The Influence of Light Weight Materials on Fuel Economy and Emissions in Heavy Duty Diesel Engine

Paul C. Becker*, Yong-Ching Chen & Martin Myers: Cummins Inc.

August 20-24, 2000

* Presenter
Effect of Weight Reduction on Emissions

For an in-line six cylinder diesel engine:

- A total 25% reduction in total engine weight
  » 6% reduction in fuel consumption
  » Saves 10 gms NOx per gallon saved per year
- 100,000 vehicle/yr running at 15,000 mi/yr/veh.
- Total NOx not produced by increase in fuel economy is 4 million gms NOx/yr.
Introduction:

- Technologies being developed that will allow for the substitution of aluminum for cast iron in engine heads and blocks, while maintaining performance and durability.
- Development of lightweight diesel engine technology: funded by NAVY, DOE and TACOM
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Spark Ignited</th>
<th>Light Duty Diesel</th>
<th>Pickup Truck</th>
<th>Heavy Duty Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability (B10)</td>
<td>150K miles</td>
<td>150K miles</td>
<td>250K miles</td>
<td>&gt; 650K miles</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>600-7000</td>
<td>600-4500</td>
<td>600-3000</td>
<td>600-2100</td>
</tr>
<tr>
<td>Cylinder Pressure (psi)</td>
<td>1100-1400</td>
<td>2000-2300</td>
<td>2200-2500</td>
<td>2000-3000</td>
</tr>
<tr>
<td>Torque Rise</td>
<td>Naturally Aspirated: very limited</td>
<td>Very Good</td>
<td>Very Good</td>
<td>Very Good</td>
</tr>
</tbody>
</table>

Engine Comparison
Fatigue Curves of Block Materials at Room Temperature

- **Aluminum Alloy-T6**
- **Cast Iron**

**Axes:**
- **Stress Amplitude, ksi**
- **Number of Cycles to Failure, Nf**
Strategy

- Develop the technology to produce lightweight diesel engine component without sacrificing performance & durability
  » Selected the Cummins 6B Engine for technology development (175-240 hp)
  » Targeted 25% total engine weight saving
  » Selected the head and block for greatest weight saving potential
  » Selected aluminum to replace cast iron
- Identify the limits of the technology for unreinforced aluminum components
  » Potential for a midrange/light duty engine
- Heavy duty applications will require selective reinforcement of critical regions
Major Elements

- Develop analytical model for the head and block
- Develop database of material properties
- Model Validation:
  » Component Testing
  » Engine Testing
- Develop selective reinforcement strategy for the critical regions of the head and block
Unreinforced Head & Block Development for Medium to Light Duty Application
6B Aluminum Head and Block Test Engine Configuration

- Head and block cast in aluminum using 1988 vintage tooling
- Cylinder liner, valve guides and valve seats are pressed-in rebuild kit components
- Main bearing cap is ductile cast iron production part
- Cast iron engine weighs 880 lbs.
- Aluminum engine weighs 668 lbs.
- Weight Saving is: Head: 70 lbs. Block: 140 lbs.
  Total: 210 lbs. (24%)
Aluminum Head & Block Photos

- Pressed-in Valve Guides
- Pressed-in Valve Seat Inserts

- Cast Iron Sleeve Pressed in
- Ductile Iron Bearing Caps
Lightweight Aluminum Engine
Stress & Thermal Analysis of Cylinder Head & Block

Temperature Distribution

Stress Distribution

Head

Block
Component Testing/Engine Testing

+ Calibrate FE model:
  » Photostress Analysis/Strain Gauging
  » Thermocouple

+ Head & Block Fatigue Testing:
  » Define baseline fatigue curves for the head/block
  » Identified potential failure modes of an reinforced aluminum head/block

+ Engine Testing
Aluminum Head Fatigue Tests

Normalized Cylinder Pressure

Run-Out after 10 million cycles

Design Limit

Peak Cylinder Pressure

Normal Microstructure

Refined Microstructure
Aluminum Block Fatigue Tests

Run-Out after 10 million cycles

Normalized Cylinder Pressure

- Block with Helicoils
- Block with Rolled Threads

Design Limit
Peak Cylinder Pressure

Cummins
Engine Test Results

- Provided strain gage data for calibration of the FE model
- Completed thermal mapping to verify thermal boundary conditions used in FE modeling
- Engine achieved max. torque of 712 ft-lb. @ 1400 rpm and 240 hp @ 2500 rpm
- Noise test indicated that the engine was similar to cast iron at full load, but was slightly higher at half and no load conditions
- Completed 500 hours of thermal cycle test. Engine was shut down due to a severe coolant leakage
- Built up one aluminum engine for NAVY for noise & magnetic signature measurements
Tools and analytical methods are available for the development.

FE model was calibrated using engine thermal mapping.

Established material properties of candidate aluminum alloys.

Various modifications were made to the head and block castings to increase durability.

Modal tests of iron/aluminum engine combinations were completed, no concerns.

Limited engine tests revealed potential issues. Most related to specific design.

Limited tests show an unreinforced aluminum head and block might be feasible for light to medium duty applications with minor design modifications.
Reinforced Head & Block Development for Heavy Duty Engine Application
Selective Reinforcement in Aluminum Heads & Blocks

- Valve Seats and Valve Guides
- Cylinder Liners
- Cast Iron Combustion face Insert
- Steel Bearing Saddle Inserts
- Bonding Study to Determine Best Attachment Methods for Inserts
(1) Combustion face Insert

(2) Steel Bearing Saddle Insert
Goodman Diagram-with Block Inserts

- Steel
- Aluminum

Plot points for different stress conditions:
- At the interface of the insert (1.5X Rated)
- At the interface of the insert (Rated)
- At the end of capscrew (1.5X Rated)
- At the end of capscrew (Rated)
Metallurgical Bonding Approaches

Two Approaches:

1. Commercially Available Zinc Coating ("Met-Bond" process developed by CMI and Reynolds Aluminum Co.): Press-in-Place approach

2. A Proprietary Coating Developed by Cummins & ORNL: Cast-in-place approach
A “Met-Bonded” Aluminum Head

- Reinforced aluminum heads manufactured in the early stage with cast iron inserts coated with zinc, press-in-place and heated to form bonds
A Reinforced Aluminum Head

Ultrasonic C-Scan Inspection of Bond Integrity:

- Completed 10 million cycles at 1.5X cylinder pressure design limit in cylinders #2 and #3 without any failure
A Reinforced Aluminum Block

- Steel inserts were bonded into main bearing saddle areas & threaded into the steel inserts instead of aluminum
- Reduce block stretch to an equivalent level as a cast iron block
A Proprietary Coating System
Developed by Cummins & ORNL

- A viable bonding system was developed by Cummins and ORNL to reinforce aluminum castings with steel inserts by a cast-in-place process.
- T6 heat treatment could be applied to aluminum castings without degrading the bond strength. This could not be achieved using other bonding systems.
- Two patents applied for.

![Steel and Al composite image]

![Graph showing interfacial strength vs. coating thickness]
Proprietary Bonding System:

- The bond layer was determined to be more ductile than the Alfin layer found in an aluminum piston.
Multi-Casting Trials:

Samples for C-Scan
Push-Out Tests of Bonded Samples:

Samples for push-out tests

Mean Shear Strength of ORNL Fatigue Samples

- Normalized Shear Strength
- Percentage of Bonding Area
- Shear stress predicted by FEA
Conclusions:

+ With the durability expectation of medium-to-light duty applications, such as an SUV engine, a lightweight aluminum block and head and is feasible to achieve improved fuel economy and reduced emission.

+ For heavy-duty truck applications, FE analysis predicts that selective reinforcement in aluminum heads and blocks is required.
Future Work:

+ Determine the durability limits for unreinforced aluminum heads and blocks
+ Optimize reinforcing technologies
+ Manufacture reinforced heads and blocks for testing
+ Conduct engine tests to verify the concepts developed
+ Technologies for selective reinforcement are still under development.