Fatigue Performance Evaluation of Forged Versus Competing Process Technologies Study

George F Mochnal
Director of Research and Education
Forging Industry Association
Forging Industry Educational and Research Foundation
For forging:

**Education**

1. To support programs at a number of universities where there is exceptional interest in forging and substantial course enrichment in forging process and application.
2. To offer to selected universities instructional materials on forging for incorporation into metallurgy and materials courses.

**Research and Development**

1. To sponsor research and development projects aimed at:
   - Easing or solving technical problems facing the forging industry;
   - Advancing technology in design, metallurgy, manufacturing and processing of forgings.
Joint Industry Alliance (JIA)
Dimensional Inspection of Elevated Temperature Parts

- Measurement of a turbine blade
- Monitoring of a 4-station horizontal press
- Monitoring of a 5-station vertical press
- Measurement of a stem pinion
Dr. Ali Fatemi and Research Assistant Mehrdad Zoroufi conducted an experimental and analytical comparative study of forged steel, cast iron and cast aluminum steering knuckles at the University of Toledo.

This research was funded by Forging Industry Educational and Research Foundation (FIERF) in cooperation with the American Iron and Steel Institute (AISI)
Results of Study

1. Yield strength of forged steel to be 140% higher than cast aluminum and 85% higher than cast iron;
2. Ductility of forged steel to be 270% higher than cast aluminum and 48% higher than cast iron;
3. Fatigue strength (at $10^6$ cycles) of forged steel to be 190% higher than cast aluminum and 40% higher than cast iron;
4. Forged steel to be superior with respect to cyclic plastic deformation - a major concern for automotive suspension components;
5. Forged steel knuckle gives about 100 times longer fatigue life than cast aluminum knuckle at the same stress level.
Connecting Rod and Steering Knuckle Optimization Technologies

Adila Afzal, Pravardhan Shenoy, Mehrdad Zoroufi
and
Ali Fatemi, Professor
The University of Toledo

Funded by:

and

American Iron and Steel Institute

www.autosteel.org
OVERALL OBJECTIVES

- Durability Comparison of Competing Manufacturing Technologies
- Optimization Study

Example Components:  
Engine (Connecting Rod)  
Suspension (Steering Knuckle)

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, 150 HP @ 5700 rpm
- Powder metal: 1.2 lb, 150 HP @ 5200 rpm
DURABILITY COMPARISONS
Connecting Rod: Specimen Tests

- **Tensile Tests**

- **Fatigue Tests**

- **Forced Steel**
  - True Stress-Amplitude, $\Delta \sigma/2$ (MPa)
  - Reversals to Failure, $2N_f$

- **Powder Metal**
  - True Strain-Amplitude, $\Delta \varepsilon/2$, %
  - Reversals to Failure, $2N_f$
DURABILITY COMPARISONS
Connecting Rod: Component Tests

Forced Steel Connecting Rod: 0.93 lb
Powder Metal Connecting Rod: 1.2 lb
DURABILITY COMPARISONS

Steering Knuckle: Specimen Tests

Tensile Tests

- Forged Steel
- Cast Iron
- Cast Aluminum

True Stress (MPa)

True Strain (%)

0.0% 0.2% 0.4% 0.6% 0.8% 1.0%

0 100 200 300 400 500 600 700 800 900
DURABILITY COMPARISONS

Steering Knuckle: Component Tests

- Forged Steel Knuckle
- Cast Aluminum Knuckle

Normalized Number of Cycles, \( N/N_f \)

Displacement Amplitude (mm)

Crack nucleates

Stress Amplitude (MPa)

Cycles to Failure, \( N_f \)
REFERENCE PUBLICATIONS

Steering Knuckle


# OPTIMIZATION STUDY

<table>
<thead>
<tr>
<th>Forged Steel Connecting Rod</th>
<th>Forged Steel Steering Knuckle</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Dynamic load analysis</td>
<td>- FE modeling (inelastic)</td>
</tr>
<tr>
<td>- FE modeling (elastic)</td>
<td>- Stress analysis</td>
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<tr>
<td>- Stress analysis</td>
<td>- Optimization</td>
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<tr>
<td>- Optimization</td>
<td>- Geometry constraints</td>
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</tbody>
</table>

[www.autosteel.org](http://www.autosteel.org)
Primary loading is bending
Spindle 2nd step fillet is the critical location
Local yielding occurs
Material model
- Elastic-plastic
- Cyclic deformation properties
OBJECTIVE
Minimize Weight and Cost

CONSTRAINTS
- Equivalent or longer life
- Geometry:
  - Strut mounting bolt-hole size and location
  - Suspension connection bolt-hole size and location
  - Spindle diameters and length

DESIGN VARIABLES
- Material
- Manufacturing process
  - Forging steps
  - Machining
  - Grinding
- Part processing
  - Heat treatment
  - Surface treatment
  - Inducing compressive residual stress
  - Fillet rolling
  - etc.

OPTIMIZATION STUDY
Steering Knuckle
OPTIMIZATION STUDY
Steering Knuckle Manufacturing Process

RAW MATERIAL INPUT
RAW MATERIAL INSPECTION
CUT TO SIZE OF PART
INDUCTION OR FURNACE HEATING
IMPRESSION-DIE FORGING
TRIMMING
SHOT CLEANING
INSPECTION & DIMENSIONAL CHECK

FORGING

TURN SPINDLE
DIMENSIONAL CHECK
MILL STRUT JOINT HOLES
MAKE STRUT JOINT CHAMFER
DRILL HUB MOUNTING HOLES
MAKE HUB MOUNTING HOLE CHAMFER
MILL TENSION STRUT STEPS

MACHINING

CUT SPINDLE THREADS
CUT HUB MOUNTING HOLE THREADS
MAKE LATERAL LINK HOLE
SPINDLE DIAMETER AND THREADS INSPECTION
SAMPLE EDDY CURRENT INSPECTION
CLEANING, FINAL INSPECTION, SHIPPING
FORGRED STEEL STEERING KNUCKLE OPTIMIZATION ALTERNATIVES

STAGE I

FOCUS:
- Minimize mass while maintaining the overall shape and attachment dimensions
- Modify manufacturing process

NO CHANGE IN ATTACHMENT GEOMETRY

STAGE II

FOCUS:
- Minimize spindle’s mass with limited attachment changes
- Modify manufacturing process

LIMITED CHANGE IN ATTACHMENT GEOMETRY
Stress distribution under primary loading at the vicinity of top strut attachment.

Higher stress in the optimized area, but still lower than the critical location.
Redesigned spindle

Tapered-bore bearing

Stress contour

Final design
OPTIMIZATION STUDY
Steering Knuckle: Process Modifications and Alternative Materials

Material Alternative Criteria
• Superior mechanical properties & fatigue strength
• Equivalent or better machinability
• Microalloyed
• Cost?

Material Alternatives
- SAE 15V24
- SAE 15R30V
- SAE 1522 MoVTi
- SAE 1522 MoVTiS
- SAE 1534 MoVTi
- SAE 1534 MoVTiSi

Very limited weight saving is achieved, due to geometrical constraints

Process Modifications
- Precision forging vs. conventional forging
- Warm forging vs. hot forging
- Reduction of machining steps (pierced mounting holes versus machined)

Improving Fatigue Performance
- Surface hardening
- Surface rolling
- Cost?
Example of Surface Hardening

Effect of induction hardening on truck stub axle and depth of induction hardened zone (Schijve, 2001)

Cost?

Example of Surface Rolling

Effect of rolling of the notch root on rotating bending fatigue of 37CrS4 steel (Kloos et al., 1987).

Cost?
## OPTIMIZATION STUDY
### Steering Knuckle: Summary

<table>
<thead>
<tr>
<th>Geometry Change</th>
<th>Process Change</th>
<th>Weight Reduction</th>
<th>Cost Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Material removed from body</td>
<td>• Strut holes pierced</td>
<td>At least 9%</td>
<td>5% + material saving</td>
</tr>
<tr>
<td>• Hub mounting thickness optimized</td>
<td>• Hub mounting bolt holes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Lateral link joint thickness optimized</td>
<td>• pierced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage II</td>
<td>Spindle redesigned</td>
<td>At least 12%</td>
<td>5% + material saving</td>
</tr>
</tbody>
</table>

### Limitations
- Many attachment compatibility constraints
- More comprehensive change on constraints can result in major design alterations in suspension system
- Significant thickness reduction in this relatively small part results in distortion of the component during forging
- Emphasis on optimization process
Forged Steel Connecting Rod
- Dynamic load analysis
- Stress analysis (elastic FEA)
- Optimization
  - Geometry constraints
  - Manufacturing processes
  - Material alternatives
  - Cost

Design loads:
- Compressive: Max gas load
- Tensile: Inertia load at 360° at max. speed
- Forces at the Crank and Pin Ends at Max. Speed (5700 RPM)
- Max Fx at each end is different.
- Fy is significant (i.e. bending).
- Multiaxial stress state at some locations
- R ratio varies along rod.
- Bending stress is significant
OPTIMIZATION STUDY

Connecting Rod: Static vs Dynamic Analysis

[Graph showing equivalent stress amplitude for different locations on the connecting rod, comparing static and quasi-dynamic analyses.]
Objective: Optimize weight and cost.
- Weight: Optimize geometry
- Cost: Use C70 “crackable” steel.

Expected cost reduction 25% (Repgen, 1998).

Focus mainly on the shank region.

Constraints: Protect against:
- Maximum Tensile Load: Yielding in tension
- Maximum Compressive Load: Yielding in compression or buckling
- Maximum Load Amplitude: Fatigue failure
- Maximum Bending Stress: Deflection in bending

- Side constraints (Dimensions compatible with existing geometry)
- Manufacturing constraints (Forging feasibility: i.e. distortion, draft angle)
The optimized geometry is 10% lighter than the original in spite of lower strength of C-70 steel.

With higher strength facture crackable materials such as micro-alloyed steels, the weight can be further reduced.

Weight reduction in the shank region is limited by manufacturing constraints (i.e. forging distortion).
Manufacturing steps eliminated by using C-70 crackable steel:

- The need to separately forge the cap and the body of the connecting rod
- Heat treatment
- Machining of the mating faces of the crank end
- Drilling for the sleeve

Cost Savings by using C-70 crackable steel

- Machining cost comprises 62% of the total cost for the conventional forged steel connecting rod (Clark et al., 1989)
- Machining cost reduction from utilization of the fracture splitting process, results in 23% total cost savings (Clark et al., 1989)
- “The development of fracture splitting the connecting rods achieves a total cost reduction up to 25% compared to conventionally designed connecting rods and is widely accepted in Europe” (Repgen, 1998, SAE Paper 980882)
• Tensile and fatigue strengths of forged steel were higher than those for the powder metal, based on specimen and component fatigue tests.

• There is considerable difference in the structural behavior of the connecting rod between static loading and dynamic loading (i.e. operating condition).

• The optimized geometry is 10% lighter than the existing rod. With higher strength crackable materials the weight can be further reduced.

• Reduction in machining operations achieved by using the fracture splitting process reduces the production cost by about 25%.

• The unique fracture surface from the fracture splitting process prevents the rod and the cap from relative movement. This results in an increase in the stiffness and reduction of stresses at critical locations.
CONCLUSIONS

Steering Knuckle

- Forged steel is considerably stronger and more ductile than cast aluminum and cast iron. Fatigue strength of forged steel is also considerably higher than cast aluminum and cast iron.

- The material undergoes plastic deformation at stress concentrations during overload cycles. The use of linear elastic FEA is not sufficient for reliable life predictions and optimization.

- Overall weight reduction of at least 12% and cost reduction of at least 5% are estimated for the forged steel steering knuckle.

- Much higher potential for weight and cost savings exists for larger components and, if a more comprehensive change to the suspension system can be made.