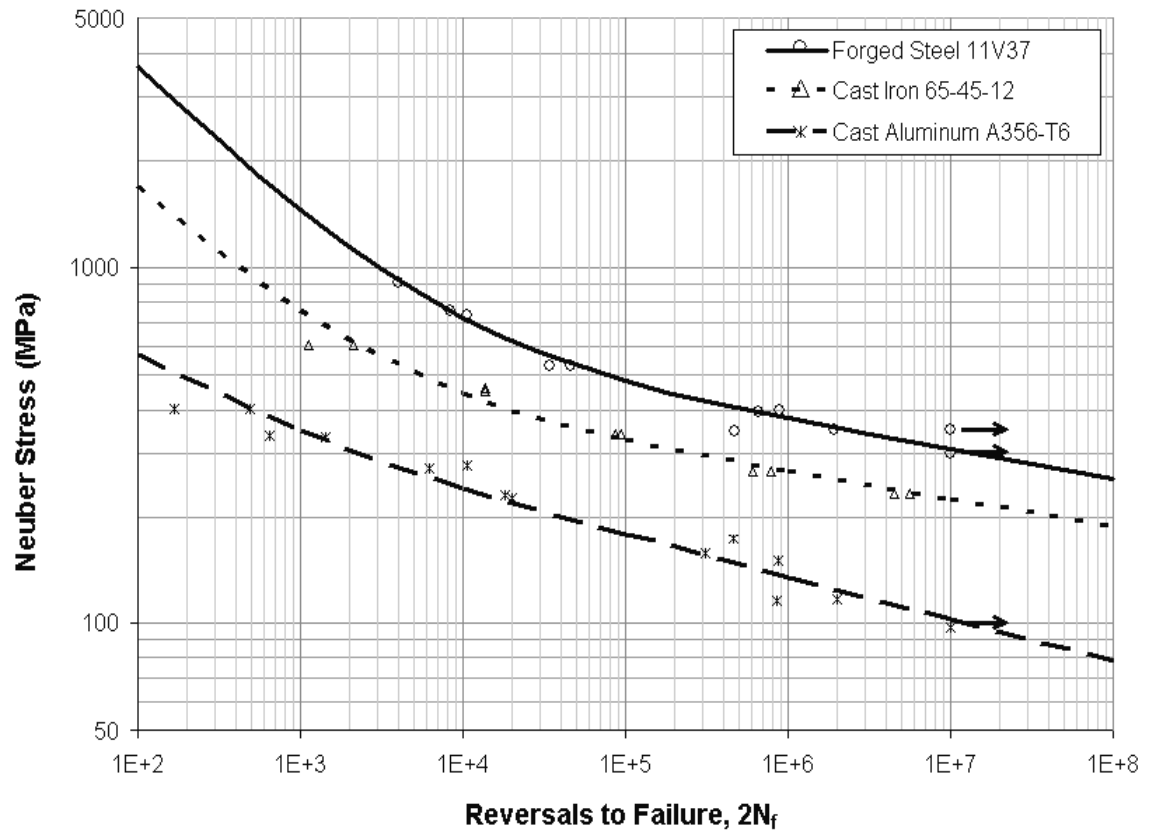
**Figure 4** Superimposed true stress amplitude versus reversals to failure for the three materials; forged steel 11V37 in direction A, cast aluminum A356-T6, and cast iron 65-45-12.



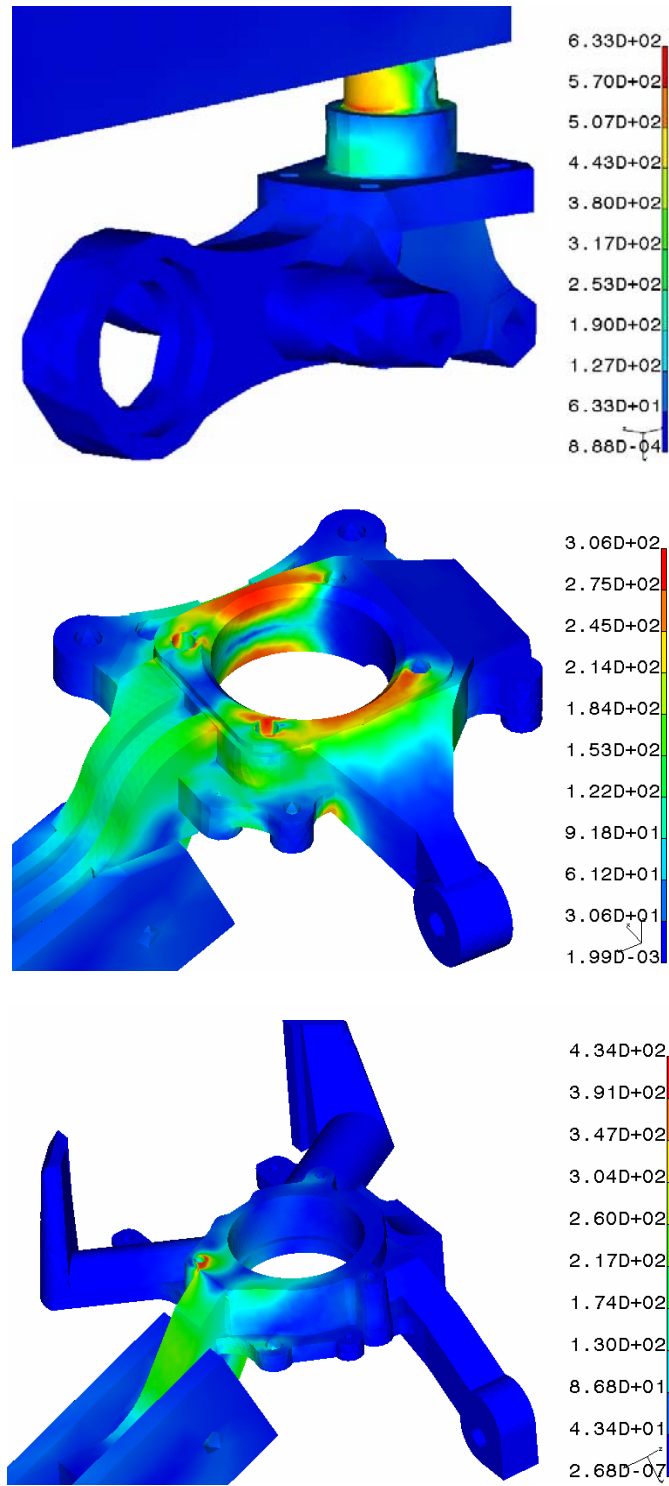
**Figure 5** Superimposed calculated true plastic strain amplitude versus reversals to failure for the three materials; forged steel 11V37 in direction A, cast aluminum A356-T6, and cast iron 65-45-12.



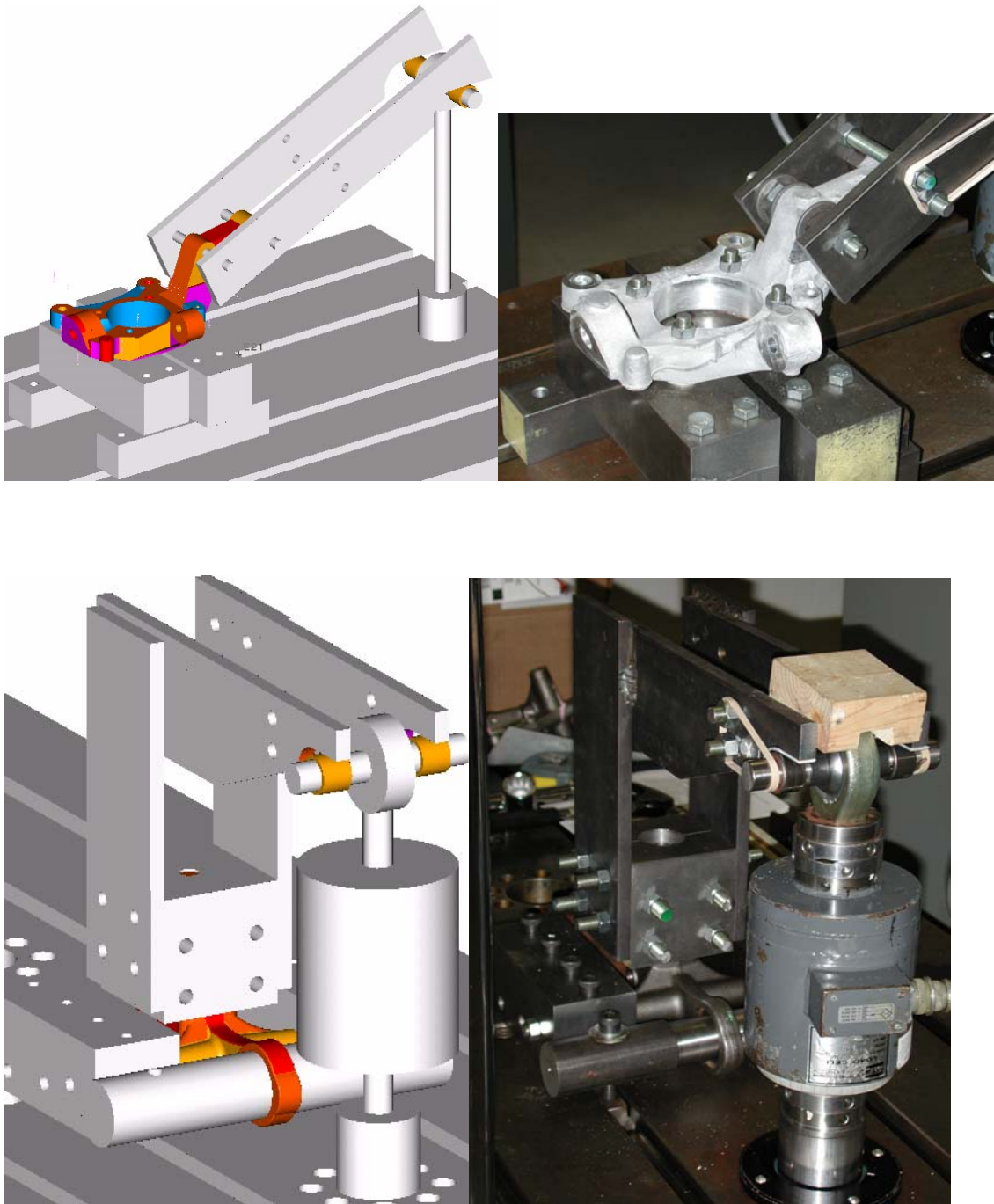
**Figure 6** Superimposed true strain amplitude versus number of reversals to failure for the three materials; forged steel 11V37 in direction A, cast aluminum A356-T6, and cast iron 65-45-12.



**Figure 7** Neuber fatigue life curves for forged steel 11V37, cast aluminum A356-T6, and cast iron 65-45-12.

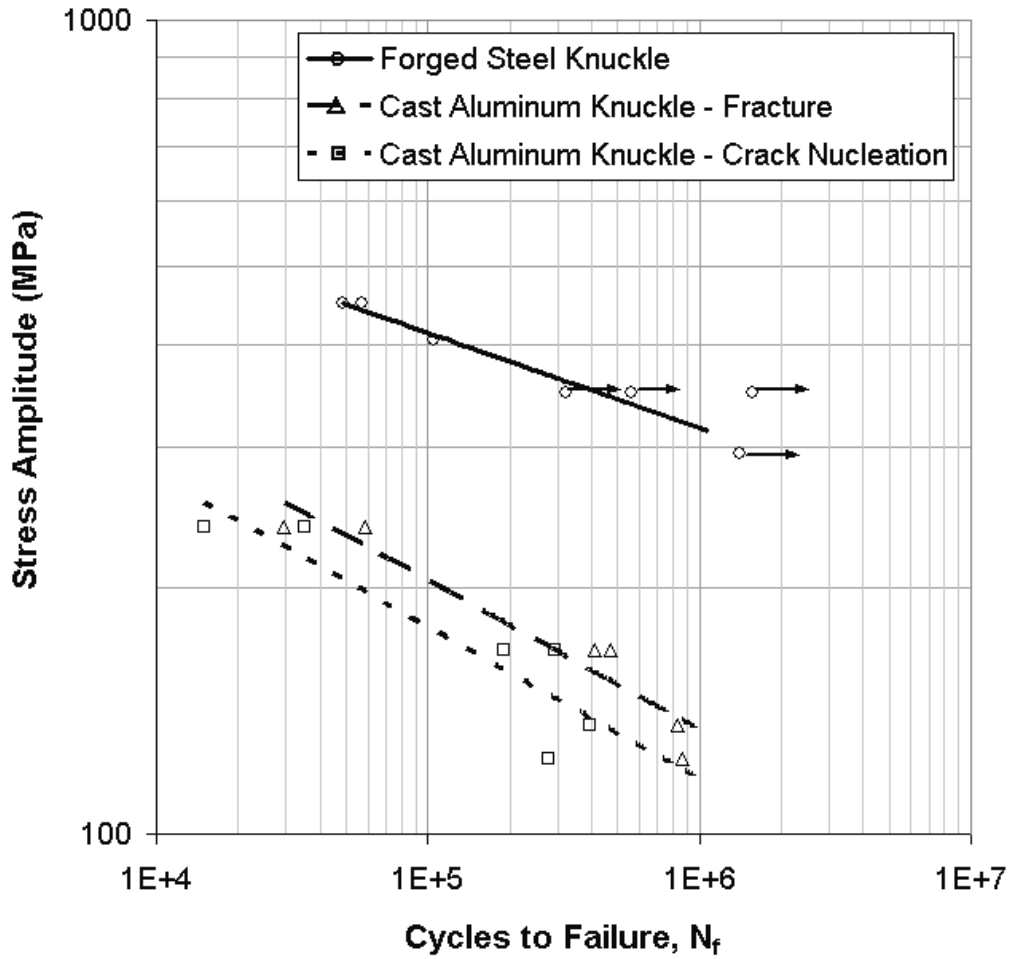


**Figure 8** From top to bottom, contours of von Mises stress at highest moment levels for forged steel, cast aluminum and cast iron steering knuckles. The stress values of the color bar are in MPa.

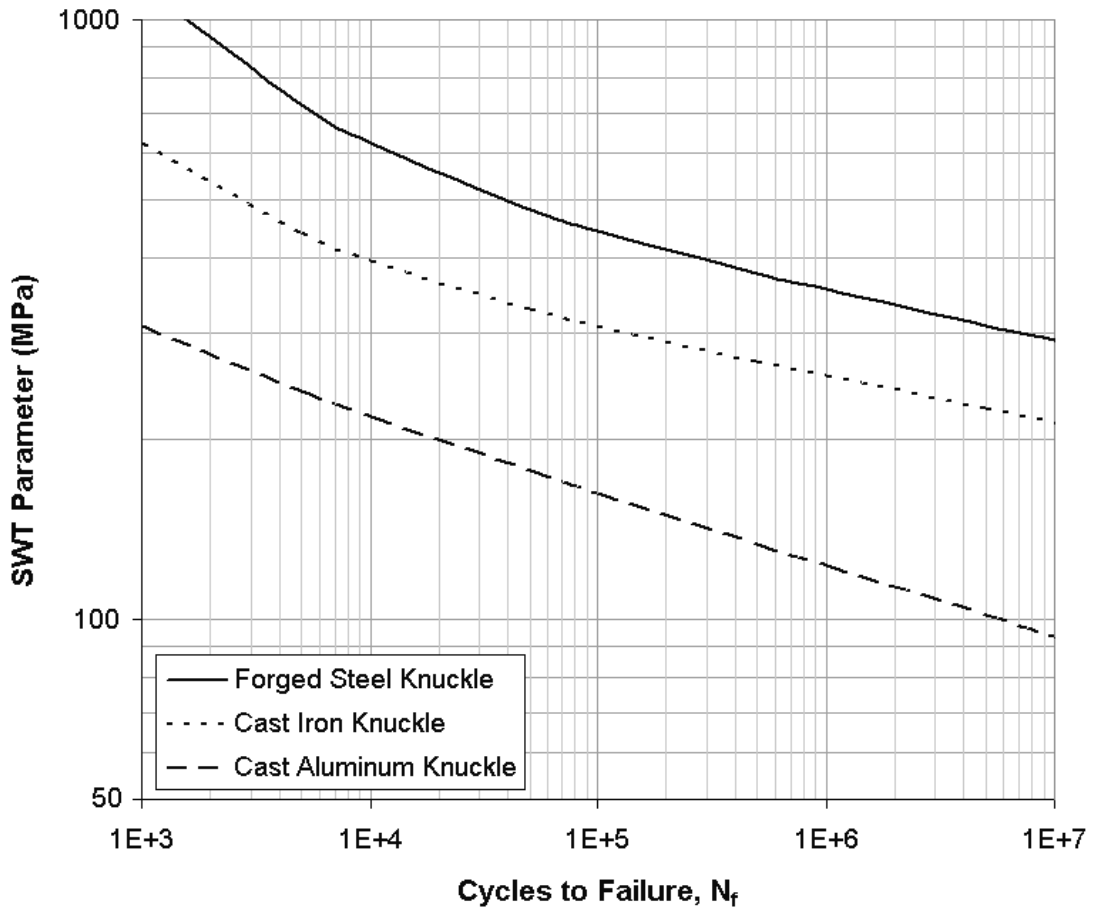


**Figure 9** Schematic drawing (left) and the fixture for the cast aluminum (above) and the forged steel (below) steering knuckle test arrangement.

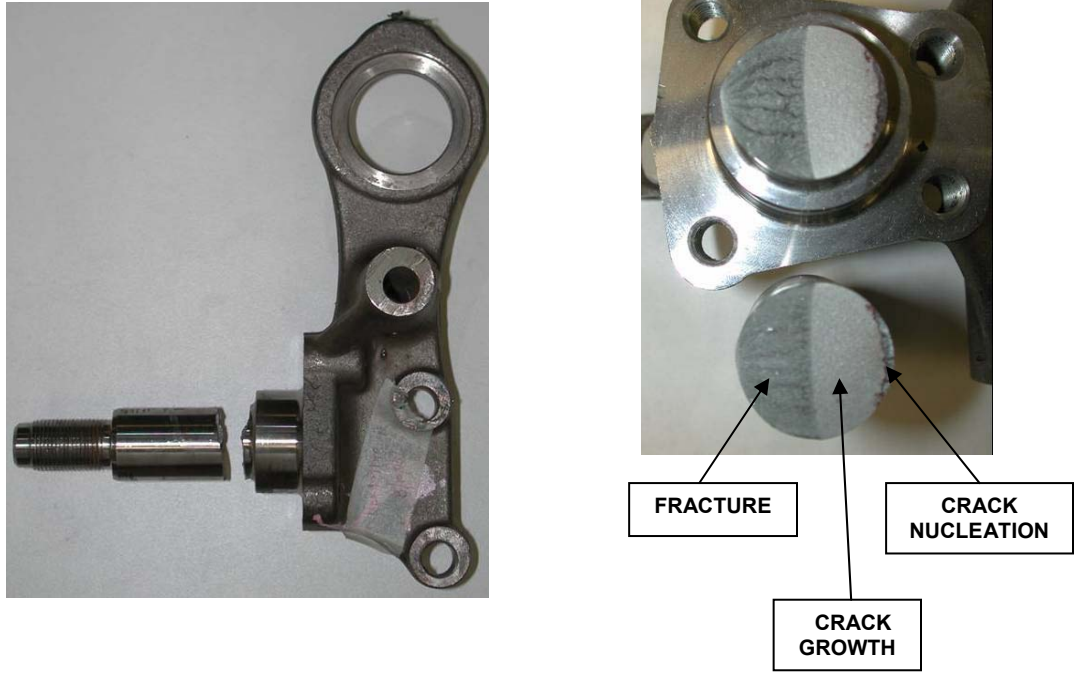




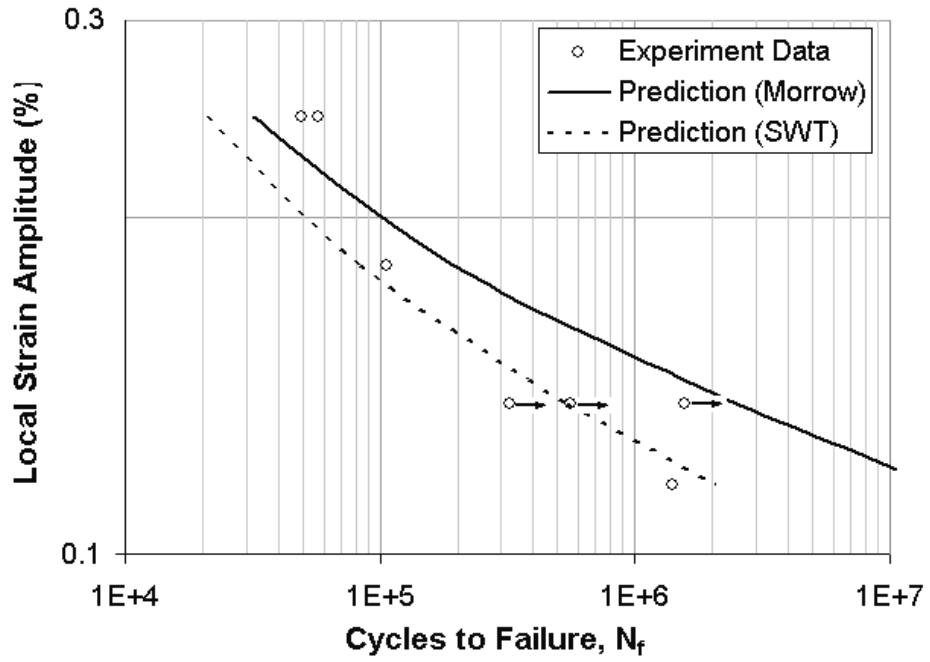
**Figure 10** Superimposed stress amplitude versus fatigue life curves for forged steel and cast aluminum steering knuckles.



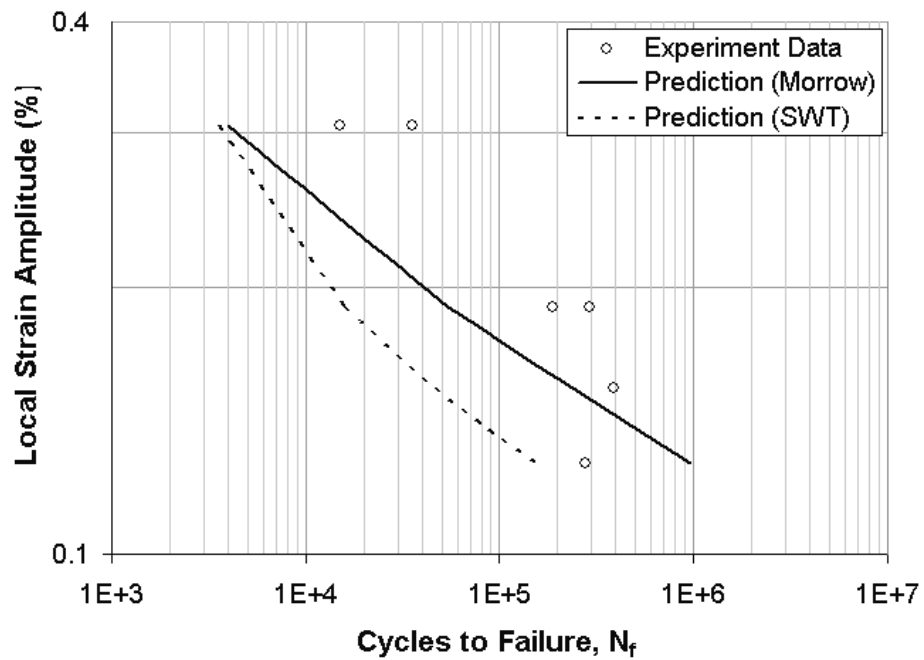
**Figure 11** SWT parameter versus fatigue life curves based on the strain-life approach for the forged steel, cast aluminum and cast iron steering knuckles.



**Figure 12** Typical fractured (left) and fracture surface of the forged steel steering knuckle.

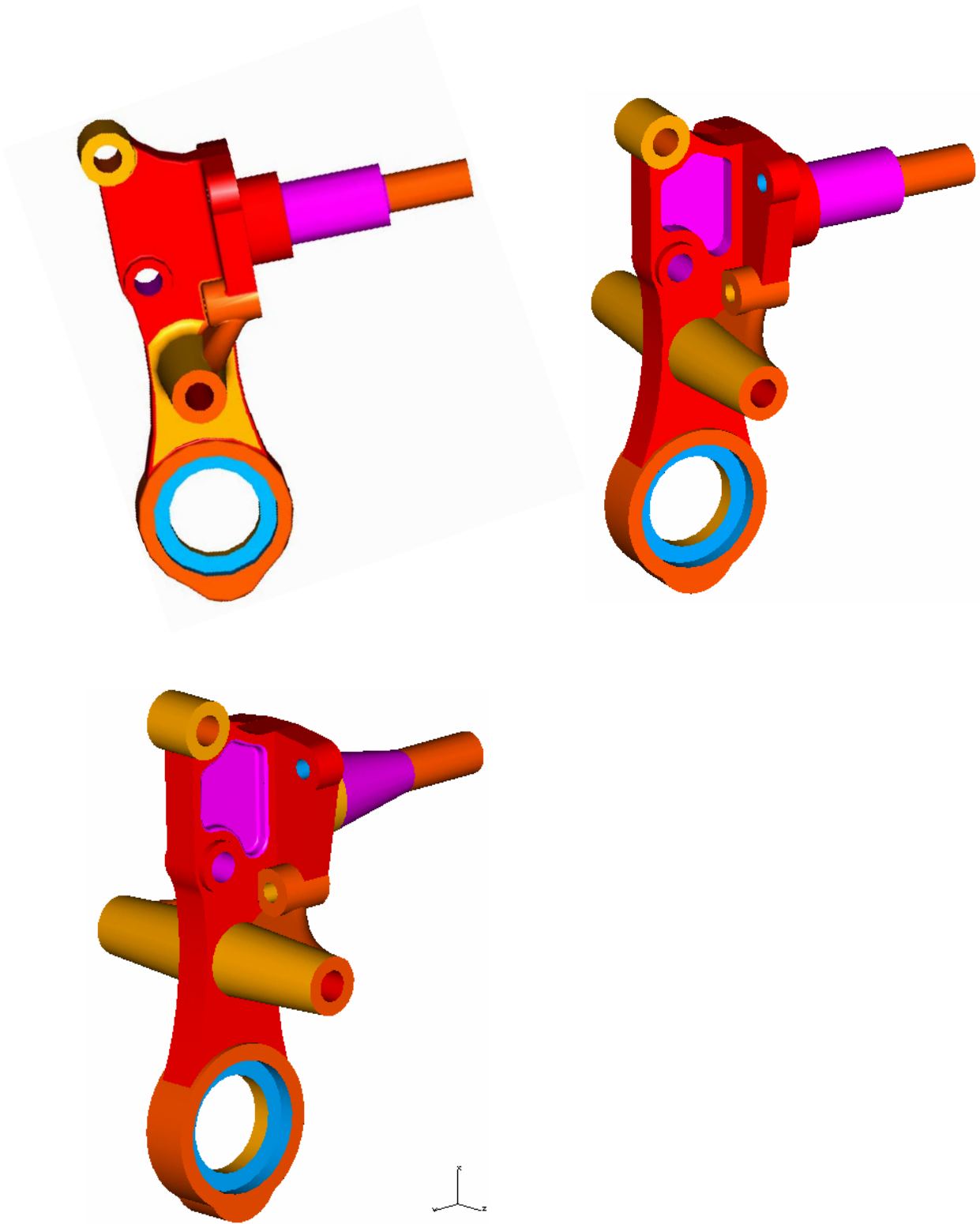


(a)



(b)

**Figure 13** Superimposed local strain amplitude versus experimental life and predictions of strain-life model for (a) forged steel and (b) cast aluminum steering knuckle using nonlinear FEA results.



**Figure 14** Original forged steel steering knuckle (top left), forged steel steering knuckle after stage I optimization (top right), and forged steel steering knuckle after stage II optimization (bottom) with redesigned spindle.

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

1. “Fatigue Performance Evaluation of Forged vs. Competing Process Technologies: A Comparative Study”, A. Fatemi and M. Zoroufi, *24th Forging Industry Technical Conference*, Cleveland, OH, October 2002.
2. “A Comparative Study of Forged Steel 11V37, Cast Aluminum A356-T6, and Cast Iron 65-45-12; Monotonic Properties, Cyclic Deformation, and Fatigue Behavior”, M. Zoroufi and A. Fatemi, *Technical Report to FIERF and AISI* (available through [www.forging.org](http://www.forging.org)), March 2003.
3. “Forged Steel, Cast Aluminum and Cast Iron in Safety Critical Automotive Components”, G. Mochal, M. Zoroufi, and A. Fatemi, *Great Designs in Steel Seminar 2004*, Livonia, MI, February 2004.
4. “Fatigue Life Comparison of Competing Manufacturing Processes: A Study of Steering Knuckle”, M. Zoroufi and A. Fatemi, *SAE Technical paper 2004-01-0628*, *SAE World Congress 2004*, Detroit, MI, March 2004.
5. “Durability Comparison and Life Predictions of Competing Manufacturing Processes: An Experimental Study of Steering Knuckle”, M. Zoroufi and A. Fatemi, *25th Forging Industry Technical Conference*, Detroit, MI, April 2004.
6. “Experimental and Analytical Durability Assessment of Vehicle Steering Knuckle”, M. Zoroufi and A. Fatemi, *Journal of Automotive Engineering*, under review.
7. “Fatigue Performance Evaluation of Forged versus Competing Manufacturing Process Technologies: A Comparative Analytical and Experimental Study”, M. Zoroufi and A. Fatemi, *Technical Report to FIERF and AISI* (available through [www.forging.org](http://www.forging.org)), September 2004.