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Review article

Evaluation of Tribological Properties of Different Coatings on Automotive Piston Rings: A Review

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ABSTRACT

Friction and wear play crucial roles in automotive engine performances and their efficiency. Overall, 40% of fuel power loss occurs in friction of various components of the engine. Frictional loss between piston rings and cylinder liner assembly contributes major loss of fuel power in the automotive engine and it is about 15% of total fuel power loss occurs due to friction. In the present scenario, thin film coating techniques are in trend to enhance the mechanical and tribological properties of machine components. In this paper, different types of wear-resistant, corrosion-resistant, and antifriction coating materials and their characteristics are discussed. Also, carbon-based coatings, nitride coating, carbide coating, oxide coating, and the intermixing of counterparts of coating material to form a composite coating, multilayer coating, and varying their percentage elemental composition composite are reviewed and compared. The synergistic effect of coating with texturing over the piston ring is discussed. Finally, recent developments and new possibilities of coatings that can be employed on piston rings are briefly discussed.

1. INTRODUCTION

IC engines are right now energizing the majority of vehicles on the earth. The environment and non-renewable energy sources have come under threat over the past ten years due to the steadily rising demand for fuel energy usage in automobiles [1, 2].

Friction is the most important parameter which has a major role in the fuel consumption of IC engines [3]. Also, the wear rate increases with an increase in the coefficient of friction, which affects the life of the engine. In IC engines, friction accounts for a loss of the overall 40% of total fuel energy, the most friction loss occurs in the I.C engine components like pistons, cylinders, gears, bearings crankshaft, transmissions, etc. Out of which, piston rings and cylinder liner alone contribute 15% of fuel energy. For an IC engine to operate more efficiently, frictional loss needs to be minimized as much as possible because piston rings have a higher rate of frictional loss than other sliding components [4-7].

The primary difficulties in engine design are reduction in friction and wear rate at elevated temperatures [8]. Various surface modification techniques have been employed to obtain low friction and adequate wear resistance surface. Surface coating is one of the best solutions to get minimum friction and wear resistance surface on piston rings. When the thin film coating is applied to IC engine parts, the hardness is increased, the frictional coefficient is decreased, the surface is better finished, and the wear protection is improved [9-13]. Nowadays, Ceramic coatings are utilized to prolong the span of sliding parts because of their promisingly low friction properties and strong wear resistance [14]. To increase tribological features of piston ring components, various coating methodologies are employed, chemical vapor deposition (CVD), physical vapor deposition (PVD), thermal sprayed [15-19] deposition techniques are used to coat monolayer, multilayer and composite coating on piston ring.

In the current review, the various types of coating materials (Targets), and their combinations to form common coatings on the piston and methodology are introduced. The advantages of coatings in the industry are then illustrated using examples of typical coating applications and associated performances. Finally, prospective advancements in coating technology are also considered, along with current trends.

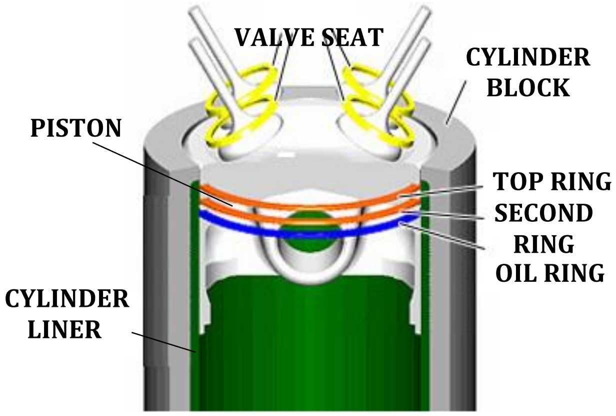
2. PISTON RING AND CYLINDER LINER PAIR

In general, three main types of piston rings are inserted into the piston grooves.

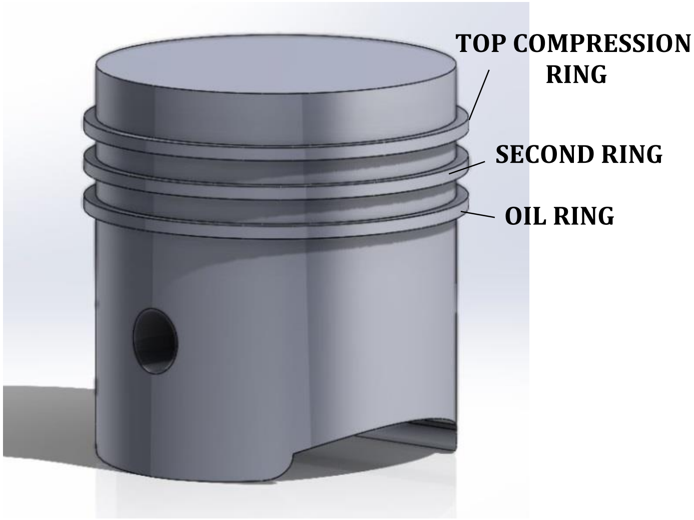
I. Top compression ring;

II. Second compression ring;

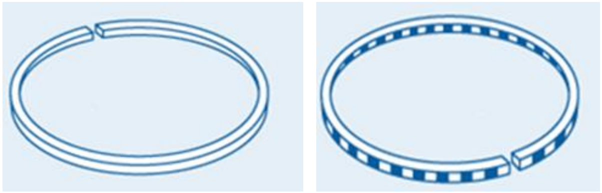
III. Oil control ring.



(a)



(b) Piston



(c) Compression ring (d) Oil ring

Fig. 1. Piston-cylinder assembly and different parts.

Each ring performs a certain task while the engine is running and has a unique geometry. Figure 1 shows the location of each piston ring. The main motive of the top compression ring is to seal up the combustion chamber. The sealing effect will prevent the flow of the fuel mixture to the crankcase [20]. It regulates the oil flow into the combustion chamber in the reversed direction. Therefore, the piston rings also regulate the amount of gasoline and oil used [19]. Thus, the sealing effect also enhances undesirable friction and wear in the top compression ring. The second is the compression ring supports the top ring and has the same function [19]. The next ring is the oil ring; its work is to regulate the oil supply so that interaction between metal asperities of the piston ring-liner pair should be minimized or avoided.

2.1 Friction and wear in piston ring – linear assembly

Friction occurs between the piston ring-liner during the sliding motion of the piston ring from the top dead centre (TDC) to the bottom dead centre (BDC) operated under the boundary/mixed lubrication mechanism. From the tribological point of view, the most critical section is the top compression ring and the top dead centre (TDC) because there is the combined action of acceleration, and deceleration to complete stop at maximum temperature, and also starvation conditions may occur between piston ring-liner pair in this region [21]. Thus, the top compression piston ring is responsible for the major power loss in the IC engine due to friction and is more prone to wear in starvation conditions.

Wear on piston rings predominately occurs because of the abrasive wear mechanism, classified as 2-body or, 3-body abrasive wear due to the small quantity of solid component debris in the circulating oil. Adhesive wear may occur because of starvation, and significant adhesive forces between piston rings and liner may develop. These forces speed up metal scratching and high friction, which in turn causes rapid wear rates and eventually engine failure. As a result, by using an appropriate lubrication technique and applying a coating to the piston rings, tribological augmentation of the piston rings and cylinder liner may be accomplished [4].

3. COATING MATERIALS

Coatings are employed over the piston ring to improve tribological characteristics i.e., frictional coefficient and wear rate to minimize power loss and enhance engine life.

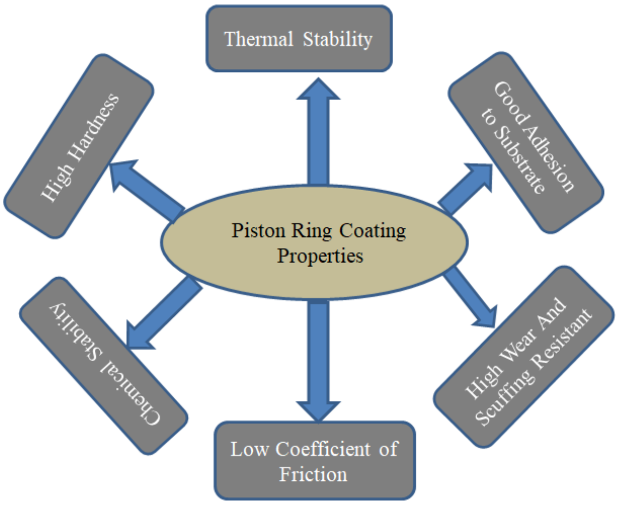


Fig. 2. Desirable properties of coating material on piston ring.

Different type of coating material and their combination are employed for these purposes carbon-based coatings, nitride coatings, carbide coatings, oxide coatings, composite/ multicomponent coatings, and multilayer coatings are discussed in this paper.

3.1 Carbon based coatings

Diamond is the known hardest material existing in nature till now, which imparts an important amalgamation of various characteristics. It also has drawbacks since it dissolves in platinum-group metals, Fe, Mn, Co Ni, and Cr react with high carbide-forming metals. On tools and different parts, polycrystalline diamonds (micro, nano, or ultra-nano crystalline [22] that have qualities that are somewhat similar to single crystal diamonds can be deposited. Although diamond films cannot solely adhere to ferrous substrates, it is seen that diamond deposited on steels and cemented carbides by employing inter layers (silicon, molybdenum disulphide, silicon nitride, graphite, chromium nitride, etc.) that allow their film formation with enhanced adherence [23].

DLC coatings, which resemble diamonds, exhibit exceptional tribological qualities. The low adhesion caused by significant internal stresses is one of the DLC films' ongoing issues. DLC layers can therefore be put on top of adjacent layers like Si, Ti, Zr, W, Nb, Cr, or WC to increase adhesion to metal substrates. DLC coating production is less expensive than regular diamond because it requires less processing time. Additionally, while the creation of CVD diamond films necessitates extremely high temperatures and pressures, DLC may be applied from gas phase composition at room temperature, even making polymer coating conceivable. Those benefits have made the application of DLC films inexpensively viable for industrial production at large scale [24].

Another carbon-based coating is a graphite-like coating (GLC). The most common hard amorphous carbon coating is amorphous graphite-like carbon (GLC), which carries a higher ratio of carbon that forms sp^2 bonds in the matrix [25]. Because of the in-situ generated minimum shear thin graphite layer by carrying, the GLC layer exhibits outstanding self-lubrication and exceptionally minimizes the wear loss, and also, it does not show significant wear on the mating surface [24]. To maximize the length of their service, much effort has been put into developing ultra-thick amorphous carbon coating [23, 26]. Unfortunately, these amorphous carbon technologies have restrictions on the thickness of the given coating and appropriateness for the implementations. To improve the performance of piston rings, amorphous carbon films provide a combined effect of hard, thick, and wear-protected coating with a minimized coefficient of friction. Because of its superb lubricity under different conditions, amorphous carbon films will help to enhance the durability and dependency of engine parts while also preventing catastrophic failures like scuffing [24].

3.2 Nitride coatings

The majority of the hard coatings used in engineering applications today are nitride coatings, such as titanium nitride (TiN), cubic boron nitride (c-BN), silicon nitride, zirconium nitride, and zirconium nitride. One of the most popular hard coatings used these days, titanium nitride combination of hardness, toughness, and inertness. It also typically exhibits strong adherence to surfaces. As a result, it is known as a "general purpose" coating and has a wide range of applications, particularly for tools [27]. Zirconium nitride and chromium nitride coatings [28], in addition to TiN, both have slightly different qualities than TiN and demonstrate high hardness and the capacity to tolerate high temperatures (up to 600°C and 700°C, respectively).

Cubic boron nitride (c-BN) is another hardest material next to diamond. Despite being one of the hardest materials, a polycrystalline c-BN coating faces problems with adhesion and stability [29]. Also, due to their high cost, they are in the beginning phase to find usage in the industry.

Another nitride coating is silicon nitride (SiN) since it has the least heat expansion coefficient and strong thermal shock resistance, it is frequently used as a mono-protective layer. In wish to increase thermal stability or as an interlayer to facilitate diamond development on cemented carbide tools, SiN may be an alternate option to place on the upper surface of other hard layers, such as nitrides of metal [30]. Because it is predicted that an alternate option of diamond under certain crystalline conditions, carbon nitride coatings (CN_x) have attracted significant interest from the coating world ($\beta - C_3N_4$) [31].

3.3 Carbide coatings

Due to its exceptional hardness, silicon carbide (SiC) is frequently utilized in the coating of different tools. To improve the mechanical qualities and tribological performance, it is frequently combined with additional components (such as thermally sprayed Si-C-N thin film layers [32] also with dry-film lubricant layers.

One of the most common coating materials is tungsten carbide (WC), which can be applied using a variety of techniques. Tungsten carbide (WC) is the most potential substitute for hard chromium is tungsten carbide and has notably demonstrated very good characteristics when applied with high-velocity oxyfuel (HVOF) [33] when combined with cobalt.

For thin film applications in elevated temperature environments, like forging and forming processes, vanadium carbide (VC), shows good thermal shock tolerance and good thermal conductivity, and is a viable choice. On substrates containing carbon, it performs well and has favorable characteristics, particularly when the thermal diffusion coating technique is used to achieve high thickness, strong adhesion, and hardness [34].

Boron carbide (BC) coatings provide lubricious, fine, anti-porous surfaces that significantly minimize friction and heat during milling. However, it should be noted that such a material may have drawbacks, including brittleness and poor substrate adherence.

Titanium carbide can be employed as a constituent in multi-layer PVD or CVD designs as well as single-layer coatings. It has been employed as one of the best hard coatings, and it is frequently used on high-load shaping equipment as well as cutting instruments.

Lastly, chromium carbide (CrC) coatings may successfully take the place of chromium coating deposited by electroplating and the electroplated TiN coatings that are used as barriers to corrosion and abrasive wear. They are currently often used for different types of applications, including metal forming and plastic injection moulding, on a variety of substrates [35].

3.4 Oxide coatings

A common oxide coating that is often used for wear-resistant is alumina (Al_2O_3). The coating formation might be amorphous or reveal some phases of crystalline, which often have excessive hardness [36]. The process parameters have a significant impact on the structure that is produced, and as a result, the characteristics of the film might differ greatly.

Zirconium oxide (ZrO_2) Films have also drawn a lot of attention for use as wear-protected layers because they offer a distinctive mix of mechanical, chemical, and thermal effects. Last but not least, other types of oxides that are frequently used for hard coating include zinc oxide, silicon- and titanium suboxides (SiO_x, TiO_x, respectively), even though these materials are primarily applied for electronic and optical instruments [37-39].

To increase adhesion and tribological qualities, chromium oxide thin coating (Cr_2O_3) may be used as mono layers, formation of interlayers (e.g., application of alumina on specific substrates), and in conjunction with different layers (like CrN).

3.5 Borides coatings

Borides for industrial applications have received less research and development attention among the various ceramic coating materials. However, they exhibit a special set of characteristics. Crystalline coatings made of transition metal diborides (such as Ti, Cr, Mo, and V) are an excellent substitute for wear-protective films because of their excessive hardness and good adherence to the underlying substrate. Diboride coatings are chemically inert and hard, which are particularly useful in machining non-ferrous materials like aluminum and its alloys in unlubricated conditions. Additionally, alloying borides with nitrogen permits the creation of highly wear and corrosion-resistant, fine-grained multiphase hard coatings [40, 41].

Iron borides thermo chemically produced on steels produce coatings that typically have a very high hardness often exceeding 20 GPa also strong in wear protection [42]. Borided Steel parts perform exceptionally well in a variety of applications used in tribology, mechanical engineering, and automobile sectors.

Industrial gas boriding methods are being developed, however there are still major issues with controlling the processing parameters as well as the composition and porosity of the boride layers. It is acknowledged that little is known about the mechanisms through which plasma interacts with metal surfaces. A few micrometres thick and including a weakly adhering FeB layer in both cases, the boride coatings formed carbon steels by plasma-enhanced chemical vapor deposition (CVD) technique in two mediums at 833 K using a $BCl_3 - H_2$ gaseous combinations are just two examples [43,44]. On the other hand, it was discovered that the wear performance of gears lubricated by an oil pump generated from pack boron cementation and plasma of boride in the same gaseous mixture were equivalent [45]. To create mono-phase layers or coatings of iron boride (Fe_2B) which is less hard and also brittleness is low therefore, for the wear-resistant application heat treatment is necessary.

3.6 Multicomponent / Composite coatings

Materials that mix two or more phases are known as composites. These phases include a continuous matrix and an immersed irregular reinforcement. These structures are ideally employed to enhance certain qualities of individual elements. A ceramic, polymer, or metal matrix can be used to create composite coatings. When high temperatures are anticipated (polymers with thermo-plastic would not be sufficient) or when ductile behavior is needed, metal matrices are employed. The most often utilized ceramic reinforcements are SiC and Al_2O_3. Due to their cheaper cost and simpler manufacturing than fiber-reinforced MMCs, Particulate-Reinforced Metal Matrix Composites (PRMMCs) have great attraction. Among the several MMC manufacturing methods [46].

A variety of information about MMCs has been done, including the incorporation of reviews on the different kinds of reinforcement, which is used in MMCs [47], nanocomposite of nickel (Ni) [48], composites of Ni-P [49], Ni-Co/ceramic electrodeposited composites [50], the tribological study of Ni-based electrodeposited coatings [51], composites of particle reinforced Al-matrix [52], fiber reinforced of MMCs [53], mechanical properties and wear of Al-based typically concentrate on the technology of these materials [54-56].

The usage of multi-components has made it feasible to achieve the perfect combination of coating qualities needed for the majority of tribological applications. The dual hard coating materials titanium carbide (TiC) and titanium nitride (TiN), whose characteristics and applications have been thoroughly investigated, were one of the very first successful uses. The wear protection and abrasion protection of parts and tools treated with titanium-based dual hard coatings has significantly improved. It has been demonstrated from these initial dual materials that alloy of metal or alloy of metalloid or a combination of both components results in a significant improvement in coating properties, especially when mixing aluminum (i.e., (Ti, Al)N) and carbo nitrides of different compositions (i.e., Ti(C, N)). The parent metal for multi-elemental hard films is typically titanium (Ti) or chromium (Cr), and a wide range of alloying components, including W, B, Al, Si Nb, Mo, Cr, Zr, and V elements with a variety of different chemical arrangements, have been explored [12].

Additionally, four or more components are selected and applied in coating technology, producing various qualities. In the latest study, it is seen that coatings like (Ti, Si, B)N, (Ti, Al)(C, N), (Ti, Al, B)N, and (Ti, Si)(C, N) have demonstrated the best combination of excessive hardness, low friction, and high adhesion strength, making them suitable composition for different mechanical applications in industries [57]. It was found that (Ti, Al, Y)N and (Ti, Al, Cr)N have a measurable enhancement in properties.

3.7 Multi-layer coatings

Utilizing a range of materials, coatings can be created in several shapes and architectures. Depending on the number of layers, coatings can have a mono-layer, a bilayer, or a multilayer (more than two layers) [58]. For instance, the capacity to regulate residual stress, the ratio of hardness to elasticity, and adherence to the substrate through the increase of tribological performance can be achieved by strategically stacking coating layers [59]. Regarding this, interest in multilayer coatings as a useful technique for lowering friction and wear has been rapidly rising.

Metals, ceramics, diamond-like carbon (DLC) solid lubricants, etc. are specific categories of materials utilized for multilayer coatings. To add enough hardness and wear resistance to multilayer systems, ceramics (transition metal oxides, carbides, and nitrides) are used. The drawbacks of hard ceramic coatings include brittleness and a high COF (0.3 to 0.8) [60]. As a result, they are constrained in tribological uses that demand a low COF by nature. To solve this problem, it is preferred to use solid lubricants, such as MoS_2, WS_2, PbO, and graphite, which have an inherently low COF (below 0.1), as the top layer [61-63]. On the other hand, DLC is a special substance with exceptional qualities, including high hardness, more ductility, chemical inertness, excellent wear resistance, and minimum COF (0.1 to 0.2). DLC is a great option for a wide range of tribological uses in different trades due to these characteristics, optical transparency, and biocompatibility [64-67].

The basic components used to create the two or more stacked films that make up multiple-layer coatings and produce complementary characteristics. The performance of adhesion or tribology is significantly improved by the application of such coatings. The adhesion to the underlying substrate is improved by common two-layer systems that combine the interlayer of metallic that is Ti/TiN, with a nitride covering. Other two-layer arrangements, that is TiN/Ti(C, N) or TiN/Al_2O_3 improved performance, while lubricating layer pairings have been used that show noble tribological properties, particularly when being machined dry or with little lubrication (such as TiC/(WC/C) or DLC/MoS_2 [68].

A periodically frequent pattern of lamellae made up of two or more layers creates multi-layer coatings up to a few tens of micrometers thick in terms of materials. As a result of the various interfaces between layers, hardness and strength are increased, and the structure is different from that of individually thicker layers. Once more, the materials that are most commonly studied are Ti complexes, where a TiN layer is frequently deposited initially due to its excellent adherence to different substrates. In terms of the various multilayer coating structures utilized specifically in the cutting tool, some examples include TiN/TiCN/TiC, CN/TiCN/TiN, CrN/CrC/(Mo, W S_2, TiAlN/CrN_x and TiN/TiCN/TiC/Al_2O_3/TiN [69-71].

3.8 Synergetic effect of surface texturing and coating

Friction reduction by surface texturing methods is one of the most common techniques used in industries. Surface textures can be produced by using different methods, such as chemical etching, laser texturing, and pellet pressing [72]. Laser surface texturing for enhancing tribological properties of the surface of materials is common nowadays in industries.

Parul et al. [73] studied the combination of surface coating and texturing on the piston ring to minimize the frictional effect of piston ring-cylinder liner contact in each lubrication regime. The cylinder liner, which is made up of cast iron, and the piston ring with 3- types of coating i.e., Diamond-like-carbon (DLC), chrome, and moly-chrome-ceramic (MCC) taken as specimen. It has been observed that the coated piston ring with texturing has comparatively better frictional execution than the non-textured coated ring. The least friction has been obtained in the case of textured and DLC-coated piston rings under the boundary lubrication regime.

4. THE CHARACTERISTICS OF COATED PISTON RINGS

To enhance the surface characteristics of piston rings, many developments are carried out by applying different materials with different deposition techniques. The chronological order of the development of coating is tabulated in Table 1. In this paper, various types of deposition procedures like PVD (Sputtering, plasma arc deposition, and cathodic arc), coating of High-velocity oxy-fuel (HVOF), and electroplating are mentioned, and their thickness and hardness are tabulated.

The use of coatings on automotive engine components, such as piston rings, can reduce frictional loss, increase efficiency, and reduce energy consumption. Coated piston ring properties are studied by Shanhong et al. [74], where different monolayer and multilayer coating on piston rings with and without application of GLC deposited by electroplated and PVD coating techniques. The deposition is carried out employing electroplating of Cr, Cr-Diamond, Cr-$\mathbf{Al_2O_3}$ and PVD- CrN coating. The GLC coating is deposited on the top of all coated samples by the means of magnetron sputtering technique. With the application of GLC, there is a great reduction in friction coefficient and rate of wear.

Table 2. Summaries the coating thickness, hardness, and deposition technique. The different hardness of coated samples is changed into the same unit i.e. Vickers hardness (HV) to plot a graph for comparative study as shown in Figure 3. The highest hardness is reported by Sevim et al. [75], through a coating of TiAlCN on ring by CAPVD technique. Also, the average coefficient of friction was reported as 0.21.

Figure 3 and Figure 4 compare the relative hardness of coated piston rings and the average COF of various coated piston rings Also the coated piston ring with an average coefficient of friction is summarized by R. Bayon et al [76] is tabulated in Table 1 with others coated ring as shown below.

Table 1. Coefficient of friction of different coated ring.

Substrate	Coating material	Average COF	Refs
F1272 steel	–	0.475	[76]
	CrN1 (Multilayer)	0.324	
	CrN2 (Minor bilayer)	0.635	
	CrN3 (Minor bilayer)	0.495	
Piston ring	TiAlCN	0.2	[75]
Piston ring	TiSiCN	0.8	[77]
Piston ring	DLC	0.1	[77]

Table 2. Different types of coating material with various deposition methods are applied on piston ring material.

Year	Substrate	Coating Material	Deposition Method	Thickness	Hardness	Refs
1996.	Piston ring	40%Ni60 + 60% WC	Laser treated Plasma sprayed	0.4mm	60 HRC	[78]
1996.	Steel SAE 9254	$(\mathbf{Cr_3C_2-NiCr})-\mathbf{Mo}$ ((80/20%)-20%	HVOF	100µm	853 HV_{100g}	[79]
1997.	Piston ring	$\mathbf{Cr_xN}$	RF Magnetron sputtering	6-8µm	13 HU	[80]
2002.	Martensitic Stainless steel	Hard Cr + $\mathbf{Al_2O_3}$	Magnetron sputtering	>100 µm	879±77 HV	[81]
2005.	Piston ring	$\mathbf{Al_2O_3}$ –SiC	Plasma spraying Magnetron sputtering	250µm 10µm	900-1150 HV 701-788 HV	[82]
2010.	Piston ring	MoN	PVD	2± 0.3µm	2000±400 HV	[83]
2012.	Piston ring	CrN 1 CrN 1 CrN 1	Plasma enhance magnetron sputtering	1 µm 5 µm 10 µm	18GPa 12GPa 16GPa	[84]
2016.	Piston ring	TiSiCN	Plasma enhance magnetron sputtering	20µm	25-30 GPa	[85]
2017.	Piston ring	H-free DLC Coating	Cathodic arc ion-plating process	1µm	60GPa	[86]
2017.	Piston ring	CrMoN/MoS_2	Magnetron sputtering	20 µm	2977 HV	[87]
2017.	SS304 Steel	CrN CrN	Arc Plating Technique Magnetron sputtering	38 µm 35 µm	1000-1200 **HV** 1100-1300 **HV**	[88]
2017.	Piston rings	Cr Cr-$\mathbf{Al_2O_3}$ Cr-Diamond CrN Cr+ GLC Cr-$\mathbf{Al_2O_3}$+GLC Cr-Diamond+GLC CrN + GLC	Electroplating Electroplating Electroplating PVD Magnetron sputtering Magnetron sputtering Magnetron sputtering Magnetron sputtering	Not mentioned Not mentioned Not mentioned Not mentioned 4.5µm Not mentioned Not mentioned Not mentioned	997±47 **HV** 930±47 **HV** 870±44 **HV** 1390±65 **HV** 980±48 **HV** 950±47 **HV** 890±45 **HV** 1400±70 **HV**	[74]
2019.	Nitrided Stainless steel	$\mathbf{SiO_2}$ + DLC	RF magnetron sputtering	50µm	1500 HV	[89]
2022.	Piston ring	TiAlN TiN/TiAlN	CAPVD CAPVD	1.97µm 2.18 µm	2667±49 $\mathbf{HV_{10g}}$ 3167±55 $\mathbf{HV_{10g}}$	[90]
2022.	Piston ring	TiAlCN	CAPVD	2.94 µm	3345±0.50 $\mathbf{HV_{10g}}$	[75]

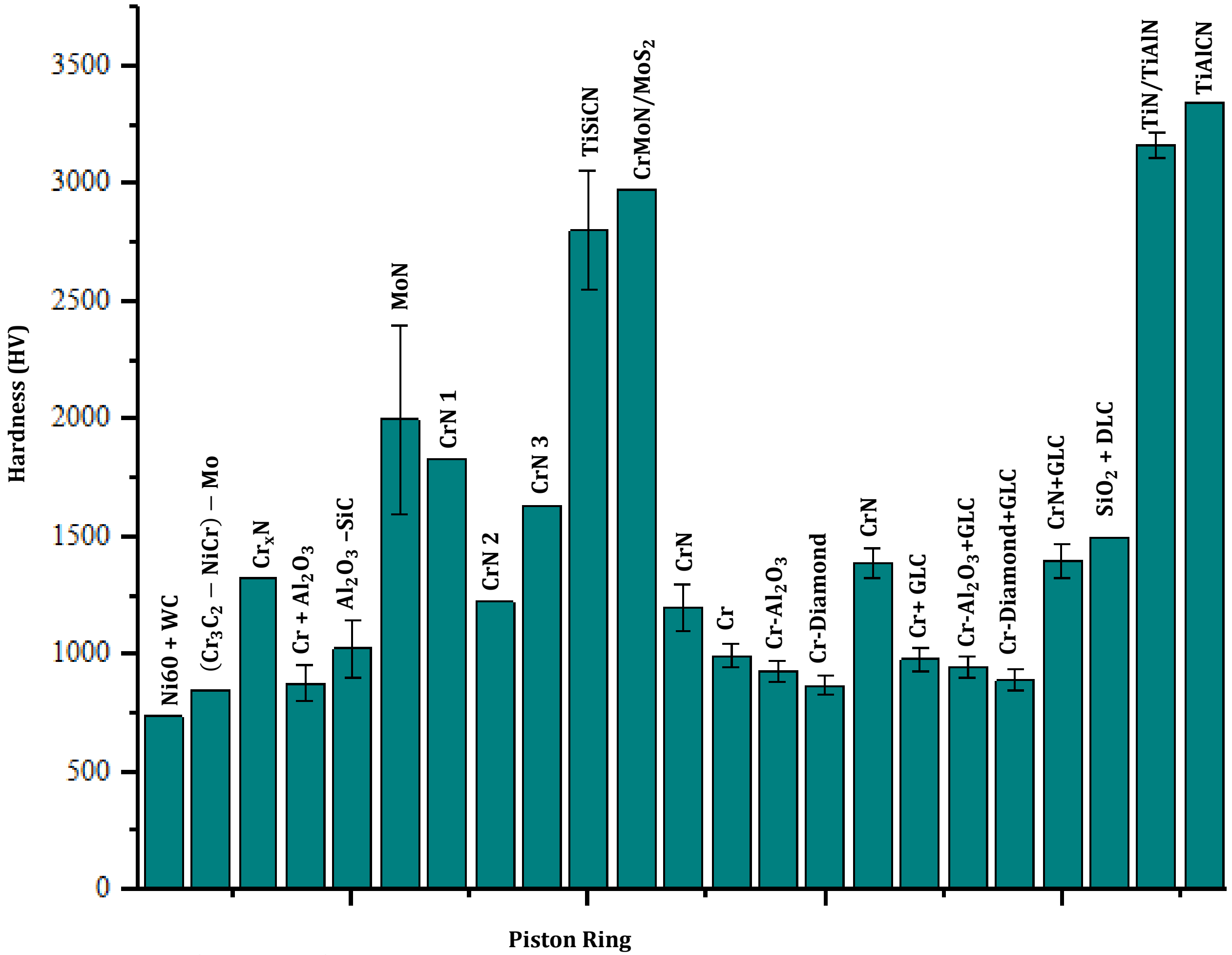


Fig. 3. Comparison of hardness of the coated piston rings.

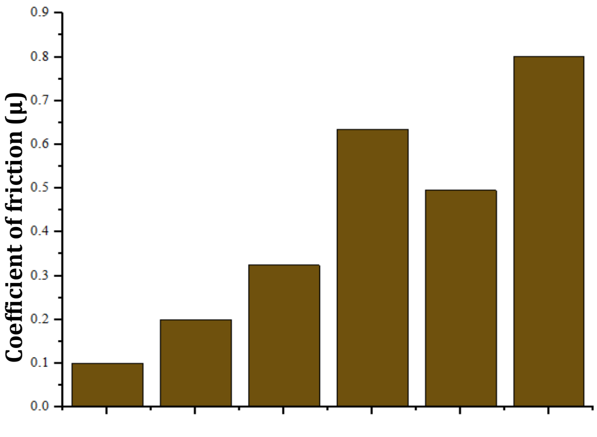


Fig. 4. Comparison of coefficient of friction of coated piston rings.

5. CONCLUSION

Coating methodology is employed on a large scale for the deposition of thin film and substrate coatings. It is being used widely in the automotive industry and is a combination of different methods to produce a coating with superb properties. In this paper, an issue related to the tribological mechanical properties of coated piston rings for I.C. engines is discussed. In the context of the automotive industry, coatings are applied to piston rings to enhance their performance and efficiency within internal combustion engines. Piston rings play a crucial role in maintaining a proper seal between the piston and cylinder walls, preventing leakage of combustion gases, and ensuring efficient engine operation. Applying coatings to these rings can lead to several benefits, such as:

1. **Reduced Wear**: Coatings like CrN, DLC, TiC, TiN, Al2O3, GLC, and others are known to have excellent wear resistance properties. When applied to piston rings, they can significantly reduce the wear of the rings as they slide against the cylinder walls during engine operation. This helps prolong the lifespan of the piston rings and the overall engine.

2. **Lower Coefficient of Friction**: Coatings with low friction characteristics can reduce the friction between the piston rings and cylinder walls. This reduction in friction results in less energy loss and improved fuel efficiency in the internal combustion engine.
3. **Improved Efficiency**: The combination of reduced wear and lower friction results in an overall improvement in the efficiency of the internal combustion engine. This can lead to better fuel economy and reduced emissions.
4. **Enhanced Performance**: Coatings can also contribute to improved performance by allowing the engine to operate under more optimal conditions due to reduced friction and wear-related issues.
5. **Extended Maintenance Intervals**: With reduced wear, the need for maintenance and replacement of piston rings could be less frequent, reducing downtime and maintenance costs.

The paper likely discusses various types of coatings, including mono-layer coatings (single material), composite coatings (mix of multiple materials), and multilayer coatings (alternating layers of different materials). Each type of coating may have specific advantages and disadvantages based on the intended application.

The significance of the research lies in its potential to contribute to advancements in engine technology and automotive efficiency. By addressing tribological issues through the application of advanced coatings, the paper likely highlights how the automotive industry can continue to improve the performance, reliability, and environmental impact of internal combustion engine

6. FUTURE SCOPE

Application of GLC film by PVD method over hard coated piston ring, the result shows a great reduction in the COF and wear rate [74]. Therefore, if we form a composite coating with doping of carbon in the hard coating material instead of multi-layered GLC film and evaluate the properties of this composite coating to achieve a low wear rate and low COF. The objective of this approach is to evaluate the properties of the resulting composite coating, aiming to achieve both a low wear rate and a low coefficient of friction.

However, some studies are carried out in this field, further investigation is required to optimize the carbon percentage within the composite coating. This optimization process involves varying the carbon content on the piston ring to attain desirable outcomes such as specific microstructural characteristics, appropriate hardness levels, optimal coating composition, reduced coefficient of friction, and minimized wear rate.

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