O. Applications of Titanium Alloys for Heavy-Duty Vehicles

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Objectives

- Determine if it is feasible to substitute a high-strength titanium (Ti) casting alloy for the heavier gray cast iron in a heavy-duty diesel engine head and block.
- Determine if it is feasible to substitute a high-strength aluminum (Al) casting alloy for the heavier gray cast iron in the same engine.
- Determine if it is feasible to substitute a high-strength magnesium (Mg) casting alloy for the heavier gray cast iron in the same engine.

Approach

- Use mechanical and physical property data for finite element analysis (FEA) to compute the temperatures, stresses and fatigue cover factors (safety factors) at various locations on the head and block of a 5.9L Cummins ISB engine, run at maximum designed power (305 hp), for three lightweight casting alloy systems.
- Compare these data to those computed for a production engine (all cast iron engine) to determine the feasibility of substituting any or all of these alloy systems for cast iron. (Ricardo, Inc. was contracted to conduct the FEA.) Note that fatigue analyses assumed that the engine was always stressed at the maximum for the life of the engine. In reality, this stress level is much higher than for typical duty cycles for this engine.

Accomplishments

- Determined the following through the FEA.
  - Cast Ti-6Al-4V can be used as a direct substitution for gray cast iron in the engine block without any design changes as long as a cast iron liner is used. Ti was far superior to cast iron from a fatigue perspective.
  - Cast Ti-6Al-4V can be used to replace cast iron in the engine head, but the valve bridge temperatures are too high (700°C); thus, without some design or materials changes, the head will not function well when made of Ti.
  - To preserve the weight reduction and superior strength benefits of Ti for the block, without any design changes, the analyses demonstrated that an engine having either a cast iron or an Al head (15% overall engine weight saving) in combination with a Ti block with cast iron liners is feasible.

— The use of a Be-Cu alloy insert in the valve bridge regions of the Ti head, in combination with up-rating the engine to 450 hp, was shown to be a feasible way of reducing the temperatures in this region. The superior mechanical properties of Ti would enable the engine to operate at a higher power rating while achieving lighter weight (11% overall engine weight saving). The Ti block had no problem withstanding the higher stresses created by the up-rating.

— A high-strength Al casting alloy, A354-T6, could be used as a substitute for gray cast iron in both the head and block of the engine running at 305 hp if a gray cast iron cylinder liner were used. This would result in a 20% overall engine weight saving. Since Al does not have a fatigue endurance limit, the use of Al would be duty-cycle limited.

— A high-strength Mg casting alloy, WE 43, could be used as a substitute for gray cast iron in both the head and block of the engine running at 305 hp if a gray cast iron cylinder liner were used. This would result in an overall engine weight saving of 33%.

— Although the head temperature at the valve bridges is about 50°C higher than the recommended maximum for WE 43, it is considered a feasible substitute for gray cast iron if design changes are made to lower the temperature.

Future Direction

- Seek funding from either a major diesel engine manufacturer or a major customer to construct and test engines. A potential customer is the Department of Defense, since there is a strong desire to reduce the weight and/or increase the power of engines in military vehicles.

Introduction

Many programs are focused on reducing the cost of Ti powder and ingot by 50%. If any of these programs reaches this target, the cost of Ti might be become attractive enough for use in heavy duty diesel engines for certain applications where weight reduction is critical. In addition, there is a desire on the part of the military both to reduce the weight of transportation and to reduce the magnetic signature. This project explores the feasibility of replacing the cast iron in diesel engine heads and blocks with Ti, which is about 40% lighter than cast iron and is nonmagnetic. Using a Ti-6Al-4V casting alloy in place of gray cast iron in just these two components could save hundreds of pounds of weight, depending on the size of the engine. In addition, because of its superior strength and fatigue properties compared with cast iron, Ti affords the opportunity to upgrade the power of the engine without extensive design changes. It is recognized that Ti has some few disadvantages compared with cast iron, including lower thermal conductivity, poorer machineability, and higher cost.

The approach used with Ti was also used to model the same engine with either an aluminum or a magnesium casting alloy. Thus this project studied the application of the three major lightweight metals systems to determine if it were feasible to replace gray cast iron in the engine head and block with alloys of one or all of these metals.

Table 1 shows the weight savings that can be achieved when Ti, Al, or Mg is used to replace gray cast iron in a Cummins ISB 5.9-L diesel engine.

Table 1. Weight savings produced by replacing cast iron with cast lightweight alloys in a Cummins ISB diesel engine (total engine wt. of about 1000 lbs)

Material	Wt. saving (lb)
Ti-6-4 head and block	147
Ti-6-4 head and block with Cu inserts and cast iron (CI) liners	107
Al(A354) head and Ti block with CI liners	149
Al head and Al block with CI liners	200
Mg (WE43) head and block with CI liners	335

Note: The liners weigh 7 lb each; the Cu inserts weigh 1.5 lb each.

Results

Ti Alloy Feasibility Study

This project employed FEA to model a Cummins 5.9-L, B-series diesel engine running at 305 hp. The temperatures and stresses were computed at various locations on the head and block castings for both the cast iron currently used and the Ti-6-4 alloy. Since the production engine is a parent bore engine (no cylinder liners), cast iron liners were incorporated into the model when evaluating the engine made with lightweight alloys. Based on the modeling and a comparison of the two materials, the feasibility of using Ti-6-4 in place of gray cast iron was determined. The modeling work was contracted to Ricardo, Inc. which has in-house the model for this engine and the experience to perform the necessary computer operations and interpret the results.

As a result of the initial modeling, additional modeling iterations were needed to obtain the optimum combination of materials for the head and block. For example, a cast iron head or an Al head coupled with a Ti block was modeled. Even a copper alloy insert to the valve bridges of the Ti head was modeled in conjunction with up-rating of the engine. Table 2 compares Ti with gray cast iron in terms of major advantages and disadvantages.

Figures 1 and 2 show the FEA model summary and block mesh; Table 3 shows the engine operating conditions.

Tables 4 and 5 show the materials properties of gray cast iron and Ti-6Al-4V, respectively. Table 6 shows the thermal conductivity data for gray cast iron, Ti, and Al. It is obvious that Ti has a much lower conductivity than the other two materials, and Al has very high thermal conductivity.

The temperatures in the flame face of the head were computed for the all cast iron engine (production engine), labeled Fe/Fe/Fe, and for three alternatives. The first was an iron head on a Ti block with a cast iron liner (Ti/Fe/Fe); the second was a Ti head on a Ti block having a cast iron liner (Ti/Fe/Ti); the third was an Al head on a Ti block having a cast iron liner (Ti/Fe/Al). As can be seen from Figure 3, the temperatures in the valve bridge areas of the Ti head are high (709°C). The temperatures in the same location on the three other combinations are low enough not to cause problems. The temperatures in the other parts of the head were considered low enough in all the combinations that they posed no problem. Figure 4 shows the temperature determina-

Table 2. Advantages and disadvantages of using Ti in place of gray cast iron

Advantages of Ti	Disadvantages of Ti
1. Weight savings —Cummins B-Series • 100 lb saving from the machined block • 47 lb saving from the whole engine. (total dry wt. of 1036 lb) • 14% weight saving from the whole engine (total dry wt. of 1036 lb)	1. Cost —Ti is about $10/lb and must be vacuum investment cast - Gray CI <$ 0.20/lb. and is green sand cast in air
2. Performance (room temp) • UTS of TI-6-4:125 ksi • UTS of grey cast iron (CI): 28 ksi • Fat. Str. of CI: 10 ksi • E for Ti-6-4: 17 msi • E for CI: 15 msi	2. Machinability —Ti has much lower throughput and much higher tool wear
3. Non-magnetic	3. NVH attenuation
	4. Thermal conductivity (300°C) —K_{CI}: 49 W/m-k —K_{Ti}: 12 W/m-k

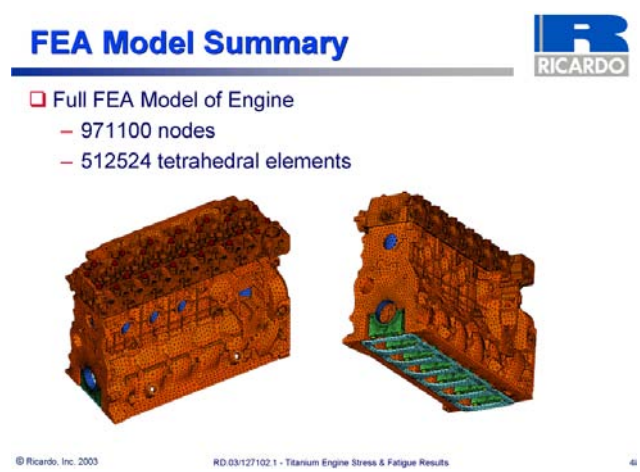

Figure 1. FEA model summary.

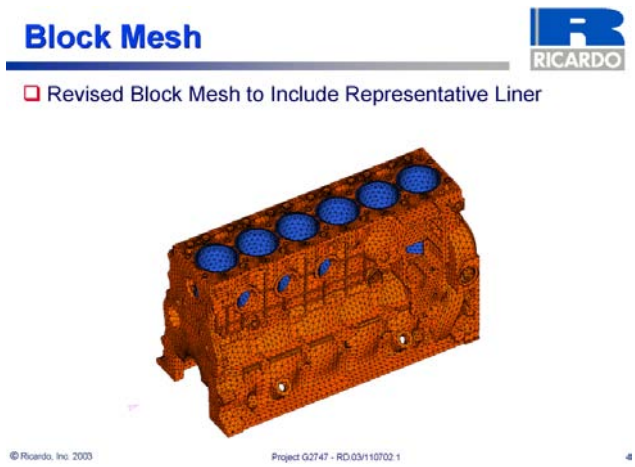

Figure 2. Block mesh.

Table 3. Engine operating conditions for the purpose of modeling

Number of cylinders	6
Engine displacement	5.59L
Rated speed	2900 rpm
Rated power	305 hp
Cylinder pressure	160 bar

Table 4. Materials properties of gray cast iron used in the Cummins engine

Block – gray cast iron —data supplied by Cummins
- —Young's modulus = 103.4 GPa
- —Poisson's ratio = 0.25
- —Ultimate tensile strength = 189.6 MPa
- —Tensile yield strength = 136.5 MPa
- —Compressive yield strength = 284.4 MPa
- —Fatigue strength = 72.39 MPa

Head – gray cast iron– data supplied by Cummins
- —Young's modulus = 103.4 GPa
- —Poisson's ratio = 0.25
- —Ultimate tensile strength = 206.8 MPa
- —Tensile yield strength = 148.9 MPa
- —Compressive yield strength = 317.2 MPa
- —Fatigue strength = 110.3 MPa

tions for the tops of the liners in the engine block, determined for the same material combinations.

Table 7 summarizes the temperatures in the key locations on the head and block for the four head and block material combinations.

Figure 5 shows how the fatigue calculations were predicted based on modified Goodman diagrams and where on the diagram the cover factors (safety margins) are determined. Fatigue cover factor is defined as the ratio of the length of the line from (0,0) through (δ_m, δ_a) to the point where it intersects the boundary of the safe working area, to the length of the line from (0,) to (δ_m, δ_a). The factor will be greater than 1 for points within the safe working area, and less than 1 everywhere else. Ricardo's acceptable cover factor for this type of application is 1.5 or greater.

Table 5. Mechanical properties of Ti-6Al-4V used in this study

Comparison of mechanical properties of Ti-6AI-4V from the literature vs. values used in this study

	Literature	
	(Crucible steel)	
Temp (°C)	UTS (Mpa)	Y.S. (Mpa)
21	1063	973
315	814	725
538	635	531
	This study	
	(Mil Handbook 5, annealed, HIPed castings)	
Temp.(°C)	UTS ,(Mpa)	Y.S. (Mpa)
21	862	820
315	608	502
538	431	362

Table 6. Thermal conductivity of gray cast iron, Al and Ti at various temperatures

Temperature-dependent conductivity
Aluminum data supplied by Cummins

	K (W/m-K)		
Temperature (°C)	Cast iron	Titanium (Ti6AI4V)	Aluminum (A354T6)
–18		6.7	
21			168.8
27		7.3	
38		7.4	
50			170.9
93		7.6	
100	48.8		175.5
149		8.1	
150			177.6
200	47.8		179.3
204		8.7	
260		9.6	180.8
300	46.8		
316		10.4	
371		11.2	
400	45.8		
427		11.9	
482		12.7	
50	44.8		
538	13.5		

Table 7. Temperatures at key locations in the head and block for four material combinations

Summary of temperatures @ areas of interest All temperature in degrees centigrade					
	From previous iterations		1	2	3
Location	All iron	All titanium	Ti block Fe liner Fe head	Ti block Fe liner Fe head	Ti block Fe liner Fe head
Top of block	227	410	228	287	194
Top of liner	-	-	248	289	214
Cylinder head exhaust valve bridge	370	710	381	709	220
Intake valve seat	357	550	360	551	249
Exhaust valve seat	444	741	455	741	326

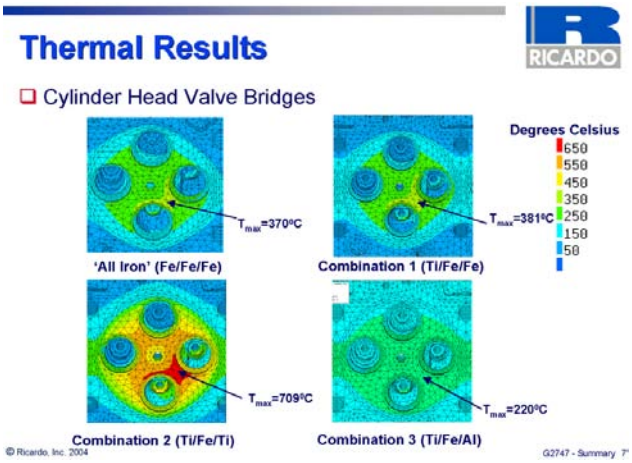

Figure 3. The computed flame face temperatures of the engine head for four head and block material combinations.

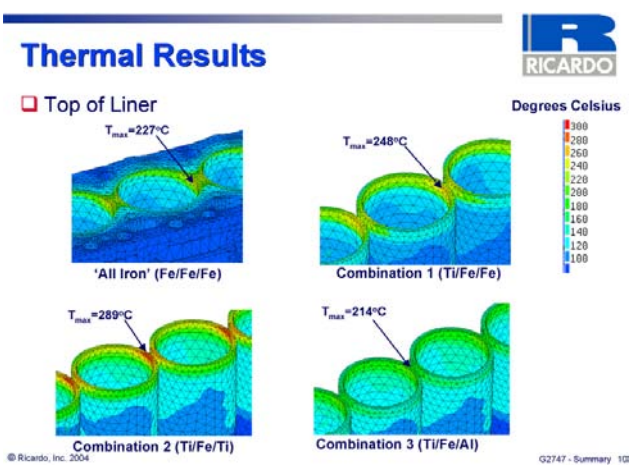

Figure 4. The computed temperatures for the tops of the cast iron liners for four head and block material combinations.

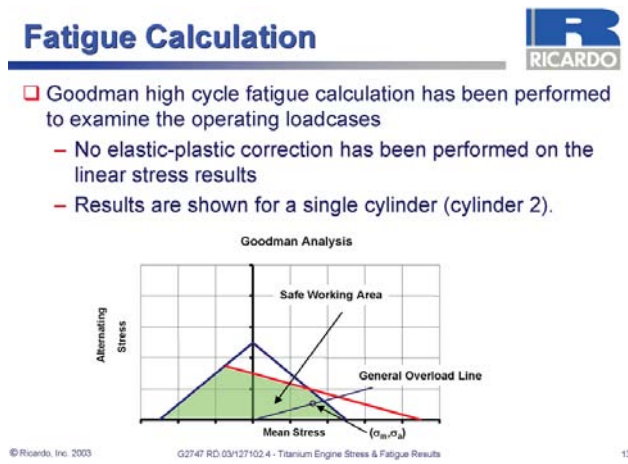

Figure 5. Goodman high cycle fatigue calculations.

Table 8 shows a summary of the computed stresses and fatigue cover factors for the cast iron head from the production engine and for the Ti head on a Ti block with a cast iron liner. The table shows many key locations on the heads.

It can be seen from Table 8 that the Ti head has more fatigue resistance than the cast iron head of the production engine in all of the key locations of the head, and that there are many locations on the production engine head that have a cover factor of less than 1. Even with the low cover factors, the production engine survives in service with a high degree of reliability. This is because, in this study, the analyses assumed that the components see only the maximum operating conditions. In real life, the engine does not operate at this maximum all the time. Thus the stresses are lower for a large portion of the duty cycle of the engine. This study can be considered a worst-case scenario.

Table 8. Computed stresses and fatigue cover factors in the head for the combinations Fe/Fe/Fe and Ti/Fe/Ti

			Cast iron							Titanium
Location	(lwj = lower water jacket) (uwj – upper water jacket) Description	Node #	Minimum stress (N/m^2)		Maximum stress (N/m^2)		Mean stress (N/m2	Alternating stress (N/m2)	Fatigue cover factor	Fatigue cover factor
A	uwj fillet between bolt box and valve guide	3759825	Cyl 5	156.3E+6	Cyl 2	279.3E+6	217.8E+6	61.5E+6	0.53	1.62
B	lwj floor fillet between exh. Port and inj. bore	3785105	Cyl 5	221.6E+6	Cyl 2	242.4E+6	232.0E+6	10.4E+6	0.61	1.22
C	lwj floor fillet to exhaust port	3783535	Cyl 5	202.5E+6	Cyl 1	228.7E+6	215.6E+6	13.1E+6	0.65	1.23
D	lwj roof fillet to head bolt boss	3784266	Cyl 1	107.2E+6	Cyl 2	219.1E+6	163.2E+6	56.0E+6	0.68	2.37
E	uwj rof fillet to head bolt boss	3759206	Cyl 6	121.4E+6	Cyl 2	217.0E+6	169.2E+6	47.8E+6	0.69	2.26
F	lwj floor fillet to exhaust port	3780615	Cyl 3	136.0E+6	Cyl 2	207.4E+6	171.7E+6	35.7E+6	0.72	1.72
G	intake port to valve seat area	3879902	Cyl 2	190.5E+6	Cyl 1	206.8E+6	198.7E+6	8.2E+6	0.72	2.07
H	lwj roof fillet to head bolt boss	3776708	Cyl 3	186.1E+6	Cyl 2	198.8E+6	192.5E+6	6.4E+6	0.75	1.68
I	exterior on exhaust side near flame deck	3793591	Cyl 2	160.2E+6	Cyl 1	184.2E+6	172.2E+6	12.0E+6	0.81	2.44
J	uwj roof fillet to head bolt boss	3777863	Cyl 1	109.2E+6	Cyl 2	181.1E+6	145.2E+6	36.0E+6	0.82	2.90
K	uwj roof fillet to head bolt boss	3779640	Cyl 6	123.3E+6	Cyl 2	174.0E+6	148.7E+6	25.4E+6	0.86	2.66
L	lwj roof fillet to head bolt boss	3775260	Cyl 1	108.7E+6	Cyl 2	170.1E+6	139.4E+6	30.7E+6	0.88	2.27
M	uwj fillet between head bolt boss exhaust port	3780476	Cyl 1	132.2E+6	Cyl 3	169.8E+6	151.0E+6	18.8E+6	0.88	2.83
N	exterior pocket @ top deck near bolt boss	3791833	Cyl3	89.8E+6	Cyl 2	161.7E+6	125.7E+6	36.0E+6	0.92	3.10
O	uwj roof fillet to top deck	3779648	Cyl 6	141.8E+6	Cyl 2	160.3E+6	151.1E+6	9.3E+6	0.93	3.10
P	lwj fillet – valve guide to fuel drilling	3787973	Cyl 6	113.8E+6	Cyl 3	158.4E+6	136.1E+6	22.3E+6	0.94	2.80
Q	top deck rib between guides	3783137	Cyl 6	85.9E+6	Cyl 2	158.4E+6	122.2E+6	36.2E+6	0.94	3.60
R	lwj floor between exh. Ports and inj, bore	3785319	Cyl 2	107.9E+6	Cyl 3	156.9E+6	132.4E+6	24.5E+6	0.95	1.47
S	top deck exterior	3783291	Cyl 6	115.6E+6	Cyl 2	156.7E+6	136.2E+6	20.6E+6	0.95	3.25
T	exterior pocket @ top deck near head bolt boss	3792836	Cyl 1	112.2E+6	Cyl 2	155.3E+6	133.8E+6	21.6E+6	0.96	2.75
U	uwj roof to coolant hole	3778568	Cyl 5	110.5E+6	Cyl 2	155.2E+6	132.9E+6	22.4E+6	0.96	3.60
V	lwj fillet – exh. guide to exh. port	3780566	Cyl 5	85.0E+6	Cyl 2	151.4E+6	118.2E+6	33.2E+6	0.98	2.50
W	lwj floor fillet to exhaust port	3776526	Cyl 3	129.3E+6	Cyl 2	150.2E+6	139.8E+6	10.5E+6	0.99	1.66

Figure 6 shows the results of the fatigue analyses of the block in cast iron and Ti, and Table 9 summarizes the results of the fatigue prediction study for various locations on the block for both cast iron and Ti. As can be seen, there is only one small location on the block with a low cover factor for both materials, although the Ti value is more than four times that of the cast iron. This location is so small that it should be easy to increase the cover factor by adding some material in that location in the casting.

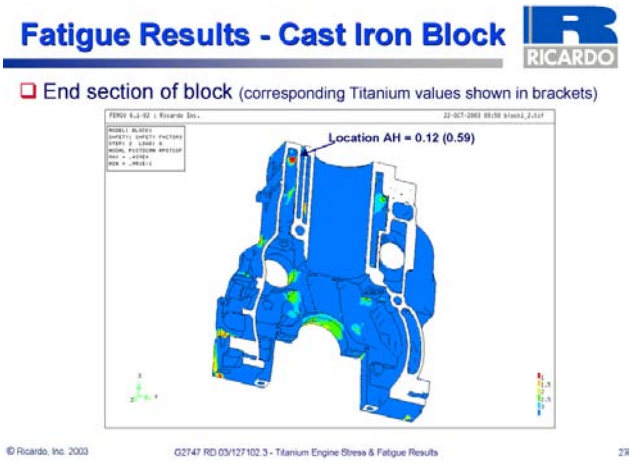

Figure 6. Description of fatigue cover factors (safety factors).

One approach for dealing with the unacceptably high temperatures in the valve bridge regions is to replace the whole head with either cast iron or Al. In the former case, the only weight saving would be from using Ti for the block. In the latter case, a further weight saving would be achieved because Al is 57% lighter than Ti but less durable at high temperatures and fatigue stresses. Another approach, which would preserve the advantages of Ti, would be to make the head of Ti but replace the valve bridge regions with an insert of a material that has a high thermal conductivity and high elevated temperature strength.

To this end, a literature study was conducted of materials of known high thermal conductivity and high strength. A copper alloy was considered to be the best candidate insert material. The insert design in the valve bridge region of the head was therefore modeled by FEA; but at the same time, the engine was up-rated to 450 hp to see if the superior mechanical properties of Ti-6-4 would enable the engine to be rated at a much higher horsepower than current production engines. Figure 7 illustrates the concept. It shows an Al head with cast iron inserts showing where the copper alloy insert would be located.

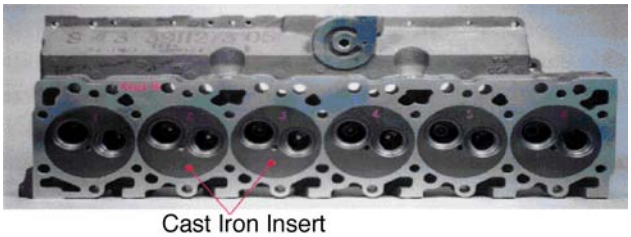

Figure 7. The FEA model of one cylinder of the block showing the only location that has a low cover factor for both materials studied

To determine if the insert strategy described was feasible, the physical and mechanical properties of a 2% Be-Cu alloy were used. Figure 8 shows a graph of ultimate tensile strength vs. temperature for Ti-6Al-4V, A354-T6, 2% Be-Cu, and gray cast iron. The 2% Be-Cu alloy has excellent elevated temperature strength and exceeds or equals Ti up to about 350°C. The thermal conductivities of the four key alloys shown in Figure 8 are shown in Figure 9. The design of the BE-Cu insert is shown in Figure 10.

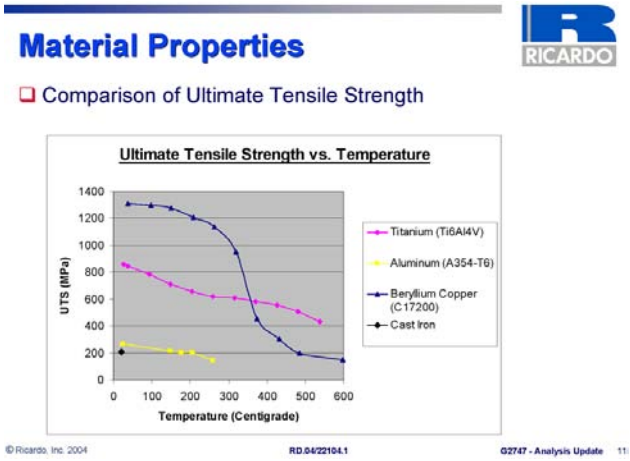

Figure 8. Photo of an Al engine showing cast iron inserts in the fire deck as a way of showing how a Cu alloy insert would be placed in a Ti head. The actual engine has four valves instead of the two shown here.

Table 9. Summary of the computed stresses and fatigue cover factors for the cast iron and the Ti blocks

			Cast iron							Titanium
Location	Description	Node #	Minimum stress (N/m^2)		Maximum stress (N/m^2)		Mean stress (N/m2	Alternating stress (N/m2)	Fatigue cover factor	Fatigue cover factor
AH	interior fillet to top deck @ end face	6187310	Cyl 1	758.0E+6	Cyl 4	1.1E+9	944.0E+6	186.0E+6	0.12	0.59
AI	oil hole edge to brg. shell	6468000	Cyl 1	130.0E+6	Cyl 6	206.0E+6	168.0E+6	38.0E+6	0.66	2.75
AJ	corner of side inlet to water jacket	6215232	Cyl 6	17.1E+6	Cyl 2	129.0E+6	73.1E+6	56.0#+6	0.87	3.76
AK	internal fillet to head bolt boss	6173813	Cyl 3	70.7E+6	Cyl 1	149.0E+6	109.9E+6	39.2E+6	0.89	3.53
AL	corner of side inlet to water jacket	6214185	Cyl 5	70.8E+6	Cyl 1	139.0E+6	104.9E+6	34.1E+6	0.98	3.54
AM	‘liner’ to top deck	6166821	Cyl 3	107.0E+6	Cyl 1	139.0E+6	123.0E+6	16.0E+6	0.98	2.86

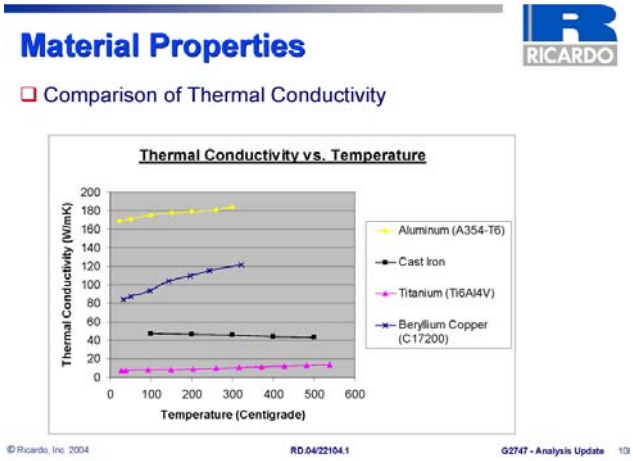

Figure 9. Ultimate tensile strength vs. temperature for four key diesel engine head and block alloys.

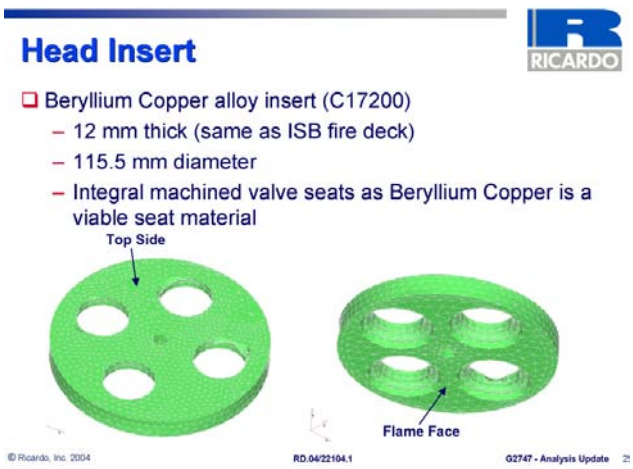

Figure 10. Thermal conductivity vs. temperature for four alloys.

Figure 11 shows the location of the insert in the flame face.

The FEA model was modified so that part of the back face of the insert makes direct contact with the coolant (Figure 12).

The engine with the Be-Cu insert was modeled with the engine up-rated to 450 hp from the standard 305 hp. This means that the peak cylinder pressure was increased from 2320 to 3191 psi. The block model showed that the Ti-6Al-4V alloy allowed the block to function acceptably at the new rating. The head temperatures were reduced in valve bridge regions from 709°C at 305 hp to 545°C at 450 hp (Figure 13). The temperature in the region of the valve seats is still about 50°C too high, but considering that this model assumes that the engine is run-

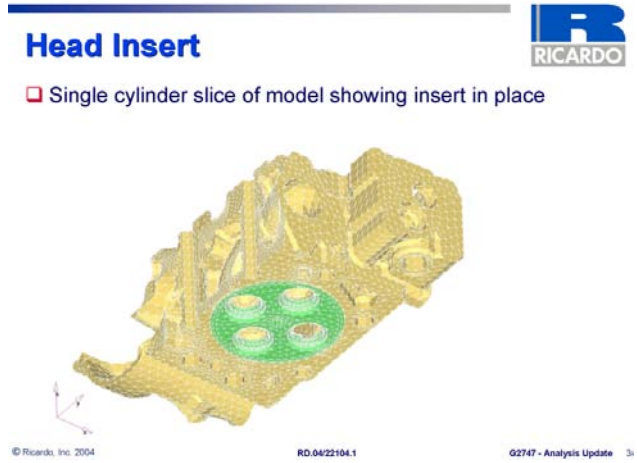

Figure 11. Solid model of the Be-Cu flame face insert.

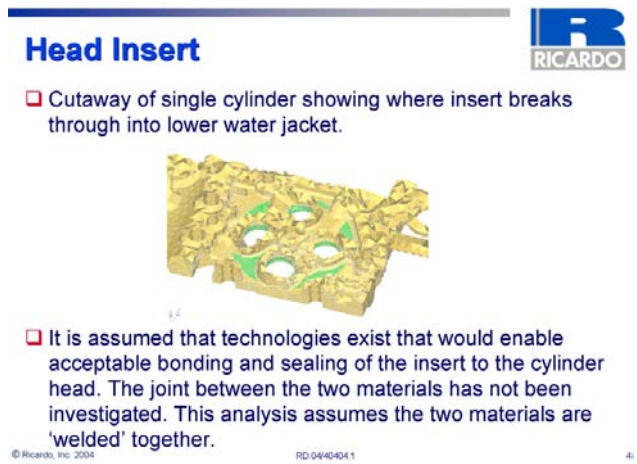

Figure 12. Location of the insert in the flame face.

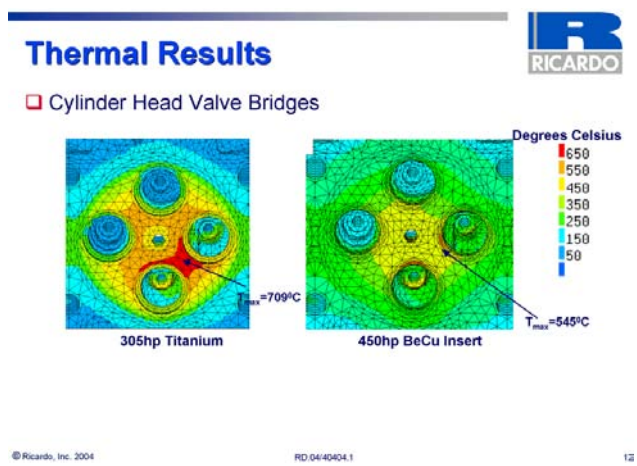

Figure 13. Model of the back face of the insert showing where the insert makes direct contact with the coolant (darker gray).

ning at 450 hp all the time, this temperature is considered acceptable from a feasibility standpoint.

Up-rated engine parameters:

- Maximum cylinder pressure increased from 160 to 220 bar (3191 psi). This was the only parameter changed.
  - Power increased by 48% to 450 hp (current ISB—305 hp)
  - All other engine operating conditions unchanged
- Speed: 2900 rpm
- AFR: 24.4:1
- Compression ratio: 17:1
  - Flame face thermal boundary conditions have been modified to account for material changes. However, the baseline coolant side boundary conditions (obtained from computational fluid dynamics analysis at 305 hp) are unchanged because the coolant flow remains the same as a result of the engine speed.

Figure 14 shows a graph of the thermal expansion coefficients vs. temperature of the Ti alloy and the Be-Cu alloy. Note that the level Be-Cu is more than an order of magnitude greater than the Ti alloy. This leads to a high stresses at the interface between the Ti and the insert, as shown in Figures 15 and 16.

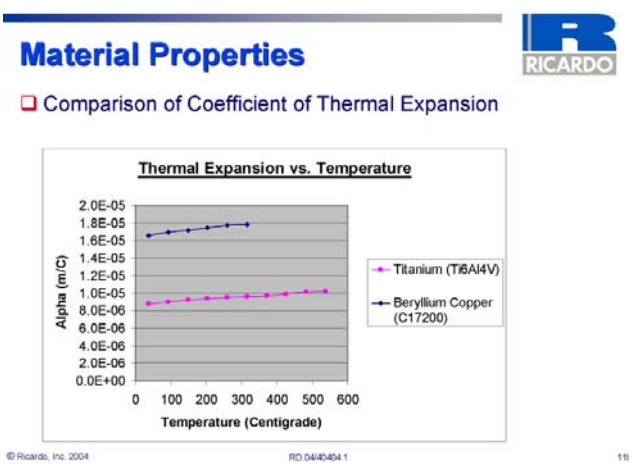

Figure 14. Description of up-rated engine parameters.

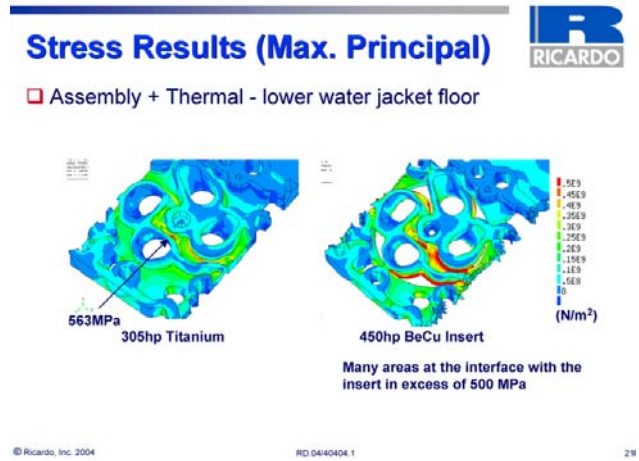

Figure 15. FEA model of the temperature distribution in the valve bridge area of the flame face for the Ti head rated at 305 hp and the Ti head with a Be-Cu insert.

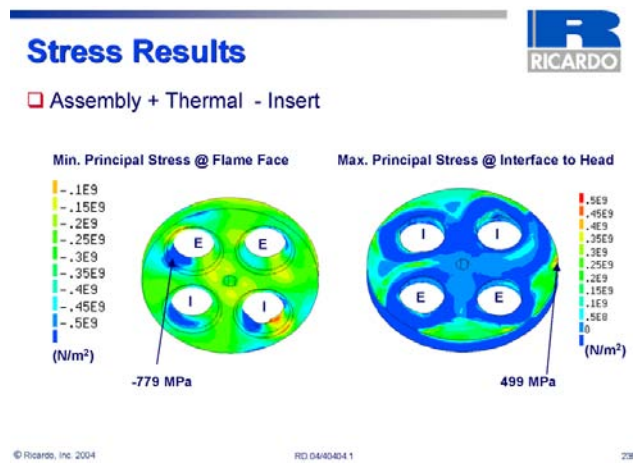

Figure 16. Coefficient of thermal expansion vs. temperature for Ti and Be-Cu.

The thermal results for the top of the block cylinder are shown in Figure 17. This region is the only location where the temperatures get high enough to be of concern.

Thermal Results Summary

- Using Ti-6Al-4V to replace cast iron in the engine block is feasible.
- Using Ti-6Al-4V to replace cast iron in the head poses some problems associated with the poor thermal conductivity of Ti compared with gray cast iron.

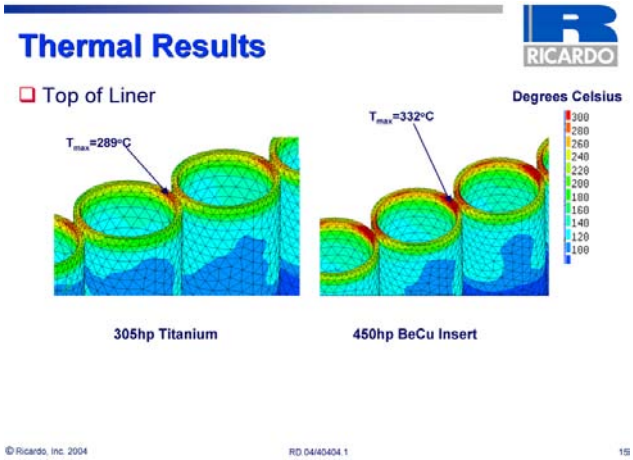

Figure 17. FEA model of the Ti alloy lower water jacket showing the principal stresses generated at the interface between the back face of the insert and the Ti as a result of the differences in thermal expansion coefficients of the two materials.

  - The valve bridge regions of the fire deck get to about 700°C, which is too high for acceptable durability.
  - The valve seats see too high a temperature for durable use.

- To take advantage of the Ti alloy's favorable properties for the block (lower weight and higher strength), the engine could be constructed with a Ti block and either a gray cast iron head or an aluminum head. This leads to the following limitations:
  - The weight advantages of using Ti for the engine are limited if a cast iron head is used.
  - A larger weight saving can be achieved by using Al for the head, but durability may be limited.

A novel approach to solving the high temperatures in the head of the "all Ti engine" was proposed: using a high-thermal-conductivity alloy as an insert in the valve bridge regions.

  - A 2% Be-Cu alloy was selected as the insert material for the purpose of FEA modeling.
  - Rather than model the insert at the normal 305 hp rating, the insert was modeled in an engine that was up-rated to 450 hp. This was done to determine if the use of Ti would allow engines normally designed for cast iron to be used at higher power ratings.

- The Be-Cu alloy insert resulted in a valve bridge temperature of 545°C when the engine was run at 450 hp (3190 psi peak cylinder pressure). Since this modeling run assumed that the engine was run at these values for its whole life, which is not the normal way an engine is used, it is concluded that the insert strategy is feasible for an up-rated Ti engine. Note that it is possible that increased coolant flow and some design changes may be needed to guarantee the durability of the engine.
- Owing to the large difference in the coefficients of thermal expansion of the Be-Cu and Ti alloys, large stresses are generated at the interface between the insert and the Ti lower water jacket.

Conclusions

- FEA modeling of stress, fatigue, and temperature shows that cast Ti–6Al-4V is a feasible replacement for gray cast iron in heavy-duty diesel engine blocks with cast iron liners, whether the engine is rated at the normal (305 hp) or a 50% higher level (450 hp).
- FEA modeling of stress, fatigue, and temperature shows that cast Ti–6Al-4V is a feasible replacement for gray cast iron in heavy-duty diesel engine heads rated at 305 hp if the high valve bridge temperatures can be overcome.
- FEA modeling shows that using a cast iron head or an Al head in conjunction with a Ti block is a feasible way of taking advantage of the high strength of Ti for the blocks without concern for high temperatures in the head for an engine rated at 305 hp. However, if a gray cast iron head is used, there will not be much of weight saving for the engine. If the head is made from Al, a great weight saving can be achieved, since Al is 54% lighter than Ti.
- FEA modeling shows that if a 2% Be-Cu insert is used to replace Ti in the valve bridge regions in the flame face for an engine that was up-rated by 50% (450 hp), the high temperatures in the flame face are reduced substantially, and it is feasible to use it at high power ratings.
- The high stresses generated at the interface between the insert and the Ti lower water jacket, caused by the differences in coefficients of

thermal expansion, can be overcome by some design changes.

Aluminum and Magnesium Feasibility Study

Aluminum

The FEA modeling for these studies was for the engine rated at 305 hp, which is the maximum for the production engine.

Thermal analysis

Table 10 provides the mechanical and physical properties of gray cast iron and the aluminum alloy, A354-T6 used in this modeling study.

Figure 18 shows the calculated temperatures in the valve bridge region of the fire deck for the production cast iron engine and for the engine having an Al head and block. Owing to the very high thermal conductivity of Al, the maximum temperature in the valve bridge region is only slightly above 200°C, well below Ricardo's recommendation for maximum temperature in this region. Figure 19 shows the calculated temperatures for the top of the engine block for both the cast iron production engine (parent bore) and the Al engine. Again, the temperatures at the top of the Al block are well below any level of concern.

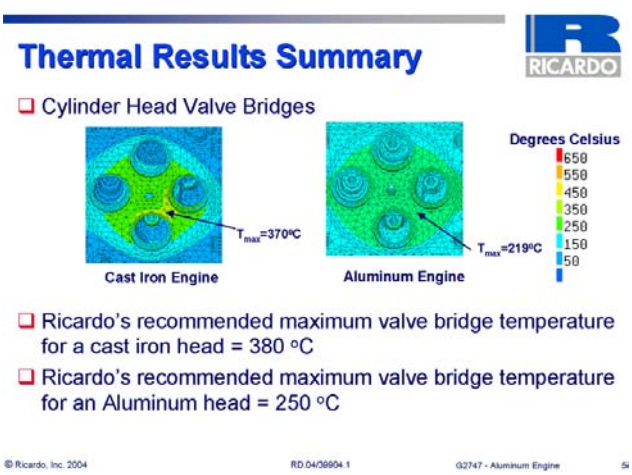

Figure 18. FEA model of the Be-Cu insert showing the stresses generated in the Be-Cu insert caused by the differences in thermal expansion coefficients between the Ti alloy head and the insert when the engine is run at 450 hp.

Table 11 shows a summary of temperatures at key locations in the head and block for cast iron and

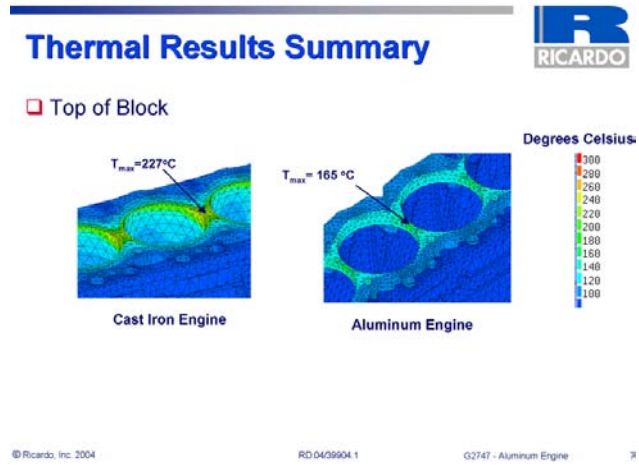

Figure 19. Computed temperatures at the top of the cylinder liner for the Ti engine rated at 305 hp and at 450 hp.

Table 11. Computed temperatures at key locations in the head and block for cast iron and aluminum

Location	All-cast-iron engine	All-aluminum engine
Top of block	227	165
Top of liner	230	192
Cylinder head exhaust valve bridge	370	210
Intake valve seat	357	249
Exhaust valve seat	444	325

Al. FEA modeling of high cycle fatigue was performed on the Al head and block and compared with modeling for cast iron. Figure 20 shows an example of the model for cover factors (safety margin) greater than 1 (no failure). It can be seen that the aluminum compares very favorably with the cast iron.

FEA modeling of fatigue was performed for the block. The cover factors at key locations on the aluminum block were compared with those locations on the cast iron production block (see Table 12). With the exception of one location, the cover factors for the aluminum block were equal to or greater than those for the cast iron block. The one exception is the region from the bearing saddle to the block fillet (location AJ), shown in Figure 21. The cover factor in this region can easily be increased by making the fillet region thicker. The higher fatigue cover factors of Al compared with cast iron are caused by lower temperatures, lower thermal stresses, and the higher strength of aluminum. The low cover factors near the head bolt bosses are caused by high compressive

Table 10. Mechanical and physical properties of gray cast iron and A354-T6

Gray cast iron (liner insert)

Temperature (Centi-grade)	Young's modulus (GPa)	Poisson's ratio	Thermal conduc-tivity (Wm-K0	Thermal expan-sion (μm/m-C)	Ultimate tensile strength (MPa)	Compressive yield strength (MPa)	Tensile yield strength (MPa)	Fatigue strength (MPa)
20.0	117.2	0.25	48.80	1.10E-05	189.6	284.4	136.5	72.4
200.0			47.80	1.10E-05				
300.0			46.80					
400.0			45.80	1.25E-05				
500.0			44.80					

Aluminum (A3540-T6) – Data supplied by Cummins, Inc.

Temperature (Centi-grade)	Young's modulus (GPa)	Poisson's ratio	Thermal conduc-tivity (Wm-K0	Thermal expan-sion (μm/m-C)	Ultimate tensile strength (MPa)	Compressive yield strength (MPa)	Tensile yield strength (MPa)	Fatigue strength (MPa)
20.0	76.1	0.33	168.80	2.03E-05	265.2	233.8	241.3	95.5
50.0			170.90					
100.0			175.50	2.09E-05				
150.0	62.1	0.33	177.60		213.3	216.7	205.0	76.8
175.0	65.6	0.33			204.1	212.6	201.7	73.5
200.0	66.7	0.33	179.80	2.16E-05	202.5	215.6	199.1	72.9
260.0	54.5	0.33	180.80		142.7	142.2	142.7	51.4
300.0				2.24E-05				

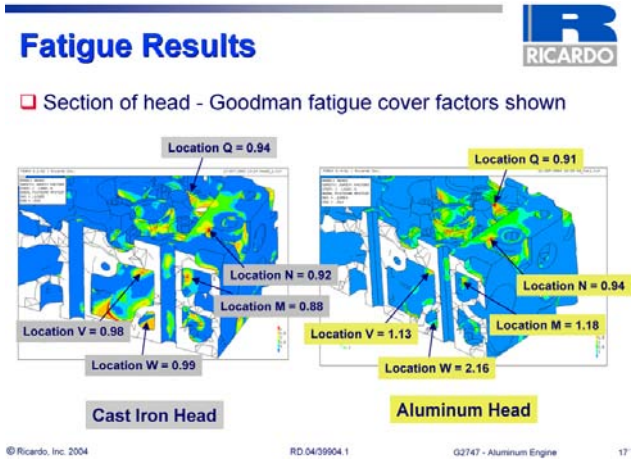

Figure 20. FEA model of temperatures in the valve bridge region of the fire deck for the production cast iron engine and the Al engine.

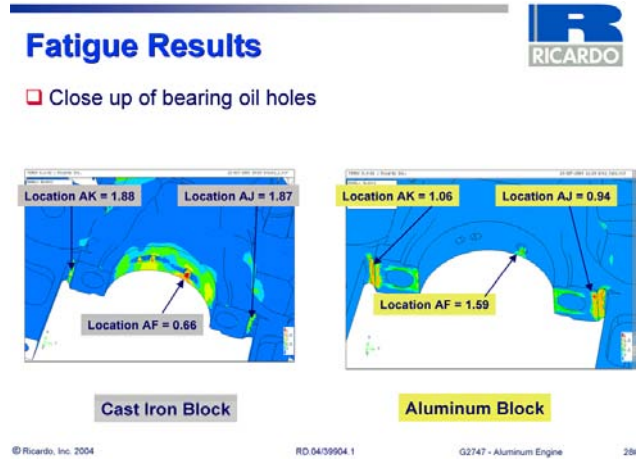

Figure 21. FEA calculations of temperature at the top of the engine block for the cast iron production engine and for the Al block.

Table 12. Fatigue cover factors at key locations of the cast iron and aluminum blocks

		Cast iron	Aluminum
Location	Description	Fatigue cover factor	Fatigue cover factor
AE*	interior fillet to top deck @ end face	0.12	0.13
AF	oil hole edge to brg. shell	0.66	1.59
AG	corner of side inlet to water jacket	0.87	1.04
AH	internal fillet to head bolt boss	0.89	0.89
AI	corner of side inlet to water jacket	0.98	1.26
AJ	Bearing saddle to block fillet	1.87	0.94
AK	Bearing saddle to block fillet	1.88	1.06

*Model geometry found not to be representative of actual casting

stresses induced by bolt loads. Washers under the bolt heads to reduce embedment are a possible solution to this issue.

Conclusions

- Aluminum can be a viable substitute for cast iron in this and many other diesel engines, resulting in at least an overall engine mass reduction of about 20%.
- Some design changes would be needed for the Al engine to
  - — support the cast iron liner
  - — increase the stiffness of the cylinder head top deck
  - — modify the interference fits between valve seat inserts and the head
- Since Al has no fatigue endurance limit, it would be prudent to determine acceptable life targets so as not to have cracking after many miles or hours of use.

Magnesium

An FEA study of Mg, identical to the one for Al, was conducted to determine if Mg is a feasible replacement for cast iron in heavy duty diesel engine heads and blocks. The FEA analysis was performed on the same Cummins ISB engine at 305 hp, but with cast iron cylinder liners.

From previous analyses, it was considered important that a Mg alloy be selected that had maximum elevated temperature properties. A high-performance Mg casting alloy, WE-43, was selected for the study. Table 13 contains the composition of the alloy along with T-6 heat treatment details.

Table 13. Composition and heat treatment of WE-43 Mg alloy

• Composition • Yttrium 3.7 – 4.3 - Rare Earths (Ce,La,Nd) - 2.4 – 4.4 - Zirconium 0.4 min.	• Optimum heat treatment - Solution treat for 8 h at 525°C. - Air cool, hot water or polymer quench. - Age for 16 h at 250°C, air cool

Table 14 shows a comparison between the mechanical and physical properties of cast iron and WE-43, while Figure 22 is a graph of the thermal conductivities of cast iron and WE-43 vs. temperature.

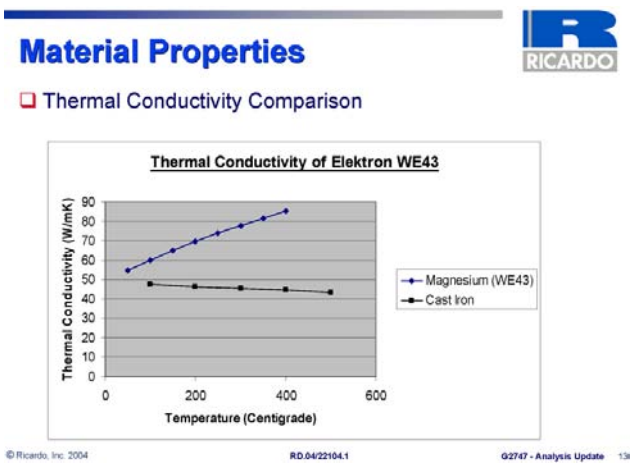

Figure 22. FEA model of the cast iron and aluminum heads showing fatigue cover factors in key locations.

The FEA of the valve bridge region of the head is shown in Figure 23 for production cast iron and for WE-43. It can be seen that although the temperature of the valve bridge region in the Mg head is lower than for the gray cast iron, it is 60°C above the maximum recommended use temperature for this alloy. Figure 24 shows the FEA temperature predictions for the top of the block. It shows that there are no temperature issues with using Mg for the block.

Fatigue cover factors were calculated for the Mg head and compared with those for the production cast iron head. The data are shown in Table 15. With one exception, location N, the cover factors for Mg (WE-43) are the same or higher than for the cast iron and are nearly the same at location N. FEA analysis of fatigue cover factors for the Mg block at key locations is summarized in Table 15. The cover factor for the Mg block is higher or the same in all key locations, compared with the cast iron block. Location AE is low no matter which material is used: cast iron, Ti, Al, or Mg. It can be raised by adding more material to that location.

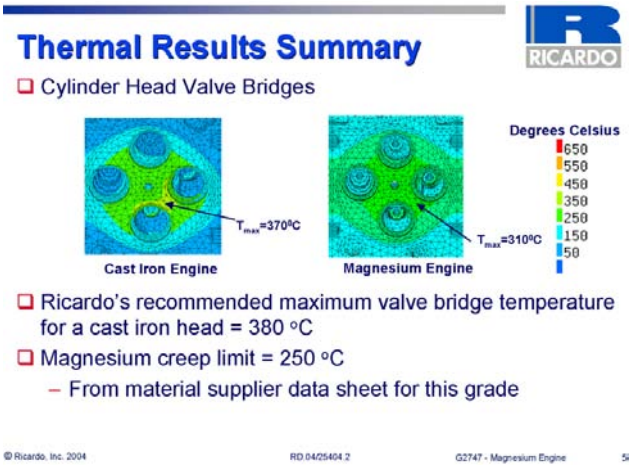

Figure 23. FEA model of the cast iron and aluminum blocks showing cover factors at key locations.

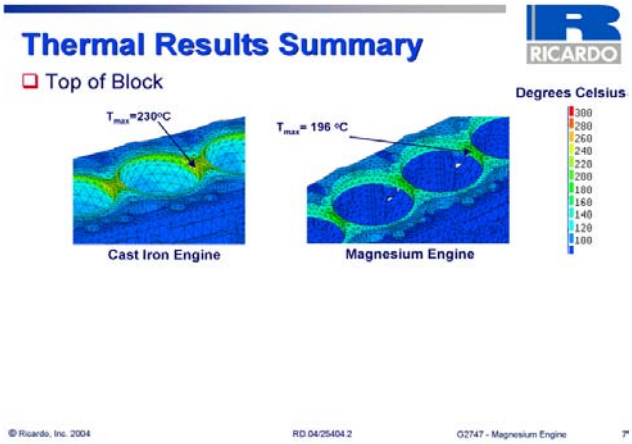

Figure 24. Thermal conductivity vs. temperature for WE-43 and grey cast iron.

Conclusions

FEA has shown that it is feasible to substitute a high-performance Mg casting alloy, WE-43, for gray cast iron in heavy-duty diesel engine heads and blocks, for a potential overall engine weight savings of over 30%. However, to do this, certain issues must be addressed:

- Compressive yielding is likely to occur in the valve bridge areas of the flame face of the head

Table 14. Mechanical and physical properties of gray cast iron and Mg (WE-43)

Gray cast iron (liner insert)

Temperature (Centi-grade)	Young's modulus (GPa)	Poisson's ratio	Thermal conduc-tivity (Wm-K0	Thermal expan-sion (μm/m-C)	Ultimate tensile strength (MPa)	Compressive yield strength (MPa)	Tensile yield strength (MPa)	Fatigue Strength (MPa)
20.0	117.2	0.25	48.80	1.10E-05	189.6	284.4	136.5	72.4
200.0			47.80	1.10E-05				
300.0			46.80					
400.0			45.80	1.25E-05				
500.0			44.80					

Magnesium (WE43-T6).

Temperature (Centi-grade)	Young's modulus (GPa)	Poisson's ratio	Thermal conduc-tivity (Wm-K0	Thermal expan-sion (μm/m-C)	Ultimate tensile strength (MPa)	Compressive yield strength (MPa)	Tensile yield strength (MPa)	Fatigue Strength (MPa)
20.0	44.1	0.27	51.30	2.67E-05	265.0	185.0	185.0	91.0
150.0	42.0	0.27	64.80	2.92E-05	250.0	175.0	175.0	83.0
200.0	39.0	0.27	69.50		245.0	170.0	170.0	
250.0	36.0	0.27	73.80	3.00E-05	220.0	160.0	160.0	62.0
300.0	36.0	0.27	77.90		160.0	120.0	120.0	
350.0			81.70					
400.0			85.20					

Table 15. Fatigue cover factors at key locations in the head for cast iron and Mg (WE-43)

	(lwj = lower water jacket) (uwj = upper water jacket)	Cast iron	Aluminum
Location	**Description**	**Fatigue cover factor**	**Fatigue cover factor**
A	uwj fillet between bolt boss and valve guide	0.53	0.58
B	lwj floor fillet between exh. port and inj. bore	0.61	1.01
C	lwj floor fillet to exhaust port	0.65	1.07
D	lwj roof fillet to head bolt boss	0.68	0.75
E	uwj roof fillet to head bot boss	0.69	0.73
F	lwj floor fillet to exhaust port	0.72	1.05
G	intake port to valve seat area	0.72	1.50
H	lwj roof fillet to head bolt boss	0.75	0.98
I	exterior o exhaust side near flame deck	0.81	1.14
J	uwj roof fillet to head bolt boss	0.82	0.94
K	uwj roof fillet to head bolt boss	0.86	0.93
L	lwj roof fillet to head bolt boss	0.88	1.18
M	uwj fillet between head bolt boss exhaust port	0.88	1.04
N	exterior pocket @ top deck near head bolt boss	0.92	0.88
O	uwj roof fillet to top deck	0.93	0.98
P	lwj fillet – valve guide to fuel drilling	0.94	1.57
Q	top deck rib between guides	0.94	0.98
R	lwj floor between exh. Ports and inj. bore	0.95	1.34
T	Exterior pocket @ top deck near head bolt boss	0.96	1.08
U	uwj roof to coolant hole	0.96	1.01
V	lwj fillet – exh. guide to exh. port	0.98	1.09
W	lwj floor fillet to exhaust port	0.99	1.47

as a result of high temperatures coupled with high stresses. Low cycle fatigue or creep could be the result.

- Ways to reduce the temperature in the valve bridges to below 250°C must be explored. Some ideas are
  - design changes to reduce the stresses in the area
  - thinning of the fire deck to improve cooling
  - higher coolant flow to accommodate the heat flow
  - slight de-rating of the engine so less heat and lower stresses would be generated in the area
- Other design changes should be explored in order to modify the interference fit between the valve seat inserts and the head and to bolster the support for the cast iron liner.
- An alternative to making the design changes is to use an Al head on the Mg block.
- Mg is well known as a metal that promotes galvanic corrosion. Should the engine contain substantial amounts of Mg, then the issues of galvanic corrosion must be explored.

Conclusions of Overall Study

- FEA modeling of a Cummins ISB 5.9-L diesel engine has shown that all three lightweight alloys, Ti-6Al-4V, A354-T6 (Al), and We-43 (Mg), are feasible substitutes for gray cast iron in a heavy duty diesel engine. The modeling incorporated a gray cast iron liner in the block for the lightweight alloys because the production cast iron engine has no liner (parent bore). The liner acts in two ways: it provides a viable tribological surface for the piston rings, and it makes the study more generic and less engine-specific.
- Each lightweight material posed unique challenges to making the material work in this engine:
  - The Ti alloy could be used as a direct substitute for cast iron in the block when the engine was rated at either 305 hp, as designed, or up-rated to 450 hp.

- The Ti alloy posed a problem in the valve bridge region of the fire deck of the head because of its low thermal conductivity. It was shown that if a Be-Cu insert were employed in that region, it would be feasible to use Ti when the engine was up-rated to 450 hp. This strategy would allow for a 10% weight saving and an up-rating of 50%.
- Using the Al alloy for the head and block would allow for a 20% weight saving. FEA of the engine rated at 305 hp showed that Al is a feasible substitute for gray cast iron. Note that since Al has no fatigue endurance limit, life cycle analysis needs to be performed to determine when to use this material.
- It is feasible to substitute a high-performance Mg alloy for gray cast iron in this engine rated at 305 hp. However, the temperatures and stresses in the valve bridge areas of the fire deck in the head are slightly too high and need to be reduced. This can be done by increased coolant flow, some design changes, or a slight de-rating of the engine.

Presentations

Presentation to TACOM, March 2004.

Presentation to Cummins Engine Co., April 2004

Presentation to Caterpillar, April 2004.

Presentation at a low-cost Ti users conference sponsored by the Defense Advanced Research Projects Agency, April 2004.