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Recent Trends in Piston Ring Coatings for Enhanced Engine Efficiency and Durability

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Abstract

Friction and wear at the piston ring–cylinder liner interface remain major contributors to mechanical losses and durability concerns in Internal Combustion (IC) engines. These issues directly impact engine efficiency, fuel consumption, and emissions. To address these challenges, advanced coatings for piston rings have gained significant attention. This paper highlights the evolving role of nanocoatings in improving piston ring performance, mitigating wear and reducing emissions. Given that frictional losses at this interface account for nearly 50% of total mechanical losses, nano-engineered surfaces have emerged as a promising strategy for achieving more efficient and durable engines. Advanced solutions such as Diamond-Like Carbon (DLC) coatings, multilayer architectures, and composite coatings are succinctly reviewed and evaluated. Emerging strategies involving engineered surface textures are poised to significantly enhance piston ring coating design, and the latest innovations in this domain are critically analysed. The paper systematically examines coating materials, deposition technologies, performance assessments, and the practical challenges associated with their application to provide a comprehensive understanding of current advancements and identify future research directions in this domain.

Major Findings: *From numerous investigations report notable gains in Brake Thermal Efficiency (BTE), enhanced wear resistance, and marked reductions in hydrocarbon (HC), carbon monoxide (CO), and particulate emissions have been reported. Nonetheless, critical research gaps remain, including the establishment of standardised tribo-corrosion testing protocols, scalable coating deposition processes, and the development of application-specific coatings suited for alternative fuels and hybrid engine systems.*

Keywords: *Emission, IC engine, Nano-coating, Surface engineering, Tribology*

1.0 Introduction

Piston rings provide the essential functions of sealing the combustion chamber, distributing and regulating oil on the cylinder walls, and transferring heat to the cylinder liner[1]. In modern internal combustion engines, they contribute substantially to fuel consumption and emissions through frictional losses. For example, piston ring–liner friction can account for a large share of engine friction (one source estimates ~45% of total mechanical friction[2]), and in heavy-duty diesels, it can consume ~4–15 % of fuel energy[1]. Minimising these losses is therefore a priority for efficiency and emissions. Historically, piston rings were made of pearlitic cast iron or steel and protected with hard coatings. Common traditional treatments include chemical nitriding or electroless Ni–P plating, and hard-chromium electroplating. Chrome-plated rings exhibit high hardness; however, they are vulnerable to fatigue cracking and scuffing, and the plating process utilises toxic substances. Research has shown

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that chromium-plated rings exhibit very high friction and wear (e.g. one SRV tribotest found the highest COF and mass loss for chromed rings[1]). Consequently, many manufacturers shifted to chromium nitride (CrN) PVD coatings. In the 1980s, CrN became popular for engines due to its hardness, corrosion resistance, and relatively low friction[2]. In the early 2000s, Mahle introduced a thick (≈30–40 µm) multi-layer CrN piston ring coating (product "MIP230") specifically to improve scuffing resistance[3]. While CrN and similar conventional coatings extended ring life, limitations remained. Nitrided or thick hard coatings can still suffer under severe boundary-lubrication conditions, and they contribute to frictional losses that reduce fuel economy. Friction and wear in IC engines account for 48% of energy losses, with piston rings contributing significantly to these inefficiencies[4,5]. Piston rings contribute 24% of total mechanical friction losses in engines.

1.1 Primary Functions of Piston Rings

Sealing Combustion Gases: Maintain compression by preventing blow-by (leakage of combustion gases into the crankcase). Poor sealing reduces power output by up to 3–5 % due to pressure loss[6].

Heat Dissipation: Transfer ~70% of the piston's heat to the cylinder walls, preventing overheating and piston seizures.

Oil Regulation: Scrape excess oil from cylinder walls, minimising oil consumption and reducing hydrocarbon emissions by 8–12 %[7,8].

Nano-coatings change the tribological regime. Compared to uncoated steel rings, DLC and related nanocomposite films offer much higher hardness and can even exhibit "superlubricity" under some conditions[9]. Solid lubricants (MoS_2, WS_2, graphene) provide ultra-low shear interfaces in dry sliding[10]. Sol–gel films can alter ring surface chemistry and oil film formation[2]. Thermal sprays produce thick ceramic layers (often micron-scale) with good load-bearing, but may need finish-grinding. In sum, nano-coating research is motivated by the need to cut friction (hence fuel burn) and improve ring life beyond what conventional coatings allow[11]. This review systematically compares coating methods and materials, and summarises their effects on engine performance (friction, efficiency, emissions, durability) as reported in the literature.

The motivation for this review is two-fold: (1) to provide a comprehensive synthesis of the past decade's advancements in piston ring coatings, and (2) to identify the remaining scientific and engineering challenges that must be addressed to further reduce engine friction and wear, particularly as powertrains diversify and emissions standards tighten.

2.0 Literature Review

2.1 Coating Materials

2.1.1 Ceramic and Nitride Coatings

CrN, TiN, TiAlN, and AlCrN coatings deposited via PVD/CVD have demonstrated significant improvements in hardness and wear resistance, with friction reductions up to 30% compared to uncoated rings[20].

2.1.2 Diamond-like Carbon (DLC)

DLC coatings are widely adopted for their ultra-low friction and high hardness; hydrogenated and non-hydrogenated variants are tailored for different oil chemistries and temperatures. In the industry of auto motives, carbon-based materials among the premium materials appeared as one of the most advantageous solutions for surface engineering[7,12].

2.1.3 Multilayer and Functionally Graded Coatings

Laminated structures (e.g., CrN/DLC, TiN/TiCN) and graded compositions enhance toughness and mitigate crack propagation. Residual tensile stress in carbon-based coatings reduces adhesion strength, leading to diminished durability and suboptimal performance in friction-intensive applications. To address these limitations, researchers have explored solutions such as implementing intermediate bonding layers and innovative multilayered architectures combining carbon-based materials[13-19].

2.2 Deposition Methods

2.2.1 Physical Vapour Deposition (PVD)

The dominant technique for hard coatings offers precise control over thickness and composition. This category includes sputtering and cathodic arc techniques that

Table 1. Effect of coating materials on tribological properties

Coating Materials	Coating Parameters	Methodology	Outcomes
CrAlN, CrAlSiN[20]	Cathodic arc PVD; Si content varied (0–8 %)	Coated on steel, SEM/XRD analysis, reciprocating wear test (dry/lubricated)	2% Si in CrAlSiN gave the best hardness and wear resistance
TiAlN, CrAlN[21]	Arc-PVD; Ti:Al = 50:50, Cr:Al = 70:30	Coated on nitrided steel; wear tests under lubricated engine conditions	CrAlN had lower wear and friction than TiAlN
DLC (Diamond-Like Carbon)[22]	PACVD; Thickness ~2 µm	Coated on piston rings; tribo-tests under boundary lubrication; SEM and Raman analysis	Significant friction reduction; excellent wear resistance
TiN/CrN multilayer[23]	Cathodic arc PVD; multilayer periodicity 50–200 nm	Applied to rings; wear/sliding tests under lubrication; hardness and adhesion tested	Enhanced hardness and wear resistance over single layers
MoS_2, MoS_2/Ti composite[24]	Sputter deposition; Ti content varied	Tribological tests (dry/lubricated); SEM and XPS analysis	MoS_2 alone had high friction; Ti improved wear resistance
CrN, CrAlN, CrAlSiN nanocomposites[25]	Magnetron sputtering; nanograin structure <50 nm	Coated on piston rings; tested under mixed lubrication in engine-like tribometers	CrAlSiN gave the lowest wear rate and best performance

create dense, nano-scale films. PVD can deposit complex nitrides (CrN, TiN, etc.) and carbon coatings (DLC) on piston rings. Advantages include producing very thin (<1 µm to tens of µm), hard, uniform coatings with excellent adhesion[3]. Physical vapour deposition technology was developed to enable the application of much thinner coatings and to provide an environmentally friendly alternative to electroplating, effectively addressing the environmental concerns associated with traditional electroplating methods[26-29].

2.2.2 *Chemical Vapour Deposition (CVD)*

Used for thicker films and complex chemistries. CVD can deposit very uniform coatings and can coat complex shapes. Common piston-ring CVD coatings include pyrolytic carbon or CVD diamond-like carbon. CVD processes can even grow crystalline diamond coatings. For example, research at FAU showed CVD-diamond coatings on silicon-carbide rings allowed dry operation over tens of kilometres with wear under a few microns[30].

Laser Surface Texturing and Photochemical Etching

Creation of micro-dimples or protrusions enhances hydrodynamic lubrication and reduces boundary friction.

2.2.3 *Sol–Gel Methods*

Sol–gel processes deposit oxide-based coatings (e.g. TiO_2, SiO_2) through liquid precursors. They can coat intricate shapes at relatively low cost and temperature. However, sol–gel films are usually very thin and brittle, with limited thickness control. There are a few reports of sol–gel coated piston rings (e.g. TiO_2 coatings by dip-coating), which showed modest friction reductions (~5–10 %) and improved wear resistance under test[31].

Table 2. Deposition methods and their applications

Method	Cost	Uniformity	Best For
PVD[3]	High	Excellent	Durable industrial coatings
CVD/ALD[30]	High	Exceptional	Atomic-scale precision
Spin Coating[28]	Low	High	Optoelectronics, thin films
Dip Coating[29]	Low	Moderate	Simple polymer coatings
Electrodeposition[27]	Low	Variable	Conductive composites
Aerosol/CLD[31]	Moderate	High	Large-area functional films

Several deposition techniques have been developed to enhance the performance of piston ring coatings, each offering specific advantages and limitations depending on application requirements. Physical Vapour Deposition (PVD) is widely preferred for producing hard, uniform coatings with excellent adhesion and precise thickness control, while also serving as an eco-friendly alternative to electroplating. Chemical Vapour Deposition (CVD) and Atomic Layer Deposition (ALD) provide exceptional uniformity and atomic-level precision for high-performance applications. Cost-effective methods like dip coating and spin coating are suitable for simpler or large-area coatings but may lack durability. Table 2 summarises these methods and their advantages.

2.3 Testing Procedures

To measure wear and friction following methods are used as per the applications and use. Different authors have applied the methods and discussed their views on the results obtained.

Table 3. Various methods of measuring wear and friction

Method	Friction Measurement	Wear Measurement	Parameters Measured
Reciprocating Tribometer[61,51]	Direct (force transducer, CoF)	Thickness/profile comparison, weight loss	Coefficient of Friction (CoF), wear volume/rate, wear scar width, temperature, load, and sliding speed
Floating Liner Engine[62,50]	Direct (real-time, in-engine)	Post-test inspection, FMEP	Friction Mean Effective Pressure (FMEP), real-time friction force, oil temperature, speed, load, wear depth
Strip Down Test[63,49]	Indirect (via FMEP, torque loss)	Direct (physical measurement)	Wear depth, wear volume, ring width reduction, surface roughness, and visual scoring
Pressure Retention[64,48]	Indirect (pressure decay)	Inferred (sealing effectiveness)	Pressure loss rate, blow-by rate, sealing efficiency, and gas leakage
Surface Analysis[65,53]	N/A	Direct (microscopy/ profilometry)	Surface morphology, roughness (Ra, Rz), microstructural changes, coating integrity

Reciprocating tribometer testing is the best and most commonly used method for measuring piston ring wear and friction in research and development, due to its ability to closely simulate engine conditions, provide direct and repeatable data, and efficiently screen materials and coatings before engine-level validation[32].

2.4 Friction Reduction

Nano-coatings typically reduce ring–liner friction by altering surface chemistry, roughness and lubrication. DLC and other carbon films give particularly low friction in lubricated sliding. In bench tests, DLC-coated rings often show friction coefficients (μ) ~0.1–0.2 under oil lubrication, compared to ~0.3–0.4 for uncoated steel[3]. For example, Stachowiak[55] reported that PVD-taC coatings on rings reduced friction by up to ~31% under oil-starvation conditions[3]. Similarly, Ferreira et al. found that carbon-containing PVD coatings (DLC, MeDLC) can outperform CrN; the study showed multi-element "Transition Metal Dichalcogenide" (TMD) coatings (e.g. W–S–C) having dry friction ~0.10 vs ~0.30 for DLC[9]. Pure solid-lubricant coatings achieve even lower shear: The Polish study by Holmberg[55] embedded MoS_2 and WS_2 nanoparticles in a nitride matrix on liners/rings; the best sample (MoS_2+WS_2) ran with μ≈0.13 (i.e. frictional shear half that of a single-phase coating and one quarter that of an uncoated reference[10]). Graphene-based coatings (not fully studied on rings) are expected to act similarly to MoS_2 with ultra-low shear planes.

2.5 Wear and Durability

All nano-coatings aim to curb abrasive and adhesive wear of the ring and liner. Harder coatings (TiN, CrN, DLC) greatly slow wear progression. In bench tests, CrN/TiN PVD stacks exhibited minimal mass loss over hours of oscillation, while Cr-plated rings wore ~16× more mass[33]. Ni–P–SiC plating provides extreme hardness (1000 HV) and shows very low wear in pin-on-disk tests[34]. Tribological coatings can also "transfer" to the liner, forming a low-shear tribolayer that protects both surfaces. For instance, the CrMoN/MoS_2 sputtered coating on rings left a lubricious MoS_2-rich film on the cast-iron liner; the wear of the coated pair was much lower than with a conventional Cr plate[35]. High-velocity spray coatings (WC–Co, Cr_3C_2) achieve similar wear resistance to plating or PVD.

However, not all coatings behave ideally. PVD nitrides can crack under thermal cycling or scuffing loads; layered designs improve adhesion and toughness. Rozario[33] noted that chromium-plated rings readily lose mass under scuffing, whereas multilayer PVD and Ni–P+Si_3N_4 coatings better survive scuffing[2]. Solid lubricants like WS_2 alone can oxidise or burn off at high T, so they are often doped or sealed in matrices. Graphene coatings also face potential tribochemical wear at high temperatures. In durability engine tests, manufacturers generally find that modern PVD and composite coatings achieve similar or better life than hard chrome, but field data on ring longevity is still limited.

3.0 Results and Discussions

3.1 Effect of Coating on Combustion and Emission Parameters

Yang wang[36] found better efficiency and post-treatment performance while applying the thermal barrier coating in a diesel engine. They also suggested that NOx increased due to high in-cylinder temperature, and CO and HC were reduced.

S. Mohamed[37] carried out an Experimental study on engine performance with zirconia-based ceramic-coated pistons with the help of plasma spray coating, with 3 materials later on tested for performance and emissions. They identified that fused zirconia coating showed the best improvements in thermal efficiency and emissions, and lower CO, HC, CO_2, and NOx

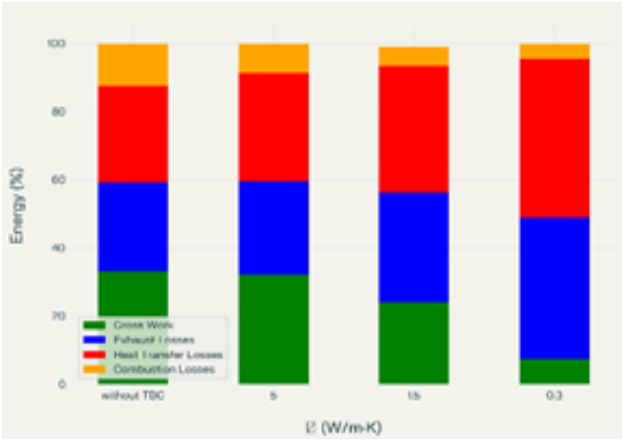


Figure 2. Influence of TBC on energy distribution[36].

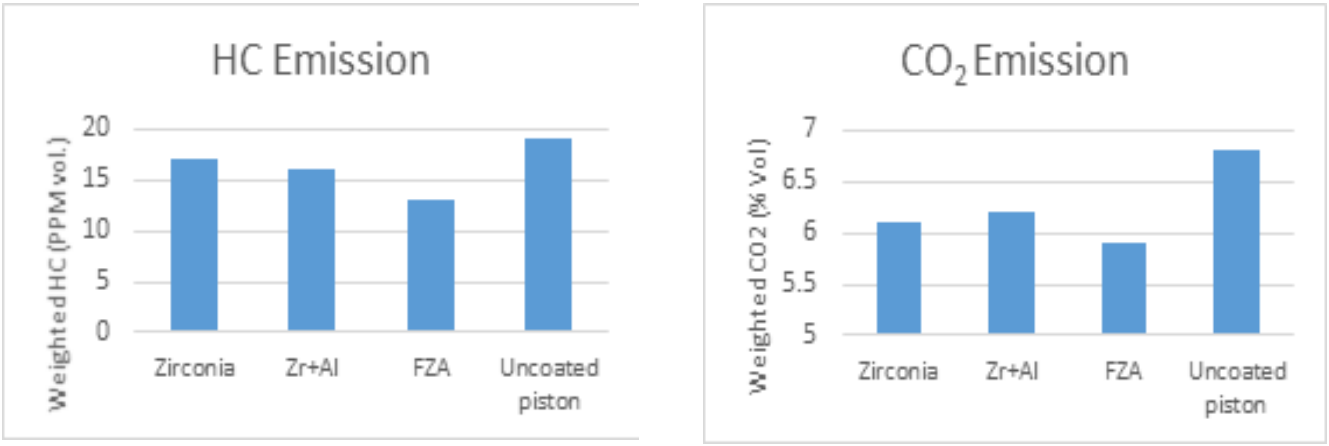


Figure 2. HC and CO_2 Emission in various ceramic coatings[37].

emissions. They further added that ceramic coatings can improve IC engine performance and promote cleaner production.

Dolatabadia[38] provided analytical modelling of coatings like Nickel Nanocomposite (NNC) and DLC on fuel consumption/emissions. They observed that NNC improved tribology and reduced fuel consumption, and DLC improved sealing but increased friction power losses. Coatings impact fuel economy and emissions

Table 4. Effect of coating on performance and emission

Effect of Coating on Performance	Effect of Coating on Emissions	Reference
Increased temp → better efficiency and post-treatment performance	Higher NOx due to high in-cylinder temp; CO and HC reduced	36
NG → good efficiency; H_2 → mixed effects, requires tuning	H_2 → lower CO, CO_2, UHC; may increase NOx	40
Fused zirconia gave the highest performance gains	Emissions reduced for all gases tested with zirconia-based coatings	37
Friction decreased with speed; critical for fuel savings	Not addressed	56
NNC reduced friction and power loss; DLC increased friction but improved sealing	NNC reduced emissions by improving efficiency; DLC reduced blow-by	38
Blends performed well under transient loads; a slight reduction in peak power	H_2 blends → lower CO/THC; increased NOx controlled via ignition timing	41
Al–Ti rings showed better performance than other material combos	Emission benefits implied via reduced friction losses	42
Graphite helped in cold starts and high load; reduced skirt wear	Reduced wear helped minimise particle generation in the start-up and running-in stages	39

significantly; selection depends on trade-offs between friction and sealing.

Zhang[39] investigated the wear behaviour of graphite coating on the piston skirt. Graphite reduced wear and scuffing during cold starts and high-load conditions. Provided effective solid lubrication. Graphite coating enhances durability and performance under harsh engine conditions.

3.2 Trends, Breakthroughs and Contradictions

Recent literature shows several clear trends. Nanocomposite coatings (e.g. TiSiCN, CrMoCN, Me-DLC) that mix hard and lubricious phases are consistently high-performing[9]. Doping PVD coatings with carbon or nitrogen (e.g. Cr–C, Ti–C, Ti–N–C) increases toughness and frictional self-lubrication[9]. Multilayer architectures (alternating carbide/metal layers) are effective for scuff resistance[43]. The use of nanoparticles in oil, along with coatings, is also a new "synergistic" approach[44]. Key breakthroughs include the identification of DLC variants (such as hydrogen-free ta-C) that maintain very low friction even under starved conditions[3,58], and the demonstration that even a sub-micron composite ring coating can yield nearly 1% fuel saving in real drivetrains[38].

At the same time, some contradictions appear. For example, while many studies show DLC lowers friction, Dolatabadi[38] found that in their multi-physics engine model, DLC on the bore increased piston-ring friction power loss (though improved sealing). This may reflect boundary-lubrication effects or high-contact pressures. Similarly, a coating that is optimal at high speeds/temperatures might be worse at low speeds (as Gangopadhyay notes[45]). There are also trade-offs between hardness and toughness: extremely hard coatings (pure TiN) can spall under shock, whereas composites or multilayers sacrifice some hardness for durability.

Across the literature, there is consensus that advanced coatings-especially multilayer, nano-structured, and surface-textured types-can reduce friction by 20–40 % and extend wear life by two to five times compared to conventional coatings. Notably, positive surface texturing (protrusions) at optimal geometries (e.g., 25 μm height, 10% area density) yields up to 28% friction reduction in PR/CL systems under lubrication1. Tribo-corrosion-resistant coatings, such as CrN and DLC, maintain performance in aggressive environments, especially when combined with post-deposition sealing or laser treatments[59].

Table 5. Effect of coating on tribological properties

Coating (Material)	Deposition Method	Tribological Effects	Fuel/Emission
DLC (Diamond-like Carbon)[46,30]	PVD (sputtering) / CVD	Lowest friction (COF ≈0.07–0.10) and wear of all coatings; eliminates scuffing.	~1% better fuel economy[31,60]
CrN (Chromium Nitride)[47]	PVD sputter/arc	greatly reduces wear vs. steel. COF ≈0.10–0.13.	Improves efficiency (reduces friction losses)
TiN (Titanium Nitride)[35]	PVD	Very hard, higher COF (up to ~0.15)	—
CrMoN/MoS_2 (composite)[44]	PVD + ion sulfuration	Solid-lubricant composite; ~40% lower COF vs Cr plating	—
NiP + Si_3N_4 (electroless)[30]	Electroless plating	Ni–P matrix with Si_3N_4 particles; moderate ↓COF.	—

3.3 Emission Benefits of Nano Coatings

Table 6. Effect of coating on emissions[52]

Coating Material	CO Reduction	HC Reduction	Smoke/PM ↓	NOx Effect
LYSZ + La_2O_3	-19.69%	-15.15%	-27.27%	Slight increase
CrN/TiN	-10–20%	-5–10%	Moderate	Neutral to ↑
DLC	↓ (sealed ring)	↓	↓	↑ unless tuned
Graphite	N/A	N/A	↓ during cold start	N/A

Table 7. Effect of coating on mechanical properties[53]

Coating	Method	Hardness (HV)	Thickness (µm)	Advantages
Nano-HVOF	HVOF	800–1000	150–200	Wear, oxidation-resistant
CrN/TiN	PVD	1800–2200	10–20	High hardness
Ni-SiC	Electroless	~700	~100	Cost-effective
DLC	PVD	~2000	2–5	Friction reduction

4.0 Conclusion

The major findings are:

- **Friction and wear**: Nano-coatings (DLC, nitrides, nanocomposite layers) can dramatically lower ring–liner friction (often by 30–70 %) and wear rates (often by 50–80 %) compared to uncoated steel or conventional chrome plating. Coatings with embedded solid lubricants (MoS_2, WS_2, graphene, carbon) are particularly effective in achieving ultra-low friction.
- **Fuel economy and emissions**: Engine tests and models consistently show modest fuel savings (roughly 0.5–1.0 % fuel economy improvement) when advanced coated rings replace standard rings. Small reductions in HC/PM are also reported, mainly attributed to reduced oil drag.
- **Durability**: Properly engineered nano-coatings can meet engine service life requirements. For example, multilayer PVD and Ni–P–SiC coatings have been shown to resist scuffing and cracking in simulated engine conditions. Coated rings often survive higher load/stress than bare rings in accelerated tests.
- **State of research**: The field is rapidly evolving. Recent advances include plasma-sprayed TiSiCN and PEMS-sputtered tribofilms, as well as hybrid approaches that combine coating with micro-texture. Computational models (multi-scale ring dynamics) are now being used to predict coating effects on friction/power. There is consensus that multi-layer and composite designs (for example, alternating hard/soft layers or carbon-doped nitrides) outperform single-material coatings. However, long-term engine data are still emerging.

5.0 Future Directions

Research should focus on real-world engine tests of promising coatings, cost-benefit analysis, and new materials. In particular, multilayer designs (combining hard carbides with lubricious graphite layers) and 2D materials (graphene, MoS_2 nanosheets) are of great interest for next-generation rings. The potential of Atomic-Layer Deposition (ALD) for ultra-uniform nanofilms is also a frontier. Integration of coatings with surface texturing (laser dimples or laser-honing of bores)

may yield synergistic friction reduction. Finally, more comprehensive emission and durability testing under varied driving conditions will be needed to fully validate the benefits. To reduce emissions in IC engines, authors are also looking for alternative fuels and blends of fuel for various applications[66].

In summary, nano-coatings on piston rings are a promising route to lower engine friction and improve efficiency. While not all challenges are solved, the consistent trends in the literature show that advanced coatings lead to clear performance gains – reduced friction, reduced wear, and slight gains in fuel economy – while opening new possibilities for durable, high-performance engine surfaces.

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