FORGED STEEL, CAST ALUMINUM AND CAST IRON IN SAFETY CRITICAL AUTOMOTIVE COMPONENTS

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Forging Industry Educational and Research Foundation
DRIVERS TO CHANGE

- Need for significant reduction in energy usage
- Advances in fundamental understanding of interactions between materials and processes
- Access to information - integration
- Environmental drivers
- Improved process knowledge based on scientific information and improved sensing and control
- Competitive pressure for sustained productivity improvements
- Emergence of net-shape processes and engineered solutions
RESEARCH PARTNERS

- Department of Defense (DOD)
  - Forging Defense Manufacturing Consortium
- Department of Commerce (DOC)
  - National Institute of Standards and Technology (NIST)
- Department of Energy (DOE)
  - Office of Industrial Technologies - Industries of the Future
- National Laboratories
  - Oak Ridge National Laboratory, Sandia National Laboratory, Argonne National Laboratory
- Universities
- Joint industry Alliances (JIA)
- Collaborative Industry projects
FORGING PROGRAMS

- Precision Forging Consortium - extend tool life
- Innovative die material & lubrication strategies
- Center of Excellence in Forging Technology - Ohio State University
- Fast non-contact dimensional and surface finish inspection of forgings at elevated temperatures.
- Effects of induction processing on the mechanical properties of steels with controlled microstructures
- Heating response of different starting microstructures and their relationships with important forging process parameters
Forging Industry Educational & Research Foundation (FIERF)
FORGED STEEL, CAST ALUMINUM AND CAST IRON IN SAFETY-CRITICAL AUTOMOTIVE COMPONENTS

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and
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The University of Toledo

Funded by:

FIERF

and

American Iron and Steel Institute

www.autosteel.org
OVERALL OBJECTIVES

• Evaluate and compare fatigue performance of forged steel components with other process technologies.

• Steering knuckle chosen as example part:
  – Forged Steel
  – Cast Aluminum
  – Cast Iron
PROJECT OUTLINE

• **Literature Survey**
  – Forging vs. Competing Manufacturing Processes
  – Potentials for Improving Competitiveness
  – Durability & Optimization of Steering Knuckle

• **Experimental Work**
  – Specimen Testing
    • Forged steel SAE 11V37
    • Cast aluminum ASTM A356-T6
    • Cast iron ASTM A536 Grade 65-45-12
  – Component Testing on forged steel and cast aluminum knuckles
    • Determining test configuration
    • Manufacturing fixtures
    • Load-control fatigue testing
• **Analytical Evaluations**
  – Digitizing steering knuckle Geometry
    • Forged steel
    • Cast aluminum
    • Cast iron
  – Stress/Strain (FEA) Analysis
    • Forged steel knuckle
    • Cast aluminum knuckle
    • Cast iron knuckle
  – Durability (Fatigue) Analysis
  – Optimization Analysis
PUBLICATIONS AND PRESENTATIONS


• Durability Comparison and Life Predictions of Competing Manufacturing Processes: An Experimental Study of Steering Knuckle, *25th FIA Conference*, Detroit, MI (April 20th 1:50 PM).

Forged steel
SAE Grade 11V37
Steering knuckle of rear suspension of a 4-cylinder sedan weighing 2.5 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
STEERING KNUCKLE WITHIN THE SUSPENSION SYSTEM

- Knuckle body connects to strut, front and rear lateral links, and tension strut/chassis bracket
- Spindle attaches to wheel hub & bearing assembly
- Steering, braking, cornering, hitting pot holes cause cyclic loads
Specimen Testing

- Strain-controlled tensile tests
- Strain-controlled fatigue tests
- Based on ASTM standards and recommended practices
- Flat specimens from forged steel, cast aluminum, and cast iron steering knuckles

Instron closed-loop servo-controlled hydraulic axial load frame and digital servo controller are utilized for the tests.
Flat plate specimen configuration and dimensions according to ASTM Standard E606

(All dimensions in mm)

Generating specimens
Forged steel knuckle:

Cast aluminum and cast iron knuckles: hub and arms
# COMPARISON OF MATERIAL MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th></th>
<th>Forged Steel</th>
<th>Cast Aluminum</th>
<th>Cast Iron</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11V37</td>
<td>A356-T6</td>
<td>65-45-12</td>
</tr>
<tr>
<td>YS (MPa)</td>
<td>556</td>
<td>232</td>
<td>300</td>
</tr>
<tr>
<td>YS Ratio</td>
<td>1</td>
<td>0.41</td>
<td>0.54</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>821</td>
<td>302</td>
<td>471</td>
</tr>
<tr>
<td>UTS Ratio</td>
<td>1</td>
<td>0.37</td>
<td>0.57</td>
</tr>
<tr>
<td>%RA</td>
<td>37</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>%RA Ratio</td>
<td>1</td>
<td>0.27</td>
<td>0.68</td>
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<tr>
<td>YS’ (MPa)</td>
<td>541</td>
<td>291</td>
<td>407</td>
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<tr>
<td>YS’ Ratio</td>
<td>1</td>
<td>0.54</td>
<td>0.75</td>
</tr>
<tr>
<td>$S_f$ (at $N_f=10^6$)</td>
<td>352</td>
<td>122</td>
<td>253</td>
</tr>
<tr>
<td>$S_f$ Ratio</td>
<td>1</td>
<td>0.35</td>
<td>0.72</td>
</tr>
</tbody>
</table>

* base of comparison is 11V37.
MATERIAL CYCLIC & MONOTONIC STRESS-STRAIN BEHAVIOR

\[ \varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left( \frac{\sigma}{K} \right)^{\frac{1}{n}} \]

- Forged Steel 11V37
- Cast Iron 65-45-12
- Cast Aluminum A356-T6
Better overall S-N fatigue resistance of the forged steel

Long-life fatigue strengths of cast aluminum 35% and cast iron 72% of forged steel
Occasional OL’s and UL’s cause inelastic deformation

Forces and Moments on the Test Road (Lee, 1995)
- **Overloads** are common for suspension components such as steering knuckle
- **Cyclic plasticity** an index for tolerance against overloads
- Higher capacity of forged steel for cyclic plastic deformation
- Better *low-cycle fatigue* behavior

**MATERIAL PLASTIC STRAIN COMPARISON**

![Graph showing True Plastic Strain Amplitude (%) vs. Reversals to Failure, 2Nf for different materials: Forged Steel 11V37, Cast Iron 65-45-12, Cast Aluminum A356-T6.](image-url)
Neuber Plot:
- is useful when analyzing component geometries with stress concentrations
- Notch root fatigue behavior is a function of both local stress and strain
Longitudinal direction experiencing the highest level of stress, exhibits best fatigue strength.
Forged steel  Cast aluminum  Cast iron
BOUNDARY CONDITIONS FOR STRESS (FEA) ANALYSIS

CAST ALUMINUM KNUCKLE

FORGED STEEL KNUCKLE

CAST IRON KNUCKLE
CONTOURS OF VM STRESS FOR FS KNUCKLE ($P_{\text{max}} = 4.9$ kN)
CONTOURS OF VM STRESS FOR CA KNUCKLE ($P_{\text{max}} = 6.2$ kN)
CONTOURS OF VM STRESS FOR CI KNUCKLE ($P_{\text{max}} = 6.2 \, \text{kN}$)
Contour windows of von Mises stress showing the critical locations for:

- forged steel knuckle (left): spindle 1st step fillet
- cast aluminum knuckle (middle): hub bolt holes
- cast iron knuckle (right): strut arm root and hub bolt hole
FORGED STEEL KNUCKLE TEST SETUP

- **Spindle** was fixed by a two-piece block
- Threaded rods tightened the block to the spindle
- A pair of L-shaped moment arms transferred the load from the testing machine loading actuator to the spindle blocks in the form of a bending load
- **Strut and suspension connections** on the knuckle body were fixed to the bench using round and square blocks
CAST ALUMINUM KNUCKLE TEST SETUP

- **Strut attachment** of the arm was connected from both sides to a pair of moment arms.
- **Moment arms** transferred the **bending load** from the loading actuator to the knuckle.
- **Four hub bolt holes** were fixed to the bench.
To verify testing configuration and FEA results.

Measured and predicted strain values at 2.2 kN static load.

All measurements after a few cycles.

Locations of the gages are shown with arrows.

FEA and measured strains are relatively close.

### Table: Measured & Predicted Strains

<table>
<thead>
<tr>
<th>Gage Number</th>
<th>Measured Strain (µstrain)</th>
<th>$\frac{P}{A}$ (µstrain)</th>
<th>Predicted Strain from FEA (µstrain)</th>
<th>Diff. Meas. and FEA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forged Steel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>542</td>
<td>575</td>
<td>583</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>-527</td>
<td>-557</td>
<td>-546</td>
<td>4</td>
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<tr>
<td>3</td>
<td>1561</td>
<td>1571</td>
<td>1716</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>-1489</td>
<td>-1536</td>
<td>-1590</td>
<td>7</td>
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<tr>
<td><strong>Cast Aluminum</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>455</td>
<td>-</td>
<td>434</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>534</td>
<td>-</td>
<td>470</td>
<td>12</td>
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<tr>
<td>3</td>
<td>228</td>
<td>-</td>
<td>268</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>-</td>
<td>320</td>
<td>11</td>
</tr>
</tbody>
</table>
To record macro-crack nucleation, growth, and fracture stages.

A marked $\Delta d$ increase considered as crack nucleation point, and a sudden increase as fracture.

For cast aluminum knuckle, crack growth portion was significant.
FRACTURE SURFACES

FORGED STEEL KNUCKLE

CAST ALUMINUM KNUCKLE

fracture

crack nucleation

crack propagation

fracture

crack propagation

crack nucleation
Forged steel knuckle gives about **two orders of magnitude** longer life than cast aluminum knuckle.

Apparent *fatigue limit* for forged steel knuckle, but not cast aluminum knuckle.

Highest load levels represent *overload conditions* for suspension components, such as steering knuckle.

![Graph showing stress amplitude vs. cycles to failure for forged steel and cast aluminum knuckles](image_url)
Predictions based on the S-N approach are **conservative** for both forged steel and cast aluminum knuckles.

This is partly due to the conservative nature of the modified Goodman equation.
COMPONENT STRAIN-LIFE PREDICTIONS

\[
\sigma_{\text{max}} \varepsilon_a E = (\sigma_f')^2 (2N_f)^{2b} + \sigma_f' \varepsilon_f E (2N_f)^{b+c}
\]

- Predictions based on the \( \varepsilon \)-\( N \) approach are relatively close to experimental lives for forged steel and cast aluminum knuckle.

- **Life Predictions:**
  - Forged steel 10X cast iron
  - Forged steel 30X cast aluminum
Forging Influencing Parameters

- Workpiece Material
- Workpiece Geometry
- Die & Tool Design
- Forging Method & Sequence
- Friction and Lubrication
- Forging Temperature
- Workpiece Temperature
- Contact Time
- Loading Rate

Influenced Parameters

- Defects: Porosity, Inclusions
- Surface Finish: Roughness, Scale
- Residual Stresses
- Microstructure: Grain Type and Size, Grain Flow

Monotonic Behavior

- Tensile Strength $S_u, S_y, \sigma_f$
- Ductility $\%EL, \%RA$

Fracture Behavior & Damage Tolerance

- Tensile Toughness & Resilience
- Stiffness $E$
- Impact & Dynamic Behavior
  - CVN Energy
  - $\epsilon$ Effect

Mechanical Properties

- Cyclic Strength $\sigma_{f'}, b, S_f, S_{f'}$
- Cyclic Ductility $\varepsilon_{f'}, c$
- Cyclic Strain Hardening $K', n'$
- Tensile Strain Hardening $K, n$
- Hardness
- Fracture Toughness $K_{IC}, K_c, J_{IC}$
- Crack Growth Resistance $A, m, \Delta K_{th}$
- Cyclic Behavior & Fatigue
  - Microstructure: Grain Type and Size, Grain Flow
  - Other Behavior & Properties: Wear Resistance, Fretting Behavior, Corrosion Resistance, Creep Behavior
### DEFINITION OF OPTIMIZATION PROBLEM

<table>
<thead>
<tr>
<th>OBJECTIVE FUNCTION</th>
<th>DESIGN VARIABLES (can change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of FS knuckle</td>
<td>• Material</td>
</tr>
<tr>
<td></td>
<td>– Replacing by microalloyed steel</td>
</tr>
<tr>
<td></td>
<td>– etc.</td>
</tr>
<tr>
<td></td>
<td>• Manufacturing process</td>
</tr>
<tr>
<td></td>
<td>– Forging steps</td>
</tr>
<tr>
<td></td>
<td>– Machining</td>
</tr>
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<td></td>
<td>– Grinding</td>
</tr>
<tr>
<td></td>
<td>– etc.</td>
</tr>
<tr>
<td></td>
<td>• Part processing</td>
</tr>
<tr>
<td></td>
<td>– Heat treatment</td>
</tr>
<tr>
<td></td>
<td>– Surface treatment</td>
</tr>
<tr>
<td></td>
<td>– Inducing compressive residual stress</td>
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<tr>
<td></td>
<td>– Induction hardening</td>
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<td></td>
<td>– Rolling</td>
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<tr>
<td></td>
<td>– etc.</td>
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</tbody>
</table>

### CONSTRAINTS (cannot change)

- Equivalent or better fatigue strength
- Geometry:
  - Strut mounting bolt-hole size and location
  - Suspension connection bolt-hole size and location
  - Spindle diameters
  - Spindle length
CONCLUSIONS

- From **tensile tests**, cast aluminum and cast iron reached 37% and 57% of forged steel **UTS**, and **percent elongation** were 24% and 48% of forged steel, respectively.

- **Cyclic yield strength** of cast aluminum and cast iron were found to be 54% and 75%, while the **cyclic strain hardening exponent** were 46% and 55% of forged steel, respectively. These indicate higher resistance of the forged steel to cyclic plastic deformation.

- Long-life material **fatigue strengths** of cast aluminum and cast iron are only 35% and 72% of forged steel, respectively.

- Comparisons of **strain-life fatigue** behavior indicates forged steel provides more than an order of magnitude longer life than the cast iron, and more than a factor of 3 longer life than cast aluminum.
CONCLUSIONS

• Neuber plots of the three materials, that is useful when analyzing component geometries with stress concentrations, show a factor of six longer life for forged steel than that of cast iron and three orders of magnitude longer life than that of cast aluminum.

• Differences between measured and FEA-predicted strains were found to be reasonable for the complex knuckle geometries considered. FEA-predicted and observed failure locations were identical.

• Crack growth life was found to be a significant portion of cast aluminum knuckle fatigue life, while it was not significant for forged steel knuckle fatigue life.
Component test results showed forged steel knuckle to have about two orders of magnitude longer life than cast aluminum knuckle, for the same stress amplitude level. This occurred at both short as well as long lives.

S-N life predictions for the components were overly conservative, whereas strain-life predictions were relatively close to component experimental results.

Comparison of the strain-life prediction curves of the components demonstrated that forged steel knuckle offers more than an order of magnitude longer life than cast iron knuckle.
Great Designs in STEEL

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