Thermal barrier coating towards improving ICE thermal efficiency

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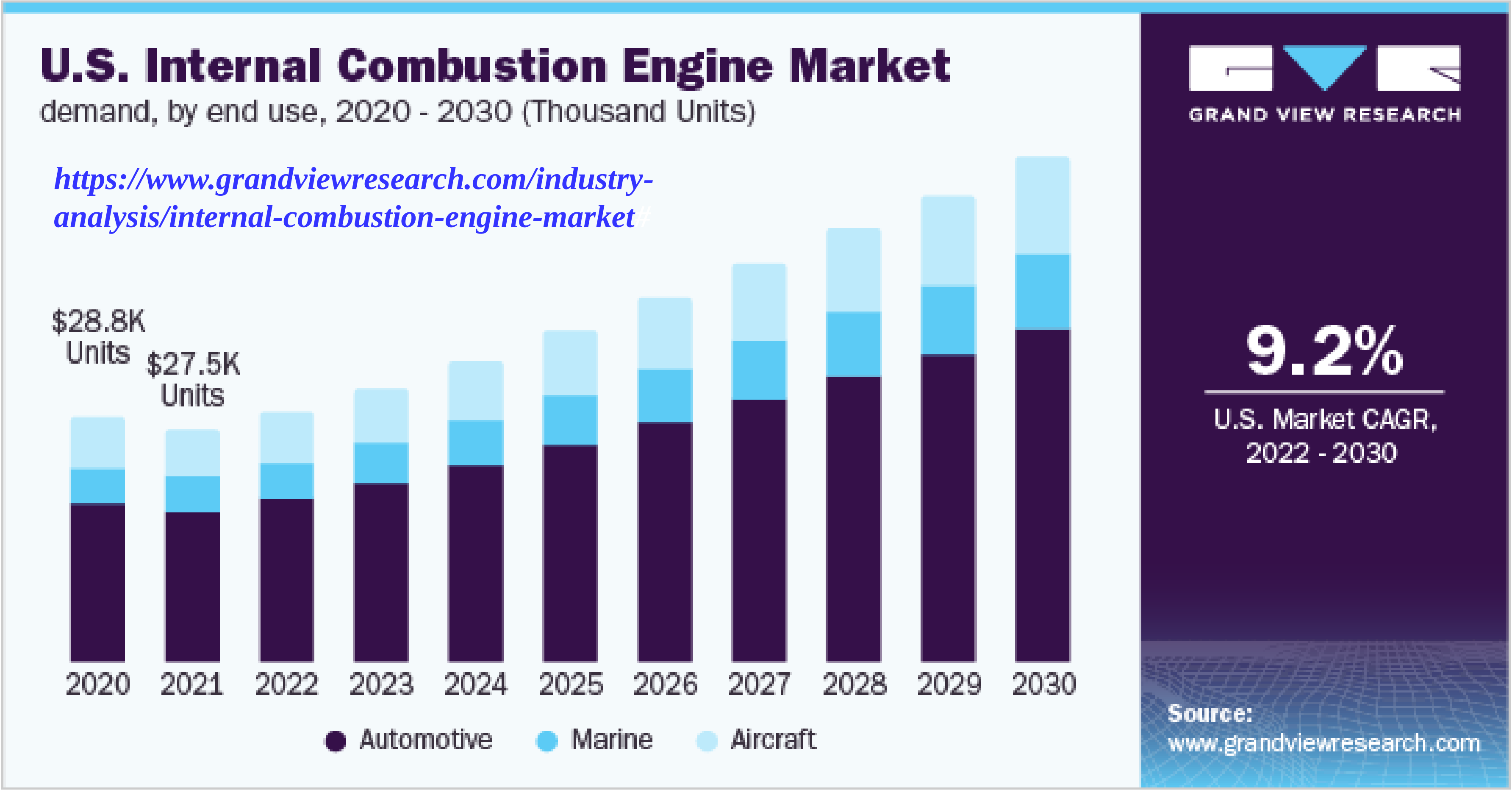
Outline

- Background /objective/strategy
- Reliable engineered coatings for ICE engine
- Thermal barrier coatings for ICE engine
- Research advance in thermal barrier coating
- Existing results from my research group
- Challenge and prospective

Future Market Share of Engines in global

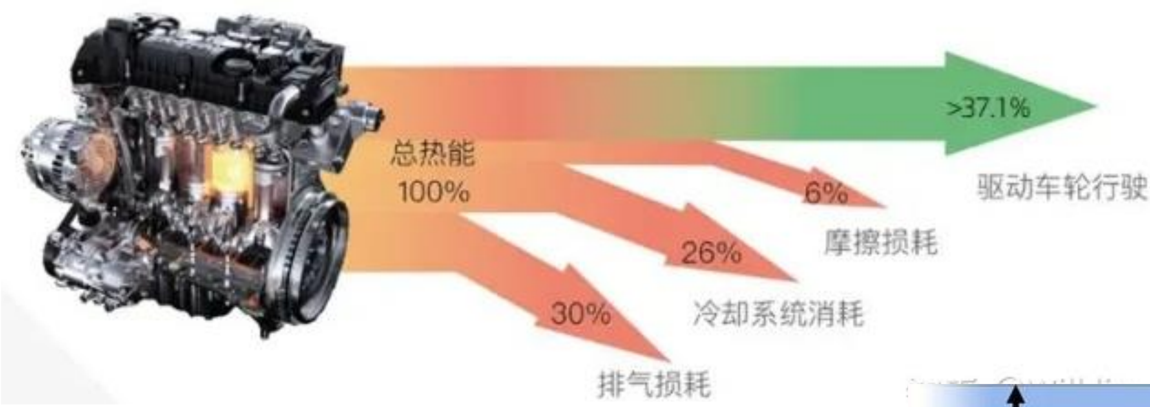


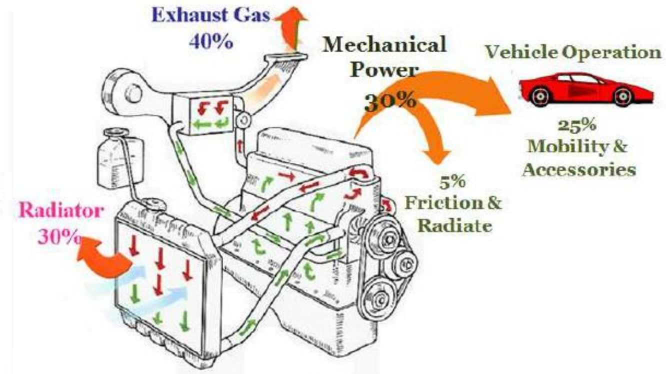
The global internal combustion engine market size was estimated at 169,603.7 thousand units in 2021 and is projected to register a compound annual growth rate (CAGR) of 9.3% from 2022 to 2030.

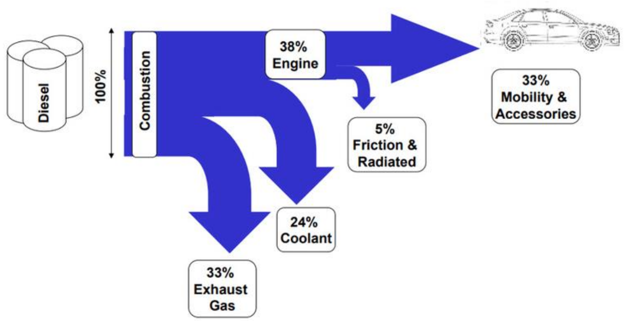
The requirements of ICE power system

- The automotive manufacturers are focused on developing efficient internal combustion engines which provide high returns on the manufacturing investments.
- Furthermore, technological advancements that increase IC engine fuel economy, emissions, and performance are expected to propel the market's growth during the forecast period.
- This growth can be attributed to the benefits offered by gasoline engines, such as they are efficient, cheaper, lightweight, and reducing emissions.
- **China is one of the primary factors driving growth of the market from the regional insight.**

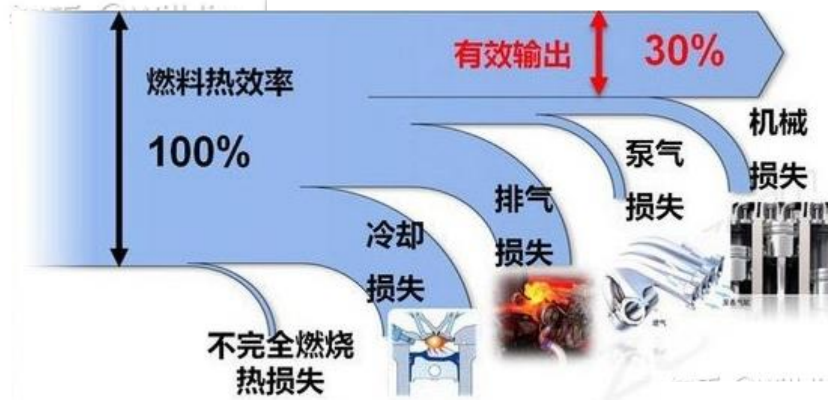
The requirements of ICE power system





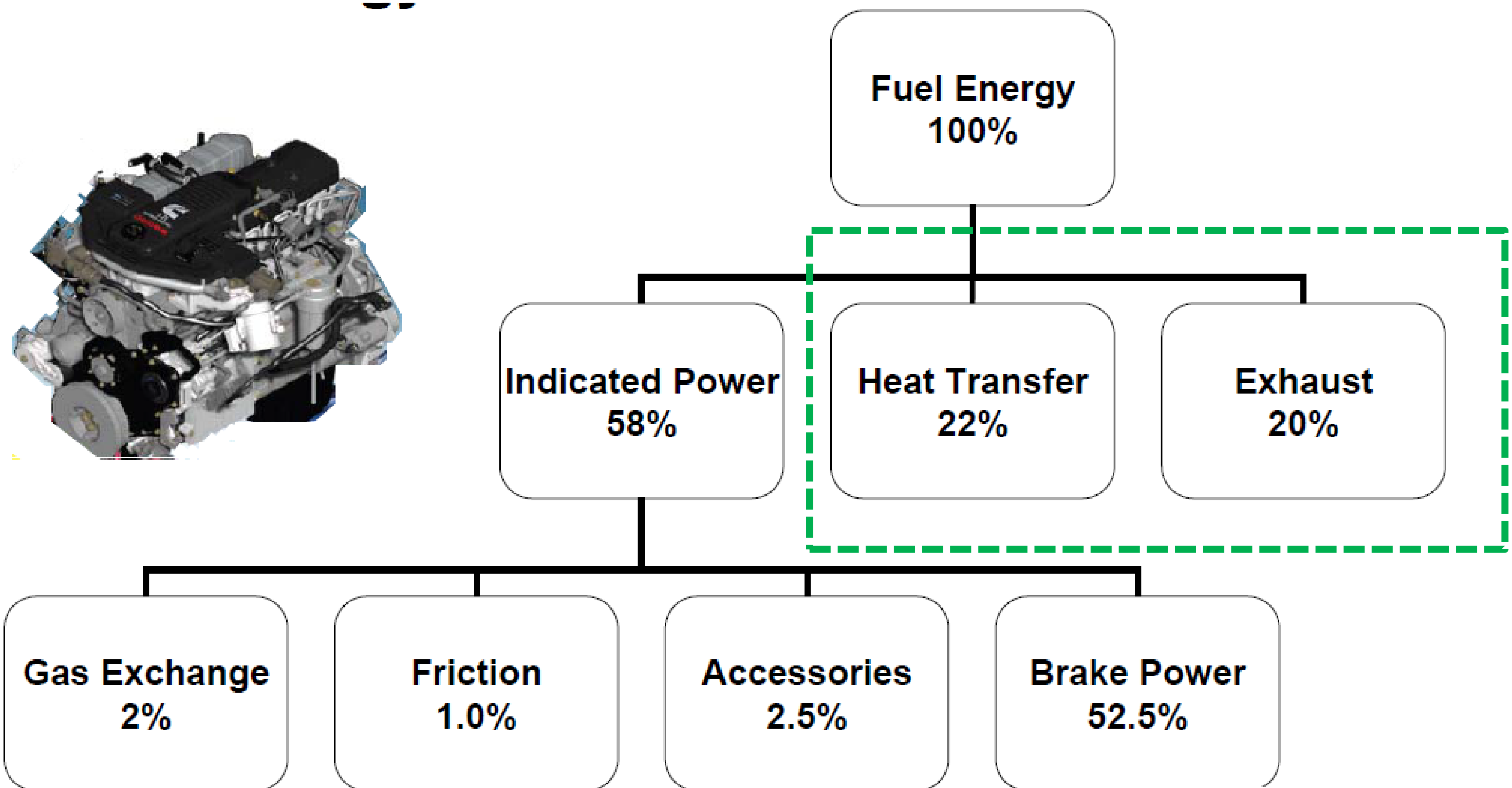


Diesel Engine (Light Truck or Passenger Vehicle)



Currently, a high level of the heat energy produced in internal combustion engines, whether gasoline or diesel, is wasted by heat loss in the forms of exhaust, coolant and mechanical ennergy.

Thermal barrier coatings for IC engine



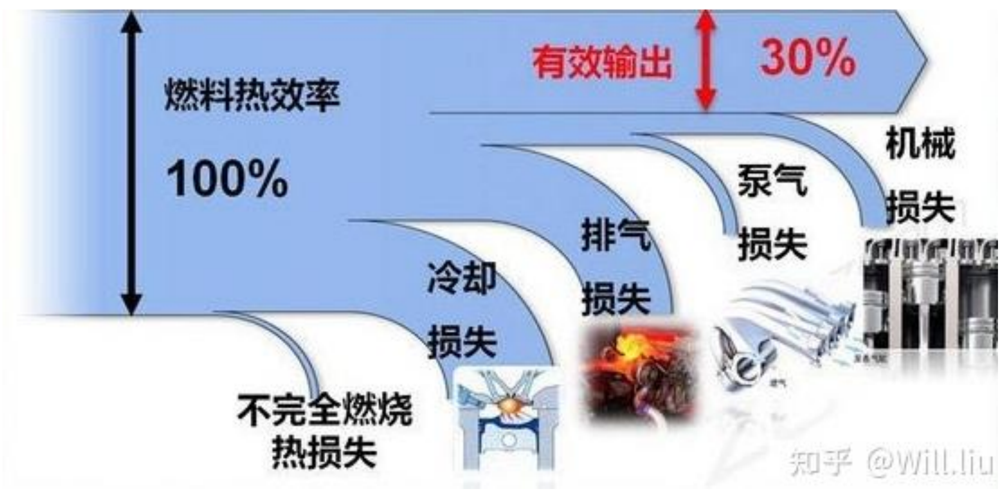
Gas Exchange
- Electrically assisted turbo
- EGR pump
- Variable valve actuation

Friction Reduction
- Piston and rings
- Bearings
- Surface treatment

Electrified Vehicle
- HVAC
- Water pump
- Oil Pump
- APU

Exhaust Energy Recovery
- Efficient PM Aftertreatment
  - lower soot loading
  - low pressure drop
  - regen controls/strategy
- Exhaust Port Heat Transfer (liners)

The requirements of ICE power system

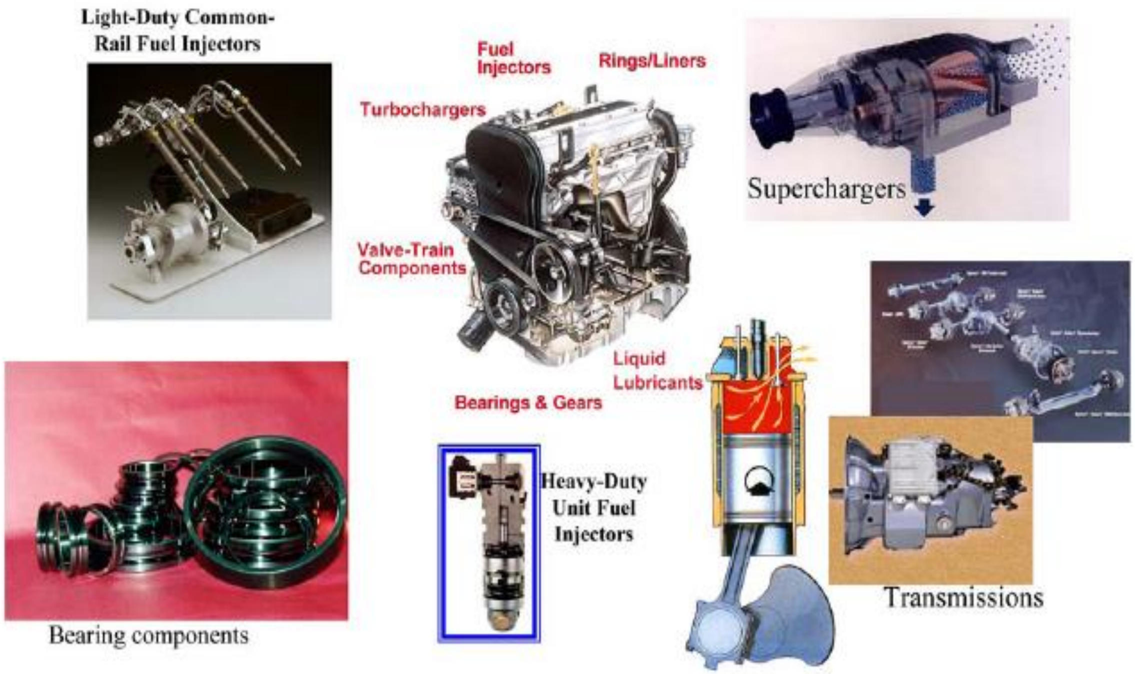


- Existing engines lose 20-25% of the fuel energy due to the irreversibility of unrestrained (non-equilibrium) combustion. The destroyed energy appears as heat that cannot be transformed into useful work.
- Achieving BTEs >60% will require radical changes to present engines including: cycle compounding; new engine architectures; and more constrained combustion reactions.
- Estimates for the maximum achievable peak BTE for modified architecture engines range considerably, but generally they were all < 85%.
- **Thermal efficiency of IC engine from Weichai increases to 51.21%, there is still a long way to go.**

《Summary Report on the Transportation Combustion Engine Efficiency Colloquium Held at USCAR, March 3 and 4, 2010》

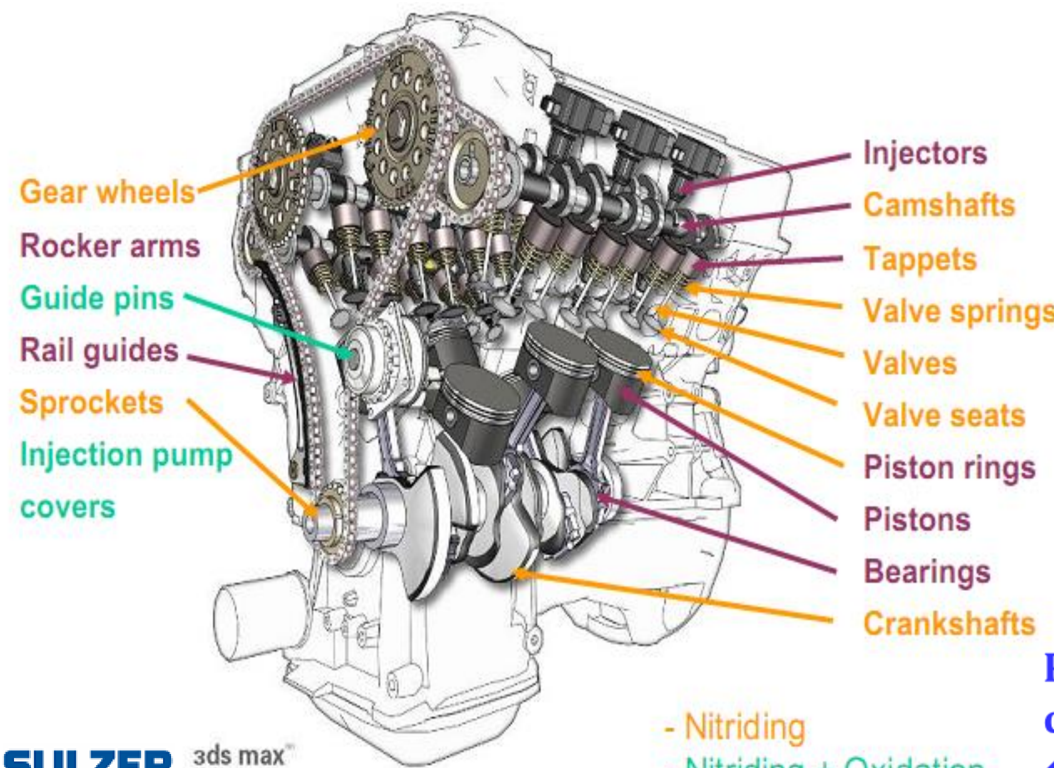
Reliable engineered coatings for IC engine

The 2nd International Conference of ICE Reliability Technology on 8th April 2013,



On behalf of Professor Liping Wang, I presented "***Development of Reliable Strengthening and lubricating Integration Technology for Engine Key Components***" as a Keynote speaker, focusing on Energy-saving Applications for Low-friction Carbon Coatings in Engines.

Reliable engineered coatings for IC engine



SULZER

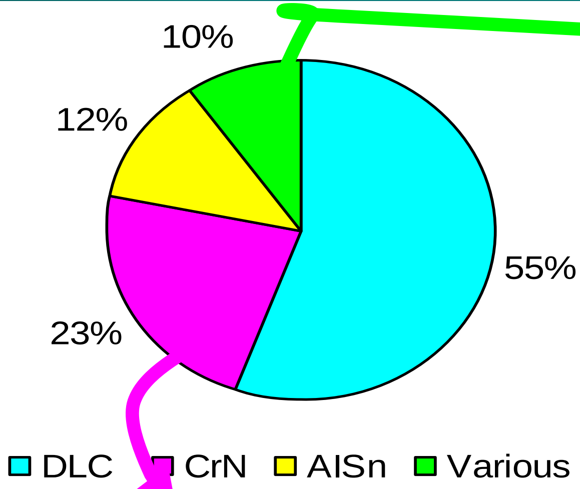
Sulzer Metco

- Nitriding
- Nitriding + Oxidation
- PVD

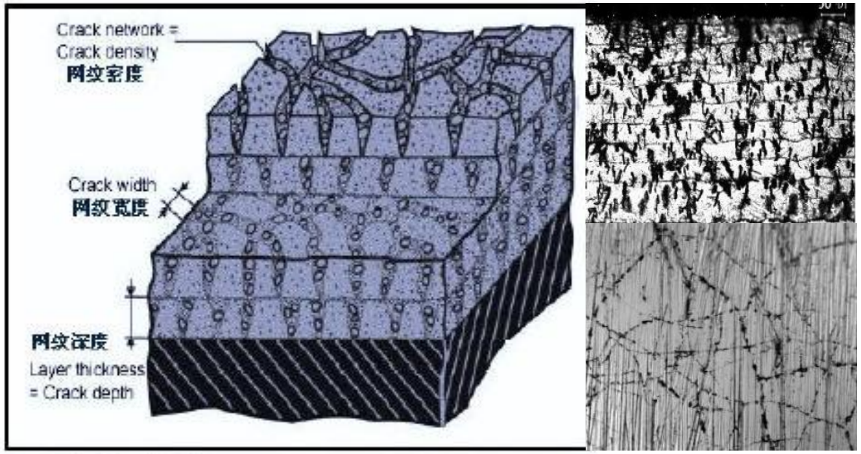
Performance Requirement of Key components in Engine:

- High Wear Resistance
- High Fatigue Resistance
- Low Friction
- High Precision
- Long Service Period
- High Operation Reliability

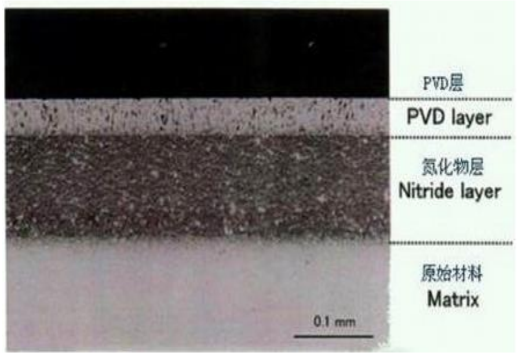
Reliable engineered coatings for IC engine



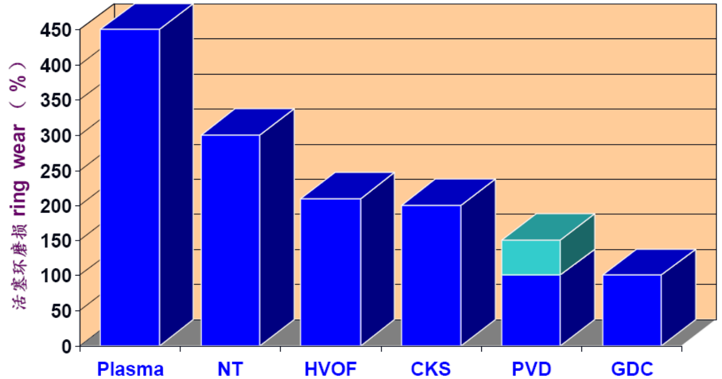
Cr-based Composite Plating Technology



PVD-CrN based coating technology



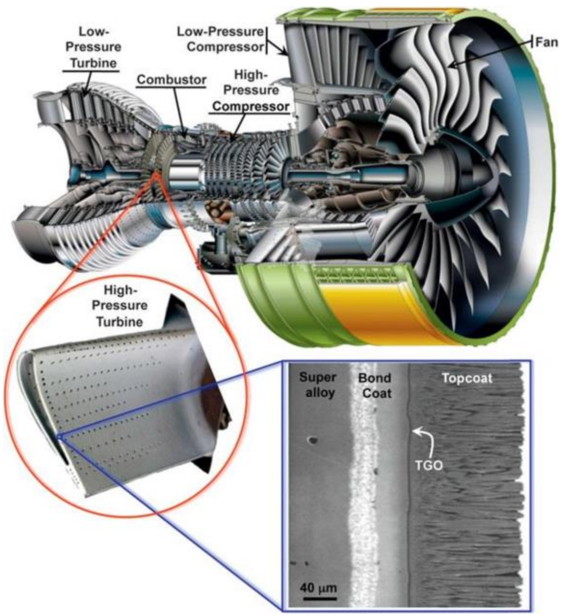
The Dominant Position in Diesel Engine Market

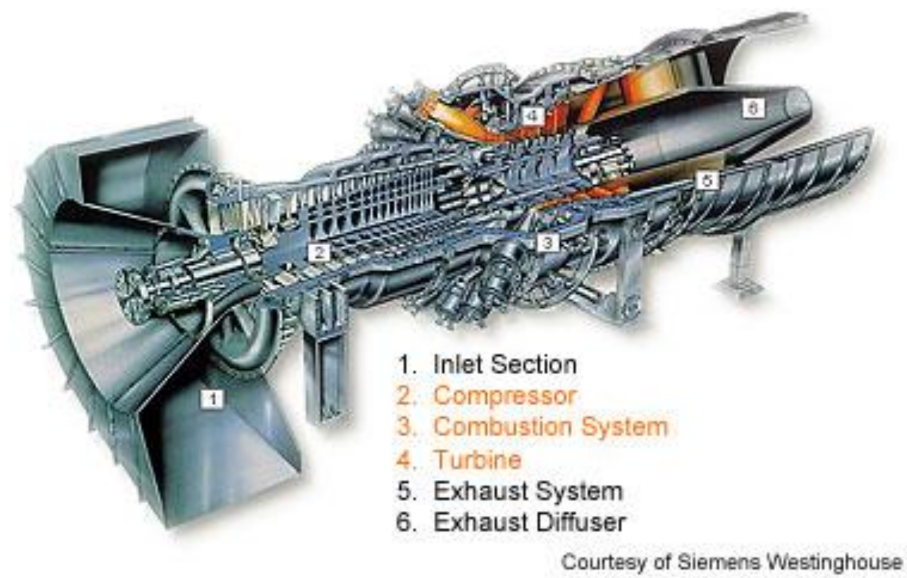


Those coatings are for reducing mechanical loss and increasing opreational reliability

Thermal barrier coatings for IC engine

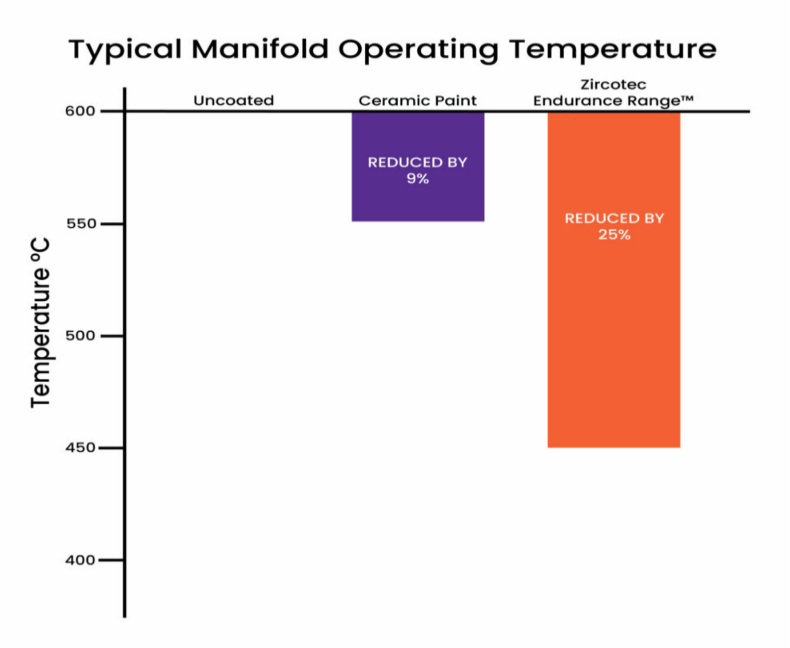
- Thermal barrier coatings enable the engines to operate at higer temperatures without raising the base metal temperatures using cooling systems inside the hot section components and thus, enhance the oeprating efficiency of the engine.
- Thermal barrier coatings perform the important function of insulating components, such as gas turbine and aeroengine parts, operating at elevated temperatures.
- Thermal barrier coatings propvides a temperature reduction of up to 300K in the surface of the superalloy components.



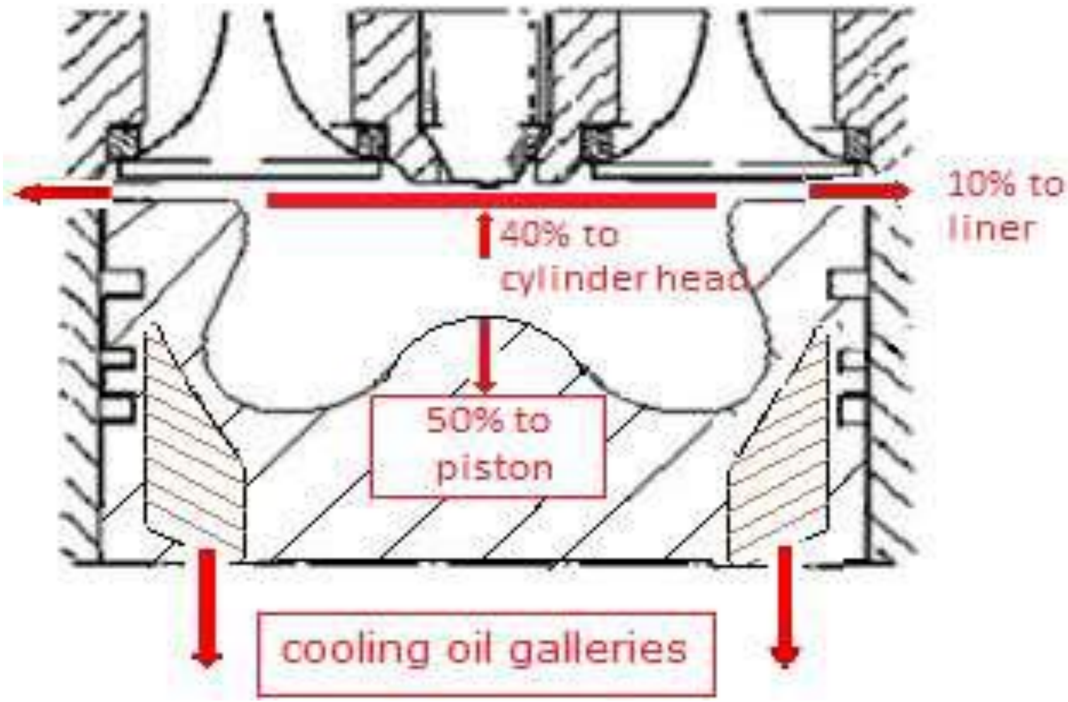


Thermal barrier coatings for IC engine

- Thermal barrier coatings have made possible the increase in operating temperature of gas turbines.
- Thermal barrier coatings are characterized by their very low thermal conductivity, the coating bearing a large temperature gradient when exposed to heat flow, further contributed to reducing metal temperature, thus improving the duration capability of components.



Thermal barrier coatings for IC engine

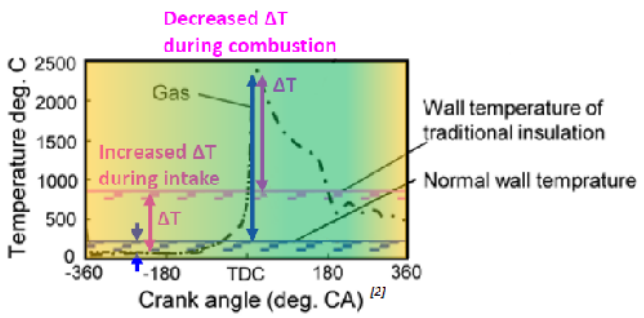


Piston head loses a high level of thermal effiency of about 12%.

How to reduce heat loss? Thermal barrier coating was adopted for heat insulation and components protection.

Thermal barrier coatings for IC engine

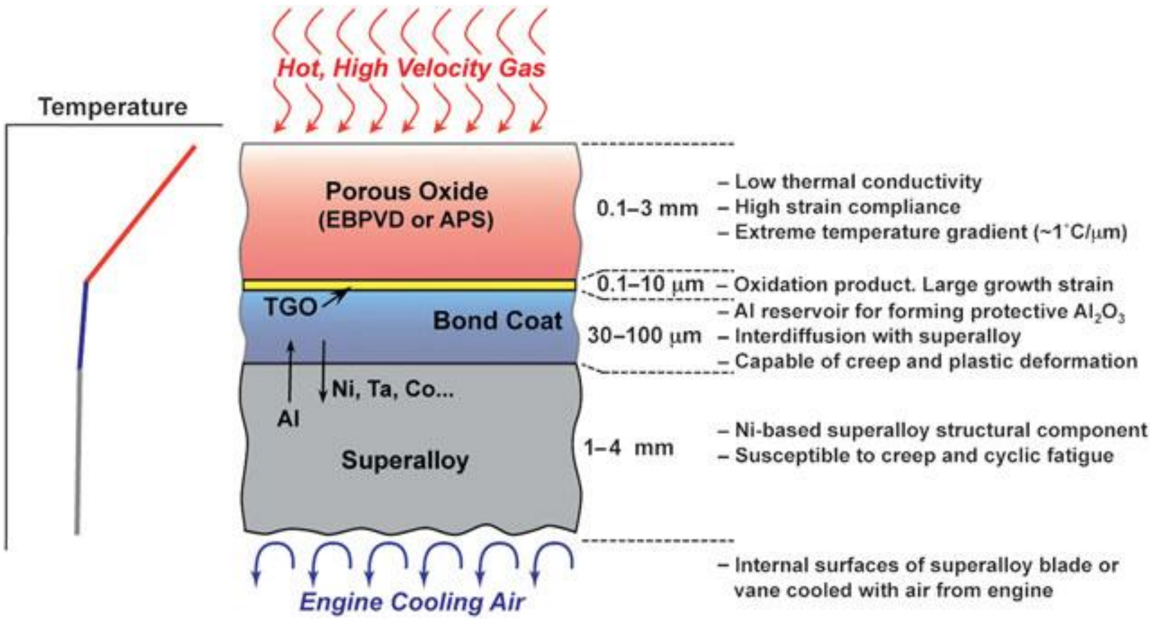
Nowadays, considerable effort is being invested in seeking new materials. the choice of TBC materials is requried to be fulfill the following parameters.



- ✓ low thermal conductivity
- ✓ high temperature capability
- ✓ phase stability during thermal cycling
- ✓ chemcial inertness with TGO and metallic bond coat
- ✓ thermal expansion match with metallic substrate
- ✓ good adherence b/w metallic bond coat and ceramic top
- ✓ mechanical properties to sustain strength in high pressure and high temperature
- ✓ good resistance to erosion
- ✓ low sintering during high temperature exposure.

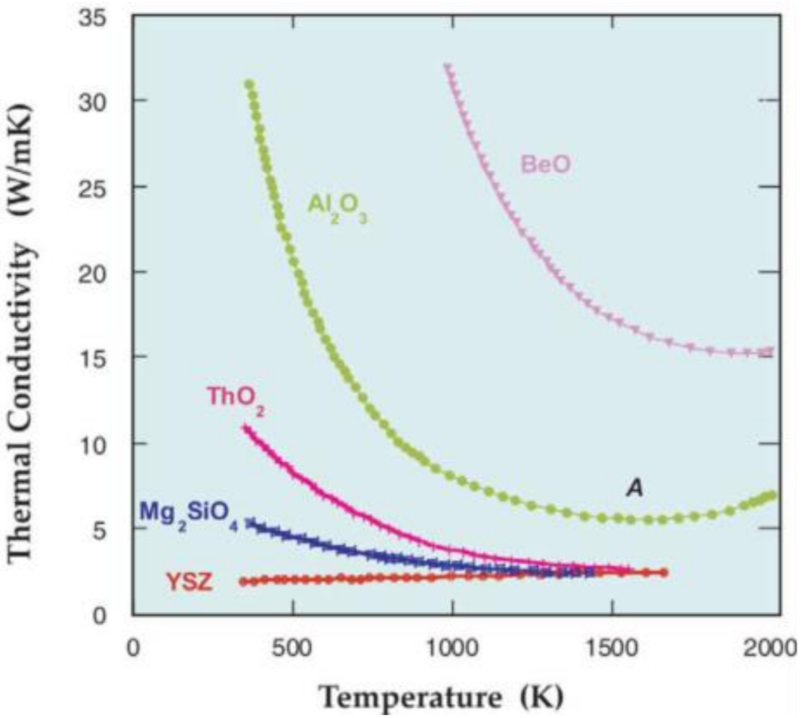
$$\dot{Q} = hA(T_{gas} - T_{wall})$$

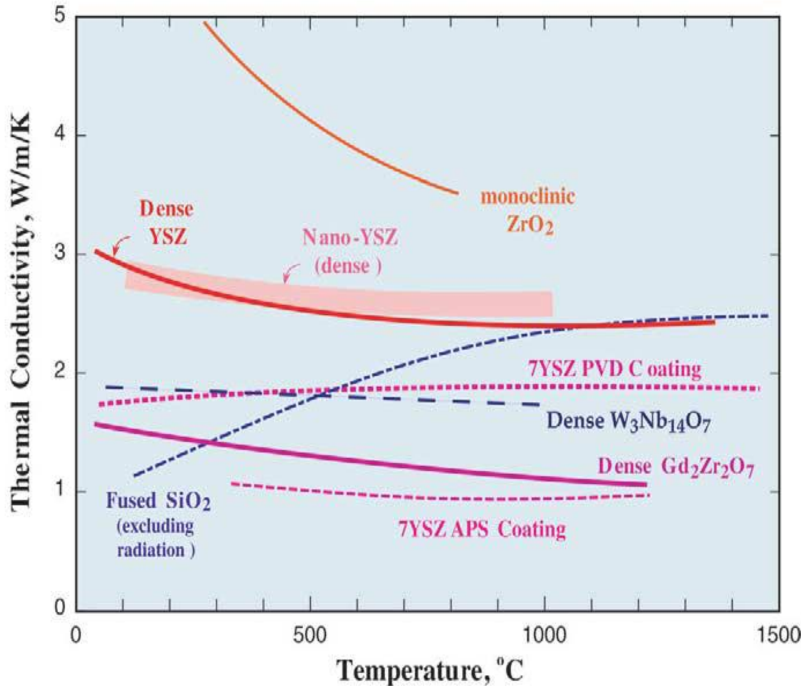
Thermal barrier coatings for IC engine



- **Coating has a gradient multilayer structure and composite in composition.**
- **The coating is tough and resistant to thermal shock.**
- **Refractory bricks are porous structure with the unique insulating fucntion of air gaps.**

Thermal barrier coatings for IC engine

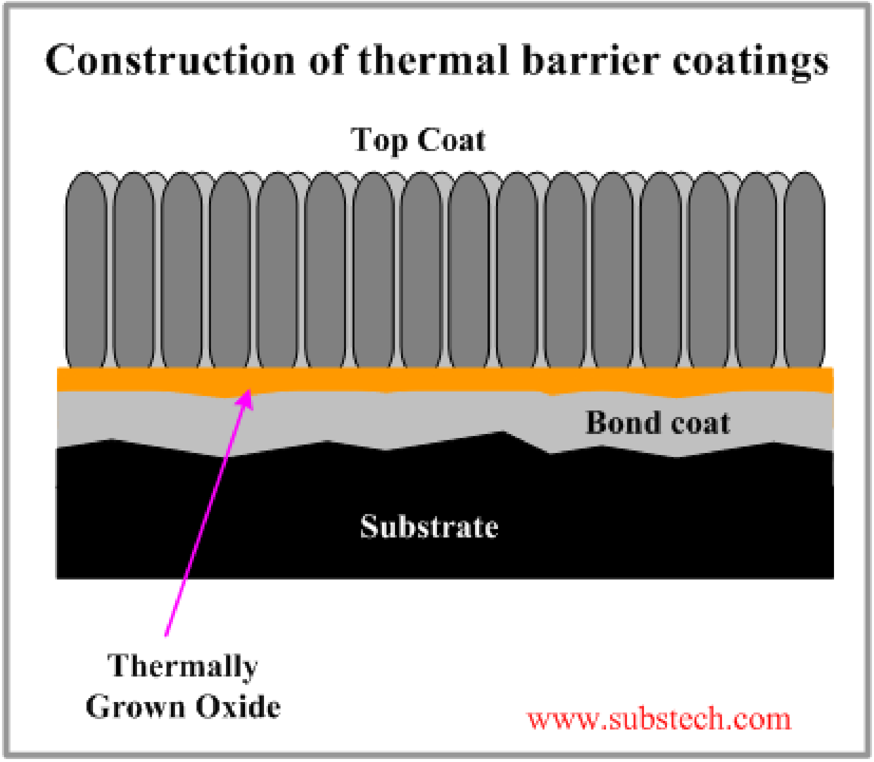




Materials	SiO_2	Al_2O_3	ZrO_2	SiC	Si_3N_4	$AlTiO_4$	Al alloy	Steel	Air
Thermal conductivity（W/mK)	1.5~7.6	27~37	2.09	270~490	2-155	0.78	121-151	13.7~43.6	0.01~0.04

From the view of thermal properties, those chemicals are compared in terms of thermal conductivity.

Thermal barrier coatings for IC engine



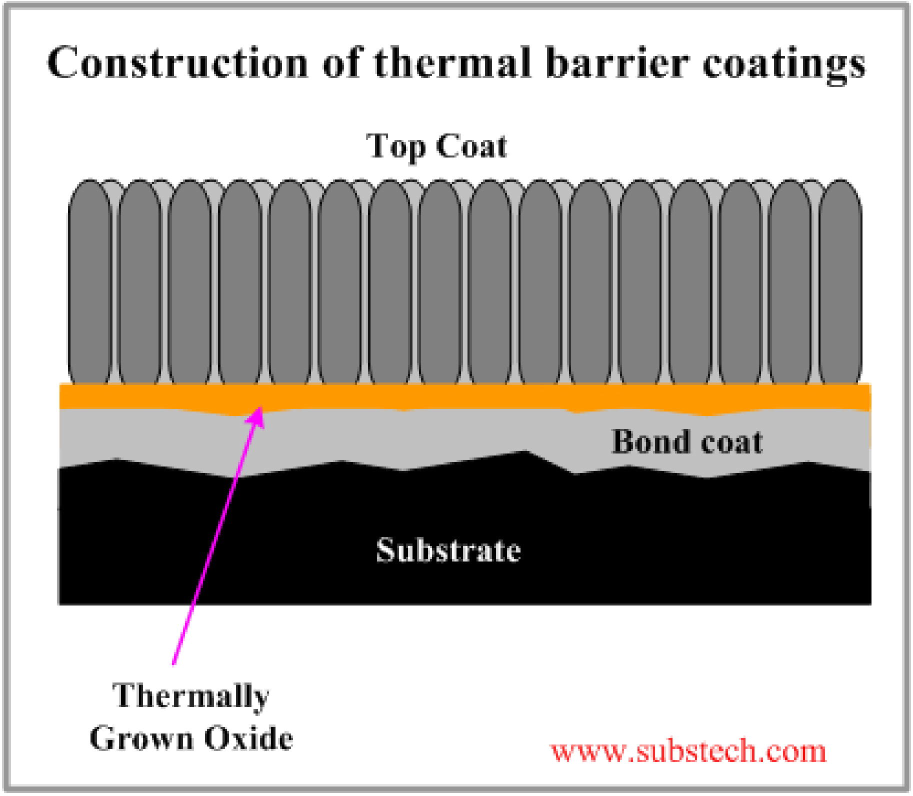
Metallic Bond Coat with a thickness of about 0.004” (0.1 mm).

The alloy of the bond coating is MCrAlY, where M is Ni, Fe or Co. Aluminum in the amount of about 10% in the bond coat is required for a formation of an oxide barrier (thermally grown oxide) on the interface between the bond coat and the ceramic layer.

The thermally grown oxide form as a result of oxidation of the bond coat with Oxygen diffusing from the combustion gases throghout the ceramic layer. The oxide layer is composed of α-Al2O3.

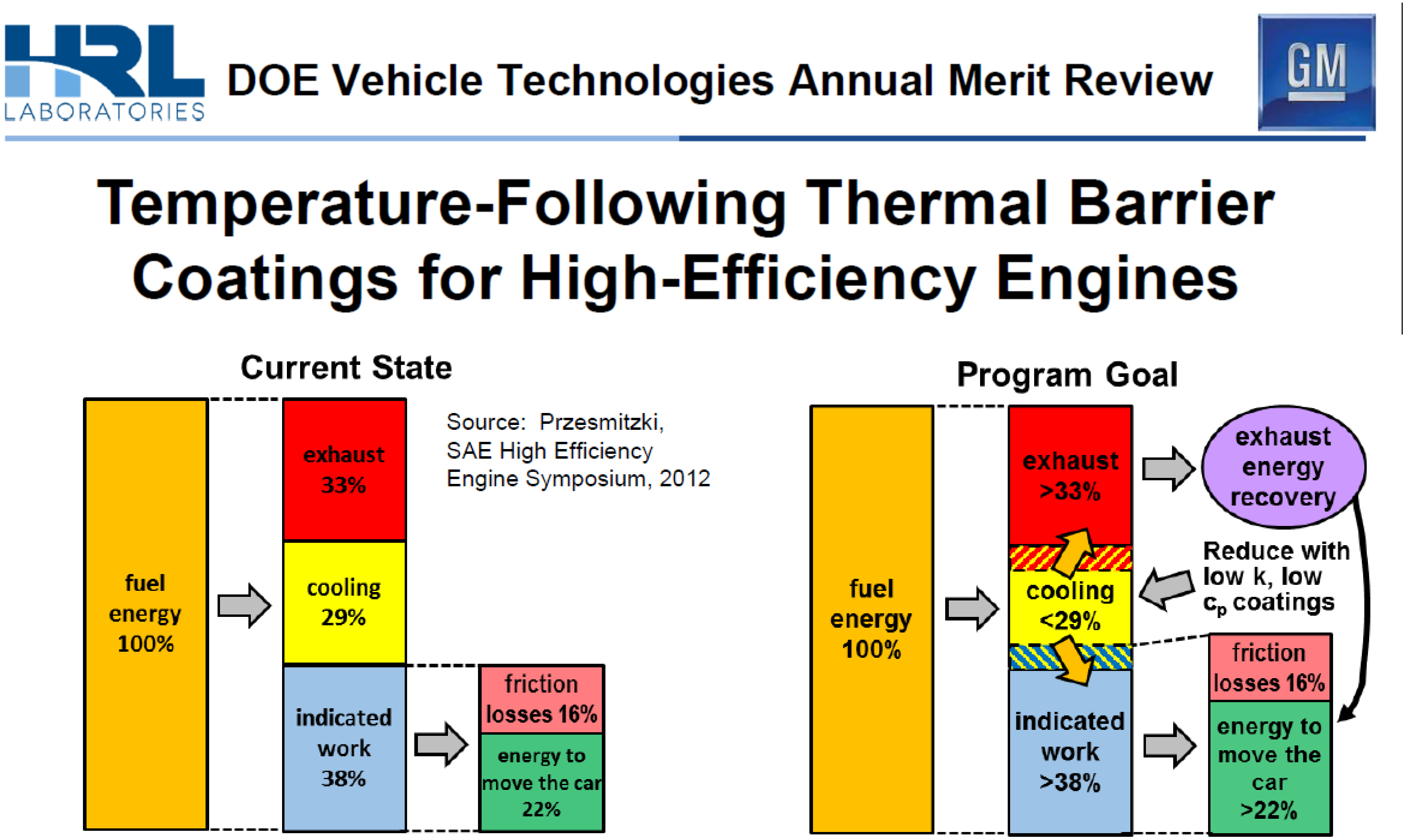
Function: The bond coat is an intermediate layer providing strong adhesion of the outer ceramic layer to the substrate surface. The bond coat also inhibits the diffusion of the substrate and the ceramic coating components.

Thermal barrier coatings for IC engine

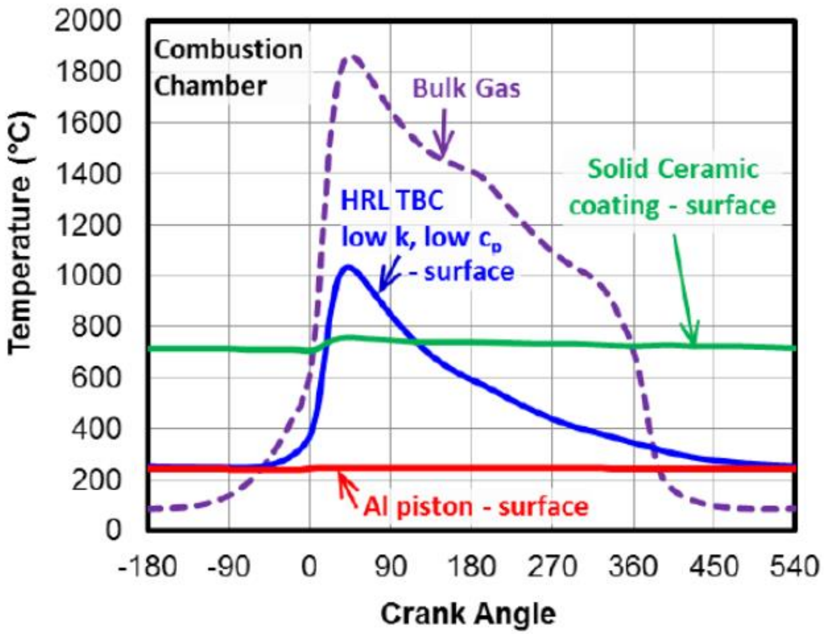


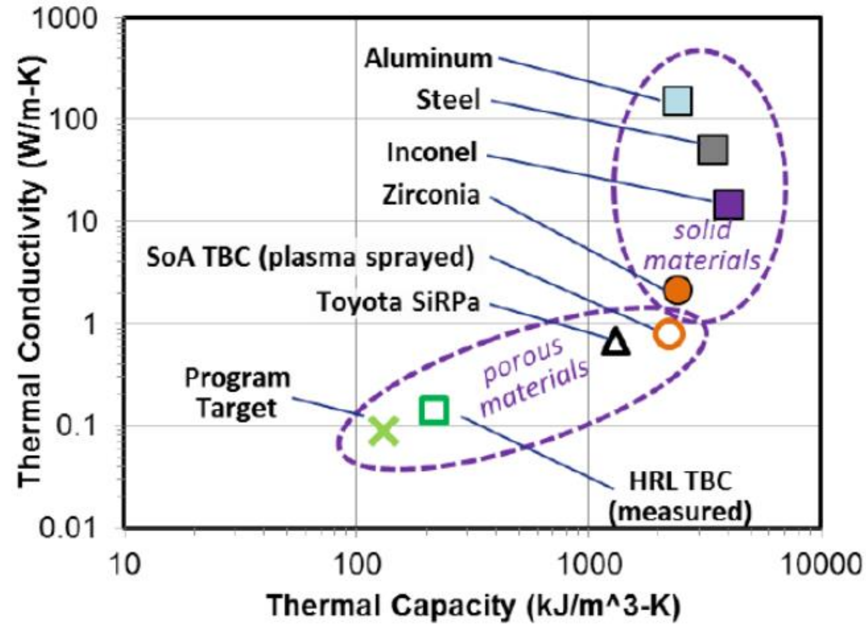
- Commonly 6-9% yttria (Y2O3) stabilized zirconia (ZrO2) with tetragonal crystal structure is used for building the outer ceramic layer.
- Yttria is added to zirconia in order to stabilize the tetragonal structure. Without a stabilizing agent tetragonal zirconia transforms to monoclinic allotrope stable at low temperatures.
- The volume change (about 8%) resulting from the tetragonal-monoclinic transformation causes internal stresses and cracking.
- Monoclinic zirconia is also undesirable because of its low Coefficient of Thermal Expansion and poor mechanica

Research advance in thermal barrier coatings



Research advance in thermal barrier coatings





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.

Research advance in thermal barrier coatings

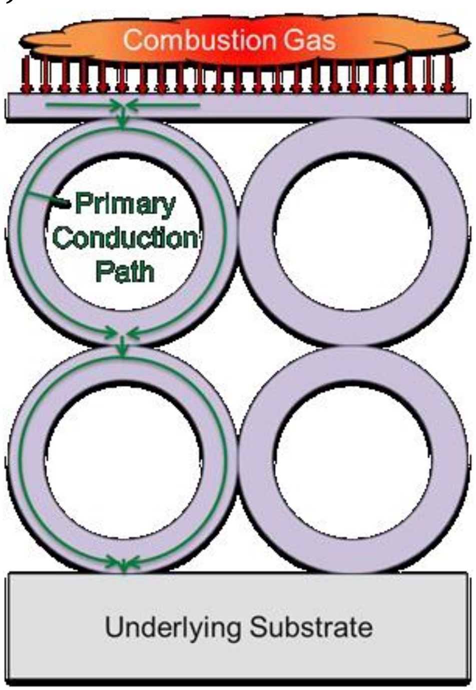
Objective: The objective of this project is to increase the efficiency of internal combustion engines by 4% to 8% with thermal barrier coatings within the cylinder and exhaust ports that add less than ~$250 in cost to a 4-cylinder engine. Benefits will be derived from:

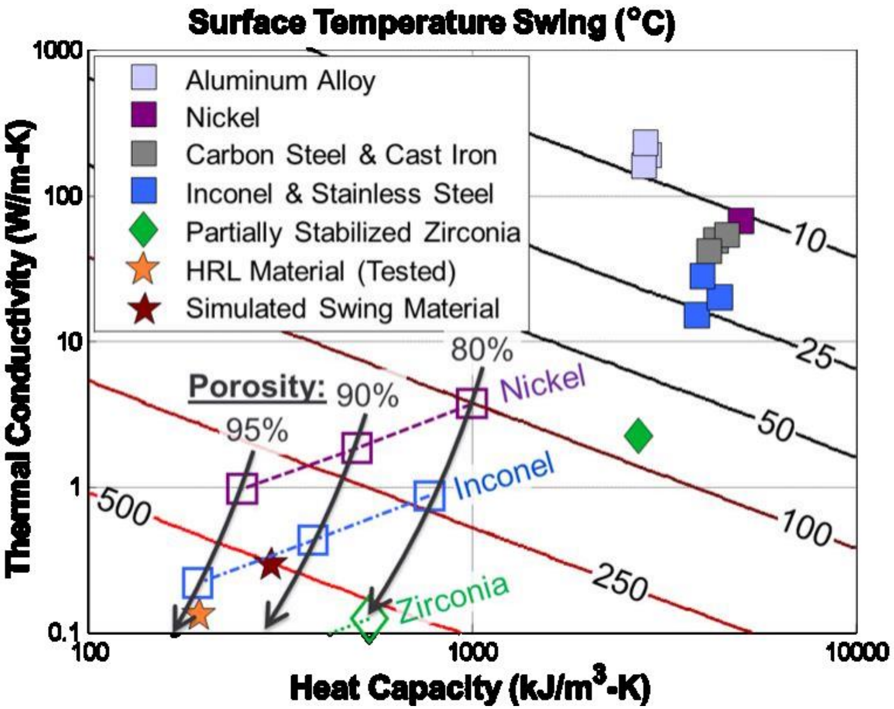
- In-Cylinder Efficiency improvements through lower heat losses
- Increased effectiveness of exhaust energy recovery and aftertreatment with higher exhaust temperatures under highly dilute conditions
- Lower parasitic losses due to reduced cooling demands

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.

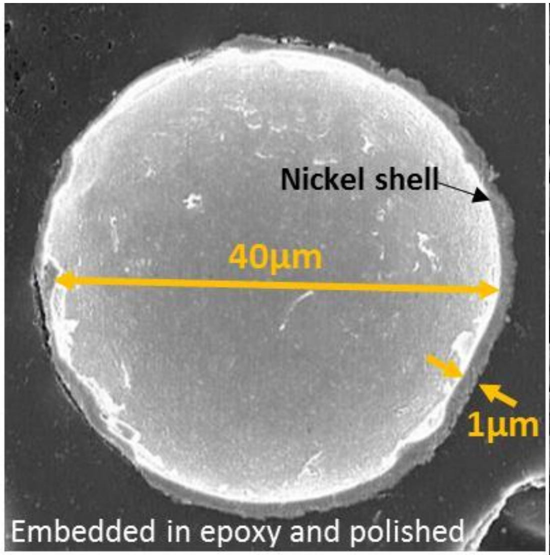
Research advance in thermal barrier coatings

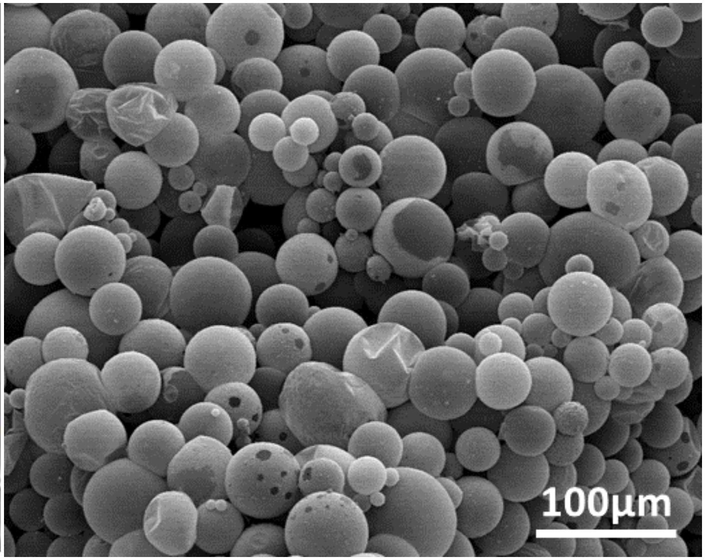
- Thermal conductivity and volumetric heat capacity were independently varied to determine the material properties necessary for maximizing the temperature swing. High levels of porosity were determined to be necessary to decrease both the volumetric heat capacity (density) and the thermal conductivity.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



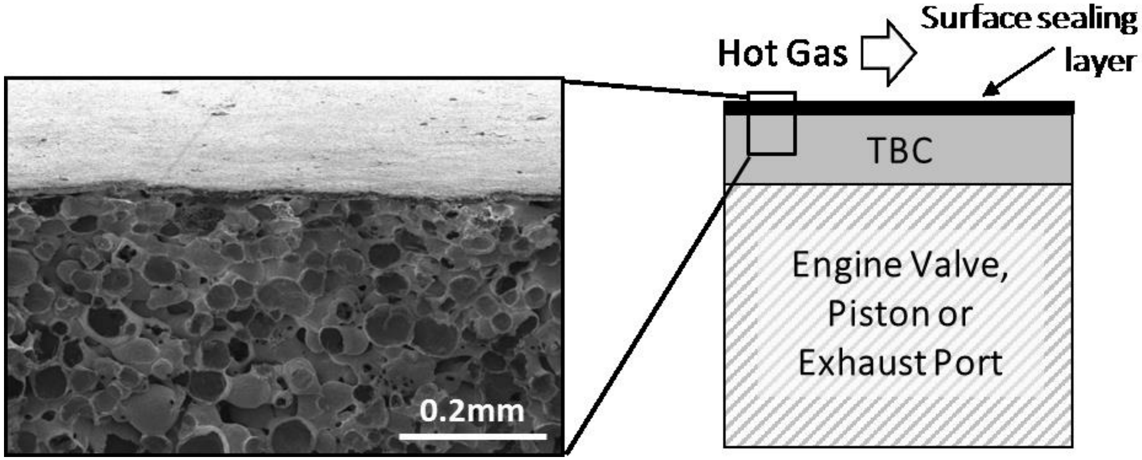


Research advance in thermal barrier coatings





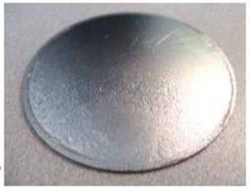
- Hollow nickel-alloy microsphere TBCs with an average diameter of 30 - 50μm and 1-2μm shell thickness.
- These microspheres can be sintered together to form high-temp metal matrices with over 90% porosity.

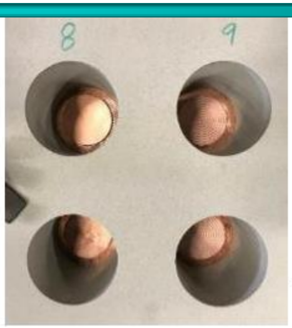


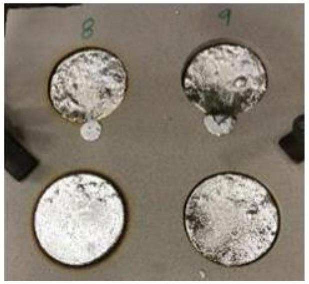
- ✓ Microsphere TBCs can be applied using dry molds, slurries, or air spraying.
- ✓ The surface must be sealed to avoid ingress of hot combustion gasses and unburned fuel vapor.

Research advance in thermal barrier coatings

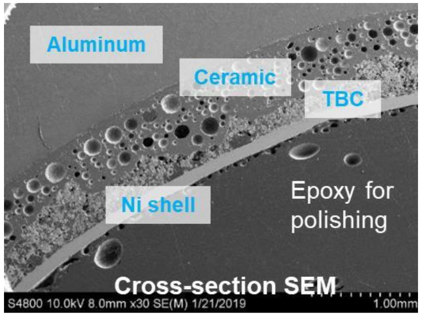
Steel components, such as the valve faces and steel pistons within the cylinder head are simpler. The Ni-alloy microspheres can sinter directly to the steel.







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



Research advance in thermal barrier coatings

•TBC structural quality, sealing methods, and valvetest:

–3rdgen. sealing layers: lower Cpceramic

–4thgen. sealing layers: nickel alloy foil seals

–Sulfur laced fuel tests to check permeability of sealing layer

•Piston integration and test:

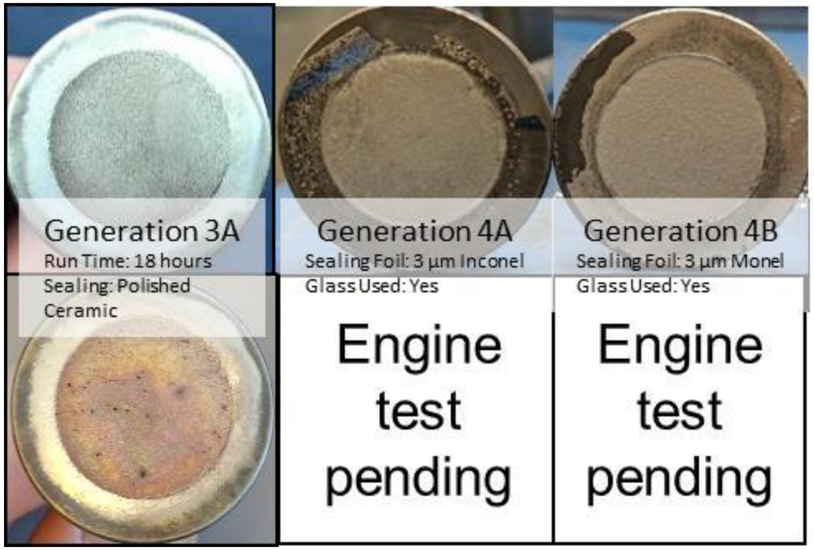
–Utilize successful sealing method developed for valves

–Fabricate steel pistons with sealed TBC for engine test

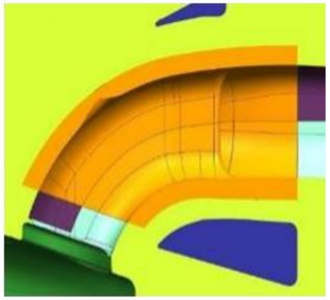
–Improve method for robust Al-Cu bond: casting

•Exhaust Ports:–Fabricate inserts specifically for casting

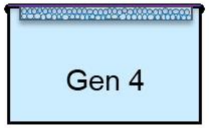
(with placement and transition features)



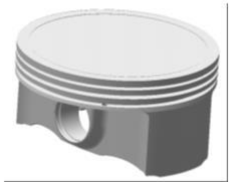
HRL supplied liner



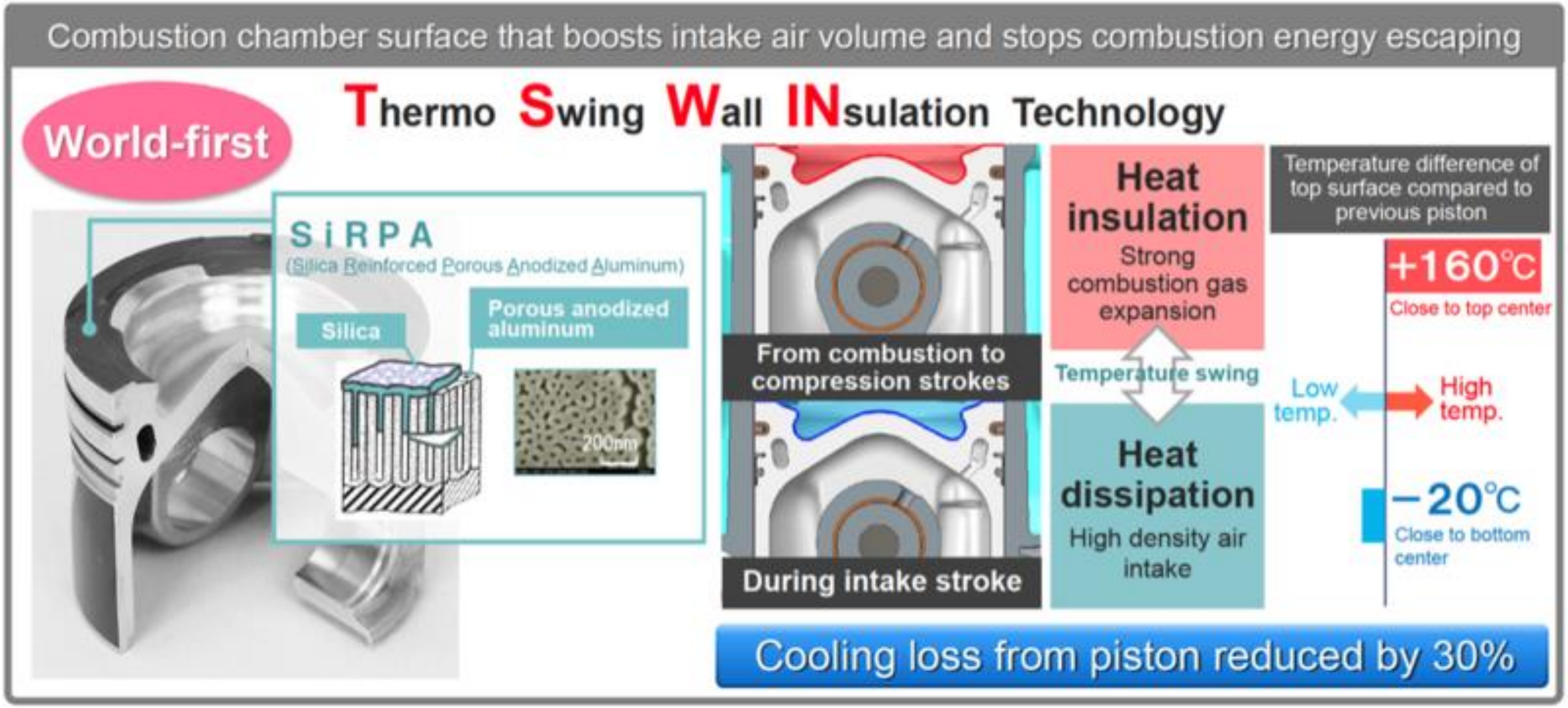
Model of a liner cast into the exhaust port



Bond: Sinter microspheres directly to steel



Research advance in thermal barrier coatings



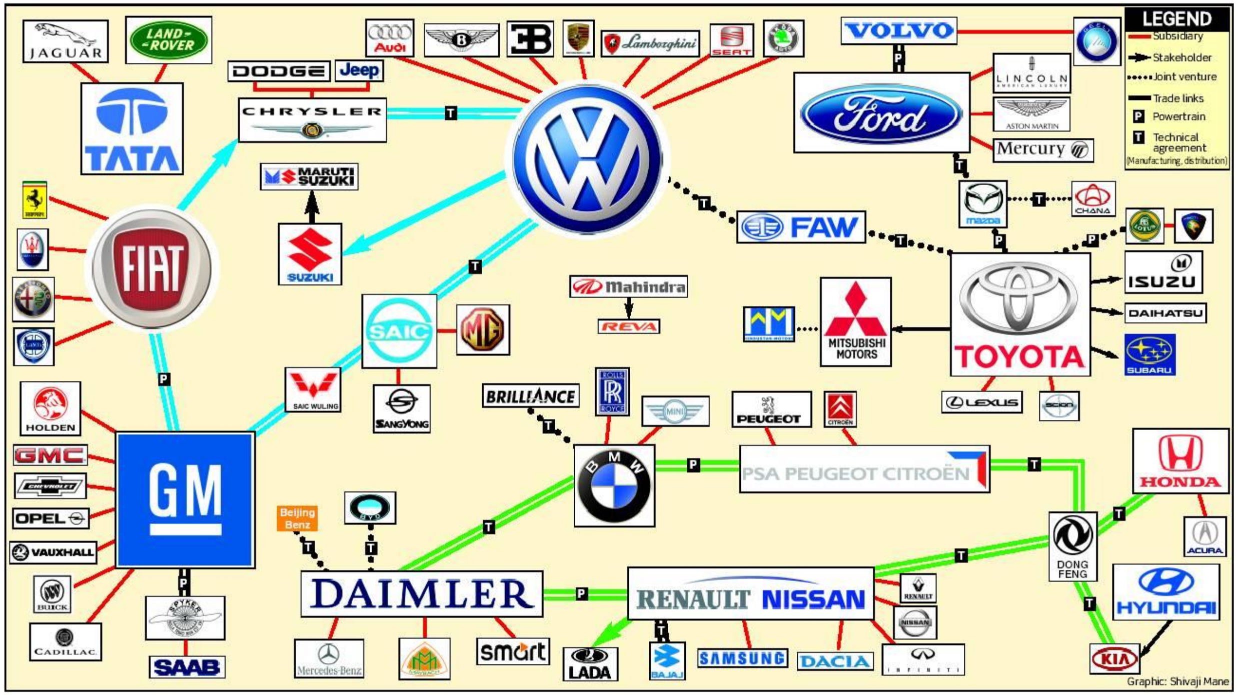
Thermal-Swing Wall Insulation Technology (TSWIN) in spark-ignitioin and compression-ignition engines was evaluated through computation. The rate of improvement of the thermal efficiency increases as the thermal conductivity and volumetric heat capacity fall.

Silica Reinforced Porous Anodized Aluminum (SiRPA)" with low thermal conductity, low volumetric heat capacity and high temperature durability.

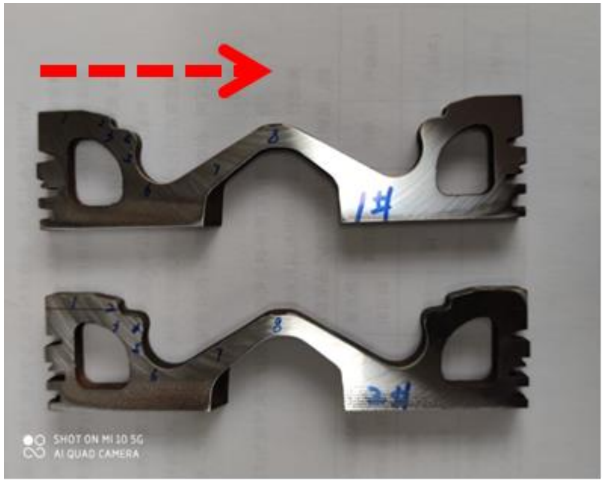
Challenge and prospective

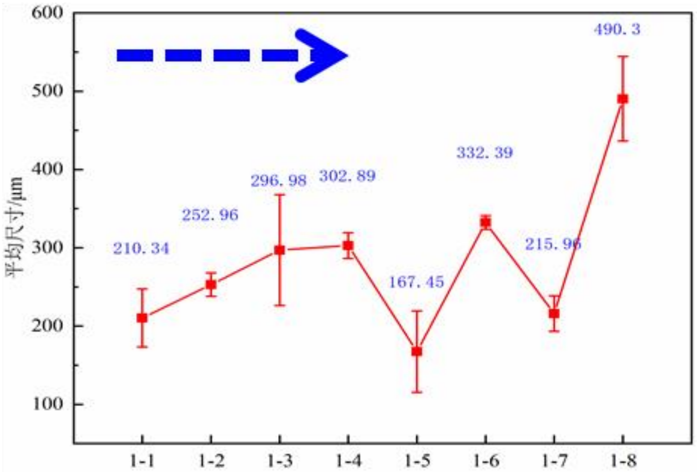
Thermal Barrier Coatings Market Players

Some of the main businesses present in the thermal barrier coatings market Air Products & Chemicals, Inc., ASB Industries Inc., Cincinnati Thermal Spray, Inc., Flame Spray Coating Co., H.C. Starck, Inc., Metallisation Ltd., MesoCoat Inc., Praxair Surface Technologies, Precision Coating, Inc., and The Welding Institute (TWI) Ltd. Significant strategic initiatives undertaken by global businesses include partnerships, new product launch, and acquisitions.



Challenge and prospective



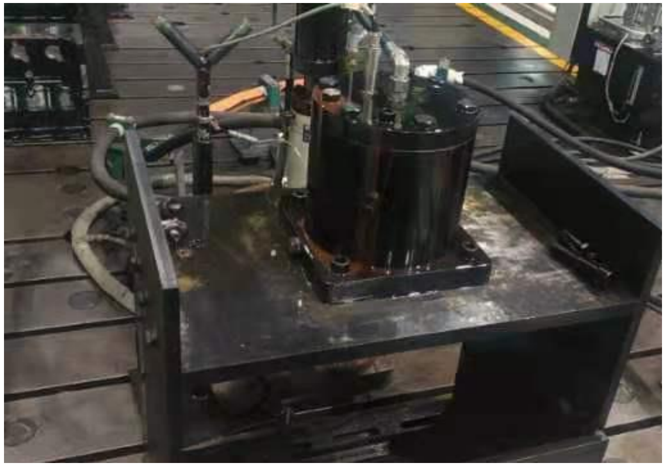


- **According to existing results and practical problems encountered, continuous improvement in bonding strength, Better thermal properties, and balanced mechanical strength are required for the next generation of TBC.**
- **Coating uniformity along with surface profiler of such piston head components is more challenging.**

Challenge and prospective

There is still lack of important values for TBC coating reliability in different components of diesel engine, thermal fatigue resistance and explosion pressure resistance, etc. With the help of Jiangbin Piston and Weichai Power Test Platform, the reliability of TBC coating is determined in service.

Thermal fatigue device



Anti-knock pressure setup in Weichai

Great thanks !!!!!!