UNDERSTANDING BORE SCORING IN AL-SI CYLINDER SYSTEMS

Charles Navarro

LN Engineering LLC

Abstract

The basic requirements for a cylinder lining are as follows: wear resistance for the liner, rings, and pistons, as well as resistance to galling and minimal oil consumption. In the beginning, internal combustion engines favored heavy, dense, thermally stable cast iron engine blocks for their durability in meeting these criteria. Besides being heavier than a modern all-aluminum engine, those made from cast iron provide poor cooling, limited performance, and are nowhere near as efficient or powerful as today's engines designed to meet tightening emissions and fuel economy requirements.[1] As aluminum has four times the thermal conductivity of cast iron or steel, it's the logical choice to overcome these thermal performance limitations.[2] However, Al-Si cylinder systems require special surface preparation and piston coatings, not to mention specific lubrication needs. Balancing these requirements has always been a challenge for engineers, especially when cost is the driving motivator for OEMs when utilizing liner-less cylinder technologies. Innovations built upon an all-aluminum engine designed to maximize efficiency and reduce emissions, coupled with hybrid technologies, will extend the life of the internal combustion engine as we transition to an all-electric future.

Keywords: Al-Si Alloys, Hypereutectic Aluminum Alloys, Internal Combustion Engine, Combustion Engine Cylinder Liners, MMC, Lokasil, Alusil, Bore Scoring, All-Aluminum Engine Block, Coatings, Piston, Piston Rings, Heat Transfer, Tribofilm, Boundary Lubrication, Wear Mechanisms, ZDDP, Friction Modifiers

---

[1] Improving Heat Transfer and Reducing Mass In a Gasoline Piston Using Additive Manufacturing. Reyes Belmonte, M. et al. SAE International 2015-01-0505.

[2] Reconditioning of Aluminum Blocks. KS Aluminum-Technologie GmbH.

Introduction

"YOU HAVE TO KNOW THE PAST TO UNDERSTAND THE PRESENT." - CARL SAGAN

Moving towards an all-electric future, innovations in engine design are required to extend the useful life of the internal combustion engine. As hybrid and full-electric propulsion systems are still evolving towards "mass electrification", innovations like Mercedes newest M139 engine will extend the life of the internal combustion engine by reducing global emissions and conserving resources.[3] The M139 is the world's most powerful four cylinder, producing 421 horsepower out of a series production turbo-charged 2.0 liter engine. At the heart of this efficient engine is a chill-cast aluminum crankcase, engineered for thermal and volumetric efficiency, strength, rigidity, and weight savings, which wouldn't be possible without the modern all-aluminum engine.[4]

Historically, cast iron was selected for use in engines due to low cost, castability, and durability. Cast iron or steel was even used for pistons in iron blocks up and through WWII, although high engine temperatures would cause the material to soften. W.O. Bentley, a British engineer who designed engines for automobiles and aircraft, as well as founder of Bentley Motors Limited, came to the realization that even though aluminum has a lower melting point, its much higher thermal conductivity could help keep the pistons cool enough to prevent softening. Besides providing cylinder sealing and oil control, piston rings are responsible for transferring heat away from the piston through the cylinder wall and into the coolant, to keep the piston from melting down.[5] With 70%[6] of the combustion chamber heat transferring from the piston through the top (compression) piston ring to the cylinder bores, increased end gaps must be provided to prevent ring-butting in high performance engines with iron bores due to increased temperatures.

Most modern engines also employ piston squirters to aide in piston cooling and control expansion rates while maintaining tight piston to cylinder clearances for quiet operation. An all-aluminum engine will provide a more efficient path to transfer the heat away from the pistons and rings, supporting elevated pressure and temperature levels required of modern, downsized and turbocharged high performance engines, like the M139.[7] The higher thermal conductivity of aluminum over cast iron or steel provides for lower cylinder surface temperatures, reducing hot spots and the likelihood of self-ignition.[8]

---

[3] Extending the ICE Age. SAE International July/August 2019.

[4] Mercedes AMG extracts world-record power from new four-cylinder engine. SAE International July/August 2019.

[5] Piston to Cylinder Wall Heat Paths. Cameron, Kevin. Cycle World. https://www.cycleworld.com/2013/12/05/ask-kevin-why-rings-are-the-highest-flowing-heat-path-from-piston-to-cylinder-wall/

[6] Piston and Piston Rings. University of Windsor. https://courses.washington.edu/engr100/Section_Wei/engine/UofWindsorManual/Piston%20and%20Piston%20Rings.htm

[7] Heat Transfer Versus PIston-Ring Endgap. Hot Rod Network. https://www.hotrod.com/articles/heat-transfer-versus-piston-ring-endgap/

[8] Introduction to Internal Combustion Engines. Stone, Richard. SAE International. Pg 404, 431-432.

Providing better temperature control for the piston at the crown and top ring land helps to reduce the engine's sensitivity to knocking and pre-ignition, allowing for increased compression ratios and boost levels.[9]

Similarly, all aircooled VW and many aircooled Porsche models used cast iron for its cylinders. One of the major problems with the use of cast iron for cylinders in an aircooled engine is that they can easily become thermally overloaded. Porsche's 911 engine, at a maximum displacement of 2.4L, produced about 22 horsepower per cylinder, when fitted with cast iron cylinders. Even Porsche realized that cast iron was not the optimal cylinder material. They eventually turned to aluminum cylinders for their aircooled engines, just like engineers switched from cast iron and steel to aluminum for pistons many decades earlier for its significantly improved thermal conductivity.[10]

In the evolution of the watercooled internal combustion engine, the next logical step was to go to an aluminum engine block. Manufacturers have turned to aluminum for reducing engine weight, with many retaining iron sleeves or liners for simplicity and durability. With the downsizing of engines and addition of forced induction, the push for ever increasing efficiency has led to problems with thermal optimization of engines. As engine output increases, the center to center distances between cylinders when using iron sleeves has to be increased to provide for sufficient liner thickness, maintain strength and rigidity between the bores, control temperatures, and ensure head gasket sealing on an aluminum engine block fitted with iron sleeves. Engine block castings are also subject to residual stresses with potential functional drawbacks in long-term operation that can lead to bore geometry issues like ovality and taper.[11] This can be further compounded by dissimilar expansion rates between cast iron and aluminum alloys, leading to deformation and local heat transfer issues. To make lighter, smaller, higher output engines, another solution other than fitting iron sleeves would be needed to allow cylinder inter-distances to be reduced to less than 5mm for both packaging and thermal considerations.[12]

Although Porsche used aluminum cylinders in the 1960s with Chromal or Ferral cylinder coatings, the first mass-produced all-aluminum watercooled engine without iron sleeves and uncoated aluminum cylinder bores was in 1971 with the Chevrolet Vega. It utilized Reynolds A390, more commonly known as KS Kolbenschmidt Alusil with iron-clad pistons.[13] Eliminating iron sleeves overcomes the problem of using different materials caused by dissimilar Young's modulus and expansion rates.[14] Mahle's Nikasil and Kolbenschmidt's Galnikal cylinder bore electro-platings have also been used for coating bores in aluminum blocks successfully for decades by Porsche, BMW, Jaguar, Ferrari, and others. The resulting nickel silicon carbide coating provides an extremely durable wear surface. It has 3 to 10 times less wear than cast iron cylinder bore surfaces due to its extreme hardness and oleophilic nature.[15] However, due to its high cost, complexity, and environmental concerns over hazardous chemicals used in its production, alternatives to these electro-platings are needed.

---

[9] Improving Heat Transfer and Reducing Mass In a Gasoline Piston Using Additive Manufacturing. Reyes Belmonte, M. et al. SAE International 2015-01-0505.

[10] Reconditioning of Aluminum Blocks. KS Aluminum-Technologie GmbH.

[11] Reconditioning of Aluminum Blocks. KS Aluminum-Technologie GmbH.

[12] The Aluminum Automotive Manual. Version 2011. European Aluminium Association.

[13] New Honing Options For Hypereutectic Aluminum Bores. Tim Meara. Modern Machine Shop Online. 9/18/2008.

[14] Metal Matrix Composites in Industry: An Introduction and a Survey, Volume 1. Alexander Evans, Christopher San Marchi, Andreas Mortensen.

[15] Nikasil and Alusil. John Goodman. Engine Professional Oct-Dec 2008.

Beyond the Vega - 50 years of Al-Si engines

Today's liner-less aluminum engine blocks allow for smaller high output engines with reduced weight, tighter bore centers, and larger bore sizes than previously possible with a similarly sized iron sleeved aluminum block. This allows for an increase in displacement and output without the need for increased cooling system capacity.[16] Improved thermal conductivity also allows water jacket depths to be reduced 30 to 65%, reducing engine weight and cooling system volume, which improves engine warm-up and reduces emissions.[17]

The long term durability of aluminum engines has always been a concern for manufacturers. In Porsche's own testing, cylinder deformation was much lower with Alusil than earlier cast iron cylinders and engine blocks. Extensive testing by Porsche with air-cooled 2.7 and 3.0 engines as well as their water-cooled 944 and 928 engines showed that early Alusil cylinders did not exhibit scoring of cylinder walls or pistons. Although wear was twice as high as cast iron, it was still within acceptable wear limits, and the use of hypereutectic aluminum alloys in the construction of both air-cooled and water-cooled engines allowed engineers to overcome thermal and geometric limitations.[18]

Alusil hypereutectic (Al-Si) engine blocks are low pressure die cast from hypereutectic aluminum with 17% silicon content. The silicon particles in the bore are exposed through an activation process and the piston skirts are coated with iron or other dissimilar material to prevent aluminum to aluminum contact. This eliminates the need for iron sleeves. Although Chevrolet's Vega was not successful, it paved the way for later engines based on this technology. For example, with the 944, Porsche was able to get 30% more power and 25% increased displacement over the 924's cast iron engine it replaced, without any added weight.[19]

Besides casting blocks in Alusil, all-aluminum liner-less blocks can be manufactured with heterogeneous cast-in hypereutectic aluminum sleeves such as Albond and Silitec, just to name a few. In the case of the Boxster, Porsche's first production water-cooled horizontally cooled engine was also the first to utilize Kolbenschmidt's "squeeze-cast" Lokasil I MMC (metal matrix composite) cylinder technology.

Asian automakers developed their own liner-less engine blocks using selective reinforcement and MMC cores. Starting in 1990, Honda first introduced a carbon fiber and alumina reinforced aluminum engine block[20] with the Prelude Si and later performance models including the NSX and S2000. Toyota's first all aluminum MMC engine was the 2ZZ-GE which also used preforms with ceramic alumina-silica fibers and mullite particles[21] rather than Lokasil's selective reinforcement with silicon and alumina.[22] Pistons are

---

[16] The Boring Truth: Everybody's got ideas about treating cylinder bores; strong ideas. Wards Auto. April 1, 1999.

[17] Reconditioning of Aluminum Engine Blocks. MSI Motor Service International.

[18] The new Porsche 944 4-cylinder aluminum engine. Paul Hensler. Porsche AG. SAE International.

[19] The new Porsche 944 4-cylinder aluminum engine. Paul Hensler. Porsche AG. SAE International.

[20] Replacing the Cast Iron Liners for Aluminum Engine Cylinder Blocks: A Comparative Assessment of Potential Candidates. John Lenny Jr.

[21] MMC All Aluminum Cylinder Block for High Power SI Engines. Toshihiro Takami, et al. Toyota Motor Corp & Toyota Central Research and Development Labs, Inc. SAE Technical Paper Series 2000-01-1231.

similarly electro-chemically treated with an Fe-P (Iron and Phosphorus) plating for wear resistance. Toyota's first engine using MMC technology was used successfully in performance vehicles by Toyota and also by Lotus in the Exige and Elise.[23] Toyota found they were able to produce 26.17% more horsepower and 4.65% more torque with the same 1.8 liters of displacement by eliminating the cast iron liners.[24] Although all the above mentioned engines are all-aluminum and linerless, that's where the similarity ends.

With Lokasil, blocks are cast using a quasi-monolithic high pressure die casting process where freeze cast sintered cylinder liner preforms, manufactured by Ceram Tec AG,[25] are infiltrated with molten under-eutectic (low silicon content) aluminum at 900-1000 bar of pressure. These inserts provide selective reinforcement with a localized high silicon hypereutectic cylinder bore composition and allows the rest of the engine block to be cast from lower silicon content aluminum. The Lokasil process results in reduced cost and greater ease in manufacturing over monolithic low pressure die cast Alusil blocks.[26] [27] The 911 and 3.4 Cayman S models received Mahle supplied forged pistons with an iron skirt coating called Ferrostan, later replaced by Ferroprint. Boxster base and S models came with cast Kolbenschmidt pistons that utilized their Ferrocoat process for the skirt coatings.

The Lokasil process was new for Kolbenschmidt and Porsche was their first OEM customer for blocks cast using this new process. They had their share of production issues initially with Lokasil blocks, with a scrap rate of 35-40% according to Motor-KRITIK. Many required re-working, including sleeving (later leading to slipped-sleeve failures), to keep up with production.[28] As the technology progressed, several improved versions of Lokasil were used by Porsche - Lokasil II with the 3.6 in 2002 and Lokasil III[29] with the introduction of the M97 engine in 2006, ending in 2008.

In the Lokasil I process, the aforementioned freeze-cast liner preforms containing the silicon matrix with particle sizes ranging from 30 to 70 µm are suspended in a synthetic resin bond. The inorganic binder holds the silicon particles in suspension until the under-eutectic aluminum casting alloy (AlSi9Cu3) infiltrates the preform during the casting process. With Lokasil I, preforms contained 5-7% fiber (alumina) and 20% silicon content. However, with Lokasil II, silicon content was increased to 25% and alumina was replaced by an inorganic binder of less than 1%; silicon particle sizes were increased to a maximum size of 120 µm.

Porsche to this day remains the only manufacturer to have utilized Kolbenschmidt's Lokasil, before returning to Alusil with the introduction of the MA1 (also referred to as the 9A1) engine in 2009. Nikasil was retained for the Mezger engine until retired by Porsche, which coincided with the introduction of the 991. In 2016, Porsche announced use of ultra-thin Rotating Single-Wire (RSW) iron lined bores (with coating

---

[22] Metal Matrix Composites in Industry: An Introduction and a Survey, Volume 1. Alexander Evans, Christopher San Marchi, Andreas Mortensen.

[23] https://en.wikipedia.org/wiki/Toyota_ZZ_engine#2ZZ-GE

[24] Replacing the Cast Iron Liners for Aluminum Engine Cylinder Blocks: A Comparative Assessment of Potential Candidates. John Lenny Jr.

[25] New materials, new thinking. Elaine Catton. Automotive Manufacturing Solutions Oct/Nov 2002.

[26] The Aluminum Automotive Manual. Version 2011. European Aluminium Association.

[27] Limited edition with ATAG engine blocks. Das Profil Newsline. Rheinmetall Group. Jan 2004.

[28] Rückrufe, Zuliefererprobleme und Produktionspannen. Wilhelm Hahne. Motor KRITIK.

[29] https://www.motor-talk.de/forum/motorschaden-997-t3947119.html?page=5

thickness of less than 0.005") in the turbocharged 3.0 liter 991.2 Carrera and Carrera S engines,[30] as well as in Panamera V6 and V8 engines that same year.[31]

With the Alusil process, the entire engine block is low pressure die cast out of the hypereutectic 17% silicon ALUSIL alloy (AlSi17Cu4Mg). After the block is cast and the cylinder bores are chemically and mechanically activated, the resulting silicon particles varying in size from 20 to 70 µm provide the wear-resistant sliding surface for the piston and ring system.

For both Alusil and Lokasil, an acid etching process to remove the aluminum surrounding the silicon particles is no longer used during manufacturing. During the honing process, care is taken to ensure the silicon particles are cut rather than torn from the surface during mechanical activation to ensure an exposure depth of 0.3-0.7 µm. The resulting size, shape, and distribution of these particles produce exposed silicon plateaus and oil retaining valleys to support piston and ring travel.[32] The ability of the cylinder bore surface to retain oil is directly related to its scuffing resistance.[33]

The distribution of the exposed silicon particles in the Al-Si matrix is critical. During normal operation, the exposed silicon particles support the loads applied to the cylinder bore by the pistons and piston rings, with at most a few nanometers per hour of wear. Modern engines with Al-Si bores utilize thinner, lower tension rings that provide improved sealing with lower friction than conventional piston rings. Critically important is the use of barrel-shaped piston ring faces, so as to glide across the surface, as opposed to a scraping action caused by some ring types. Excessive ring tension or incompatible ring types can damage the exposed silicon particles, resulting in a failure of the cylinder sliding surface to support the piston and ring system due to plastic deformation of the aluminum matrix.[34] [35] Coatings like DLC (diamond like carbon), that when applied on piston rings, can also reduce Al-Si cylinder wear, reduce friction, and improve fuel economy.[36]

---

[30] MMC All Aluminum Cylinder Block for High Power SI Engines. Toshihiro Takami, et al. Toyota Motor Corp & Toyota Central Research and Development Labs, Inc. SAE Technical Paper Series 2000-01-1231. https://flatsixes.com/cars/porsche-991/makes-porsches-new-3-liter-turbocharged-carrera-engines-special/

[31] https://www.sae.org/news/2016/07/inside-porsches-new-v8-and-v6-powertrains

[32] Reconditioning of Aluminum Engine Blocks. MSI Motor Service International.

[33] MMC All Aluminum Cylinder Block for High Power SI Engines. Toshihiro Takami, et al. Toyota Motor Corp & Toyota Central Research and Development Labs, Inc. SAE Technical Paper Series 2000-01-1231.

[34] MMC All Aluminum Cylinder Block for High Power SI Engines. Toshihiro Takami, et al. Toyota Motor Corp & Toyota Central Research and Development Labs, Inc. SAE Technical Paper Series 2000-01-1231.

[35] Nikasil and Alusil. John Goodman. Engine Professional Oct-Dec 2008.

[36] Wear of different material pairings for the cylinder liner - piston ring contact. Thomas Wopelka, et al. Industrial Lubrication and Tribology. DOI 10.1108/ILT-07-2017-0218.

Normal wear of the Al-Si matrix can be described by the ultra-mild-wear (UMW) regime. The UMW regime can be broken down into three stages:

- Stage I: Silicon particles fracture and are embedded into the supporting aluminum matrix.
- Stage II: Increased wear occurs as exposed aluminum matrix is removed.
- Stage III: A smooth and stable surface supported by ultra-fine aluminum grains with a ZDDP and molybdenum (moly) rich tribofilm forms followed by a reduction in wear and friction.

Along with proper lubrication, surface modification techniques must be applied to these components for use in an Al-Si engine.[37] Depending on what type of piston is used, cast or forged, and its silicon content, extremely tight piston to cylinder clearances of 8 - 32 µm (0.0003-0.0012") require durable piston skirt coatings that reduce friction and prevent wear. The process, originally referred to as "tining", provides a thin coating on the piston skirt that provides a wear barrier between the aluminum piston and the aluminum bore. These coatings are critical to the long-term reliability of aluminum cylinder bores. Due to the abrasive nature of the Alusil or Lokasil sliding surface with its exposed silicon particles, when the piston skirt coating fails, galling caused by aluminum on aluminum contact will occur. This will result in cylinder and piston scoring and/or seizure, primarily on the thrust side of the piston skirt with localized wear starting at the bottom of the bore (BDC) moving upwards towards the mid-stroke region on the corresponding cylinder surface.[38]

When the UMW regime can no longer be supported, the severe wear regime begins the progression to catastrophic surface failure.[39] An area without sufficient silicon exposure or with more than 40% of the primary silicon particles crushed[40] will experience accelerated wear of the softer aluminum matrix that supports it, resulting in premature engine failure from scuffing and scoring.[41] When silicon particles fracture and become dislodged from the Al-Si matrix, the aluminum substrate that supports the silicon particles becomes pitted, generating a large amount of wear debris, accounting for high wear rates and high total wear volume.[42] Cold start conditions with insufficient lubrication and higher porosity from the aforementioned pitting of the aluminum matrix further reduce scuffing resistance.[43] The coefficient of friction in the piston and liner system increases when surface finish roughness increases with highest areas of

---

[37] Improved Engine Performance Via Use of Nickel Ceramic Composite Coatings (NCC Coat). K. Funatani, et al. Metal Matrix Composites (Sp-1010). SAE Technical Paper Series 940852. 1984.

[38] Friction and Wear of Tribo-Elements in Power Producing Units For IC Engines - A Review. Roop Lal, et al. International Journal of Engineering Trends and Technology - Vol 14 no. 5 - August 2014.

[39] Sliding wear behavior of eutectic Al-Si alloy under lubricated conditions: An investigation on the effect of ethanol (E85) addition. Victor Vimalrajan Francis. University of Windsor.

[40] The new Porsche 944 4-cylinder aluminum engine. Paul Hensler. Porsche AG. SAE International.

[41] Replacing the Cast Iron Liners for Aluminum Engine Cylinder Blocks: A Comparative Assessment of Potential Candidates. John Lenny Jr.

[42] Wear of different material pairings for the cylinder liner - piston ring contact. Thomas Wopelka, et al. Industrial Lubrication and Tribology. DOI 10.1108/ILT-07-2017-0218.

[43] Sliding wear behavior of eutectic Al-Si alloy under lubricated conditions: An investigation on the effect of ethanol (E85) addition. Victor Vimalrajan Francis. University of Windsor.

wear occurring at TDC and BDC due to a failure to maintain adequate hydrodynamic lubrication.[44] Severe wear manifests itself as cylinder bore and piston scoring with the formation of grooves and ploughing of the aluminum matrix by the fractured silicon particles in the wear track.[45] [46]

Tribology and the Al-Si Cylinder System

Significant oil deposits on the cylinder surface fills uneven areas on the aluminum matrix, providing the required tribofilm for proper lubrication.[47] Wear resistance mechanisms are reliant on the formation of this tribofilm and the subsequent formation of anti-wear additive films on the Al-Si matrix.[48] An analysis of the cylinder surface anti-wear films shows that zinc (Zn), from ZDDP, and molybdenum (MoS_2), from MoDTC friction modifiers, are deposited onto the load bearing silicon particles and the aluminum matrix that supports these particles.

In normal operation, transfer of ferrous material from the piston skirt coating and rings to the bores allows for the formation of ZDDP wear pads on exposed Si particles. Formed under stress or high temperatures, these thermal- and tribo-films are thinnest at low temperatures, forming at temperatures as low as 25°C (77°F),[49] reinforcing perhaps the reason we see more scoring with engines operated in colder climates or those driven primarily short distances. Where ZDDP forms through chemical desorption, moly films form glassy plates initiated through sliding motion that reduce friction and wear. Moly lowers the shear strength of the tribofilm resulting in a reduction in friction, enhancing the performance of ZDDP. In testing of Al-Si engines with start-stop, the presence of moly reduced the static coefficient of friction (μ) during restarts by 83.3% from 0.8-0.9 to 0.15.[50] Changes in loads, speeds, or even lubricant temperatures have a direct affect on the characteristics of this tribofilm, as do the types and amounts of ZDDP and moly used.[51] The thickness of these films varies depending on the concentration of ZDDP and moly, suggesting a ratio of 0.1

[44] Failure of Piston in IC Engines: A Review. R.C. Singh, et. Al. International Journal of Modern Engineering Research, Volume 4/Issue 9 - Sept. 2014.

[45] Combustion Engine Cylinder Liners Made of Al-Si Alloys. A.W. Orlowicz, et. Al. Archives of Foundry Engineering. DOI: 10.1515/afe-2015-0041.

[46] Sliding wear behavior of eutectic Al-Si alloy under lubricated conditions: An investigation on the effect of ethanol (E85) addition. Victor Vimalrajan Francis. University of Windsor.

[47] Friction and Wear of Tribo-Elements in Power Producing Units For IC Engines - A Review. Roop Lal, et al. International Journal of Engineering Trends and Technology - Vol 14 no. 5 - August 2014.

[48] Wear of different material pairings for the cylinder liner - piston ring contact. Thomas Wopelka, et al. Industrial Lubrication and Tribology. DOI 10.1108/ILT-07-2017-0218.

[49] On the Mechanism of ZDDP Antiwear Film Formation. Zhang, Jie; Spikes, Hugh. Imperial College London, London, UK. DOI: 10.1007/s11249-016-0706-7

[50] The influence of start-stop transient velocity on the friction and wear behavior of a hyper-eutectic Al-Si automotive alloy. J.C. Walker, et al. National Centre for Advanced Tribology at Southampton.

[51] Sliding wear behavior of eutectic Al-Si alloy under lubricated conditions: An investigation on the effect of ethanol (E85) addition. Victor Vimalrajan Francis. University of Windsor.

wt% ZDDP to 500 ppm moly may provide balanced wear and friction reduction.[52] To have a stable tribofilm that can support the UMW regime, four things are needed:

- Sufficient temperature to convert ZDDP and moly present in the oil to an anti-wear film
- The hardness and yield strength of the two surfaces rubbing (piston and piston rings against the cylinder bore) must be similar to maintain the oil film
- The resulting "glassy-plate" anti-wear film results in a reduction in the coefficient of friction, indicating a stable film
- No abrasive foreign object debris such as fractured silicon particles can be present[53]

Considering the importance of this tribofilm and knowing that 50% of the friction in an internal combustion engine comes from the pistons and rings, selecting the right lubricant for this application is critical. Legacy and performance engines might benefit from a full-SAPS (sulfated ash, phosphorus, and sulfur) oil with increased ZDDP and elevated moly levels, over levels found in OEM specified lubricants. Zinc-free oils tend to form tribofilms more slowly than ZDDP and are more sensitive which surfaces they bind to. Choosing a lubricant designed to minimize wear, but not necessarily provide optimum fuel savings or emissions system protection, may extend cylinder, piston, and ring life.[54] The introduction of ash-less and zinc-free oils optimized for emissions systems protection are on the horizon, making choosing an oil that much more difficult.

The aforementioned operation of Al-Si engines in colder climates and increased prevalence for scored bores can also be attributed to acid formation in the crankcase at temperatures below 40°C (104°F). Many familiar with failures of BMW V8 and V10 engines with Nikasil were attributed to high sulfur content in U.S. fuels, however Porsche and other manufacturers did not experience similar failures, but sulfur content of fuels have steadily decreased since 2000. Tests carried out by Toyota, with results published in 2000, measured the effect of sulfur in fuel on wear in Al-Si engines. Toyota found North American regular grade (87 octane) fuel to have the highest levels of sulfur at a maximum of 1350 ppm, followed by European fuels at 1000 ppm, and Japanese fuels having nearly zero sulfur content. The quality of North American premium grades of unleaded fuels varied greatly, with a maximum of 650ppm and an average of 175 ppm of sulfur. The study also found that as sulfur content increased, wear rates also significantly increased at coolant temperatures below 40°C (104°F), resulting in three times the wear at 1000 ppm sulfur versus unleaded fuels with 200ppm or less. At low temperatures, acids are created as byproducts of combustion, with a higher concentration of acid associated with high sulfur fuels. It is these acids that break down the lubricant film between the bores and the piston rings, causing abrasive wear associated with the plastic deformation of the aluminum matrix. As expected, ring wear rates saw similar increases with increased sulfur concentration. For fuels with a sulfur content less than 200 ppm, wear rates

---

[52] Influence of temperature and ZDDP concentration on tribochemistry of surface-capped molybdenum sulfide nanoparticles studied by XANES spectroscopy. Bakunin, V. N. et al. Tribology Letters, Vol. 26, No. 1 April 2007. DOI: 10.1007/s11249-006-9180-y

[53] The influence of start-stop transient velocity on the friction and wear behavior of a hyper-eutectic Al-Si automotive alloy. J.C. Walker, et al. National Centre for Advanced Tribology at Southampton.

[54] On the Mechanism of ZDDP Antiwear Film Formation. Zhang, Jie; Spikes, Hugh. Imperial College London, London, UK. DOI: 10.1007/s11249-016-0706-7

level off at coolant temperatures of 60°C (140°F) and above. For fuels with higher sulfur content up to 1000 ppm, wear rates level off at higher operating temperatures of 80-100°C (176-212°F).[55] In the almost twenty years since these findings were published, sulfur has been all but eliminated from fuels in North America and Europe. Automakers now use advanced thermal management to allow rapid engine warmup, that when coupled with reduced sulfur fuels, neutralize the low temperature acid formation.

Reducing sulfur content helps engines run cleaner and improve the efficiency of emissions control devices. Since the 1990s, the EPA has been working towards cleaning up fuels and reducing sulfur content. The EPA finalized their Tier 2 standards for sulfur content of domestic fuels in 2000 which reduced its content by some 90%. Tier 3 standards in effect since 2017 limit sulfur content to 10 ppm, providing the market what is considered "ultra-low sulfur fuels." In most markets, these fuels are also enriched with ethanol, typically not to exceed 10%. The prevalence of ethanol enriched fuels also raises the concern that it too can cause damage to Al-Si engines, however limited research would indicate that the presence of ethanol does not significantly affect the formation and function on tribofilms required to support the Al-Si cylinder system.[56]

Taking into consideration engines operated since new in 2017 with ultra-low sulfur fuels in cold climates have benefitted from reduced acid formation, engines built and operated prior to the implementation of the Tier 3 standards would be expected to have experienced higher wear in cold climates proportional to the sulfur content of the fuel available at that time. Although the coolant thermostat helps to bring the engine up to proper operating temperature, oil and coolant temperature will take longer to normalize, even when the engine is fitted with a modern laminar flow oil to water heat exchanger. The result could be an engine that reaches the desired coolant temperature however the oil may still be in the danger zone for acid formation. This is particularly of concern for vehicles driven short distances, even in warmer climates, as combustion byproducts combine with moisture in the crankcase to form acids that can damage both the piston rings and cylinder bores. In instances where the oil does not reach full operating temperature regularly, like in stop and go traffic in cold weather, Porsche advises changing the motor oil more frequently in these instances to ensure the engine oil is 100% effective in protecting all internal engine components.[57]

Some auto manufacturers recommend that vehicles driven in cold climates may benefit from a short 10-30 second warmup[58] to allow all areas of the engine and transmission to be properly lubricated above -18°C (0°F) but below 0°C (32°F), however above freezing temperatures, modern engines do not need to be warmed up.[59] Besides causing excess emissions and wasting fuel, extended periods of idling under cold start introduces extra fuel into the cylinder bores that can wash the lubrication off the cylinder walls. Manufacturers recommend driving at moderate speeds for a short distance to allow the engine to come up

---

[55] MMC All Aluminum Cylinder Block for High Power SI Engines. Toshihiro Takami, et al. Toyota Motor Corp & Toyota Central Research and Development Labs, Inc. SAE Technical Paper Series 2000-01-1231.

[56] Sliding wear behavior of eutectic Al-Si alloy under lubricated conditions: An investigation on the effect of ethanol (E85) addition. Victor Vimalrajan Francis. University of Windsor.

[57] 2007 Porsche Cayman S Owners Manual. Maintenance, Car Care. Pg. 210.

[58] Summary of OEM Idling Recommendations from Vehicle Owner's Manuals. Blackmon, et al. ORNL/TM-2016/50. Oak Ridge National Laboratory.

[59] http://idlefreevt.org/how-long-a-vehicle-should-warm-up.html

to full operating temperature in cold weather. As a point of reference, Mercedes restricts engine performance at oil temperatures below 20°C (68°F) on AMG models.[60]

Just as Al-Si engines can be negatively affected by cold weather operation, at higher engine temperatures the minimum oil film thickness (MOFT) required varies depending on the regime of lubrication (hydrodynamic, mixed, or boundary) as well as the oil used. The struggle for engineers seeking higher fuel economy is that higher viscosity oils cause higher viscous power losses, requiring either higher operating temperatures or thinner oils to reduce these losses. Higher oil temperatures resulting in lower lubricant viscosity help to reduce oil intrusion into the combustion chamber as well as evaporation and consumption, reducing the likelihood of low speed pre-ignition (LSPI) in direct injected, forced induction engines. Controlling liner temperatures have a direct effect on surface lubricant temperature, HC, and NO_x emissions, so an optimal temperature has to be found to balance emissions as well as thermal and frictional losses. Frictional losses from the piston rings are at their lowest with a liner temperature of 80°C (176°F)., but at higher temperatures, MOFT may transition lubrication from mixed to boundary layer, causing increased friction due to asperity contact, such as the plastic deformation of the aluminum matrix of Al-Si bores. A temperature increase of the liner from 80-120°C (176-248°F) can result in a 40-55% reduction in MOFT mid-stroke, in areas where bore scoring can occur. In fact, once operating in boundary lubrication regime, an increase of temperature has little effect in the MOFT, and it is the anti-wear additives like ZDDP and moly that provide the needed wear protection for these surfaces in the cylinder system.[61]

With both extreme hot and cold operation, driving short distances, as well as mixed city and highway driving, determining oil change intervals (OCI) is quite the challenge. With modern synthetics, most manufacturers have extended their OCI to multiple years and 15,000 miles or more. GM in conjunction with their DEXOS oils that are calibrated to their oil life monitoring system, utilize an oil health monitoring system that continuously monitors engine-operating conditions.[62] The system has proven itself to be very accurate at estimating the remaining life of the engine oil to determine when to change oil. However, most manufacturers still utilize time or mileage limits, whichever comes first. Some provide severe service intervals, typically three to six months and 3,000 to 5,000 miles, and is especially important for vehicles operated in colder and hotter climates alike.[63] Even with a system as advanced as GM's oil life monitor, the only way to accurately measure an oil's performance for a given application and the component health lubricated by an oil is with regular used oil analysis. In Al-Si engines, knowing the primary wear metals from the cylinder bores would be comprised of aluminum and silicon, regular testing can provide a baseline wear profile for a given lubricant and engine combination. Not only is it possible to validate changes to OCI and the effectiveness of lubricants used, but also to detect accelerated wear of the aluminum matrix and silicon particles that support the Al-Si cylinder system.

---

[60] 2015 Mercedes S-Class Sedan Operators Manual. Driving - pg 189. Mercedes Benz USA.

[61] The effect of cylinder liner operating temperature on frictional loss and engine emissions in piston ring conjunction. R. Rhamani, et al. Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, UK.

[62] https://assets.cobaltnitra.com/teams/repository/export/975/c7820afba1004895010145efa6b30/975c7820afba1004895010145efa6b30.pdf

[63] http://www.hastingsfilter.com/Literature/TSB/94-1R1.pdf

The Future of the ICE

Innovations in automotive engineering will extend the life of the internal combustion engine for many years to come. It is estimated that nearly 3 billion new internal combustion engines will be manufactured over the next 30 years. Manufacturers are currently working on the next generation of all-aluminum engines, evaluating surface modification techniques for the Al-Si cylinder system to further reduce friction and wear that result in increased emissions.

As parasitic losses in the cylinder/piston/ring system make up for 4-7% of total losses,[64] the use of lower tension piston rings under negative crankcase pressure coupled with lower viscosity 0w8, 0w12, and 0w16 oils will further improve fuel economy and reduce tailpipe emissions. The application of low friction coatings such as DLC (diamond like carbon) on piston rings further reduce the friction between the piston ring and cylinder surfaces. Similar application of specialized coatings to cylinder bores can provide added benefits to all-aluminum engines over current technologies. Ford Motor Company is an innovator in this area with its patented plasma transferred wire arc (PTWA) process which has been used on several models including the Ford Mustang Shelby GT350 and was licensed to Nissan for their GT-R. Ford demonstrated that their PTWA cylinder wall coatings resulted in a wear reduction of 50% in their 300 hour endurance test, an increase in fuel economy of 5%, and a reduction in friction of 6.8% over an aluminum engine block fitted iron liners.[65] Oerlikon's SUMEbore plasma vaporization (thermal spray) iron-ceramic composite coating was first used by Porsche in the 918 Spyder. SUMEbore provides a mirror-like cylinder finish, resulting in 20% less friction over a cast iron bore and 35% reduction in oil consumption as well.[66] But as with PTWA, the process is still cost-prohibitive and typically reserved for low volume applications such as high-end sports cars.

Significant gains in efficiency have also been afforded by gasoline direct injection (GDI), however direct injection with increased compression ratios and lean burn have introduced new complexities to overcome, like soot. Oils with lower concentrations of ZDDP are now required to protect emissions system components, like the gasoline particulate filters (GPF) that capture the soot created by GDI engines. New technologies will require similar advancements in lubrication. One example of this pioneering work is currently being carried out jointly by Oak Ridge National Labs, the U.S. Department of Energy, General Motors, TARDEC,

---

[64] The effect of cylinder liner operating temperature on frictional loss and engine emissions in piston ring conjunction. R. Rhamani, et al. Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, UK.

[65] Replacing the Cast Iron Liners for Aluminum Engine Cylinder Blocks: A Comparative Assessment of Potential Candidates. John Lenny Jr.

[66] Optimizing the Cylinder Running Surface / Piston System of Internal Combustion Engines Towards Lower Emissions. Ernst, Peter et al. SAE International. 2012-32-0092

NETL, and Driven Racing Oils in the area of ionic liquids and additives such as phosphonium phosphate to replace ZDDP.[67]

Similar advances in engine management and design are on the horizon with variable compression ratio engines, pre-chamber jet ignition combustion, and gasoline compression ignition (GCI), all of which will improve the thermal and mechanical efficiency of the internal combustion engine. Mazda's Skyactiv-X engine provides spark controlled compression ignition with a 20-30% increase in fuel efficiency over current gasoline engines.[68] Infiniti's VC-T engine is the world's first variable compression ratio engine, allowing for 8:1 to 14:1 compression ratios to optimize the engine for varying loads and speeds, switching between port and direct injection as well as between normal and Atkinson cycle on the fly.[69] Mahle's pre-chamber jet ignition (MJI) technology is demonstrating a potential for 45% thermal efficiency allowing diesel-like efficiency with significantly reduced NO_x and CO_2 emissions over current GDI engines.[70]

By 2026, it is expected that nearly 40% of vehicles will utilize downsized, forced induction four- and six-cylinder all-aluminum engines paired with 48-volt mild, full, and plug-in hybrid systems. Experts in powertrain development expect diesel engines to remain viable for 20 years and gasoline engines for at least another 30 years. Mass electrification is coming, however the development of bio- and synthetic fuels, pre-chamber combustion technologies, fuel cells, and EV drivetrains with ICE range extenders are just a few of the innovations bridging the gap to an all-electric future.[71]

---

[67] ORNL-GM: Development of Ionic Liquid-Additized, GF-5/6 Compatible Low-Viscosity Oils for Automotive Engine and Rear Axle Lubrication for 4% Improved Fuel Economy. Qu, Jun et al. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States). DOI: 10.2172/1342688.

[68] https://www.roadandtrack.com/new-cars/car-technology/a15912314/mazda-skyactiv-3-gas-clean-as-ev/

[69] https://www.roadandtrack.com/new-cars/car-technology/news/a30392/infiniti-vc-t-variable-compression-turbo/

[70] https://www.sae.org/news/2019/06/mahle-mji-pre-chamber-combustion

[71] Automotive Engineering. SAE International July/August 2019

Conclusion

The first fifty years of liner-less all-aluminum engines have brought forth a great many advances in the internal combustion engine. Where engines once lasted at most 100,000 miles, modern engines have longer usable service lives, all while providing lower emissions, improved efficiency, and everyday performance that rivals supercars from the not so distant past. There are millions of vehicles on the road worldwide currently using Al-Si technologies. As demonstrated, the longevity of these engines is highly dependent on fuel and lubricant quality, but also on some factors out of an owner's control, such as operational and environmental constraints. Future engineers will have to rise to the challenge of meeting ever more stringent emissions requirements while solving design restrictions including cost, weight, performance, and longevity at a time when the future of the internal combustion engine is in question. Although an all electric future may be on the horizon, many tough questions must be answered. How do we fix an aging and over-stressed electrical grid? How do we handle tomorrow's end-of-life e-waste crisis caused by batteries from EV and hybrid vehicles. How are we going to generate power cleanly to feed the added demand of all these electric vehicles reliably? Until these questions can be answered and a lower total cradle-to-grave carbon footprint for EVs is realized, the consumption of fossil fuels will continue as technology catches up to the demands of the modern world.

Glossary

Albond - Cylinder liner composite technology from MAHLE GmbH.

Alumina-Silica Fibers - Alumina (aluminum oxide) and silica (silicon oxide) are used to reinforce MMC liners in Al-Si engines.

Alusil - Alloy of aluminum containing silicon patented by Kolbenschmidt Aluminium-Technologie GmbH.

Asperity Contact - Refers to the roughness of a contact surface. Even surfaces that appear to be smooth have a roughness to them on a microscopic scale.

Atkinson Cycle - The intake valve closing is delayed until 20 to 30% of the compression stroke has taken place. Although some of the intake charge is lost, an Atkinson Cycle engine benefits from an increased expansion ratio resulting in greater efficiency at higher engine speeds. The loss of low end torque is the tradeoff. Typically Atkinson cycle engines are used in hybrid vehicles, like the Toyota Prius.

BDC - Bottom Dead Center, referring to engine timing, more specifically the position of the engine where the piston is at its lowest position in the cylinder bore.

Biral Cylinder - A cylinder with an iron liner and aluminum cooling fins. The Porsche 912 used biral type cylinders that had an iron bore with aluminum fins, providing slightly better cooling than a cast iron cylinder but nowhere near as good as a Chromal, Ferral, or Nikasil cylinders.

Boost - In a forced induction engine, boost refers to intake charge above atmospheric pressure.

Boundary Lubrication - The lubrication regime where oil film thickness is reduced to the point where solid surfaces can make contact with each other.

Chemical Desorption - The release of one substance from another.

Chromal Cylinder - Hard chrome has been used for cylinder wear surfaces for many years. In this case, Porsche used aluminum cylinders with chrome bores that were dimpled to provide improved lubrication, as chrome has poor oiling characteristics. Lycoming is another example of a manufacturer that uses hard chrome in their FAA approved aircraft engines.

CO2 - Emissions released during the combustion of fossil fuels account for the majority of greenhouse gasses.

Coefficient of Friction - The amount of friction between two moving surfaces. This is symbolized by the Greek character μ, is dimensionless, and has no units.

Combustion Byproducts - Gasses and small particles emitted through incomplete combustion.

Compression Ratio - The ratio of the maximum to minimum volume of a cylinder in an internal combustion engine.

DEXOS - This standard was introduced by GM to work in tandem with their Oil Life Monitoring System to provide optimal fuel economy, extend emissions systems component life, and extend oil change intervals.

DLC Coating - Class of amorphous carbon material that displays some of the typical properties of diamond that when applied to surfaces, reduces wear and lowers friction between surfaces.

ESP - Emission System Protection, typically referring to a low ash or ash-less lubricating oil designed to extend emissions system component life.

Eutectic Aluminum - A eutectic alloy has a lower melting point than any of its components. Al-Si alloys become eutectic at 11.7% silicon content.

EV - Electric Vehicle

Expansion Rate - The coefficient of linear thermal expansion is the ratio change in length per degree temperature to length.

Ferral Cylinder - Prior to hard chrome, Porsche used splatter-coated iron on its aluminum cylinders that once honed, would provide a good wear surface for pistons and rings to ride on with improved thermal conductivity over a solid cast iron cylinder.

Ferrocoat – KS iron-coated piston skirts.

Ferroprint - A environmentally friendly alternative to the Mahle Ferrostan/FerroTec® providing a stainless steel particle reinforced synthetic resin coating to prevent wear between Al-Si cylinder liners and piston skirts to a thickness of 20 um.

Ferrostan - Also known as Ferrotec, this coating is for applications with an aluminum bore, an iron coating is required to prevent high wear and seizing. It is applied 10-13 um thick and can be topped with a thin layer of tin for run-in protection.

Galling - A form of mechanical wear caused by adhesion between sliding surfaces.

GCI - Gasoline Compression Ignition relies on compression, rather than spark ignition, to ignite the intake charge, similar to a diesel engine.

GDI - Gasoline Direct Injection delivers fuel directly into the combustion chamber, like a diesel engine, at several thousand PSI of pressure, allowing for higher compression ratios, more accurate fuel delivery, and increased engine efficiency.

GF-6 - ILSAC GF-6 focuses on turbocharged-engine specific standards including addressing issues with LSPI, or low speed pre-ignition. GF-6A covers oil viscosities 5w30 and higher where GF-6B is for viscosities 0w16 and lighter for increased fuel economy. GF-6 also brings engine durability testing and start/stop protection.

GPF - Gasoline Particulate Filters are used in engines with gasoline direct injection to capture soot particles created during operation at high fuel pressures and compression ratios, similar to soot generated by diesel engines.

Hardness - A measure of resistance to localized plastic deformation.

HC Emissions - High hydrocarbon emissions (HC) reflects unspent fuel in the exhaust.

Heterogeneous Casting - Aluminum engine blocks cast with cylinder liners or cylinder liner inserts.

Honing - An abrasive machining process that produces the functional surface finish for cylinder bores. Typical parameters are cross-hatch angle and surface finish.

Hybrid - Hybrid drivetrains come in several types: mild, full (sometimes referred to as strong), and plug-in varieties. Hybrid drivetrains combine an internal combustion engine with batteries and an electric motor.

With mild hybrids, the electric motor cannot power the car on its own. Full hybrids can operate on electric only and also provide a power boost. A plug-in hybrids typically have larger batteries and can operate longer distances and at higher speeds on electric only.

Hydrodynamic Lubrication - When sufficient oil film is present between surfaces to prevent contact. A journal bearing like the main or rod bearings in an internal combustion engine are supported by a layer of pressure fed oil operate under hydrodynamic lubrication.

Hypereutectic Aluminum - An aluminum alloy with 12% or more silicon content. Typically, hypereutectic alloys used in automotive engine pistons is between 16% and 19%, however some use up to 25-30%, however there is a loss of strength at these elevated levels. Adding silicon improves wear resistance and also reduces the rate of expansion for the aluminum alloy to which it is added.

Hypoeutectic Aluminum - An aluminum alloy with 11% or less silicon content. A356 is an example of a hypoeutectic aluminum alloy that is commonly used in cylinder head and other automotive castings.

ICE - Internal Combustion Engine

Inorganic Binder - An inorganic material used to bind two or more materials. For example, with Lokasil freeze-cast liner inserts, an inorganic binder is used to hold the silicon particles in suspension. When the molten aluminum is injected into the mold, the inorganic binder is consumed and replaced by aluminum, leaving the localized silicon particles suspended in the aluminum matrix.

Ionic Liquids - ILs are room temperature molten salts that can be dissolved in motor oil. Its use as an additive has been shown to reduce friction and wear. It is being considered as a supplement or replacement for ZDDP.

Knocking - Also known as spark knock, pinging, or detonation, knocking occurs when uncontrolled combustion not propagated by the flame front occurs in the combustion chamber.

KS - KS Kolbenschmidt GmbH is part of Rheinmetall Automotive and is a global first-tier supplier to the automotive industry supplying pistons, engine blocks, and main bearings.

Laminar Flow - flow characterized by high momentum diffusion and low momentum convection.

Liner - A cylinder insert fitted to an engine block to form a cylinder.

Lokasil - Developed by KS Aluminum Technologic, Lokasil is a “sacrificial” bore freeze-cast liner insert made up of silicon fibers in an inorganic binder. When infiltrated by molten aluminum during the casting process, it provides selective reinforcement of cylinder bores.

LSPI - Low speed pre-ignition, also referred to as stochastic pre-ignition (SPI), mega-knock, or super-knock, is an abnormal combustion event that cannot be prevented by engine management or detected by an engine’s knock sensors. LSPI occurs at high loads and low speeds and is most prevalent in direct injection engines with forced induction.

Mahle - MAHLE GmbH is a German automotive parts manufacturer based in Stuttgart, Germany. It is one of the largest automotive suppliers worldwide.

Mahle Jet Ignition - The MAHLE Jet Ignition® system is a new combustion technology which replaces the standard spark plug in SI engines with a jet ignition chamber assembly. MAHLE Jet Ignition® facilitates the implementation of ultra lean-burn operation in gasoline engines, improving their efficiency and reducing the formation of pollutants such as nitrogen oxide and particulates.

Mechanical Activation - As opposed to chemical etching process to expose the silicon particles from the aluminum matrix, Kolbenschmidt has patented a process by which the aluminum is removed mechanically using special honing stones. This results in silicon particles with rounded edges, rather than sharp ones, that reduce piston ring wear. The mechanical process is faster and more environmentally friendly than the chemical etching or method of exposure using lapping paste.

Mezger Engine - Designed by Hans Mezger, the Mezger engine is commonly referred to the horizontally opposed flat six engine used by Porsche starting with the air-cooled 911 in 1965 and adapted to use water-cooling in the 1990s with the Porsche GT1. The Mezger engine was used in Turbo, GT2, and GT3 models up until the current 991 generation of engines.

Mixed Lubrication - Refers to the lubrication regime between hydrodynamic and boundary lubrication.

MMC - A metal matrix composite is a material typically comprised of a metal and often a ceramic or organic compound.

MOFT - Minimum oil film thickness can be calculated using the Dowson-Higginson equation for when the load is highest, and the film is thinnest.

Molybdenum - Mo, in the form of MoDTC friction modifier, is used as an extreme pressure additive that forms a protective film between surfaces in contact and reduces friction between those surfaces.

Monolithic Casting - Alusil is an example of a monolithic hypereutectic Al-Si alloy engineered for sliding surface performance in aluminum engine blocks. Cylinder liners, liner inserts, or coating of sliding surfaces are not needed as the Alusil alloy with the silicon particles runs through and through the whole casting. Chemical or mechanical activation is required to expose the silicon particles prior to installation.

Mullite - a rare, high performance ceramic material consisting of aluminum silicate. It is commonly used for selective reinforcement in MMC materials.

Negative Crankcase Pressure - Many modern engines run with crankcases under vacuum, sometimes in combination with an air/oil separator, also referred to as an AOS, to separate crankcase windage consisting of air and oil mist. When coupled with low tension piston rings and near mirror finish bores to reduce frictional losses, running negative crankcase pressure improves ring seal and reduce windage and oil consumption.

Nikasil - Invented and trademarked by Mahle in 1967, Nikasil is an electrodeposited lipophilic nickel matrix silicon carbide coating for engine components, mainly piston engine cylinder liners. It can also be applied to other surfaces providing an ultra-low wear and low friction. Nikasil is characterized as being oleophilic, providing excellent oil retention. It is typically applied to cylinder bores in a thickness of .004-.005", allowing for excellent heat transfer away from cylinder bores when paired with aluminum cylinder liners.

NOx - When a fuel source if burned at high heat, NOx emissions are generated from the reaction of nitrogen and oxygen gasses in the air during combustion. High NOx can also result from lean operation. NOx can be reduced by using EGR to recirculate part of the engine's exhaust back into the cylinders as part of the intake charge.

NSC - An electroplating consisting of nickel, silicon, and carbide, similar in appearance, function, and performance to Nikasil.

OCI - Oil Change Interval. OIl change intervals are typically broken down into "normal" and "severe service." Manufacturer intervals are for normal driving habits; severe duty requires more frequent service.

If you drive the car short distances, experience excessive idling, tow or haul heavy loads, operate in extreme heat or cold, you may benefit from shorter oil change intervals.

Octane - Octane is a volatile and flammable hydrocarbon and one of the components of gasoline.

Octane Rating - The anti-knock rating of gasoline. The higher the octane rating, the more resistant to ignition and less prone to detonation. Octane rating is measured using RON, MON, and AKI. In the United States and Canada, AKI, or (RON+MON)/2 is the typical measure of octane. AKI ratings tend to be four to six octane numbers lower than ratings elsewhere in the world.

Oleophilic - Having a strong affinity for oils.

Parasitic Loss - Refers to loss of energy in a system that reduce overall efficiency. Examples can include aerodynamic drag and rolling resistance.

Piston Squirters - Oiling devices that deliver targeted oil spray to the piston under-crown and cylinder bores. Their primary purpose is to cool the pistons and limit their expansion.

Plastic Deformation - Permanent distortion of a material subjected to stresses that exceed its yield strength.

Plug-In Hybrid - A plug-in hybrid typically provides increased battery capacity coupled with the ability to charge the battery from the power grid, allowing for operation for short periods under electric only motivation.

Port Injection - Port Fuel injection provides fuel delivery into the intake port. Port injection has been replaced by direct injection in modern engines, allowing for more precise fuel delivery. However, port injection also provided cleaning of the intake port and intake valve, which when replaced by direct injection, allows for buildup in the intake and on the valve that reduces performance and can lead to increased wear. It is common to have to have the intake ports cleaned on direct injected engines at normal intervals to address this issue. Some manufacturers have switched to hybrid fuel systems that use both port and direct injection to provide cleaning and also improved performance across the entire powerband of the engine.

Pre-Ignition - Combustion that occurs before the ignition event and can occur alone or as a result of detonation.

PTWA - A thermal spraying process that deposits a coating on the cylinder wear surface, eliminating the need for cylinder liners in an aluminum block.

Quasi-monolithic high pressure die cast - Lokasil is an example of this casting process where molten aluminum infiltrates the freeze-cast Lokasil pre-forms which suspend the silicon particles in a binder that is replaced by the molten aluminum.

Range Extender - Range extenders are internal combustion engines that can be added to electric vehicles providing the ability for extended operation beyond the electric only range.

Residual Stresses - These are stresses that remain in a solid material after the original source of the stress is removed.

RSW - Rotating Single Wire is another form of cylinder bore spraying technology that allows for the elimination of liners in an aluminum engine using a molten metal in a rotary motion down the bore.

Scoring - Scoring, scuffing, galling, or seizing of the cylinder bore and piston can be characterized as an adhesive-wear failure between two sliding surfaces that weld together under high localized pressure and temperature. A lack of lubrication between the loaded surfaces can also cause plastic deformation of the cylinder liner surface.

Self-Ignition - The spontaneous or auto-combustion without an external source of heat or ignition. A diesel engine is an example where diesel fuel is ignited without a flame or spark due to ignition under high compression.

Shear Load - A shear load is a force that produces a sliding failure between two surfaces moving on a plane parallel to the force.

Shear Strength - A material's ability to resist forces that case the internal structure to fail in shear.

Silitec - An Al-Si cylinder bore liner technology using spray-compacted, hypereutectic aluminum-silicon alloy that is cast into aluminum cylinder blocks using a high pressure die casting process. Silitec was used starting in 1996 in the production of Mercedes V6 and V8 engines. Silitec bores require exposure of the silicon particles just as with Alusil or Lokasil bores to prepare the surface the pistons and rings will run on.

Sleeve - A sleeve or liner is a cylinder insert that can be installed into an engine block, that once machined and prepared for operation, will support the piston and ring system.

Soot - A substance composed of amorphous carbon formed by incomplete combustion.

Sulfated Ash - ASTM D 874 tests for sulfated ash as a quantitative measure of ash forming metallic compounds in lubricating oil.

Sulfur - Sulfur provides lubricity to fuels and lubricating oils, however, today ultra-low sulfur fuels require lubrication enhancers to be added, especially to offset the lack of lubricity of ethanol enriched fuels over ethanol free fuels.

SUMEbore - Cylinder bore coating technology using powdered metal matrix composites allowing for liner-less engines blocks by Oerlikon Metco. It is designed to provide low friction, reduced wear, and increased corrosion resistance where low quality fuels or high exhaust gas recirculation rates are used.

TDC - Top Dead Center. When the piston is located at the top-most point of the cylinder bore closest to the cylinder head.

Thermal Conductivity - The measure of a material's ability to conduct heat.

Thermal Film - When discussing the formation of ZDDP films as an example, a thermal film forms when there is sufficient temperature to allow for the spontaneous formation of an anti-wear film on a surface in the absence of mechanical activation.

Thermal Overload - Condition where the maximum temperature of a component is exceeded resulting in a reduction of operating life of the component or a catastrophic failure.

Tining - Originally, tining consisted of applying a thin layer of tin as a wear or scuff barrier between aluminum pistons and aluminum cylinders. The term tinning is loosely used to describe any type of wear barrier applied to the piston.

Tribofilm - A film formed on mostly solid surfaces as a result of a chemical reaction of the lubricant components or surface.

Under-Eutectic Aluminum - Aluminum with less than 12% silicon content.

Viscosity - Measure of a fluid's resistance to deformation at a given rate, informally referred to as thickness.

Young's Modulus - The measure of the ability of a material to withstand changes in length under tension or compression - its elasticity.

ZDDP - Zinc dialkyldithiophosphate was developed in the 1940s as an anti-wear additive for motor oils. ZDDP forms protective tribo- and thermal-films on solid surfaces.

Contact

Charles Navarro is the President and Founder of LN Engineering LLC.

Questions can be submitted in writing to info@LNengineering.com.