Lost in the Cracks

(Or Where Oil Meets the Ring)

KEY CONCEPTS:

Using the theory of elasticity and Fourier Transform analysis, researchers have developed simple formulas to estimate piston ring conformability and help engineers design better engines.

Despite initial skepticism, researchers have proven that aerosol formation—not just evaporation from cylinder walls—contributes significantly to oil consumption.

The honed finish of the cylinder wall plays a surprising role in creating aerosols. New tools make it possible to evaluate this finish in three dimensions.

COVER STORY

Linda Day / Contributing Editor

Critical factors affecting oil consumption and deposit formation in engines and compressors come to light from research in two disciplines

Editor's Note: *This month's cover story was conceived by STLE's Engine and Drivetrain Technical Committee. Send comments to:* ***mhunter@kingindustries.com.***

We all know that engine performance and oil consumption are related—but how exactly? (And we mean *really* exactly.) Engineers tend to focus on piston design, ring tension, compression ratios, valve timing and other mechanical delights. Oil formulators worry about oxidative stability, viscosity index, TBN retention.

Yet many critical interactions where the "oil meets the ring" have until recently been lost in the cracks between disciplines. Now some researchers are bridging the gap, modeling how piston rings conform to cylinder bores that are never completely round at operating temperatures and how fluid mechanics affects oil sneaking around the rings—including the surprising effects of the bore's surface finish.

This article reviews some of this work and highlights potential synergies.

PISTON RINGS UP CLOSE

"Improving the conformability of piston rings is very important," says STLE-member Dr. Val Dunaevsky, a leading engineer in reciprocating compressors for Ingersoll Rand Climate Control in Minneapolis. "Conformability affects all piston-ring functions and the performance of the compressor or engine. It's especially important nowadays with the current emphasis on reducing oil emissions."

Piston rings—generally three of them—sit in grooves in the piston and ride up and down on a film of oil as the engine fires. Until fairly recently, most engineers have treated the rings and cylinder bores as perfectly round, focusing on rings with asymmetrical cross-sections that can help control the amount of oil that slips past.

But there are other issues.

First is the ring's end gap: Before a ring is installed in the engine, the gap may be as large as .4 inches. After installation, when the ring is compressed into the cylinder, the gap is down to .005-.010 inches, but it's still big enough to let oil go where it shouldn't.

The second issue is roundness. "There is almost no such thing as a round cylinder," says Dunaevsky. He notes the many factors that distort cylinder bores and sleeve liners: variations in machining, distortion caused by the installation of cylinder sleeves and the clamping of the cylinder head, thermal distortions created as the engine heats to operating temperatures; pressure distortions caused by compressed and exploding gas, and even micro-variations at the level of surface asperities.

THE CRUX

Given that cylinder bores are never quite round, to what extent can a ring conform? This really is the crux of the situation for Dunaevsky, because any non-conformability creates a gap for oil transport. The end gap is not the only macro-gap in the seal between the combustion chamber and the crankcase.

Intuitively, one can understand that a flexible ring will conform to a certain amount of out-of-roundness. But there are limits. "It's like trying to force a sheet of steel into a small depression in a table," Dunaevsky explains. "If the curvature of the table distortion is smaller than the curvature which can be produced by elastic distortion in the sheet of steel, the steel will not conform. It's the same with piston rings, which are too rigid to conform to small distortions. This is the big challenge—designing the ring so it can tolerate as much bore distortion as possible."

Dunaevsky attacks the problem by first describing com-

Experiments show that the various forces that can distort a cylinder affect each order of distortion differently.

The Researchers:

Ever since his doctorate studies at Riga Technical University in Riga, Latvia, **Dr. Val Dunaevsky** has focused on the tribology of internal combustion engines, friction brakes and compressors. In his work for Westinghouse Air Brake, Bendix, Emerson Electric, and currently Ingersol Rand refrigeration compressors Dr. Dunaevsky has authored or co-authored numerous technical papers and received patents for his technical solutions and software. He has been a long-standing member of STLE, SAE and ASME and served for several years as chairman of the STLE Engine and Drivetrain Technical Committee.

Harold McCormick is president of C-K Engineering, Inc., in Ballwin, Mo. He is the author or co-author of 25 technical publications covering cylinder bore components and materials and has been issued 37 patents for his work. For more than 20 years, he has conducted seminars on piston-ring design and materials for SAE.

plex out-of-roundness in a mathematical way.

"It's challenging math because all of this happens in three dimensions," he says. "The distortion varies at different levels within the cylinder."(*See Figure 1*).

"We've approached it analytically rather than numerically because then we can work from actual engines," he continues. "My goal was to develop simple formulas that would let engineers estimate the conformability of a piston ring and design better engines."

BORE WAVES & CLOVERLEAVES

At the heart of Dunaevsky's work is a notion of the "order of distortion." Since the actual distortion of a bore at operating temperature is both irregular and unpredictable, Dunaevsky uses Fourier Analysis, which allows him to present an irregular distortion as a collection of individual wave forms. "You can even describe a square this way," he says.

The wave forms used for a cylinder bore reflect the number of potential lobes on a distorted shape (*see Figure 2*): a 0-order distortion is an enlarged or reduced bore; a 1st-order is a displaced or eccentric bore; a 2nd-order is an oval shape (two lobes); a 3rd-order is three-lobed; and the 4th-order is a cloverleaf; etc.

It's easy to see that the radius of curvature of a 4th-order harmonic is much smaller than a 3rd-order and so on. While any ring should be able to conform to a 0-order or 1st-order distortion (at least in 2D and with a nominal bore diameter), it becomes progressively more difficult to conform as the orders go higher. As proof, Dunaevsky's experimental data show that it takes only a small 3rd- or 4th-order distortion to create a relatively large oil flow past the ring.

Actual bore distortion can be expressed mathematically by combining the various harmonic waveforms in different ratios and with different offsets around the radius of the cylinder. "By doing this, we transform the bore from an arbitrary shape to certain numerical functions," says Dunaevsky. "Experimentally, we use special tools to measure the bore, and then the Fourier Transform provides the amplitude for each of the bore's waveforms."

Experiments show that the various forces that can distort a cylinder affect each order of distortion differently, as shown by Abe and Suzuki (8). In their work, thermal distortions had a greater effect than cylinder head clamping in a well-designed cast iron block with an aluminum cylinder head, while operating gas pressure had a minimal effect on bore shape (*See Figure 3*).

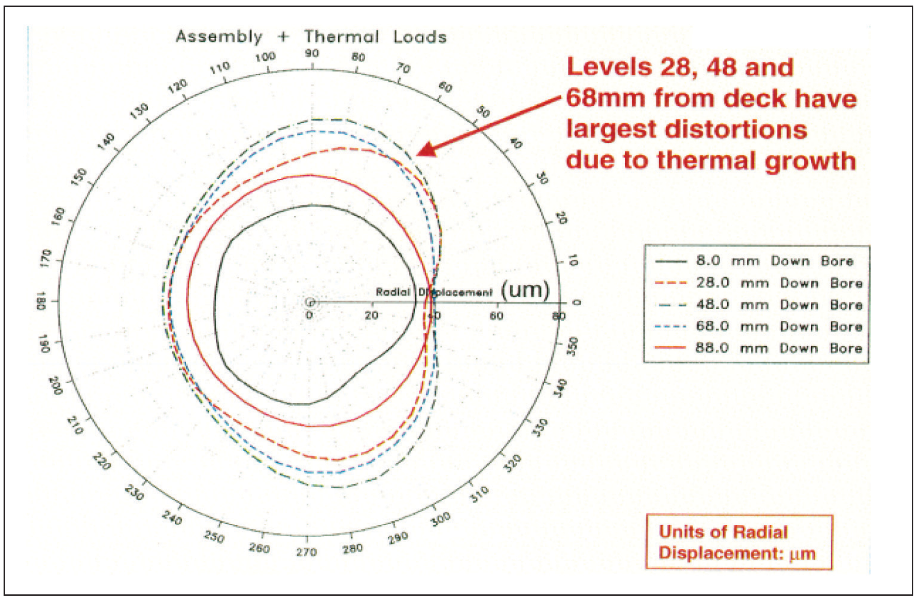

Figure 1 | **Polar plot of a cylinder bore after the head has been assembled and operational heat applied. Note that the distortion is different at different levels within the cylinder.**

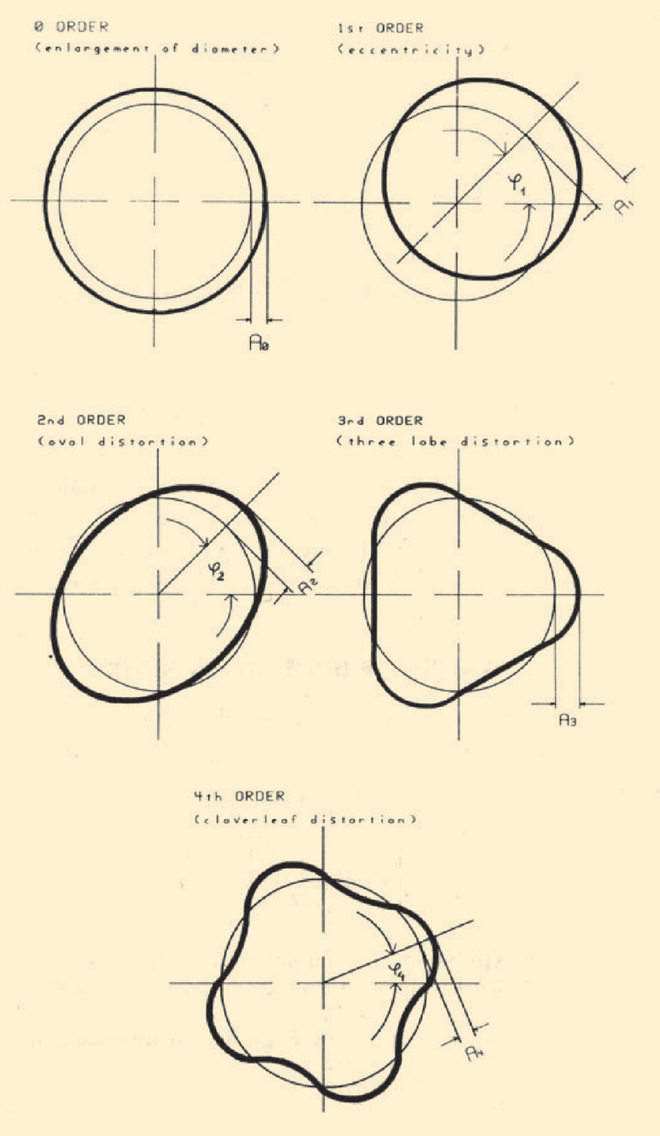

Figure 2 | **Five orders of distortion of a cylinder bore.**

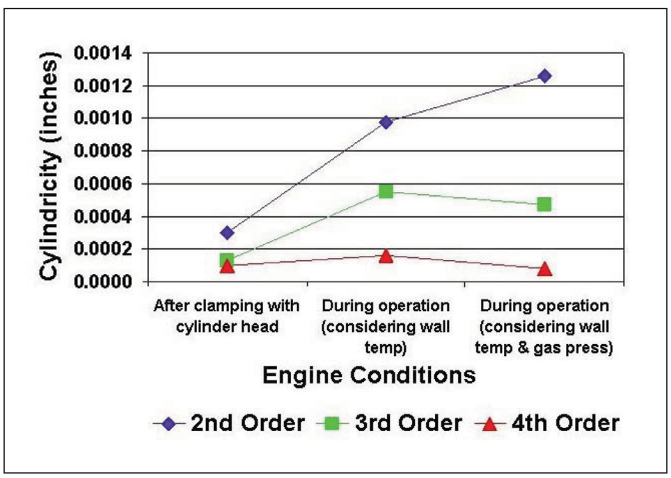

Figure 3 | **This graph from Abe and Suzuki (8) shows 2nd-, 3rd- and 4th-order distortions caused by clamping on the cylinder head, increasing temperatures to operating levels and introducing gas pressure.**

RING CONFORMABILITY

But now comes the more complicated task: "The question is how much a ring can distort itself to fill the nooks and crannies," Dunaevsky explains. "We cannot use pure mathematical functions here—we have to use the mechanical properties of the elastic ring to describe how it tries to push itself into the distorted bore."

Dunaevsky has written several papers on this topic using approaches that combine the theory of elasticity with Fourier Transform analysis and piston-ring mechanics. His result is surprisingly simple and effective:

$$A_\omega \le C \frac{Kr}{3(\omega^2-1)} \qquad (1)$$

Where: A_ω = Limit of bore distortion to which the ring can conform
- ω = Order of distortion
- K ≈ $FD^2/4EJ$ = Piston ring parameter
- r = Piston ring radius
- F = Tangential tension of a ring
- D = Nominal bore diameter
- E = Elastic modulus of piston ring
- J = Moment of inertia of a ring cross-section
- C = Empirical factor related to bore size and ring design. Its derivation is described in (7). For many applications using C ≈ 0.15 is satisfactory.

"I verified this model through empirical analysis," Dunaevsky says, "and it allows me to predict whether there will be conformability. I also developed a computer code with one of my colleagues (6), which takes into account more detailed characteristics of the piston rings than those shown above. You punch in the data, and in a matter of seconds, you get the results."

According to Dunaevsky, this model helps engine builders and piston-ring manufacturers design better engines that consume less oil (8)-(9).

THE OIL TRANSPORT MECHANISM

Dunaevsky's work focuses on one side of the oil emission conundrum—preventing ring non-conformability—but there is another side: What actually happens to oil that blows by the rings, regardless of whether it slips through the end gap or non-conformability gaps? This question has driven the work of C-K Engineering, Inc., in Ballwin, Mo., whose president is Harold McCormick.

McCormick is fascinated by the interaction of the mechanical and the chemical. "Formulators get frustrated when they develop formulations that work well in the standard ASTM tests but may not work at all in some engines. But it's really a simple story—what the mechanical engineer does with the engine design can either help or hurt the chemist on the liquid side, and what the chemist does can help or hurt

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the mechanical guy. Sometimes I think one side is making progress and the other side is taking it away. The interaction of mechanics and fluids is a key topic that needs to be talked about.

“At the time we got involved in this, a few of us thought there had to be more to oil consumption besides evaporation of an oil film on the cylinder wall,” McCormick continues. “As we began to work with it, we became convinced that the aerosols were possible contributors.”

To form an aerosol, all you need is an orifice, a pressure differential across it, and a source of liquid on the high-pressure side. The factors that influence the concentration of the aerosol and the size of particles are the pressure differential, the size of the orifice, the viscosity of the fluid and the surface tension of the fluid.

Initially, the concept of aerosol formation was met with a lot of skepticism. “People tend to think about oil properties related to the sump, where temperatures are only about 250 F,” McCormick says. “But in the ring-belt area, the temperatures can reach 400-450 F, and there may be pressures of 200-250 PSI acting across the ring face. Aerosols are going to form more easily, and the oil in the aerosol will also oxidize more easily.”

PROVING AEROSOL FORMATION

The first aerosol studies employed only a simple air compressor with a small hole drilled in the cylinder wall and a paper towel held a few inches away to collect any aerosol produced. Sure enough, an oily spot appeared on the towel. But what if the piston moving across the hole had just forced the oil out?

To prove the aerosol concept more convincingly, the C-K research group constructed a more elaborate static test fixture utilizing a stationary piston and ring, as shown in Figure 4.

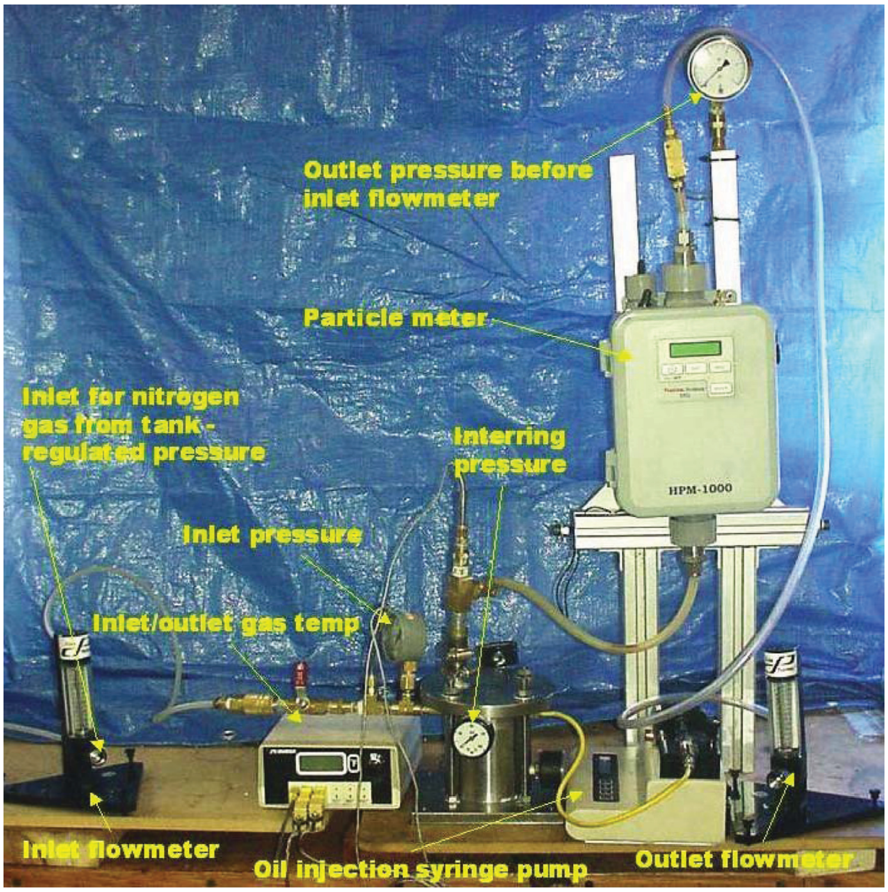

Figure 4 | **C-K Engineering’s static test fixture mimics conditions in the ring-belt without involving a moving piston.**

The test cylinder has a fixed piston inside, plus several ports around the circumference at the third land, between the second and third rings of the piston: One port admits pressurized and heated nitrogen gas, while other ports at offsets up to 180 degrees provide for the injection of controlled amounts of oil. The nitrogen flows up through the second ring gap into the second land and then out through the ring gap in the top ring. Above the top ring gap, a sampling device collects the mixture of nitrogen and oil, and a particle meter tallies the concentration of oil in the aerosol.

Results from the first batch of experiments were all over the map. Something was leaking. “When we opened the fixture and put some soapy water on the piston head to see where the leaks were, the results were amazing,” McCormick says. As Figure 5 shows, gas and entrained oil were bubbling up all around the top of the piston. In this case, there was no question of out-of-roundness and non-conformability, so the escaping gas could only have come from one source—

Table 1 | **DOE factors and levels investigated.**

Factor	-1 Low Level	+1 High Level
A: Interring Pressure 3rd Land (bar)	3.3	8.3
B: Oil Injection Rate 3rd Land (ml/hr)	0.2	2.0
C: Top/2nd Ring Gap Alignment	Aligned	180° apart
D: Oil Type (special chemistry)	A	C
E: Top Ring End Clearance (mm)	0.4	0.5
F: 2nd Ring End Clearance (mm)	0.8	1.0
G: Oil Injection Location with Respect to 2nd Ring Gap	Beneath gap	180° to gap

Table 2 | **DOE results.**

Test No.	Mass Flow Rate g/min	Particulate Concentration mg/m^3
1	8.3	10.4
2	25.7	9.5
3	8.1	400
4	8.2	31.4
5	17.6	21.7
6	15.7	400
7	26.0	2.9
8	8.1	176.6

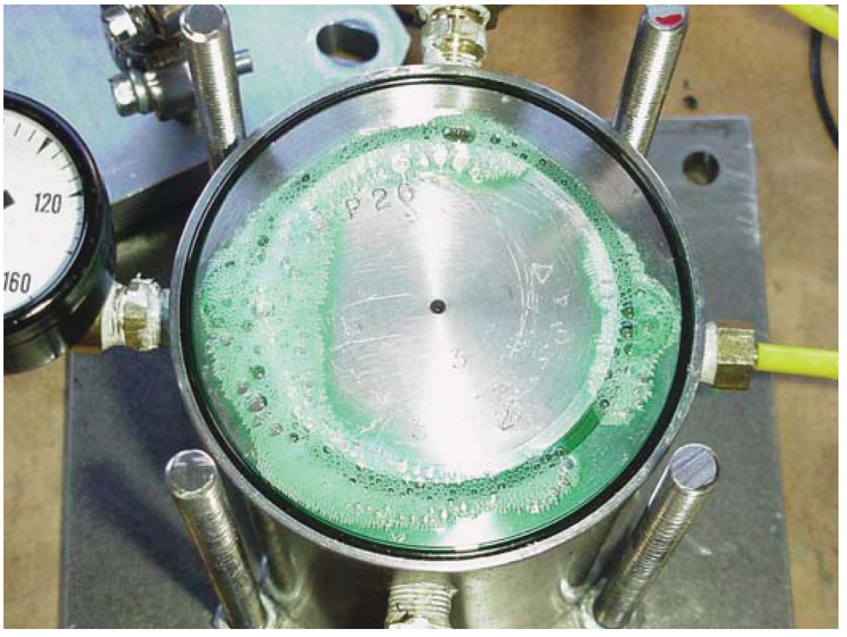

Figure 5 | **Bubbles around the piston reveal the flow of gas and oil in the static test fixture.**

the tiny scratches in the surface finish of the cylinder bore! "We had no idea we'd have so much gas flowing through the scratches. We sealed all around the cylinder except for the ring gap, and then we got consistent data."

Analyzing the data was the next challenge. It was clear that aerosol formed, but McCormick and his group wanted to understand the exact causes, including all seven factors shown in Table 1. They built a Design of Experiments (DOE) utilizing a 1/16 2^7 fractional factorial test plan to establish the relative influence of the seven factors on mass flow rate and particle concentration in the gas flowing through the top-ring end-gap.

DOE software called Design Ease 5® produced the charts shown in Figures 6 and 7. The blue boxes in the charts represent the effects of each of the factors listed in Table 1 on top-ring end-gap blowby: The vertical axis represents the probability of an impact on blowby (only factors above 50% are considered meaningful), and the horizontal axis shows the measured result of the experiment.

The major factors affecting mass flow rate (Figure 6) were A: Interring Pressure 3rd Land, C: Top/2nd Ring Gap Alignment, and E: Top Ring End Clearance.

The major factors affecting particulate concentration (Figure 7) were C: Top/2nd Ring Gap Alignment, D: Oil Type (controlled chemistry), and G: Oil Injection Location. Factors A: Interring Pressure 3rd Land and E: Top Ring End Clearance had a lesser effect.

In the next series of tests, pistons and rings having geometries identical to those utilized in the static aerosol fixture were installed in a Yanmar L100 single-cylinder diesel engine. The data developed (Figure 8) showed significant correlation between aerosol concentration and oil consumption. The blue diamonds are experimental data, and the red line represents the regression analysis.

Now that C-K had figured out the geometry affecting blowby, *what about the scratches in the cylinder bore?*

To form an aerosol, all you need is an orifice, a pressure differential across it, and a source of liquid on the high-pressure side.

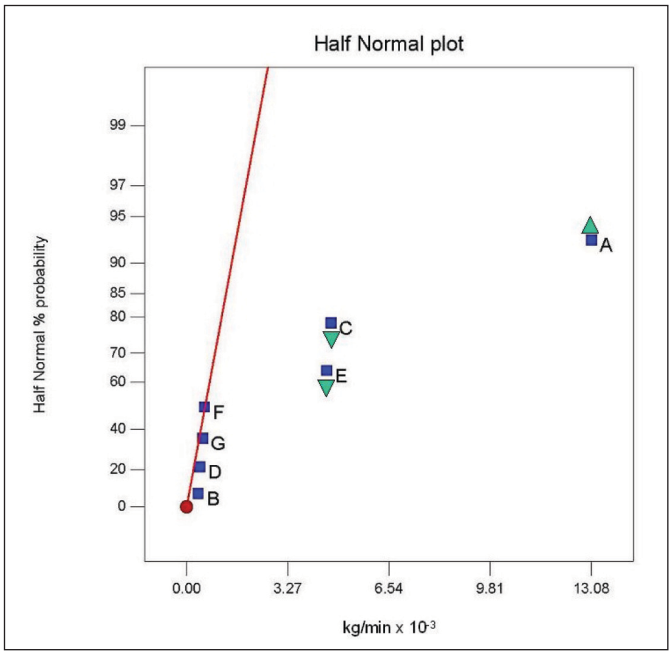

Figure 6 | **Effect on mass flow rate of changing factors from low level to high level. The primary factors increasing flow rate are an increase in Factor A and decreases in Factors C and E.**

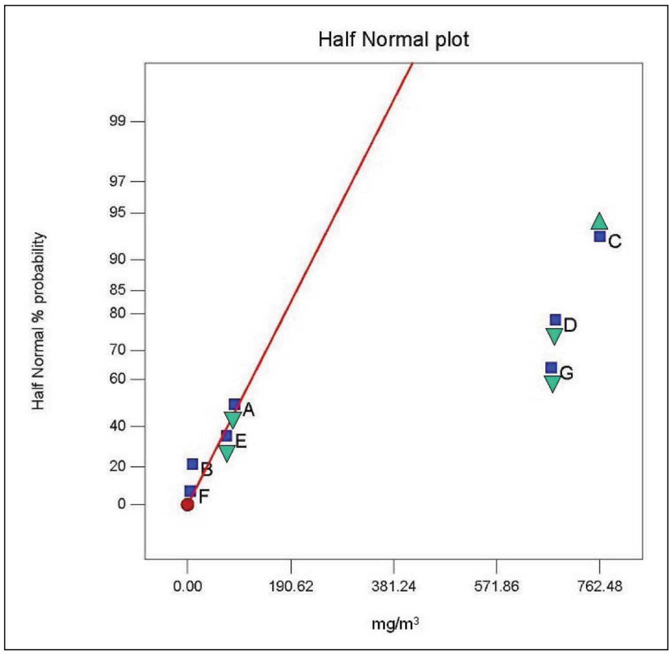

Figure 7 | **The effect on particulate concentration of changing factors from low level to high level. The primary factors increasing particulate concentration were an increase in C and decreases in D and G.**

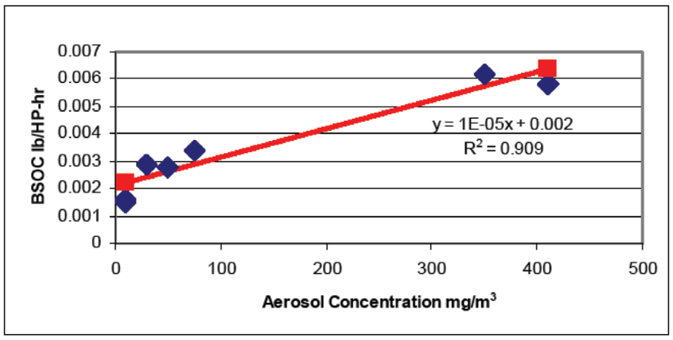

Figure 8 | **Aerosol concentration at 100 psi vs. Brake Specific Oil Consumption (BSOC).**

BRINGING SCRATCHES TO LIGHT

To evaluate the impact of surface scratches on blowby, aerosol formation and oil consumption, the C-K research team would have to be able to compute the "scratch volume." A 15-year European effort had led to the development of three-dimensional analytical software, but early interferometers that could map a 3-D surface at a microscopic level cost upwards of $400,000. Not to mention the fact that interferometers couldn't fit inside a cylinder bore! Any engine to be measured would have to be destroyed first.

So C-K Engineering came up with two clever inventions: One is a mechanism holding a rod loaded with a strip of

Figure 9 | **Insert mechanism for obtaining replicate of cylinder bore surface finish.**

Figure 10 | **SEE 3-D® Analyzer System.**

proprietary replicating material (Figure 9). The rod is lowered into a cylinder bore and precisely pressed against a portion of the wall to obtain an exact impression of the surface finish—no engine destruction required.

The second invention is a low-cost interferometer (Figure 10).

Two-dimensional analysis can only show a single surface profile, a solitary line tracing of one journey across the surface. But 3-D mapping and analysis (Figure 11) shows the surface in its full richness. It's easy to envision those deep scratches as little aerosol generators. C-K Engineering are now using the new 3-D system with both castiron and aluminum cylinder bores.

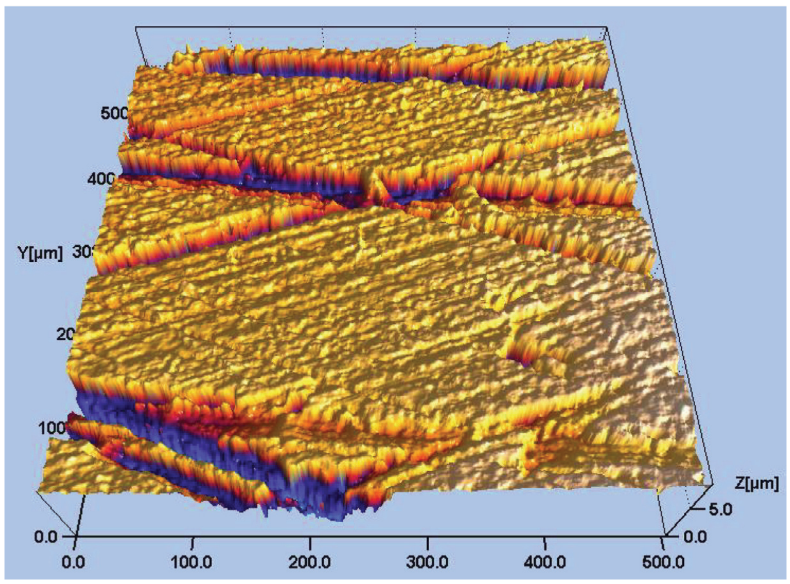

Figure 11 | **3-D analysis of a honed cast-iron cylinder bore clearly shows the scratches that help create blowby and oil aerosol formation at the interface of the cylinder bore surface and the ring face.**

"The successful operation of an aluminum engine with hypereutectic cylinder bores depends almost entirely on the size and distribution of silicon particles in the aluminum," McCormick says. "Aluminum itself has very poor lubricity—it's the silicon that carries the piston ring load.

"The great advantage of the 3-D system is that we can look for and define the size and distribution of the free silicon particles, monitor their height above the aluminum matrix and quantify areas for aerosol formation and its effect on oil consumption," McCormick adds. "With just a 2-D profile, you really can't sort this out. We're just now making the transition to a routine production use of 3-D."

AND FOR THE FUTURE?

"We believe that 3-D technology will replace 2-D profilometer measurements in engines, so that we can predict the effect of cylinder-bore finish on oil consumption," McCormick says. "We also need to know about porosity and void volumes, and then we should be able to build a theoretical model that will predict the amount and concentration of aerosol any given system will generate for a particular finish."

He notes that oil properties play into this equation, because aerosol formation depends on the oil's viscosity and surface tension at ring-belt temperatures. In the future, oil formulators may be as concerned with high-temperature surface tension as they are about oxidative stability, and new ASTM tests may more closely mirror actual engine performance.

How does C-K Engineering's work tie into Dunaevsky's non-conformability studies? "Ring non-conformability creates additional void areas," McCormick says. "When we look at oil consumption, we have to look at the contribution of each void area: the ring gap, the ring face to bore (the non-conformability), the back side of the ring, and through the bore surface texture itself." McCormick incorporates Dunaevsky's models into his own, not surprising since they two have known each other and collaborated for years.

"I think we're on the verge of a marvelous step-function in terms of understanding a fundamental mechanism of engine and compressor oil consumption and deposit formation," McCormick concludes. TLT

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REFERENCES AND ADDITIONAL INFORMATION

Harold McCormick recommends the following PDF link as a good source for overview information: **www.vtt.fi/inf/pdf/tiedotteet/2002/T2178.pdf.**

You may also want to review these technical papers:

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