

Performance-based selection of cathodic-arc PVD TiAlN and AlCrN coatings for SR34 piston-ring steel: Tribological, tribocorrosion and thermal assessment

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Abstract

Piston rings operate under severe sliding conditions, high temperatures, and corrosive environments, making surface degradation a critical factor affecting engine durability. This study presents a comparative evaluation of cathodic-arc physical vapor deposition (CA-PVD) TiAlN and AlCrN coatings on SR34 martensitic stainless-steel piston-ring material using structural, mechanical, tribological, thermal, and tribocorrosion assessments. FTIR, XRD, XPS, and SEM–EDAX analyses indicated that the TiAlN and AlCrN coatings had thicknesses of approximately 3.98 μm and 3.78 μm , respectively, and were continuous. AlCrN exhibited the lowest thermal-mismatch stress (12.47 MPa), a thermal expansion coefficient that closely matched that of SR34, and the smoothest surface ($R_a = 0.0783 \mu\text{m}$). In contrast, TiAlN exhibited superior mechanical properties, with an average Vickers hardness of 2626.46 HV and a nanoindentation hardness of 28.02 GPa. During lubricated sliding tests under 10 kg and 15 kg loads, TiAlN displayed the lowest COF, weight loss, and specific wear rate. Additionally, the critical failure loads determined through scratch testing were higher for TiAlN. Tribocorrosion tests revealed that TiAlN possessed the noblest corrosion potential, the lowest corrosion current density, the highest charge-transfer resistance, and the most stable friction response. Overall, TiAlN is recommended for applications where wear and tribocorrosion resistance are paramount. In contrast, AlCrN is preferable for applications prioritizing surface smoothness and thermal compatibility in piston-ring design and selection.

Keywords

SR34 piston-ring steel, TiAlN coating, AlCrN coating, cathodic-arc PVD, sliding wear, tribocorrosion, surface engineering

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Highlights

- TiAlN and AlCrN coatings were deposited successfully on SR34 steel.
- AlCrN achieved the smoothest surface and closest CTE match.
- TiAlN produced the highest hardness and nanoindentation response.
- TiAlN showed superior sliding wear and tribocorrosion resistance.
- TiAlN is promising for high-performance piston-ring applications.

Introduction

Piston rings are among the most heavily loaded parts in internal combustion engines due to their continuous sliding contact, varying combustion pressures, high temperatures, lubricant starvation, abrasive particles, and chemically aggressive combustion by-products.^{1–3} The upper piston ring is especially crucial, as it acts as a gas seal, regulates oil consumption, and transfers heat generated by the piston

to the cylinder liner.^{4,5} The latest reviews on piston ring coatings confirm that surface coating is a widely used practice to reduce the friction coefficient and wear rate, enhance the service life of piston rings, and reduce fuel consumption in internal combustion engines.^{6,7} When in service, the piston-ring surface is subjected to frictional heating, adhesive wear, abrasive wear, oxidation, corrosion, and tribocorrosion.^{8,9} These synergistic degradation processes may increase surface roughness, enhance material removal,

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Table 1. Recent literature on TiAlN, AlCrN, and related PVD hard coatings.

Author(s), year	Coating/ system	Substrate/application	Key findings	Limitation/gap
Dalibón et al. (2026) ²⁵	PVD AlCrN	AISI 420 martensitic stainless steel	AlCrN improved sliding/abrasive wear and corrosion protection.	Focused on AISI 420; no comparison with SR34 piston-ring steel.
Aktarer et al. (2025) ²³	CrN and AlCrN	Grey cast-iron cylinder liner	AlCrN performed well at low loads; adhesion dominated the high-load behavior.	Studied cylinder liner, not SR34 piston-ring substrate.
Soranansri et al. (2025) ²⁶	AlCrN, TiAlN, Arc-DLC	Hot forming tool surface	PVD coatings reduced material transfer under severe contact.	The application was forming, not piston-ring tribocorrosion.
Liu et al. (2025) ²⁷	Multilayer TiAlSiN/AlCrN	High-temperature hard coatings	Multilayer design improved oxidation and wear behavior.	Did not study SR34 steel or ring–liner wear conditions.
He et al. (2024) ²⁸	AlCrN/AlTiSiN	Super duplex stainless-steel threading	Coating strategy improved surface performance and wear response.	Machining-focused; no thermal expansion or tribocorrosion analysis.
Hwang et al. (2024) ²⁹	TiN, AlTiN, AlTiCrN	Coated sliding surfaces	Arc-PVD coating performance depended on the atmosphere and wear-track chemistry.	Did not compare TiAlN and AlCrN on piston-ring steel.
Maskavizan et al. (2024) ³⁰	Cathodic arc PVD CrN	AISI 4140 steel	Nitride coatings improved wear/corrosion, but defects enabled electrolyte ingress.	CrN-focused; limited relevance to TiAlN/AlCrN piston-ring coatings.
Pereira et al. (2023) ³¹	TiSiN/AlCrN	WC-Co cutting tools	Temperature strongly affected tribological behavior.	Tool-coating context: no SR34 or piston-ring evaluation.
Sousa et al. (2023) ³²	TiAlN, TiAlSiN, AlCrN	Duplex stainless-steel milling tools	Different PVD coatings showed different wear evolution and mechanisms.	Machining application: no coupled wear–corrosion testing.

diminish sealing performance, and shorten engine service life.¹⁰

The martensitic stainless steel SR34 is designed for piston-ring applications due to its high strength, hardness, heat resistance, and dimensional stability under engine operating conditions.¹¹ Nevertheless, direct metal-to-metal contact, local plastic deformation, abrasive attack, and electrochemical degradation can still take place on the uncoated SR34 surface during sliding.^{12,13} As piston ring failure often initiates at the surface, a surface-modification method is a viable approach to improving the performance of the SR34 without altering the bulk substrate. Thin hard layers may be applied to the steel surface to protect it by reducing asperity contact, hardening the surface, inhibiting wear, and serving as a barrier against corrosion and tribocorrosion.^{14,15} Recent studies on PVD AlCrN-coated martensitic stainless steel have also revealed that AlCrN can enhance resistance to sliding and abrasive wear and provide corrosion protection in harsh environments.^{16,17}

Physical vapor deposition (PVD) is a convenient coating route for piston-ring materials, enabling thin, dense, and adherent coatings with controlled thickness.^{18,19} PVD coating technologies are reported to provide smooth surfaces, good film–substrate adhesion, and excellent tribological properties for piston-ring applications. Cathodic arc deposition is of particular interest for growing hard nitride films because of its highly ionized metal plasma and the energetic ion bombardment it promotes during film growth.^{20–22} Recently, Aktarer et al.²³ deposited CrN and AlCrN coatings on gray cast-iron cylinder liners by cathodic arc deposition and demonstrated that coating hardness, adhesion, and crack resistance are critical for durable metallic-on-metallic sliding contacts in piston rings. TiAlN and AlCrN are new

nanostructured nitride coatings that can be employed in severe tribological conditions. High hardness, wear resistance, oxidation resistance, and aluminum content promote the formation of a highly alkaline oxide protective layer during exposure to elevated temperatures.^{16,24} AlCrN is a composite with aluminum-based oxidation resistance, chromium-assisted chemical stability, good hardness, and thermal stability. Recent studies indicate that TiAlN- and AlCrN-based coatings exhibit good tribological performance under extreme sliding temperatures and conditions.

Although the benefits of such coatings are well known, their relative performance on SR34 piston-ring steel needs to be systematically evaluated. A piston-ring service coating should be hard, homogeneous, adherent, thermally compatible, wear-resistant, and stable under combined mechanical and electrochemical attack. Hence, the present study deposited TiAlN and AlCrN nanostructured coatings on SR34 steel using cathodic arc PVD and tested their performance using FTIR, XRD, SEM/EDAX, surface roughness, microhardness, abrasion, sliding wear, coefficient of thermal expansion, tribocorrosion, scratch adhesion, and nanoindentation. The aim was to determine the coating that offered the best balance of surface finish, hardness, wear resistance, thermal compatibility, adhesion, and tribocorrosion protection for high-performance SR34 piston-ring applications. Recent literature in Table 1 demonstrates that nitride-based PVD coatings remain among the most effective surface-engineering strategies for reducing friction, wear, and corrosion damage in steels and engine-related sliding components.

While TiAlN and AlCrN are well-established commercial PVD nitride coatings, it is not safe to assume that their performance is the same across all engineering substrates. Therefore, the use of TiAlN or AlCrN coatings individually

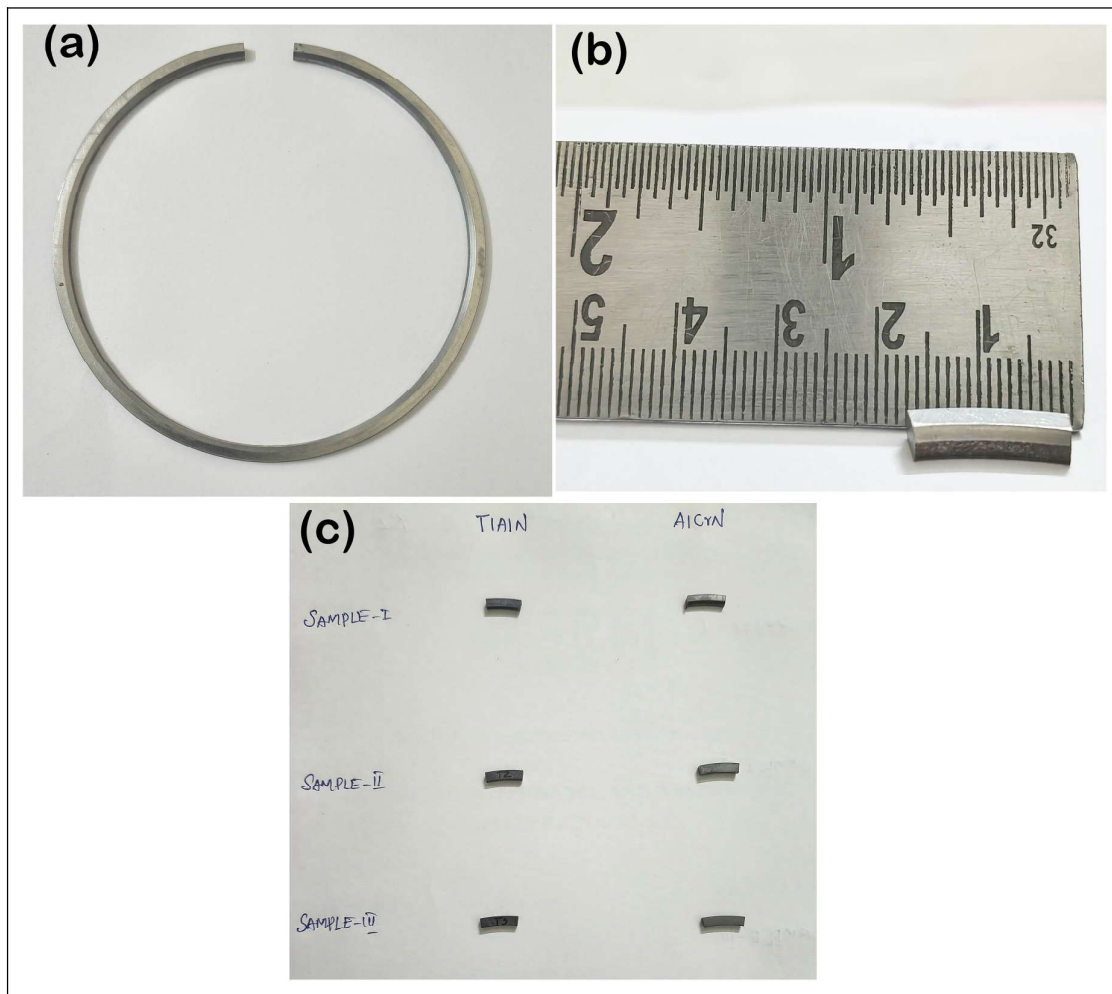


Figure 1. (a) Piston ring (b) sample for coating (c) TiAlN and AlCrN coated samples.

is not the scientific novelty of the present work, but rather the evaluation and performance-based selection of these coatings for the SR34 martensitic stainless-steel piston-ring material as a function of the substrate. SR34 is a high-hardness, dimensionally stable, and thermally resistant piston-ring material with relatively high contents of carbon, chromium, molybdenum, and vanadium. These properties affect coating support, thermal-expansion compatibility, interfacial stress development, wear response, and tribocorrosion behavior. Thus, the performance of the coating must be tested on SR34 and not extrapolated from other steel or cast-iron systems.

The novelty of this work is an integrated coating-selection framework for TiAlN- and AlCrN-coated SR34 steel under relevant piston-ring operating conditions. The present study demonstrates correlations among coating structure, coating thickness, surface roughness, microhardness, abrasion response, lubricated sliding wear, coefficient of thermal expansion, tribocorrosion behavior, scratch adhesion, and nanoindentation response, in contrast to earlier studies that have focused on individual parameters such as hardness, wear, corrosion, and machining performance. This integrated assessment results in the categorization of the two coatings: TiAlN offers high load-bearing capacity, hardness, wear resistance, adhesion, and tribocorrosion protection, while

AlCrN provides a smoother surface and a closer thermal expansion match with SR34. Therefore, the work provides a scientifically valid basis for selecting coatings suitable for SR34 piston-ring applications, rather than merely demonstrating the deposition of commercial PVD coatings.

Materials and methods

Materials and coating deposition

SR34 martensitic stainless-steel piston-ring material was used as the substrate (uncoated SR34, TiAlN-coated SR34, and AlCrN-coated SR34, Figure 1(a)). SR34 was chosen for its use in top piston-ring applications and for its high strength, heat resistance, and dimensional stability under engine operating conditions. TiAlN and AlCrN were selected as hard nitride coatings for their high hardness, oxidation resistance, thermal stability, and wear resistance. The nominal composition and basic properties of SR34 are given in Table 2.

SR34 is not a generic steel substrate but a high-carbon, high-chromium martensitic piston-ring steel designed for high hardness, strength, and dimensional stability during engine operation. Its relatively high C and Cr contents, together with Mo and V additions, provide a hard martensitic

Table 24. Nanoindentation properties of uncoated and coated SR34 samples.

Sample	Hardness H (GPa)	Reduced modulus E_r (GPa)	Maximum depth $h_{\max}$ (nm)	H/E_r	H^3/E_r^2 (GPa)
Uncoated SR34	3.98 ± 0.12	202.8 ± 3.49	540.0 ± 9.08	0.0196	0.0015
AlCrN-coated SR34	22.30 ± 0.60	334.0 ± 6.04	205.4 ± 6.35	0.0668	0.0994
TiAlN-coated SR34	28.02 ± 0.74	371.2 ± 7.85	177.2 ± 4.97	0.0755	0.1597

contact loading. TiAlN had the highest E_r , implying that it maintains good load support in sliding contact. The mechanical performance indices also demonstrate TiAlN's high response. The H/E_r ratio improved from 0.0196 for the uncoated SR34 to 0.0668 for the AlCrN and 0.0755 for the TiAlN. H^3/E_r^2 also increased, starting at 0.0015 GPa for the uncoated SR34 and reaching 0.1597 GPa for the AlCrN and TiAlN, respectively. These indices are typically associated with elastic strain-to-failure and resistance to plastic deformation. Thus, the increased H/E_r and H^3/E_r^2 values for TiAlN suggest improved toughness-related mechanical response and resistance to contact-induced damage.

Overall, the nanoindentation measurements indicate that both TiAlN and AlCrN coatings significantly improve the localized mechanical performance of SR34 piston-ring steel. TiAlN exhibited the highest hardness, the lowest modulus, the shallowest penetration depth, and the highest mechanical performance indices. These results are consistent with the sliding wear data, in which TiAlN showed a lower coefficient of friction and a lower wear rate than AlCrN. The ranking of nanoindentation performance is thus: TiAlN-coated SR34 > AlCrN-coated SR34 > uncoated SR34.

The superior overall performance of TiAlN-coated SR34 is primarily due to its higher hardness, load-bearing capacity, and resistance to mechanical-loading-induced coating damage. Results from sliding and tribocorrosion testing indicate that surface smoothness alone did not determine final performance, despite AlCrN's smoother surface and closer thermal expansion match compared with SR34. TiAlN had a higher average microhardness of 2626.46 HV than AlCrN (2097.48 HV), making it more resistant to asperity penetration, micro-cutting, and local plastic deformation. This explains the lower COFs and specific wear rates for TiAlN under lubricated sliding conditions. These scratch-adhesion results also support this mechanism, as TiAlN exhibited higher critical loads for cohesive cracking, edge chipping, and delamination, indicating greater damage tolerance under concentrated contact loading. This mechanically stable surface also reduced coating disruption, limited electrolyte access to active sites, decreased OCP disturbance, reduced the corrosion current density, increased charge-transfer resistance, and improved friction behavior. Therefore, TiAlN is superior to AlCrN, as a hard, damage-resistant nitride layer provides better mechanical support and barrier stability under combined sliding and electrochemical attack. In contrast, AlCrN is more beneficial for improving surface smoothness and thermal expansion compatibility.

Conclusions

The successful deposition of nanostructured TiAlN and AlCrN coatings on SR34 martensitic stainless-steel piston-ring material was achieved using cathodic-arc PVD.

SEM was used to verify the presence of continuous layers close to the nominal target thickness (4 μm), with measured thicknesses of 3.98 μm for TiAlN and 3.78 μm for AlCrN. EDAX, XRD, FTIR, and XPS analyses confirmed the Ti–Al–N and Al–Cr–N nitride coatings on the SR34 substrate. Both coatings improved the surface and functionality of SR34, though the benefits differed. AlCrN produced the smoothest surface, with an R_a of 0.0783 μm , and it had the closest match in coefficient of thermal expansion to SR34. Thermal-mismatch stress was estimated at 12.47 MPa for AlCrN-coated SR34 and 110.86 MPa for TiAlN-coated SR34. Hence, AlCrN offers a superior surface finish and thermal-expansion compatibility.

TiAlN exhibited the best mechanical and tribological response. The average Vickers hardness was 2626.46 HV for TiAlN, 2097.48 HV for AlCrN, and 390.40 HV for uncoated SR34. Nanoindentation confirmed these results, showing that TiAlN had the highest hardness and lower reduced modulus and mechanical performance indices. Under lubricated sliding at 10 kg and 15 kg, both coatings significantly reduced friction, weight loss, and specific wear rate, even compared with uncoated SR34. However, TiAlN showed the lowest COF and wear rate, indicating it was least susceptible to micro-cutting, plowing, and local plastic deformation. Both coatings exhibited good coating/substrate integrity, with TiAlN showing higher critical failure loads in abrasion and scratch-adhesion tests. Tribocorrosion results also showed that TiAlN's protective properties are superior, as evidenced by its more noble corrosion potential, lower corrosion current density, higher charge-transfer resistance, and stable friction response. In summary, TiAlN-coated SR34 is the most suitable coating system for high-performance piston ring applications requiring hardness, wear resistance, and tribocorrosion protection. AlCrN remains important in applications where surface smoothness and thermal compatibility are the primary design considerations. Longer-duration wear tests at different sliding speeds, temperatures, and lubricant conditions are suggested for future research.

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Ethical statement

This study complies with ethical standards and does not involve human or animal subjects. The research is original, unpublished, and not under consideration elsewhere. All data and materials are generated by the authors or appropriately cited.

Author contributions

Uthirapathy Chandrasekaran: Investigation, Writing - Original Draft. **Saravanan Raju:** Research methodology; Research

Administration; **Hariharan K**: Formal analysis, Writing - Review & Editing; **Vivekananda A S**: Visualization, Writing - Review & Editing.

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Data availability

The data generated and analyzed during this study are included in this article. Additional supporting data are available from the corresponding author upon reasonable request.

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