Titanium Engine Components

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Organization: ORNL

9/13-15/05

PM_10458

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Titanium Engine Components

21CTP Technical Goal: Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system efficiency from ~42% today to 50% by 2010.

Project Objectives

1. Using FEA, predict operating temperatures and stresses of a Cummins ISB diesel engine with a Ti cylinder head and block (with cast iron liners) rated at 305 hp and compare to the production grey cast iron. **2.** Determine the technical feasibility of using Ti for engine cylinder heads and blocks from temperature, stress and fatigue predictions. **3.** Predict operating temperatures and stresses of the engine with a titanium cylinder block and cylinder head, (with inserts in the flame face of each cylinder). Determine feasibility of simultaneously increasing the rating of the engine from 305 hp to 450 hp. **4.** Investigate Al and Mg as cylinder block and head materials and compare to cast iron.

FY 2005 Focus

Complete modeling work and explore potential of manufacturing and testing prototype engines.

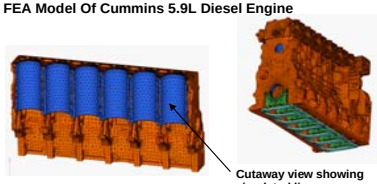
Planned Duration

October 2003 to September 2005

DOE Funding/Industry Cost Share

FY04: $100K; FY05: $235K

FEA Model Of Cummins 5.9L Diesel Engine



Cutaway view showing simulated liners

Principal Investigator(s)

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Accomplishments

1. FEA modeling demonstrated that Ti is a feasible substitute for grey cas iron in the head and block castings allowing a diesel engine to be up-rate by 50% in hp and still achieve a 10% overall weight savings. –4/5/05
2. FEA modeling has shown that it is feasible to replace cast iron in a diesel engine head and block with Al and achieve an overall engine weig saving of 20%. – 10/5/04
3. FEA modeling had shown that it is feasible to replace cast iron in a die engine head and block with Mg and achieve an overall weight saving of 33%. - 8/10/04

Milestones

1. Final report on the FEA modeling work. 9/30/05

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
PM_10458	Materials Technology	HV Propulsion Materials	Applied Research	8-11-05

Objectives

- Determine if light weight materials can replace cast iron in diesel engine heads and blocks in order to accomplish the following:
  - Increase the fuel economy of commercial vehicles by reducing the weight of the engine
  - Reduce the size of the engine by up-rating the horsepower
    - Realize additional weight savings from smaller block and head
    - Enable aerodynamic improvements in the design of the cab by reducing the size of the engine

Approach

- Using FEA modeling, predict operating temperatures and stresses of a Cummins ISB diesel engine with light metal replacements for cast iron
  - Ti engine block and cylinder head
    - With cast iron liners
    - With and without inserts in the cylinder heads
    - Rated at normal 305hp and up-rated to 450hp
  - Al engine block and cylinder head with C.I. Liners.
  - Magnesium engine block and cylinder head with C.I. Liners.
- Determine technical feasibility of using light metal replacements for cast iron

Relevance to 21CTP Goals

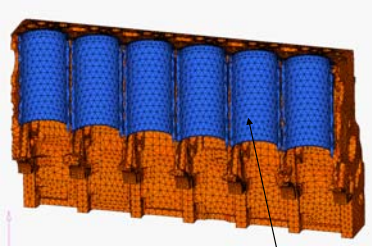
- **Relevant 21CTP Goal**
  - **Develop and demonstrate lightweight material and manufacturing processes that lead to a 15% to 20% reduction in tare weight.**
- **Light weight metals offer significant potential weight savings in heavy duty diesel engines**
  - **30% of overall engine weight with Mg head and block**
  - **20% with Al head and block**
  - **10% with Ti head and block***

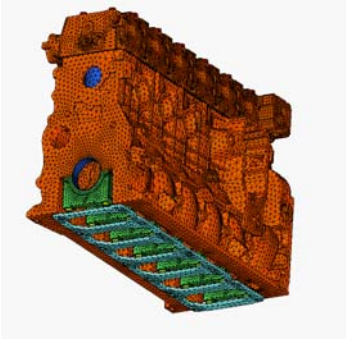
    *** Engine can be up-rated in hp by 50% and thus reduced in size and weight.**

Comparison of Key Engine Requirements for Various Types of Engines

Requirement	Spark Ignited (gasoline)	Light Duty Diesel	Pickup Truck, Class 2b or greater	Heavy Duty Diesel
Durability, miles (B10)	200K	200K	250K	> 650K
Speed (rpm)	600-7000	600-4500	600-3000	600-2100
Cylinder Pressure (psi)	1100-1400	2000-2300	2200-2500	2000-3000
Materials Head Block	 Al Al	 Al Cast Iron	 Cast Iron Cast Iron	 Cast Iron Cast Iron
Typical Weight, lbs	400-600	400-600	800-1000	1100-2900

FEA Model Of Cummins 5.9L Diesel Engine with Cast Iron Cylinder Liners



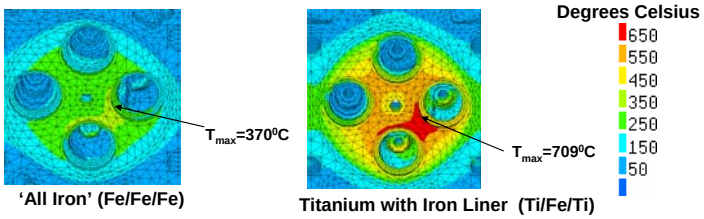


Cutaway view showing simulated liners

Technical Accomplishments/Progress/Results

Thermal Results - Titanium

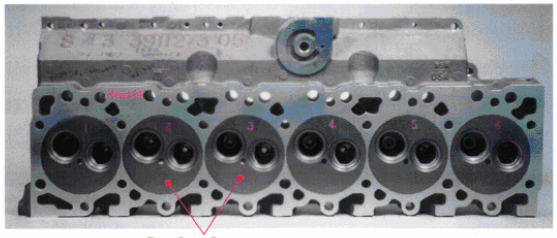
- Cylinder Head Valve Bridges



Temperature Reduction Strategy

- There were problem with excessive temperatures in the valve bridge regions of the Ti head
- The feasibility of replacing the Ti in valve bridge regions with inserts was FEA modeled
  - Copper alloy with high thermal conductivity and good elevated strength
  - with an insert of a material having high thermal conductivity and good elevated
  - The feasibility of rating the engine at >> hp was determined
    - Ti-6Al-4V has much higher strength than cast iron

Photo of an Al head with cast iron inserts

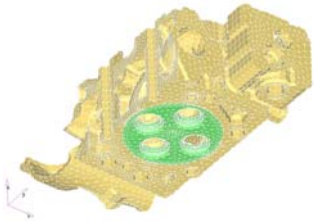


Cast Iron Insert

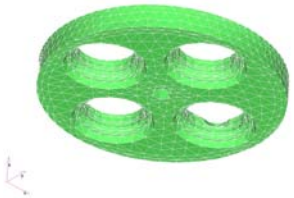
Head Insert Details

- Beryllium Copper alloy insert (C17200)
  - 12 mm thick (same as ISB fire deck in this region)
  - Integral machined valve seats as Beryllium Copper is a viable seat material

Head 'slice' Showing Insert

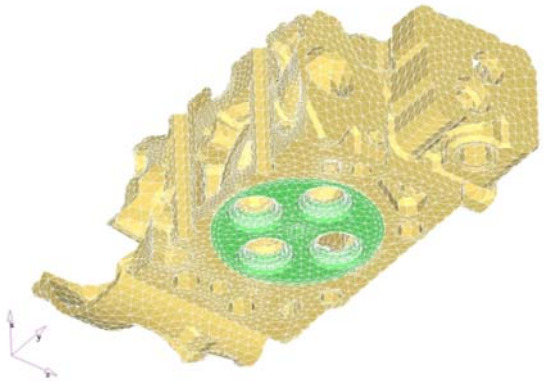


Cu Alloy Insert



Head Insert

- Single cylinder slice of model showing insert in place



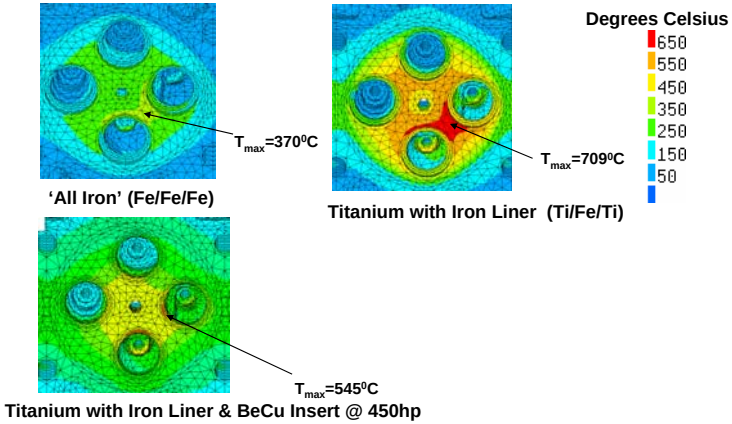
Head Insert

- Cutaway of single cylinder showing where insert breaks through into lower water jacket.

- It is assumed that technologies exist that would enable acceptable bonding and sealing of the insert to the cylinder head. The joint between the two materials has not been investigated. This analysis assumes the two materials are 'welded' together.

Technical Accomplishments/Progress/Results

Thermal Results - Titanium valve bridge area



'All Iron' (Fe/Fe/Fe)

Titanium with Iron Liner (Ti/Fe/Ti)

Titanium with Iron Liner & BeCu Insert @ 450hp

Conclusions (Ti)

- FEA modeling of a Cummins ISB engine has shown that employing cast Ti-6Al-4V for the head and block as a replacement for grey cast iron, is feasible as long as a high thermal conductivity, high elevated temperature strength insert is used to replace the Ti in the valve bridge regions of the fire deck of the engine head.
- FEA modeling has shown that by using cast Ti in place of grey cast iron while employing a Cu alloy insert in the valve bridge regions of the head, a diesel engine rated at 305 hp can be successfully up-rated to 450 hp while achieving an overall engine weight saving of 10%.

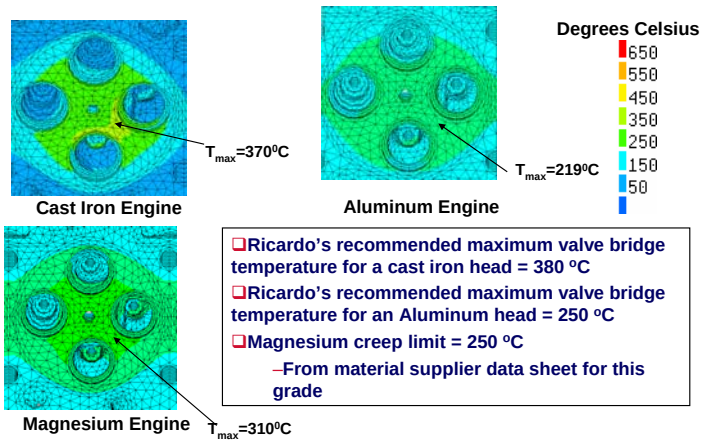
Technical Accomplishments/Progress/Results

- Al and Mg as Substitutes for Grey Cast Iron

- Al
  - A354-T6 is a high - performance Al-Si casting alloy containing about 2% Cu. It has excellent mechanical properties up to 250°C.
- Mg
  - WE-43-T6 is a high - performance Mg alloy containing rare earth elements. It has the highest temperature resistance of all Mg alloys and is recommended up to 250°C for long time exposures (creep).

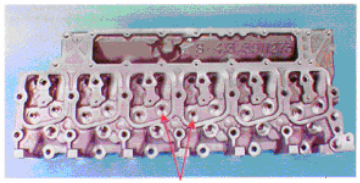
Thermal Results - Al & Mg (305 hp)

- Cylinder Head Valve Bridges

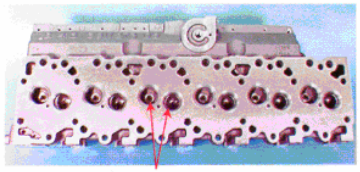


- ❑Ricardo's recommended maximum valve bridge temperature for a cast iron head = 380 ^{o}C
- ❑Ricardo's recommended maximum valve bridge temperature for an Aluminum head = 250 ^{o}C
- ❑Magnesium creep limit = 250 ^{o}C
  - –From material supplier data sheet for this grade

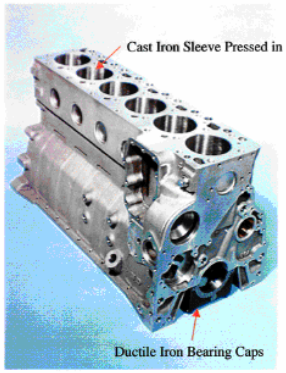
Aluminum Head & Block Photos



Pressed-in Valve Guides



Pressed-in Valve Seat Inserts



Conclusions (Al)

- FEA modeling of a Cummins ISB engine rated at 305 hp indicates that a substitution of Aluminum for Cast Iron is possible, providing for reduced engine mass. However, the head and block would require some design modifications, including:
  - Modified interference fits between seat inserts and head
  - Increased stiffness of the cylinder head top deck
  - Support of the Cast Iron liner
- Although cast Aluminum cylinder heads and blocks are commonplace in light duty automotive applications, their application in a heavy duty environment would require a determination of acceptable life targets, as Aluminum does not have a classical “knee” in the S-N curve.

Conclusions (Mg)

- The overall fatigue safety factors on the Magnesium head and block are improved compared to Gray Cast Iron.
  - Therefore, a direct substitution for Cast Iron could be made (casting issues, interference fits between seat inserts and head, Cast Iron liner and block aside) giving some durability increase and a significant weight reduction.
- However, due to the temperatures at the cylinder head exhaust valve bridges exceeding the material creep limit, Magnesium's creep behavior should be investigated under engine operating conditions.

Technical Accomplishments/ Progress/Results

- FEA modeling demonstrated that Ti is a feasible substitute for grey cast iron in the head and block castings allowing a diesel engine to be up-rated by 50% in hp and still achieve an 11% overall weight savings. – 04/05/2005
- FEA modeling has shown that it is feasible to replace cast iron in a diesel engine head and block with Al and achieve an overall engine weight saving of 20%. – 10/05/2004
- FEA modeling has shown that it is feasible to replace cast iron in a diesel engine head and block with Mg and achieve an overall weight saving of 33%. - 08/10/2004

Future Work

- Complete the modeling work and explore the potential of manufacturing and testing prototype engines.
  - Develop an experimental data base of mechanical and physical properties from castings of the 3 light weight materials modeled in the project.
  - From this data base make a determination whether:
    - The model's predictions, based on literature data are accurate.
    - Ti can be used in the as-cast and un-heat treated conditions for minimum cost.
    - The actual elevated temperature mechanical properties of the Mg and Al alloys selected for modeling are adequate for use in a heavy-duty diesel engine.
- Use the above developed data to determine how prototype engines can be made and tested.

Technology Transfer

- FEA study indicated feasibility
- Presentations have been made to OEMs, engine manufacturers, DOE and DOD technology managers.
  - Site visits.
  - Conferences.
- Testing of prototype engines required for commercialization.
  - Need to partner with an engine and/or a truck company to produce engines for testing.
    - Make necessary design changes to accommodate the new materials.
    - Partner with a casting foundry to produce head and block castings.
    - Perform machining studies in order to determine if and what bottlenecks need to be overcome and determine cost.
    - Test cell engine testing.
      - Measure the engine's stresses and temperatures and calibrate the FEA model.
      - Durability test the engines.

Publications, Presentations, Patents

- Invited Presenter
  - U.S. Army Tank Command (TACOM) – 03/12/2004
  - Cummins Engine Co. – 04/13/2004
  - Caterpillar, Inc. – 04/15/2004
  - “Ti Initiative”, conference sponsored by DARPA – 04/22/2004
  - “Advanced Materials Conference - Ship and Ground Vehicle Applications” – 02/01/2005
  - TACOM – 04/15/2005
  - Cummins Engine Co. – 04/25/2005
  - Caterpillar, Inc. – 04/27/2005