2015-IDE Conference

Hot Hydroforging for Lightweighting

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What is Hot hydroforging?

Definition: Hot forging of lightweight products from a hybrid billet of a metal shell and a low melting core.

Concept: Hot hydroforging is done at temperatures where the core material is in viscous state and builds up uniform pressure thereby enabling a uniform deformation of the metal shell.

Goal: Lightweight net shape forging with complex topologies
Hybrid lightweight gear

The outer structure is steel, the inner structure is a low melting lightweight material.
Objectives

• Forging light weight hybrid gears with net teeth and near net center.
• The hybrid gear has all steel outer structure.
• Investment forging is enabled (molten core can be emptied).
• Press loads are reduced and larger gears can be forged.
• 30% to 50% weight reduction per gear is targeted.
• Up to 10% weight reduction per transmission is expected.
• 60% to 70% reduction in machining scrap rate due to near net teeth.
• Gear teeth can be induction hardened with significant energy savings.
Steels and low melting point materials

- Melting ranges of alloys
- Viscous ranges of oil, wax, polymer and glass
- Hot forging temperatures of steel
Structural FEA Modeling of Hybrid Gears
2.5 mm thick steel cover

Out side body with Steel

Gear B

Gear D

Inside core body with Aluminum
Subassembly Deformation and Stress, All Steel Gear and Hybrid Forged Gear

<table>
<thead>
<tr>
<th>Deformation</th>
<th>Hybrid-Bi-Metal forging</th>
<th>All Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gear B</td>
<td>Gear D</td>
</tr>
<tr>
<td>Total (mm)</td>
<td>0.48</td>
<td>0.425</td>
</tr>
<tr>
<td>Angular (°)</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>Radial (mm)</td>
<td>-0.063</td>
<td>-0.127</td>
</tr>
<tr>
<td>Axial (mm)</td>
<td>0.081</td>
<td>-0.0442</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>Hybrid-Bi-Metal forging</th>
<th>All Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gear B</td>
<td>Gear D</td>
</tr>
<tr>
<td>Von-Mises</td>
<td>825</td>
<td>876</td>
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<tr>
<td>Max principal</td>
<td>730</td>
<td>728.96</td>
</tr>
<tr>
<td>Min principal</td>
<td>-934</td>
<td>-977.87</td>
</tr>
</tbody>
</table>

No stress or deflection is increased more than 8% for the bimetal gear compared to the all-steel gear.
Hybrid billet design for hot hydroforging

Steel tube
- seamless, and w/ seam
- 0.25" and 0.5" wall

Al bar

Interference fit
- 0.003", and 0.005"

Factors
- Wall thickness
- Steel tube type
- Interference fit
- Forging technique

Levels
- Wall thickness: 0.25" (6.25 mm) and 0.5" (12.5 mm)
- Steel tube type: seamless and with seam
- Interference fit: 0.003" (0.075 mm) and 0.005" (0.125 mm)
- Forging technique: Hot (solid state) and Hot hydroforging

Weld bead
- Electron beam welding
Die design and simulations

The pockets in the top and the bottom dies keep the weld zone of end caps under compression during busting forging.
Die stress analysis

Forging temperature: 1100°C

<table>
<thead>
<tr>
<th>Ram displacement (mm/406mm)</th>
<th>Forge load (ton)</th>
<th>Fill radius, d (mm)</th>
<th>Stress at the die fillet, d (MPa)</th>
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</thead>
<tbody>
<tr>
<td>405.90</td>
<td>973</td>
<td>1.50</td>
<td>2120</td>
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<tr>
<td>405.87</td>
<td>758</td>
<td>2.30</td>
<td>1750</td>
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<tr>
<td>405.68</td>
<td>552</td>
<td>4.25</td>
<td>1320</td>
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</table>
Interpower High Frequency Induction Power (10 kHz, 500 kW)

Interpower Induction controller being built up

New Interpower coil for high frequency
Induction heating simulations for solid state hot forging

Temperature vs. time in the radial direction

Both steel and aluminum are in solid state
Due to differential heating rate steel shell pulled away from the core
Billet induction heating simulations for hot hydroforging, on-off control strategy

Iso-temperature lines showing the temperature distribution in the radial direction from the center axis to the outer diameter of the billet at mid height of the billet as function of the heating time. The heating simulation shows the effect of on/off control strategy.

Heating simulation shows that aluminum core reaches 1000°C in 6 on/off cycles in 60 seconds.
Solid state hot forging simulations predicted folds and shrinkage gap.
Steel wall thickness uniformity simulations with hot hydroforming

Boundary conditions

Top surface constrained

Linearly increasing hydrostatic pressure

Symmetrical plane

bottom surface constrained
Concept: Two-blow hot hydroforming simulations for uniform wall thickness

The teeth profile is formed half way in the first die (top). The preform is indexed by half width of tooth and placed in the second die for final forging (bottom).
Tooth profile wall uniformity comparison

2 blow operation with hydrostatic pressure

1 blow operation Solid state forging simulation

<table>
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<tr>
<th>Non-uniformity index</th>
<th>1.3</th>
<th>6.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-steel ratio</td>
<td>2.7</td>
<td>0.6</td>
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</table>

- Non-uniformity index: largest thickness / smallest thickness. 1 means ideal uniform.
- Al - steel ratio: area of the Al / area of the steel in the tooth.

The steel wall thickness uniformity can be improved significantly with 2-blow, indexed, hot hydroforging as compared to 1-blow solid state forging.
Forging Trials at Walker Forge

Interpower Induction 10 kHz heater installed at Walker Forge

Walker’s Erie 4000 ton mechanical press

Bi-Metal billets before forging

Heating

Transferred to the die

Right after forging

A few seconds after forging

Forged parts
Comparison of hot forging and hot hydroforging experiments

Solid state hot forging
Steel @1100C
Al core @400C

- Fractured wall
- Incomplete fill
- Non-uniform wall
- Fold
- Gap due to CTE mismatch
- Cracks

World’s 1st Hot hydroforging
Steel @1100C
Al core @1100C

- Void due to CTE mismatch
- No fracture or crack
- Uniform wall

Hot hydroforging is promising if CTE mismatch is eliminated
Weld zone healing in hot hydroforging

Dendritic structure of weld zone disappeared after hot hydroforging

Before forging
Dentritic structure

After busting hot hydroforging
Normalized structure
“Investment Forging”

- Investment forging is a term coined at Eaton.
- It describes a process where the molten core is evacuated from the forged part after a hot hydroforging process leaving behind a hollow part.
- Investment forging provides the ultimate weight reduction up to 50% for a gear.
- Investment forging can also be applied to many other forged parts. For example forged hollow engine exhaust valves can be created by investment forging.
Eliminating CTE Mismatch with Glass

- Glass is identified as the core material of choice with matching CTE to that of steel, 10-12 \(10^{-6} \text{ m/mK}\).

- The other advantages of glass:
  - Low cost
  - Low density
  - Good bonding to steel
  - Lower elastic modulus than steel
  - Working temperature can be optimized
  - May enable and temper a through-hardened steel wall
Heating/cooling simulations of hybrid billets, Displacement and gap formation in solid state

Steel/Glass

No gap predicted

Steel/Aluminum

Significant gap predicted

Glass is a promising lightweight core material.
Histories of temperature, radial displacements and radial gap

Steel/Glass

Steel/Glass

Steel/Aluminum

No gap predicted

Significant gap predicted

* N165 is on steel bore, and N4442 is on outer surface of core.
Conclusions

• Feasibility of hot hydroforging and investment forging for lightweighting, net shape forging and waste reduction are demonstrated.
• Steel/aluminum hybrid billets were prepared. Then, the billets were hot hydroforged in closed dies.
• A uniform steel wall thickness was observed all around the hot hydroforged part upon cross sectioning.
• Weld seams are healed (normalized) upon hot hydroforging.
• Steel/glass is a more promising hybrid than steel/aluminum for hot hydroforging due to the CTE match.
DRAFT REPORT

U.S. DEPARTMENT OF ENERGY

VEHICLE TECHNOLOGIES PROGRAM

WORKSHOP REPORT:
Trucks and Heavy-Duty Vehicles
Material Technical Requirements and Gaps

July 2012

DRAFT REPORT
## Light Duty Truck and SUV Cab and Body (including interior)
### Targets (Relative to 2010 Baseline)

<table>
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<tr>
<th></th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
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<tbody>
<tr>
<td>Weight Reduction of cab and body</td>
<td>25%</td>
<td>35%</td>
<td>45%</td>
<td>50%</td>
<td>55%</td>
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<tr>
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<td>10%</td>
<td>10%</td>
<td>20%</td>
<td>20%</td>
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<tr>
<td>Stiffness and NVH</td>
<td>Match Baseline</td>
<td>Match Baseline</td>
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<td>Match Baseline</td>
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<td>Durability</td>
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<td>Match Baseline</td>
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<tr>
<td>Production time</td>
<td>Match Baseline</td>
<td>Match Baseline</td>
<td>+10%</td>
<td>+20%</td>
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<td>60%</td>
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<tr>
<td>Cost Penalty</td>
<td>Match Baseline</td>
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<td>&lt;10%</td>
<td>&lt;20%</td>
<td>&lt;20%</td>
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<td>$4.15/lbs. Saved*</td>
<td>$4.33/lbs. Saved*</td>
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