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Adaptive Graphite Coatings Improve Fit and Function of Pistons, Turbos and Other Precision Devices

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ABSTRACT

Additive/Abradable Powder Coatings (AAPC's) are field proven, thick, solid film graphite coatings that wear in to the ideal functional geometry of mechanical components. Lubed or dry, devices lap in and run with minimized clearance and friction for highest efficiency, quietest operation, and longest life in sandy environments. AAPC's will improve military readiness, reduce sustainment costs, and cut components logistics and fuel consumption. Processing is easy, robust and effective on new and used components in prototyping, production and remanufacturing. Worn components can be restored in theater to achieve durable, 'better than new' performance levels. Applications include turbos, IC pistons, lube pumps, hydraulics, roots blowers, screw compressors, refrigerant compressors, lip seal seats, and others. This paper will focus on the AAPC benefits observed on pistons and turbo compressor housings.

INTRODUCTION – Thick, Graphite Powder Coatings

A relatively new class of dry film lubricant coatings known as Additive/Abradable Powder Coatings (AAPC's) improve fit and efficiency and overcome tribological challenges in engines and other precision equipment. These coatings also offer unique mechanisms of component protection from ingested sand.

AAPC's are blends of thermoset resins and solid lubricants, such as epoxy and graphite respectively. AAPC's can be applied relatively thick (often 150 um or more per surface) and are routinely used to build up components and/or bury surface damage from operational wear.

For the maximum benefit in specific applications, AAPC formulations are tailored to balance properties such as strength, lubricity, porosity and wear resistance.

After coating normally toleranced components with a build-up of graphite AAPC, devices are assembled with minimal clearance, often with a slight interference fit. During initial operation, the coating wears away in areas of high stress, until the contact stresses balance with the strength of the coating. The break-in process is complete when the wear stops, yielding a permanent, ideal, operational shape of the coated component. The final shape and fit of the coated component accounts for tolerancing, assembly distortions, thermal expansion and operational distortions because all are present during break-in. Noise, vibration, and wear are often reduced when fit of mating components is optimized.

AAPC safely minimizes clearances and promotes uniformly distributed contact loading between mating parts. This paper provides brief field case study segments and experimental data to illustrate AAPC benefits to pistons and turbos.

Other applications include gerotor and gear pumps, superchargers, compressors, refrigerant compressors, rotary valves and other precision equipment, but these are not included in this introductory paper.[1]

PISTONS

Modern profile and tolerancing of piston designs allow significant piston rock, which generates wear modes among piston assembly components and the bore. Piston designs set up a limited contact patch with high loading at relatively small contact areas between the piston skirt and bore. At these peak loading areas, boundary lubrication is likely and the thin coatings tend to wear through at these high friction, scuff-prone spots. Foreign particles trapped in the lubricant film, such as sand, grind in these areas as pistons rock and slide.[2]

Even state of the art pistons have inherent problems with fit which affect ring seal and life.[3] To avoid scuffing risks under demanding/special operating conditions, pistons are designed with excess Integrated Piston to Wall Clearance (IPWC). IPWC is the total volume of space between the skirt and the cylinder wall. It changes with crank angle and operating condition because pistons rock and expand.

Minimizing IPWC increases stability of the piston and rings for enhanced sealing and oil control, and reduced noise, vibration, ring wear, blow-by and oil consumption. However, reducing IPWC by piston machining alone is self-limiting due to risk of scuffing at the piston skirt-cylinder bore interface when pistons are too tight.

For many military engines, operation in sandy environments presents another problem, accelerating degradation of in-cylinder components. Sandy environments require more frequent engine overhauls, more spare parts, labor, down time, and life cycle costs. Mechanisms to extend life of cylinder components in sandy environments are desirable.

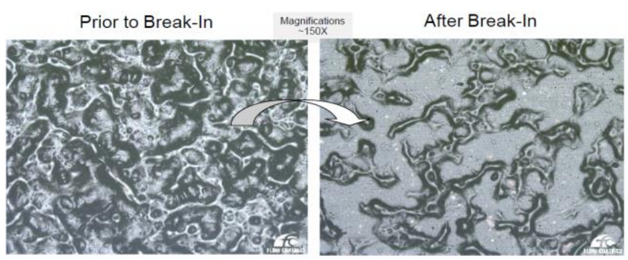
For decades, coatings have been applied to piston skirts for reduced friction and scuff resistance. Tin plating and solvent born organic coatings loaded with solid lubricants such as molybdenum disulfide and graphite have enjoyed wide spread use. Phosphate coatings such as manganese phosphate are broadly used on steel pistons to limit corrosion and hold oil. These coatings, however, all lack mechanisms for piston and ring stabilization, and tolerance of sand at the skirt oil wedge.

More exotic coatings such as metallic bound solid film lubricants and diamond like carbon have been tried with limited success. Problems with durability, thermo-chemical stability, quality control and high cost have limited use on piston skirts.[4] Electrolytic oxide coatings like anodizing can prevent micro-welding of rings to pistons, but when applied to piston skirts they suffer from high hardness, which leads to wear of the adjacent bores.

A limiting common denominator among traditional piston coatings is that they are thin. Thin coatings have limited ability to reduce IPWC for better fitting and operational stability. A stable piston with less rock and slap promotes uniform loading of piston related tribo-surfaces and avoids piercing and cavitation of oil films. Traditional, thin piston skirt coatings also have limited ability to limit damage from foreign particles.

AAPC's safely minimize IPWC for stability, and provide unique mechanisms to resist damage from foreign particles like sand. Examples are presented below after some generic attributes of AAPC's are introduced.

As shown in Figure 1A, AAPC's have a fuzzy texture in the 'As Sprayed' condition. After break-in (Figure 1B), the coatings take on a plateaued topography with randomly distributed oil pockets.



1A **1B**

Figure 1A: Micro-photo "before" operation
Figure 1B: Micro-photo "after" operation

. Table 1 reports surface profilometry results on Slick+ coating applied to 0.0016" thickness before and after break-in.

Slick+ 0.0016"	Ra	Rz	Mr1	Mr2
As Sprayed	114	141	11.3	91.2
Plateaued (Used)	55	68	7.2	80.3

Table 1: Profilometry in microinches (μin)

During initial operation the piston expands into the bore and the Stribeck Fitting process takes place as illustrated in Figure 2. The texture of the coating safely laps in to fit the bore as the piston expands and the bore takes on its operational shape. Oil starved areas abrade more graphite coating away. When there is enough clearance for a stable oil film, asperities no longer touch and the wear stops. The ideal shape for a stable piston with minimal friction in that bore is thereafter preserved by the stable oil film.

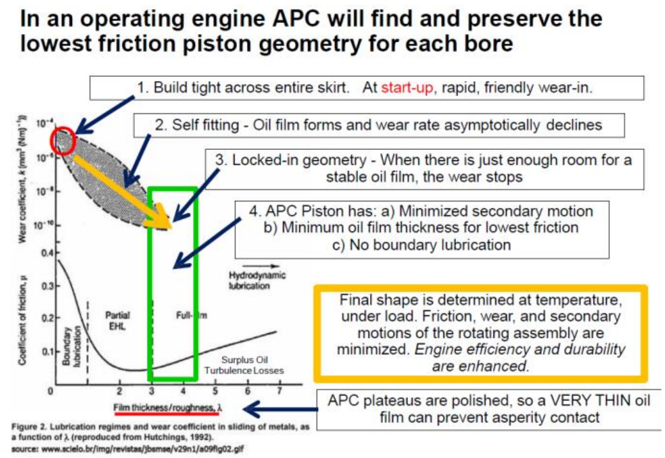


Figure 2: Stribeck Fitting Process[5]

With minimized IPWC, AAPC's reduce secondary motions, vibrational shock loads, wear, noise, and friction of the piston assembly. These coatings also reduce peak contact pressures by transferring contact loads to adjacent areas.[5] Comparison of Figures 3A and 3B shows the improved fit and enlarged contact area, which extends the macroscopic oil leak paths and reduces the peak stress on the oil film. Like in Figure 1B, micron sized pockets of oil are held in reserve to protect the piston skirt and the mating bore surface during periods of oil starvation.

AAPC piston skirts have been commercially available since 2008 and have been used on over 5000 engines with architectures including 2-stroke and 4-stroke, opposing diesel and other advanced engines.

Normally dimensioned and undersized pistons are routinely coated with AAPC and installed with about 20% of the gage point clearance recommended by the piston manufacturer. Approximately 80% of the PWC is occupied by the coating.

AAPC's simplify manufacturing and improve consistency of high performance power cylinders, since piston substrates can be produced with looser tolerances and surface finish requirements. Thick AAPC coating will optimize the shape and running surface during operation.

The following case studies of field and experimental data demonstrate engine benefits observed with AAPC coated pistons.

Figure 3A: Thin coating with normal IPWC. Narrow contact area, foreign particle scratches visible

Figure 3B: Stribeck Fitting Results, Armor AAPC; reduced IPWC, larger contact area, extended oil leak path, reduced peak stress on oil film, limited rocking room, nearly scratch free while running alongside Figure 3A piston

Photo documentation of AAPC pistons show the increased life span of piston assembly components and interfaces including ring-bore, ring-piston, skirt-bore, piston-pin and rod bearing-journal.[2]

In the same case study, a modern piston shape with large IPCW called for a minimum Gage Point Piston to Wall Clearance (GPPWC) of 0.0018" gap on diameter, but after 4000 miles of racing AAPC had GPPWC of 0.0008", so AAPC cut the clearance by 50%. The clearances of the sides of the skirts are reported in Table 2. AAPC cut cold peripheral clearance by an average of 22%. The percentage reduction at operating temperatures was much higher because this engine has a water cooled block.

	Cold Clearance (in)	
Location	Thin Coating*	AAPC**
Gage Point	0.0180	0.0008
45 Deg. CW	0.0064	0.0048
45 Deg. CCW	0.0056	0.0046

*New **After Extended Duty Cycle

Table 2

With AAPC, piston designers can safely and reliably minimize IPWC, which improves cylinder kit performance,[6] extends piston assembly life[7], and significantly cuts vibration (Figure 4A) and noise of engines (Figure 4B) across the audible frequency spectrum.

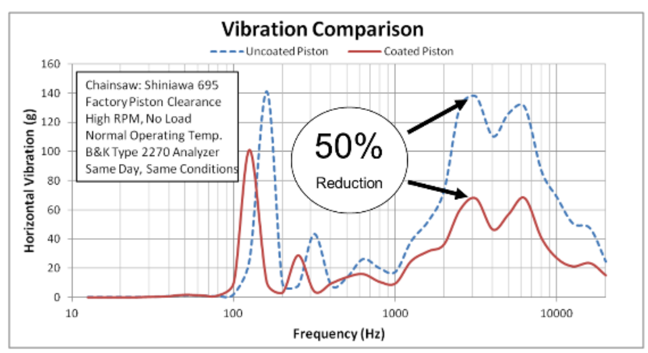


Figure 4A: Slick+ AAPC reduces Vibration

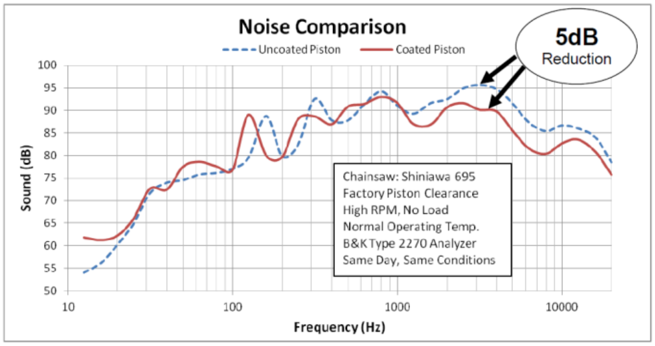


Figure 4B: SlickCC AAPC reduces Noise ~ 5db across audible spectrum

AAPC also resists damage from sand and is often used to restore pistons worn by general use or foreign particles like sand. The high thickness of AAPC's allows unfiltered foreign particles to imbed safely into the coating (Figure 5A). In other cases, particles can plow a groove into the coating without creating raised metal furrows or generating more hard particles at the interface (Figure 5B). These advantages of AAPC's extend Time Between Overhaul (TBO) and life span of military engines in sand and other harsh environments, like racing.

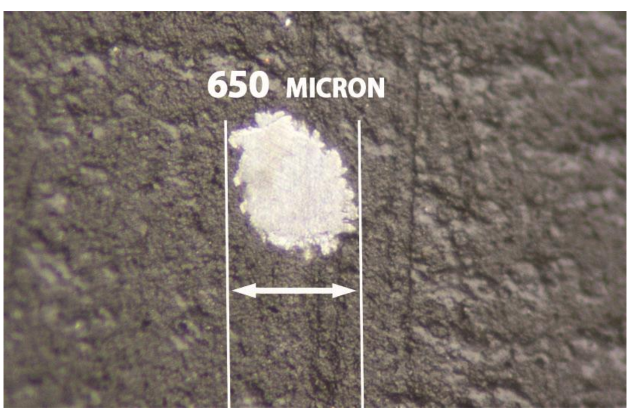


Figure 5A: Free Aluminum particle safely smashed and embedded in Slick+ AAPC piston skirt coating

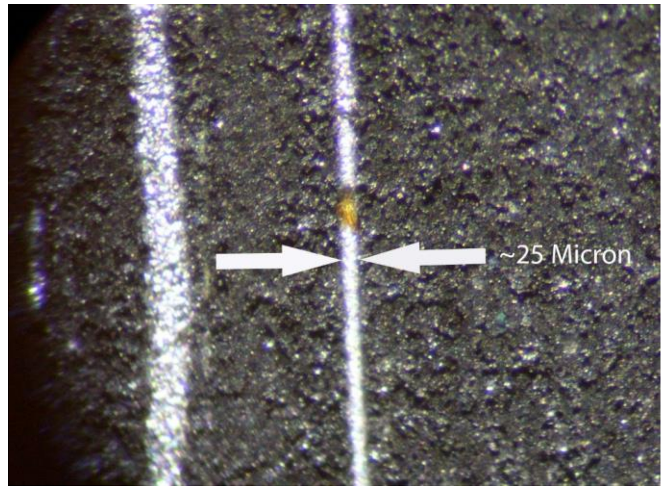


Figure 5B: Slick+ AAPC coated piston skirt with trapped crystallite particle

Worn pistons are easily refurbished, so they need not be replaced (Figure 5C). AAPC simply covers the scratches until they are irrelevant. The block can be touch honed or opened to 0.010" over and the original pistons can still be coated to fit the new bore size. Thousands of documented engines have benefitted this way. During 5000+ engine builds with AAPC coated pistons, field reports indicate extended Engine TBO and piston assembly life.[8]

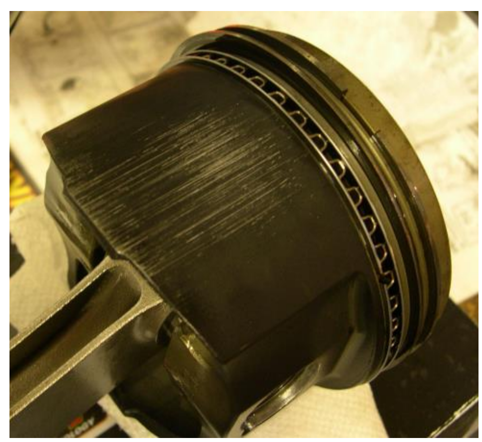


Figure 5C: AAPC protected this piston from ingested sand, and was used to restore the surface and resize the skirt for the newly honed bore dimension during overhaul. (Courtesy of Line2Line Coatings)

For some engines, improved ring seal and lower friction results in higher power density across the RPM range, which also provides a significant acceleration advantage.

AAPC has documented increased power and durability in many engine categories. Figure 6 shows power and torque curves from same day A-B testing of a 2-stroke methanol 440 twin. After break-in, AAPC coated pistons delivered ~7% higher power and torque across power band due to better ring seal and charge transfer (Figure 6).

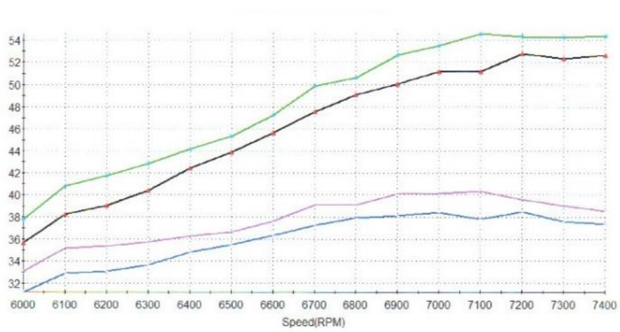


Figure 6: A-B dyno runs, same day. SlickCC AAPC coated 2 stroke pistons made approximately 7% more power across the rpm range

Kawasaki ZX-6R (600cc) SuperSport Motorcycle Race Engine Power Curves

Two identical engines were built side-by-side except for one having AAPC applied to the piston skirts (Figures 7A & 7B.) They were then raced side-by-side under identical track and weather conditions. Figures 7A and 7B illustrate measurable performance gains from using AAPC in high RPM, 4 stroke engines[2], which are expected to produce benefits in some US military equipment.

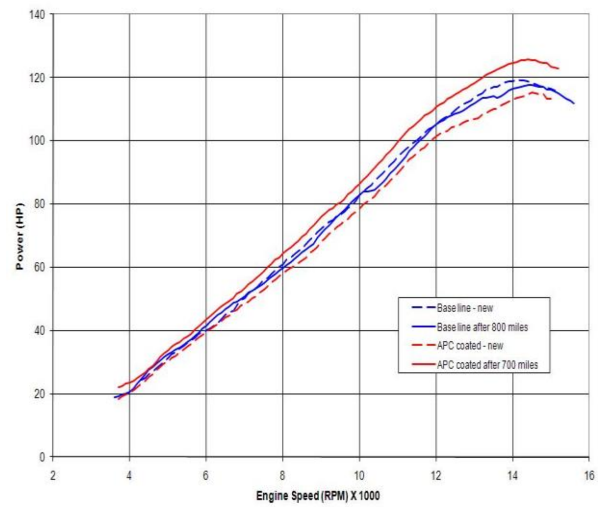


Figure 7A: A-B Peak HP 2% higher

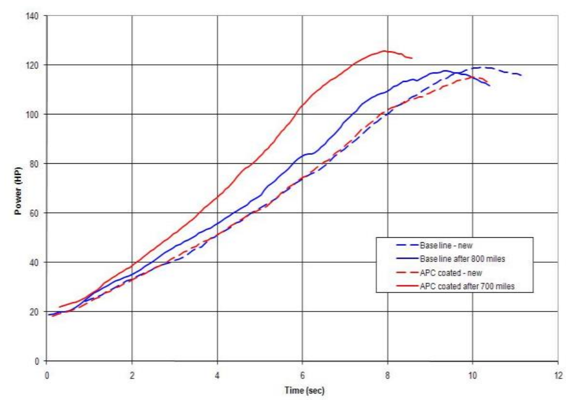


Figure 7B: A-B Acceleration 15% faster

Field data from a freight company owner-operator found approximately 50% less oil consumption in a NTC-300 855 CI (14.7 L) Cummins Gen III 400HP diesel during over 400,000 miles of operation[5]. A carefully controlled experiment with rigorous documentation is needed to confirm this effect.

AAPC successfully sizes and profiles pistons even when Piston to Wall Clearance (PWC) is wildly out of specifications. Ford Escort 1.9L pistons were turned in a lathe using a straight path to remove profiling and create a range of PWC's up to 0.019." Figure 8 shows the individual clearances after machining (tall bars). The pistons were then coated using TriboLiv 9 to create a snug fit for each piston. The set was re-installed and ran for 5000 city driving miles. After operating 5000 miles, the clearances were in a narrow band and skirts appeared uniformly loaded (short bars).

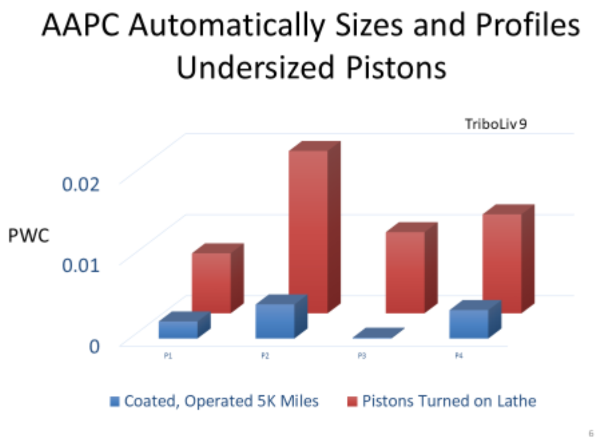


Figure 8: Piston to Wall Clearance (PWC) was corrected by AAPC after turning piston skirts to undersize straight on a lathe, coating them to fit. Coated pistons operated 5000 miles before remeasuring.

INTRODUCTION – AAPC on TURBOS

Turbo equipment efficiency relies in part on minimized clearances between the compressor rotor and housing. Gaps at the rotor blade tips allow back-flow of compressed intake air, lowering efficiency and heating the air charge. Larger gaps cause more lag and poor throttle response. Turbo manufactures minimize the gaps, but they must avoid any potential contact between the rotor and housing as contact insures catastrophic failure of the unit. Casting, machining, and stack-up tolerances for turbo components and bearing runout require manufacturers to design in large gaps of up to 600 microns which inherently limit performance and call for clearance control mechanisms.

Like pistons, turbo-chargers function better when rotor to housing clearances are minimized. AAPC's offer a safe, reliable, low cost method of improving efficiency and performance within the existing design envelope. The coating is applied thick and fuzzy, and contains lots of graphite. Upon assembly and initial operation the rotor beds into the coating, effectively forming a Zero Clearance, Zero Friction Seal of a turbo as shown in Figure 9. Figures 9, 10 and 11 are of a Holset BHT3C Turbo after 150K miles of service on the coating, hauling 37 ton loads in the hills of Wisconsin. The owner-operator estimated an average of 7% lower fuel consumption with the coated compressor housing compared to uncoated baseline turbo housings[5].

Figure 9: Rotor bedded into soft coating - perfect seal (zero clearance and zero friction) after 150,000 miles

Figure 10 illustrates that the tips of the blade are polished but otherwise unaffected by the graphite coating.

Figure 10: Polished blade tips

Figure 11 shows a coated housing after 150,000 miles of heavy hauling. The coating maintained a burnished, smooth surface which mates perfectly to the rotor's shape and rotational orientation. Careful inspection of the assembled unit revealed that the rotor operated at effectively zero clearance and zero friction.

Figure 11: Coated compressor housing after 150,000 miles in service

With Pencil Hardness ranging from HB-2H, the high thickness and relative softness of AAPC's allows unfiltered foreign particles to imbed safely into the coating as in Figure 5A. In other cases, particles can plow a groove into the coating to prevent or delay seizure from grit in the air stream similar to Figures 5B & 5C.

AAPC's by nature can be used to repair and restore housings worn by sand and other intake air stream contaminants. The coating can be stripped and reapplied to keep equipment running at peak performance in sandy environments. The process is simple and is easily conducted at depots or in theater within a standard shipping container.

SUMMARY

AAPC's are a mature technology, commercially successful in all piston engine architectures. Superior performance and power cylinder life have been documented in development, high performance/race and remanufacturing of engines. The self-polishing coating refines the fit of each piston in each bore and maintains a stable oil film to prevent scuffing even in the most severe operating conditions.

For pistons, an ideal fit stabilizes the rings for better function and life. Reduced piston harmonics quiets engines and cuts friction and wear of power cylinder components.

For turbos, a Zero Clearance Fit with no added friction is an advantage.

Efficiency and durability enhancements have been documented in a wide range of devices including 8M automotive superchargers, as well as pumps, blowers, compressors and similar precision equipment.

The advantages of AAPC in manufacturing, efficiency, durability, restoration of components have potential to improve readiness, reduce sustainment costs, and prolong life of precision military equipment like engines, pumps, and compressors.

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