Temperature-Following Thermal Barrier Coatings for High-Efficiency Engines

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Tobias Schaedler, Principal Investigator

Team:

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Program Overview

Prime Performer: HRL Laboratories (Malibu, CA)

Subcontractor: GM R&D (Pontiac, MI)

Scope: This project includes work to develop, implement and test temperature-following thermal barrier coatings (TBCs) that will decrease heat loss from the combustion chamber.

Barriers Addressed:

- Dilute Gasoline Combustion – Thermal Management
- Parasitic Loss Reduction and Waste Heat Recovery
- Dilute Gasoline Combustion – Knock Mitigation

Period of Performance: 1/1/2017 – 6/31/2020

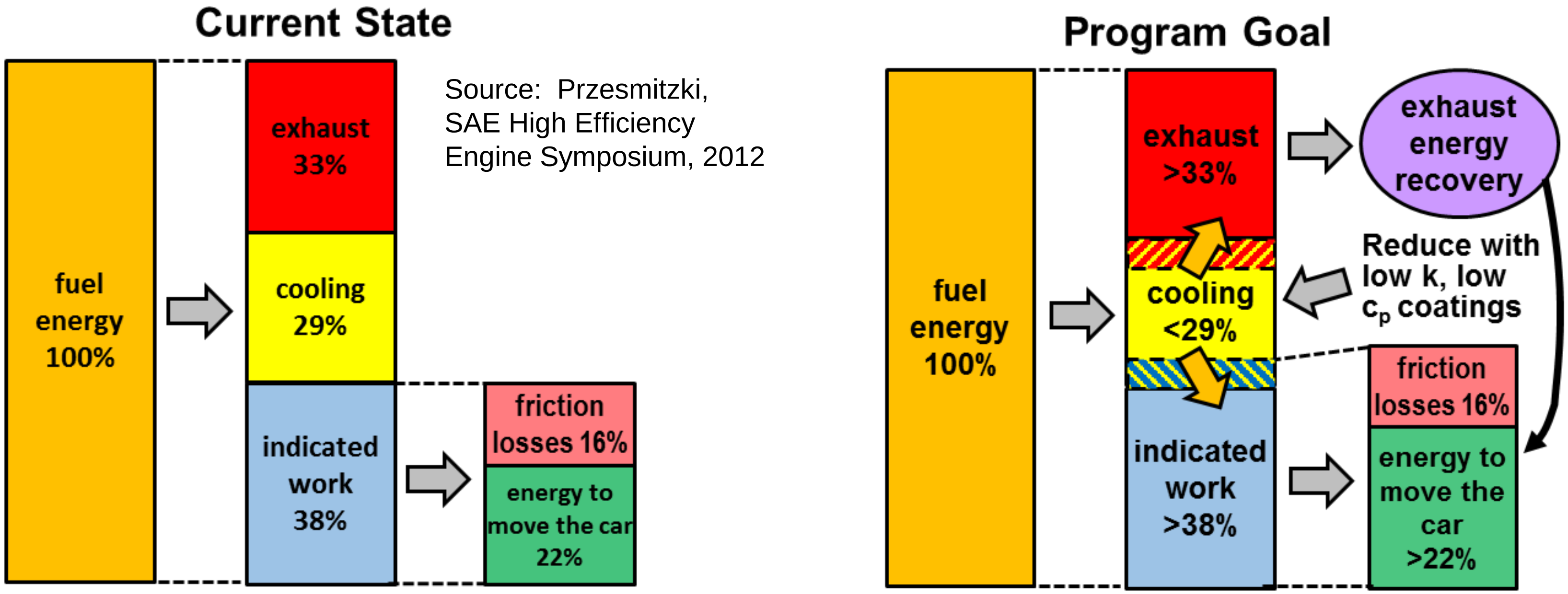
- 3 budget periods of 12 months with go/no-go milestone after BP1 & 2

- No-cost extension on BP2 for 6 months (through 6/31/2019)

Award Amount: $2.8M (50% cost share provided by GM)

- $730k in 2017, $1,137k in 2018 including cost share

Objective / Relevance

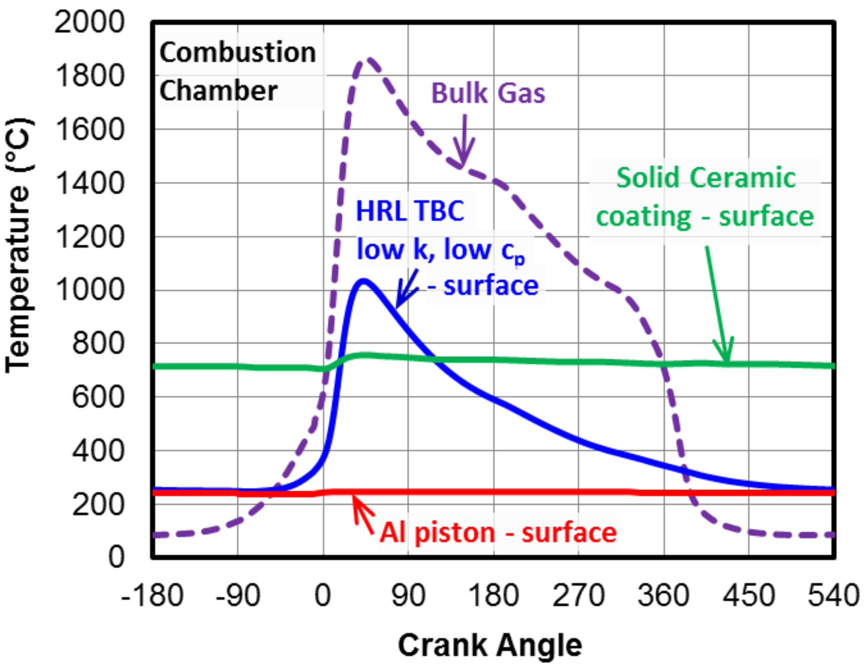


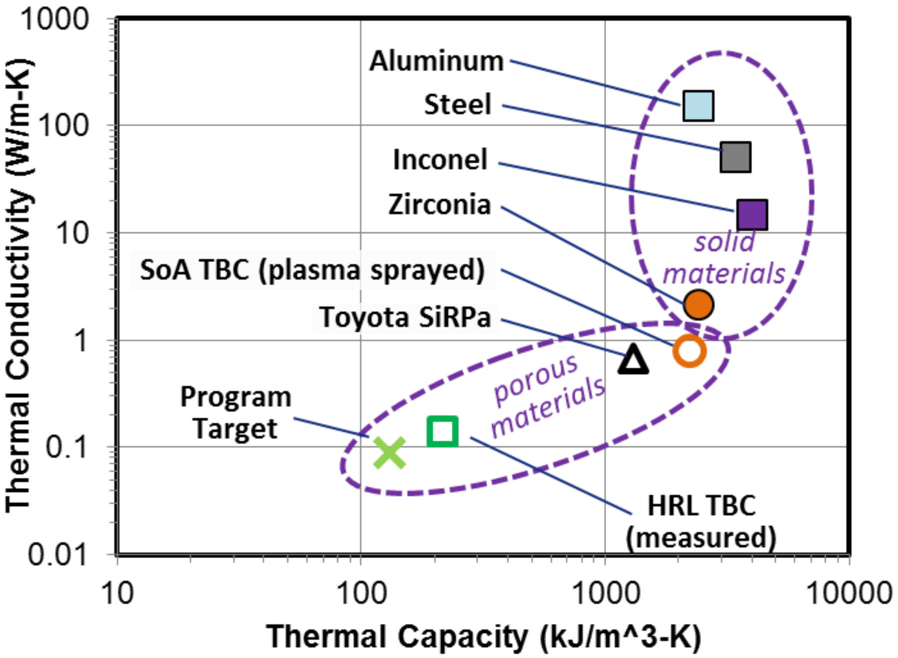
Source: Przesmitzki, SAE High Efficiency Engine Symposium, 2012

Objective: The objective of this project is to increase the efficiency of internal combustion engines by 4% to 8% with thermal barrier coatings within the cylinder and exhaust ports that add less than ~$250 in cost to a 4-cylinder engine. Benefits will be derived from:

- In-Cylinder Efficiency improvements through lower heat losses
- Increased effectiveness of exhaust energy recovery and aftertreatment with higher exhaust temperatures under highly dilute conditions
- Lower parasitic losses due to reduced cooling demands

Objective / Relevance

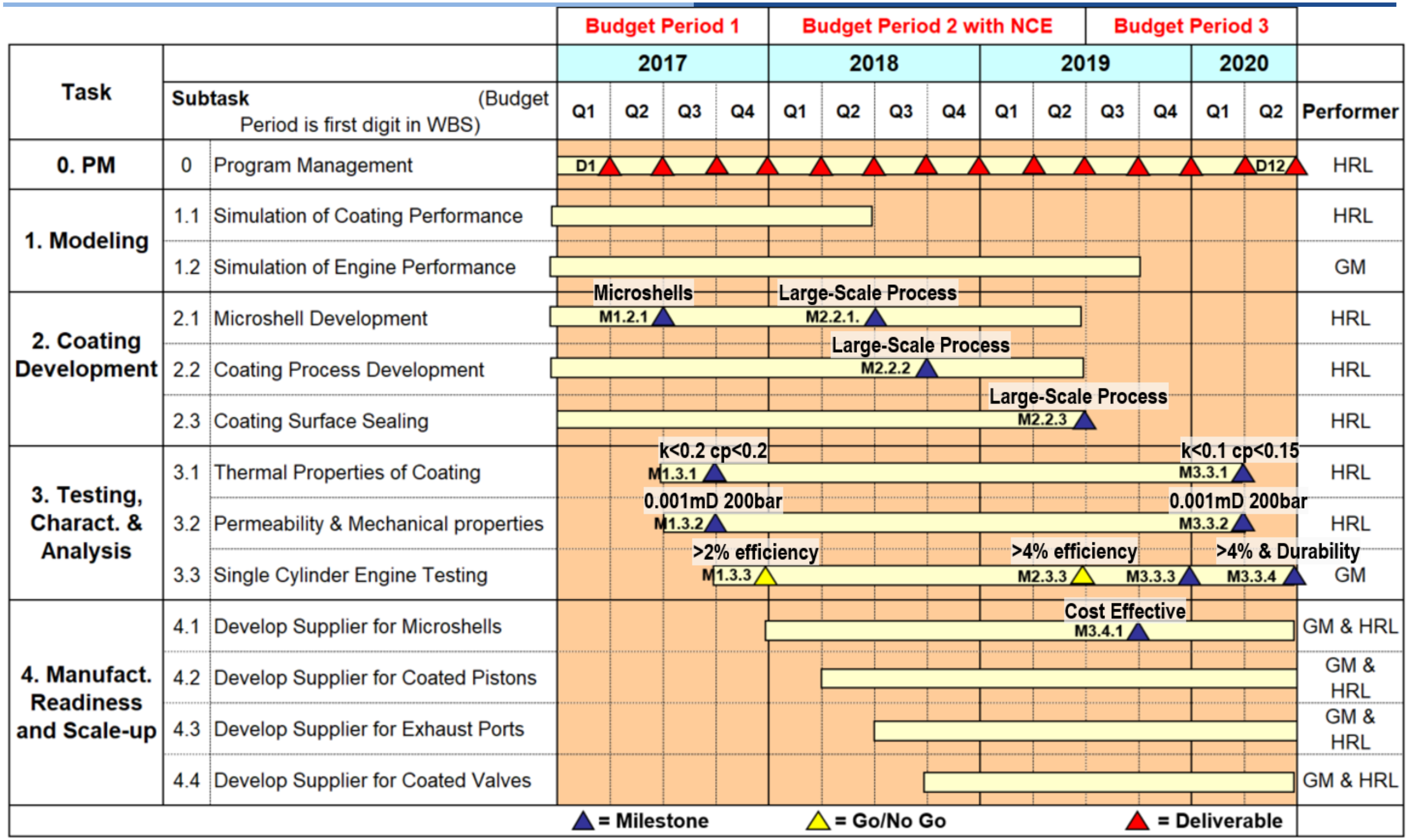




TBC must have low k and low c_p to follow the combustion gas temperature closely and reduce heat loss. This mitigates both knock tendencies and volumetric efficiency losses, unlike solid ceramic coatings with high c_p.

HRL's microshell TBCs exhibit 10X lower thermal conductivity (k) and heat capacity (c_p) than state-of-the-art materials. Further improvements will enable 4% to 8% efficiency gains and increase durability.

Project Milestones



Task	Subtask (Budget Period is first digit in WBS)		2017 Q1	2017 Q2	2017 Q3	2017 Q4	2018 Q1	2018 Q2	2018 Q3	2018 Q4	2019 Q1	2019 Q2	2019 Q3	2019 Q4	2020 Q1	2020 Q2	Performer
			Budget Period 1				Budget Period 2 with NCE						Budget Period 3				
0. PM	0	Program Management	D1 🔺	🔺	🔺	🔺	🔺	🔺	🔺	🔺	🔺	🔺	🔺	🔺	🔺	D12 🔺	HRL
1. Modeling	1.1	Simulation of Coating Performance															HRL
	1.2	Simulation of Engine Performance															GM
2. Coating Development	2.1	Microshell Development		Microshells M1.2.1 ▲				Large-Scale Process M2.2.1. ▲									HRL
	2.2	Coating Process Development							Large-Scale Process M2.2.2 ▲								HRL
	2.3	Coating Surface Sealing										Large-Scale Process M2.2.3 ▲					HRL
3. Testing, Charact. & Analysis	3.1	Thermal Properties of Coating			k<0.2 cp<0.2 M1.3.1 ▲										k<0.1 cp<0.15 M3.3.1 ▲		HRL
	3.2	Permeability & Mechanical properties			0.001mD 200bar M1.3.2 ▲										0.001mD 200bar M3.3.2 ▲		HRL
	3.3	Single Cylinder Engine Testing				>2% efficiency M1.3.3 △						>4% efficiency M2.3.3 △		M3.3.3 ▲		>4% & Durability M3.3.4 ▲	GM
4. Manufact. Readiness and Scale-up	4.1	Develop Supplier for Microshells											Cost Effective M3.4.1 ▲				GM & HRL
	4.2	Develop Supplier for Coated Pistons															GM & HRL
	4.3	Develop Supplier for Exhaust Ports															GM & HRL
	4.4	Develop Supplier for Coated Valves															GM & HRL

▲ = Milestone △ = Go/No Go 🔺 = Deliverable

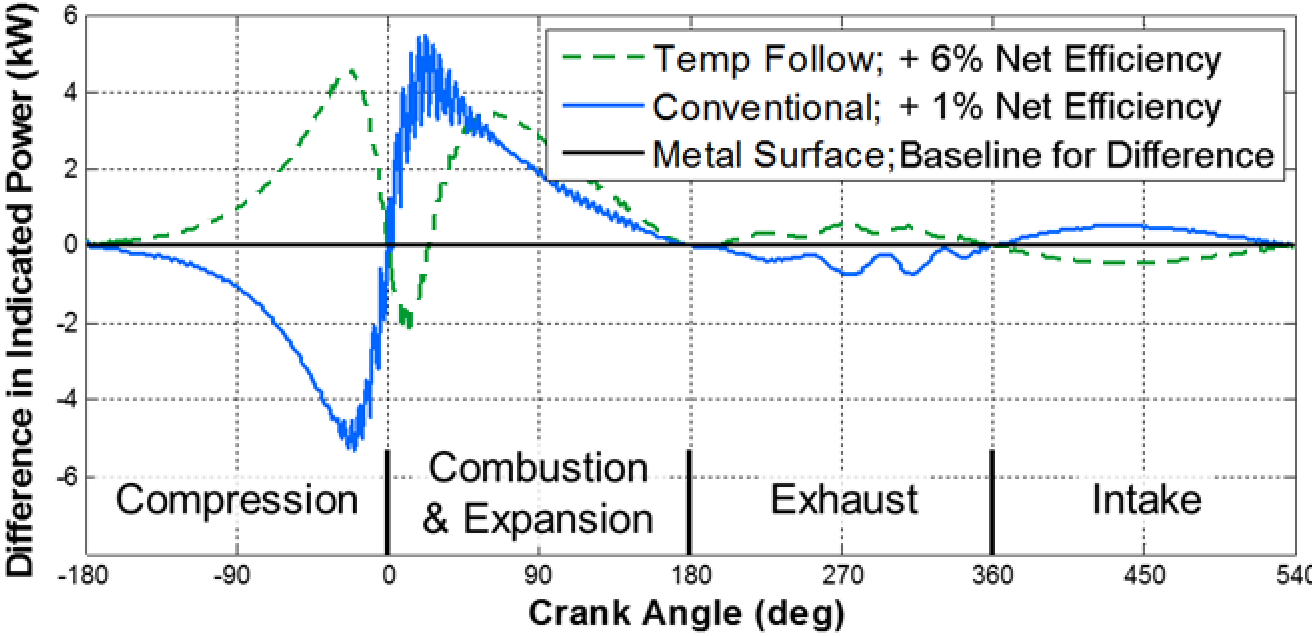
Any proposed future work is subject to change based on funding levels

Approach

Temperature-Following insulation allows surfaces to stay cool during the intake and compression stroke, which will help volumetric efficiency and compression work. During combustion, the Temperature-Following coating surface can increase rapidly to provide insulation benefits.

Over the entire cycle, Conventional insulation’s expansion benefits are negated by the increased compression work, while Temperature-Following shows improvements over Metal in compression & expansion.

This allows in-cylinder insulation to provide all the benefits of lower heat rejection, but with none of the volumetric efficiency or knock drawbacks.

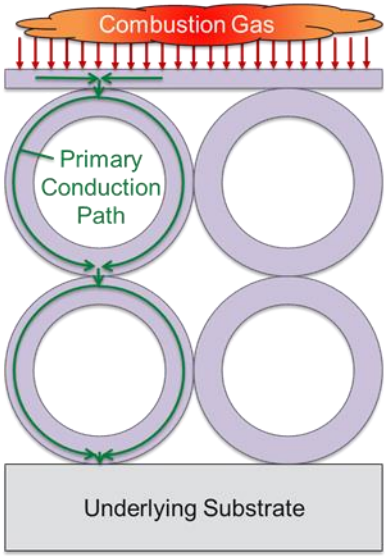


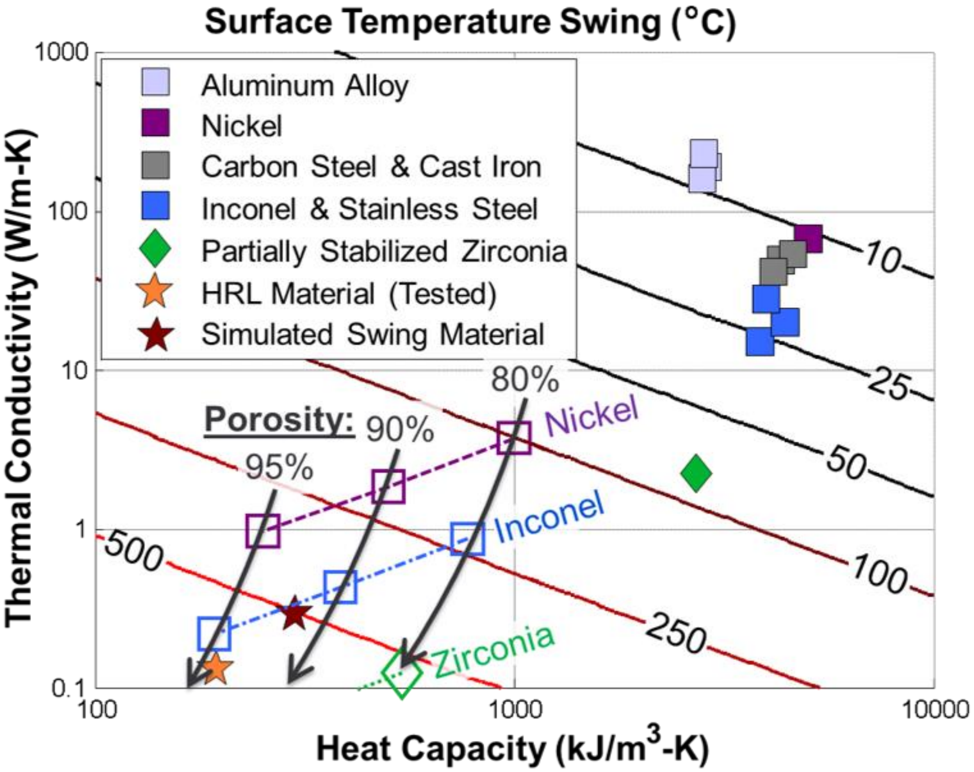
Approach

Thermal conductivity and volumetric heat capacity were independently varied to determine the material properties necessary for maximizing the temperature swing. High levels of porosity were determined to be necessary to decrease both the volumetric heat capacity (density) and the thermal conductivity.

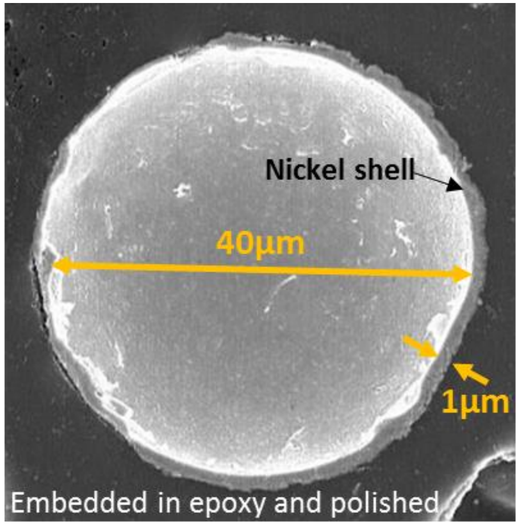
Estimated material properties for various solid materials and levels of porosity are overlaid on the plot.

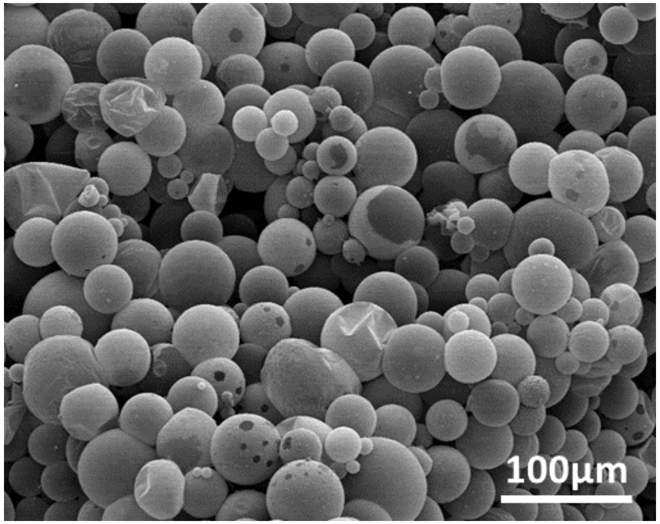
90 - 95% porosity is necessary to achieve large enough surface T-swing. Approx. half the volume is within spheres, half is interstitial.



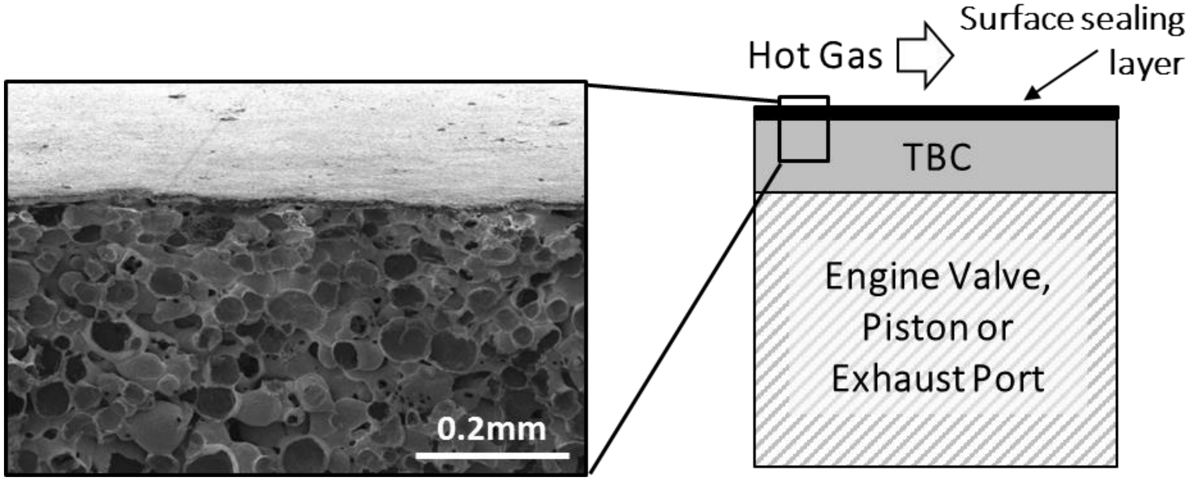


Approach





HRL has developed hollow nickel-alloy microsphere TBCs with an average diameter of 30 - 50µm and 1 - 2µm shell thickness. These microspheres can be sintered together to form high-temp metal matrices with over 90% porosity

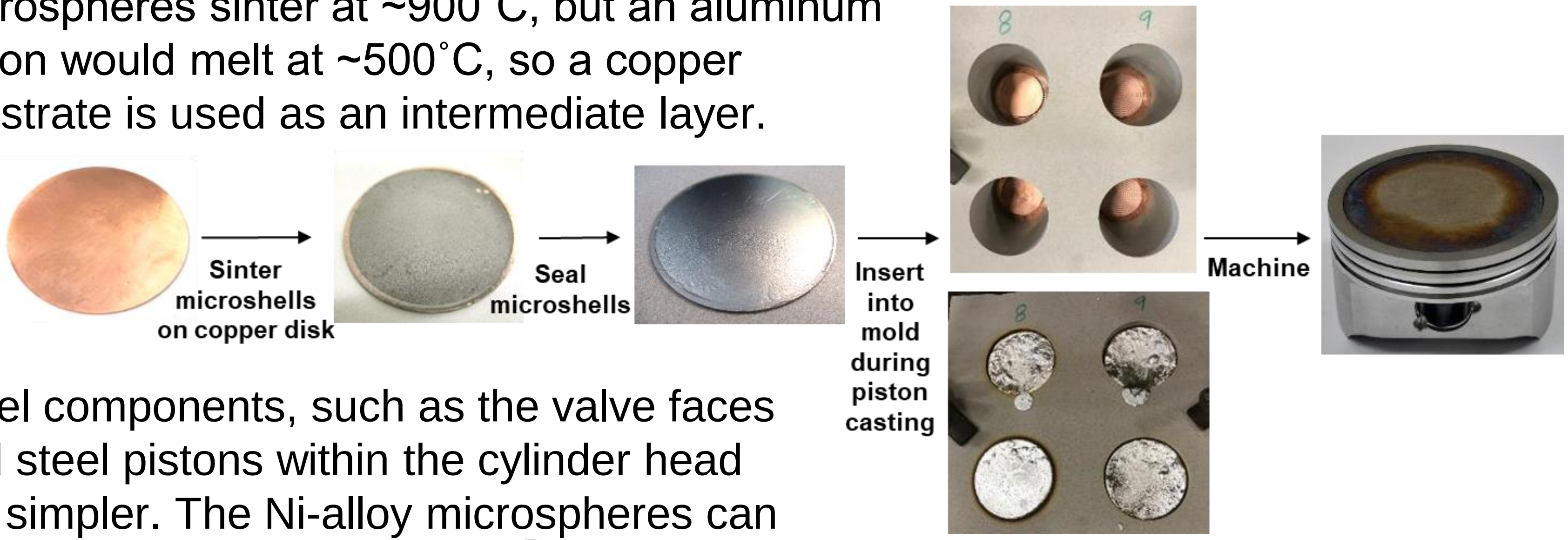


Microsphere TBCs can be applied using dry molds, slurries, or air spraying. The surface must be sealed to avoid ingress of hot combustion gasses and unburned fuel vapor.

Approach

A set of processes were created for applying the microsphere-based insulation to aluminum and steel components, as well as curved surfaces.

- Microspheres sinter at ~900˚C, but an aluminum piston would melt at ~500˚C, so a copper substrate is used as an intermediate layer.



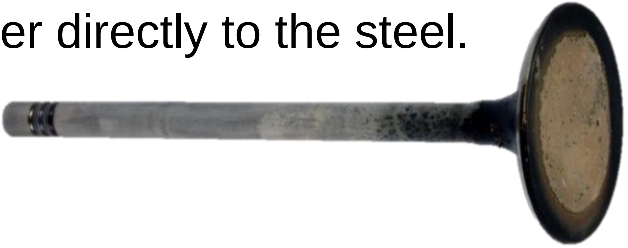
Sinter microshells on copper disk

Seal microshells

Insert into mold during piston casting

Machine

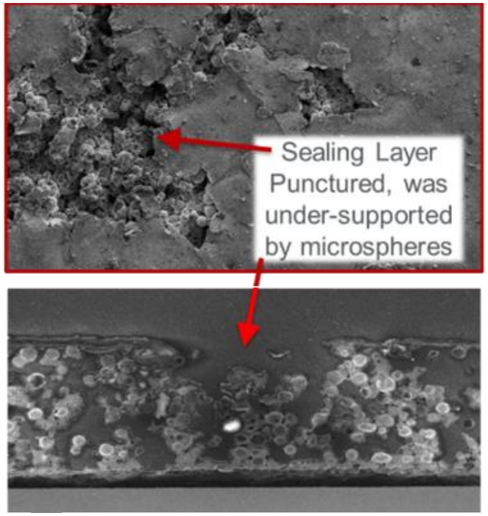
- Steel components, such as the valve faces and steel pistons within the cylinder head are simpler. The Ni-alloy microspheres can sinter directly to the steel.



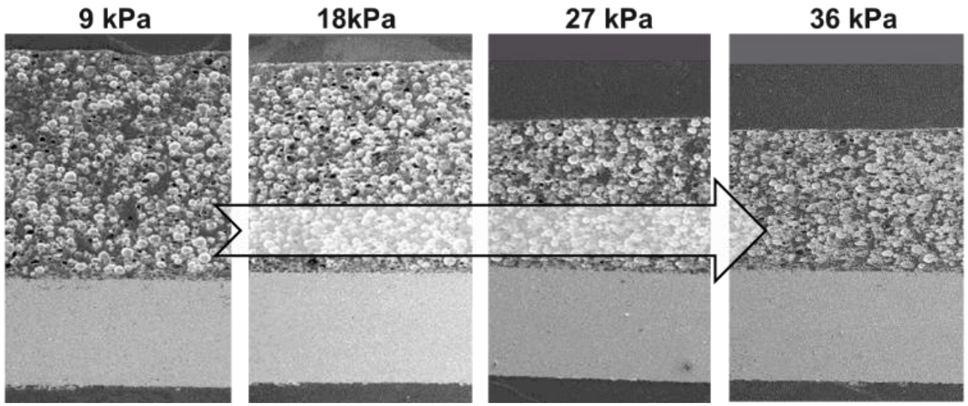
- Nickel exhaust port shells were coated and sintered, then placed in cylinder head mold for casting.

Progress – Coating Surface

- Uneven packing density caused punctures in the sealing layer
- Coating surface uniformity was improved by increased sintering pressure and reduced diameter spheres at the top layer



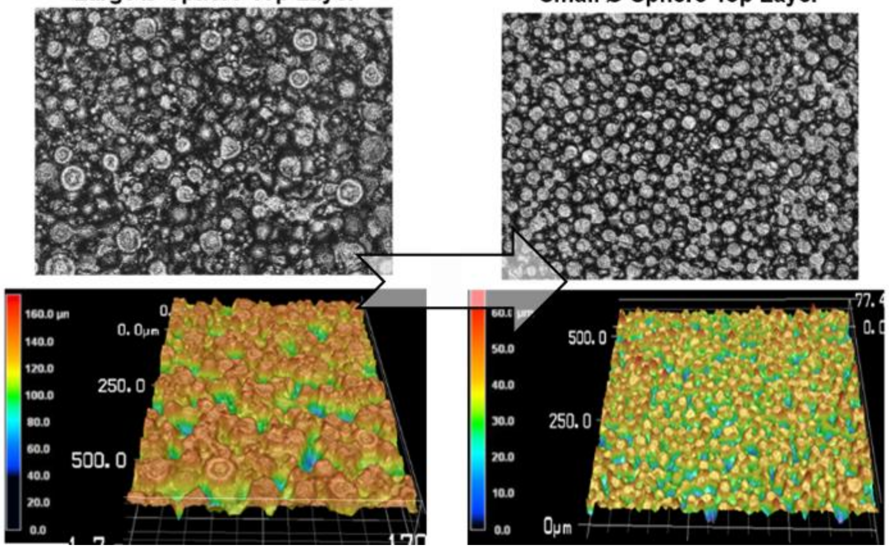
Sealing Layer Punctured, was under-supported by microspheres



Pressure (kPa)	TBM Thickness (µm)	Thermal Conductivity (W/mK)	Heat Capacity (J/m³K)
9	1312	0.139	0.46
18	1240	0.154	0.49
27	990	0.193	0.61
36	902	0.290	0.63

9 kPa Sintering Pressure, Large Ø Sphere Top Layer

30 kPa Sintering Pressure, Small Ø Sphere Top Layer

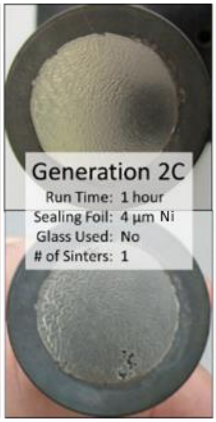


Conductivity increases with sintering pressure but is still <0.3 W/mK

Progress – Coated Valves

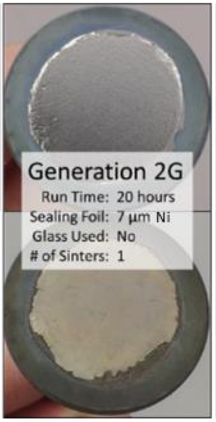
- Exhaust valve testing has shown that the sealing foil layer is robust over the bulk of the microsphere surface, however there is still considerable erosion around the periphery of the coated portion
- Glass was used during the sintering process to more evenly distribute the applied pressure, but it appears to make the erosion around the edge at the transition from the stainless steel valve face to the Ni-P microspheres worse
- This transition is still a challenge due to differential thermal expansion and the potential for a larger step-change in underlying surface. Additionally, there is no phosphorus to facilitate Ni sintering between the foil and the stainless steel.

Generation 2A
Run Time: 10 hours
Sealing Foil: 4 μm Ni
Glass Used: No
# of Sinters: 2



Generation 2C
Run Time: 1 hour
Sealing Foil: 4 μm Ni
Glass Used: No
# of Sinters: 1

Generation 2F
Run Time: 6 hours
Sealing Foil: 5.5 μm Ni
Glass Used: Yes
# of Sinters: 2



Generation 2G
Run Time: 20 hours
Sealing Foil: 7 μm Ni
Glass Used: No
# of Sinters: 1

Generation 2H
Run Time: 22 hours
Sealing Foil: 4 μm Ni
Glass Used: Yes
# of Sinters: 2

Generation 2I
Run Time: 18 hours
Sealing Foil: 4 μm Ni
Glass Used: No
# of Sinters: 1

Generation 3A
Run Time: 18 hours
Sealing: Polished Ceramic

Generation 4A
Sealing Foil: 3 μm Inconel
Glass Used: Yes

Engine test pending

Generation 4B
Sealing Foil: 3 μm Monel
Glass Used: Yes

Engine test pending

Progress – Coated Valves

- The polished ceramic sealing layer valve survived testing well, with minor pock-marking across the surface.
- No distinct failures were noted around the transition from valve face to microspheres
- No difference in engine performance was noted with this valve

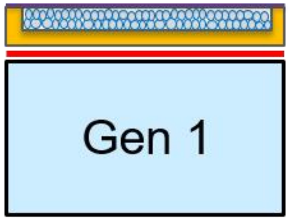
Permeability Evaluation:

- Special fuel laced with sulfur will be used for coating permeability testing.
- Various components will be tested with this fuel for a set period of time, then removed from the engine.
- Components will then be sectioned and the amount of sulfur present within the microsphere layer will indicate the permeability of the sealing layer.

Any proposed future work is subject to change based on funding levels

Progress – Coated Pistons

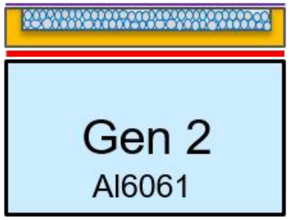
Compacted microsphere surface, 2.5µm sealing foil, copper pocket



Cu-Al Bond: Zn braze

Limited Success

Higher melting point aluminum allows for stronger braze materials

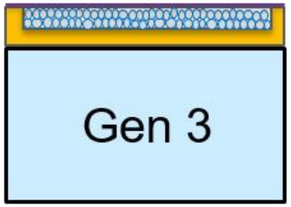


Cu-Al Bond: Al-Si braze

Failure on 1st try

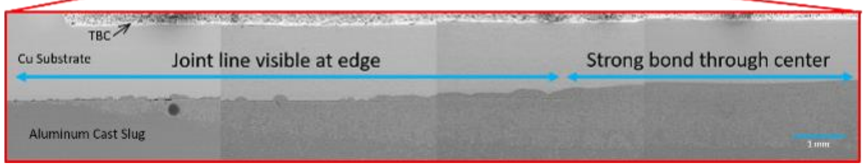
In Progress

Cast aluminum over copper pocket with sealed microspheres

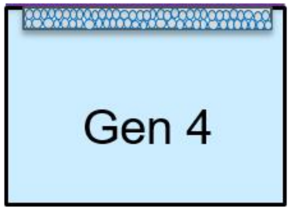


Cu-Al Bond: Mechanical integration during casting

In Progress



Steel piston



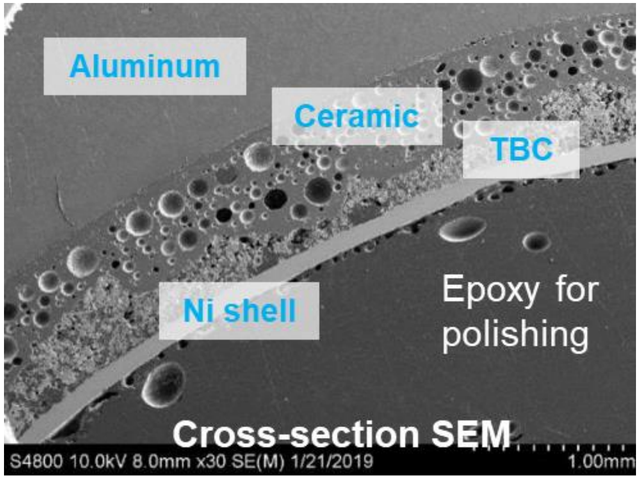
Bond: Sinter microspheres directly to steel

In Progress

Any proposed future work is subject to change based on funding levels

Progress – Coated Exhaust Ports

- A microsphere coated exhaust port liner was fabricated and successfully demonstrated its ability to survive the aluminum casting process
- Next step is fabrication of single cylinder heads with similar exhaust port liners to demonstrate performance and durability



- Aluminum adheres to ceramic without damaging or penetrating through this protective layer
- Exhaust port is strong enough to withstand casting process

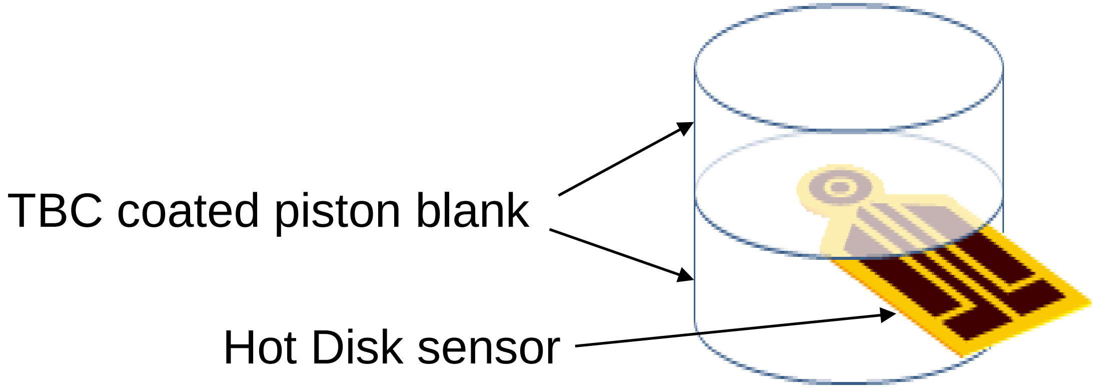
Any proposed future work is subject to change based on funding levels

Response to Previous Comments

Reviewer 6 asked how thermal conductivity and thermal contact resistance was measured

Thermal conductivity was measured by 2 methods:

- TBC on steel piston blanks by Transient Plane Source (TPS) method with a Hot Disk TPS 2500 S instrument at Sandia NL (Dr. Karla Reyes)
- TBC on 1mm Cu sheet by laser flash with a Netzsch LFA 447



Measured thermal transport properties of engine relevant set-up (similar contact resistance)

Reviewer 5 suggested de-emphasizing the engine tests until the material coating and sealing can be improved to raise the confidence that engine tests will be more successful

Collaboration / Coordination

HRL Laboratories - Primary Investigator (Malibu CA)

GM Research - Subcontractor (Pontiac MI)

Multiple other US companies have been engaged for different parts of this program

- Mass Production of Microspheres for use in coating – **3M**
- Design and production of steel pistons – **Federal Mogul**
- Discussions running for alternate sealing layer solutions – **Agreements pending**

Remaining Challenges

1. Further work on sealing layer properties is necessary for temperature-swing performance, durability, AND impermeability.
2. Bonding techniques to aluminum components need to be refined to ensure a robust, reliable solution with desired temperature-swing range.
3. Steel pistons will be tested as an alternative solution for insulating the piston.
4. Capability for more complicated surface geometries must be developed and refined.
5. Processes must be scaled or adapted to achieve mass-production capacity, performance, and cost targets.

Any proposed future work is subject to change based on funding levels

Future Research

To address the challenges stated previously, we plan on:

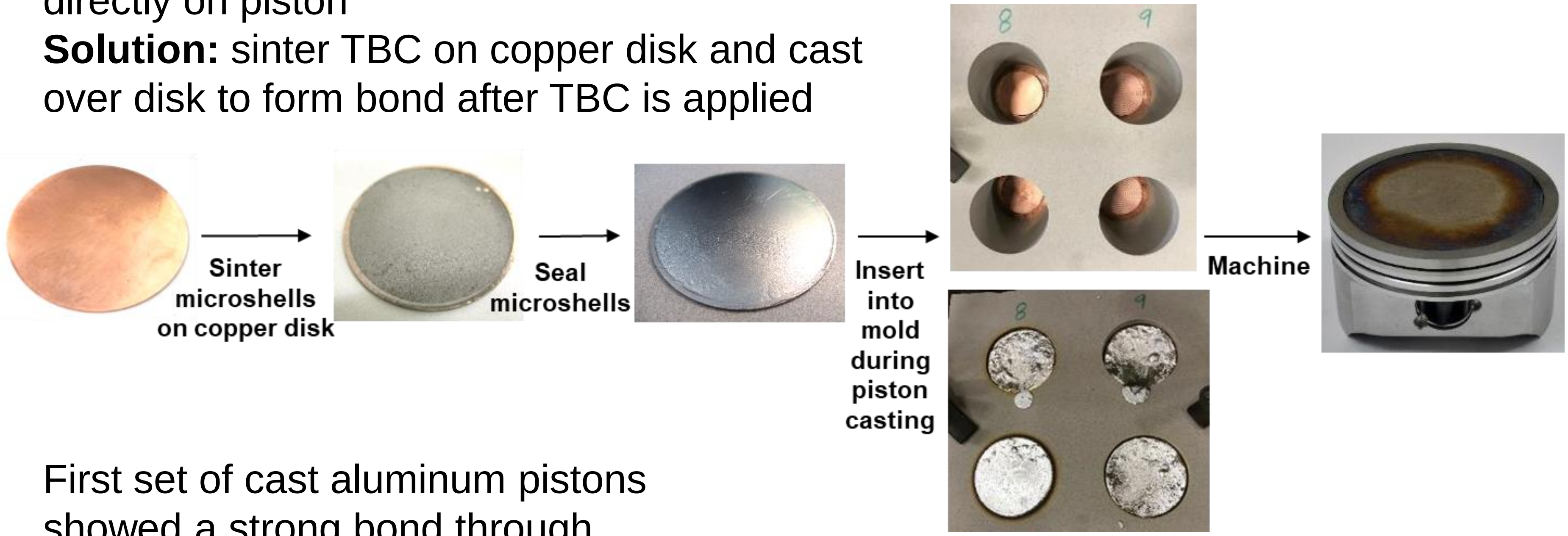
1. Using various materials such as stronger nickel alloy foils and ceramics, that combined with an increased microsphere packing density will achieve a more durable surface sealing layer.
2. Aluminum piston casting, directly over the coated and sealed substrate is being explored to address aluminum bonding.
3. Sintering insulation to steel components will be used to validate thermal barrier solutions, may allow other avenues of improvement.
4. Alternate methods for constructing the insulating layer around molds, shaping it after sintering, maintaining sealing layer integrity across curvature, and attaching to curved surfaces are all being explored.
5. Corporate partners and internal manufacturing assets are being engaged to create and evaluate inclusion of insulation in production.

Any proposed future work is subject to change based on funding levels

Future Research – Al Pistons

Challenge: low melting point of aluminum piston prohibits sintering of TBC directly on piston

Solution: sinter TBC on copper disk and cast over disk to form bond after TBC is applied



Sinter microshells on copper disk

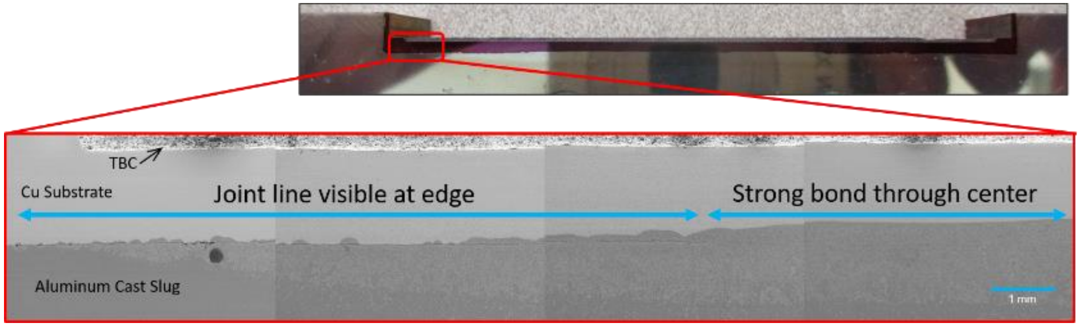
Seal microshells

Insert into mold during piston casting

Machine

First set of cast aluminum pistons showed a strong bond through the center of the sample, with the outer ~7mm not bonded.

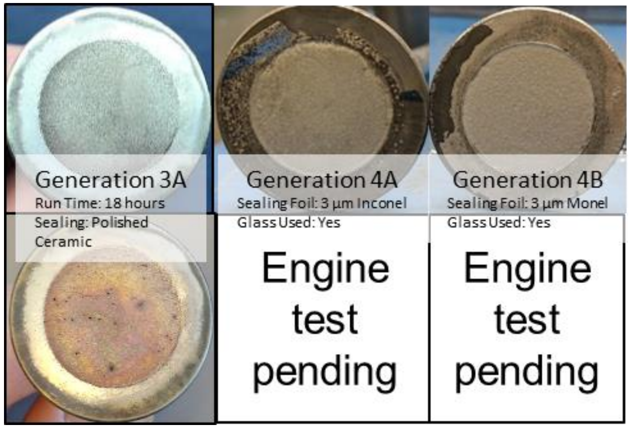
Changes are being made to the casting procedure to control pour parameters to increase the bonding area.

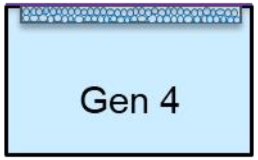


Any proposed future work is subject to change based on funding levels

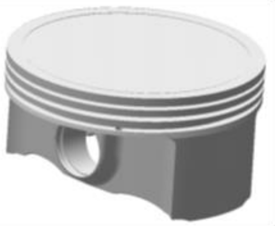
Future Research – Engine Test

- TBC structural quality, sealing methods, and **valve** test:
  - 3rd gen. sealing layers: lower C_p ceramic
  - 4th gen. sealing layers: nickel alloy foil seals
  - Sulfur laced fuel tests to check permeability of sealing layer
- **Piston** integration and test:
  - Utilize successful sealing method developed for valves
  - Fabricate steel pistons with sealed TBC for engine test
  - Improve method for robust Al-Cu bond: casting
- **Exhaust Ports**:
  - Fabricate inserts specifically for casting (with placement and transition features)

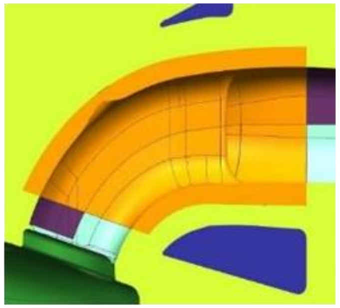




Bond: Sinter microspheres directly to steel



HRL supplied liner



Model of a liner cast into the exhaust port

Any proposed future work is subject to change based on funding levels

Summary of Work

- The microsphere-based insulating material is meeting the target material properties of 0.2 W/m-K Conductivity and 0.2 MJ/m^3-K for temperature-swing insulation.
- Drastic improvements in the impermeability of the sealing layer have been made and the ceramic sealing layer survived the in-cylinder environment with minimal damage.
- Promising bonding results when aluminum pistons are cast over TBC coated substrate.
- Steel pistons have been designed and are being coated and machined for engine tests.
- TBC coated exhaust ports were successfully fabricated and cast over without damage to the microsphere layer or distortion.
- Analytical tools have been developed and validated allowing accurate assessment of potential design solutions.

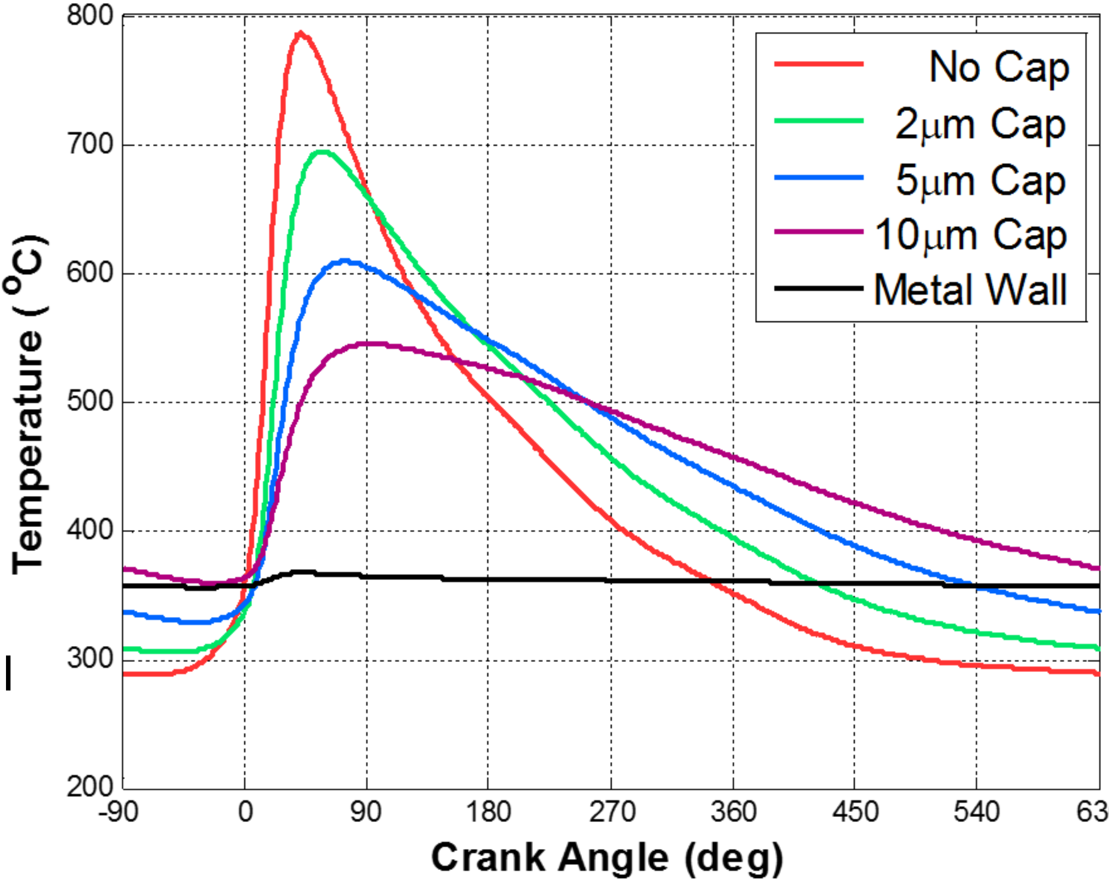
Technical Backup Slides

Influence of Sealing Cap

Highly porous coatings, especially with a large portion of open-cell porosity such as the void spaces between packed microspheres spheres, will require an impenetrable sealing layer to prevent permeable porosity losses, which impacts the surface temperature swing by concentrating mass where it is most detrimental.

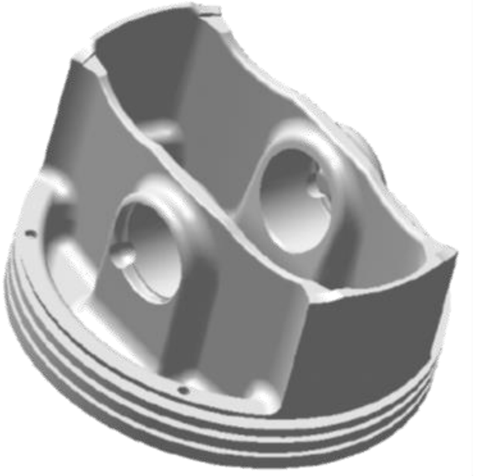
Thicker metal sealing caps substantially dampen the surface T swing while increasing the wall temperature during intake and compression; These effects are somewhat mitigated by adjusting the insulating layer thickness beneath the sealing layer

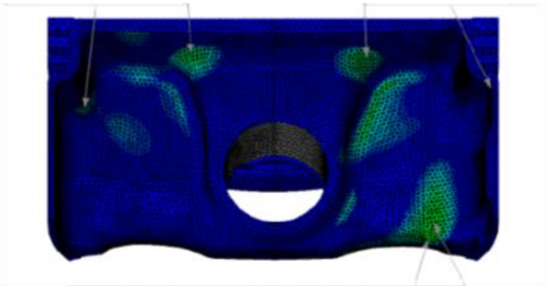
Ultimately a very thin or low-mass sealing layer is critical to the overall coating performance

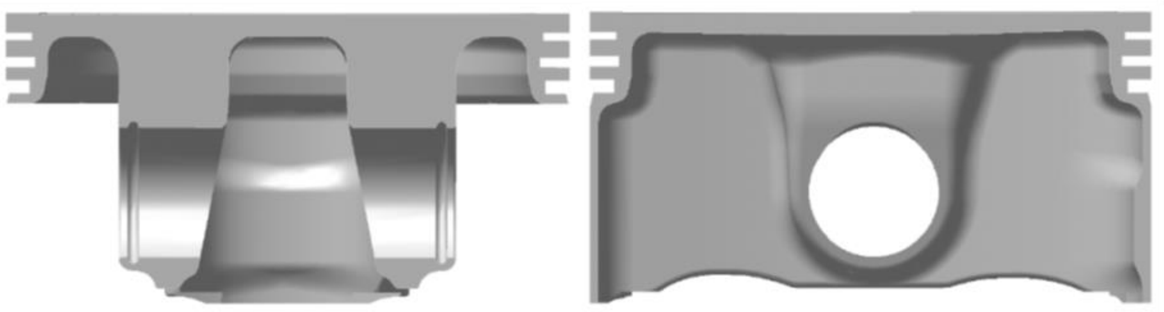


Progress – Coated Pistons

- A new steel piston and wrist pin were designed by Federal-Mogul
- The design was completed and passed the F-M internal FEA quality gate for the operating conditions provided by GM
- TBC Processing steps:
  - F-M provides pre-machined piston blanks
  - HRL sinters on TBC and sealing layer (also serves as Austenitizing period)
  - HRL quenches piston blank with TBC
  - HRL tempers piston blank/TBC to achieve desired hardness - 28 to 34 Rockwell C
  - F-M performs final machining on piston
  - GM tests
- Several coated and sealed pistons have been sent back to F-M for machining and engine tests will follow





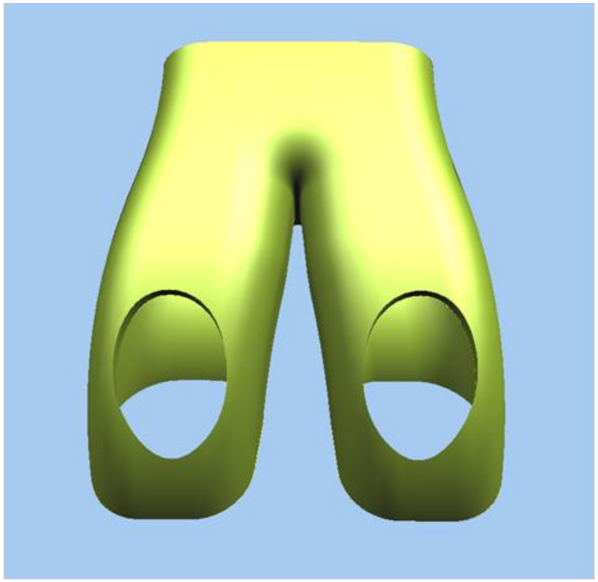


Any proposed future work is subject to change based on funding levels

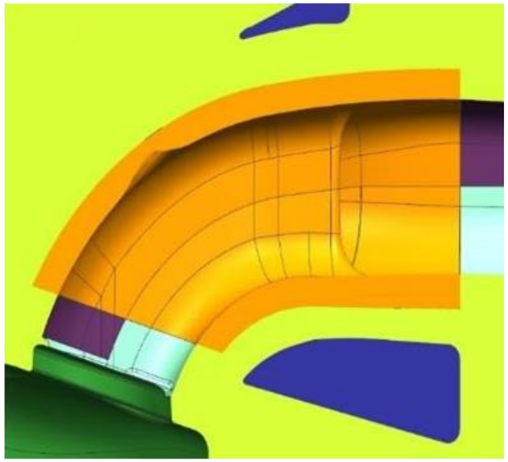
Progress – Coated Exhaust Ports

- Grainger and Worrall will be fabricating 2 heads with TBC coated exhaust port liners
- Actual port liners will be scanned to create the 3D printed core boxes
- The new heads will be the same design that has been used for all of previous port liner testing to facilitate comparison of different port liner materials
- Expected delivery of heads is Q3 ’19

HRL supplied liner



liner model



Model of a liner cast into the exhaust port

Any proposed future work is subject to change based on funding levels