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Friction Reduction in Compressed Natural Gas Direct Injection Engine using Piston Rings with Diffusion Chromium Coating

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Abstract: In order to combat dry lubrication occurred in the combustion chamber of a compressed natural gas direct injection engine, the piston or piston rings have to be equipped with measures to address this boundary lubrication issue. Hence, the aim of the study is to address the issue which can minimize sliding friction in the combustion chamber between the piston ring and the cylinder liner. To solve this problem, the wear resistance level toward friction for piston ring during its interaction with the cylinder liner was enhanced using diffusion coating technique. The piston ring is made of ASSAB DF-3 steel and several substances such as 0.9% carbon (C), 0.85% chromium (Cr), 96.6% ferric (Fe), 1.2% manganese (Mn) and 0.55% titanium. The chemical substance which is used for the diffusion process are the mixture of three substances i.e., chromium, ammonium chloride (NH_4Cl) and aluminum oxide (Al_2O_3). The piston ring together with the chromium mixtures were heated at different periods of time. In order to improve friction and wear, the piston ring which is coated with 99.5% chromium dust using a diffusion coating technique yields higher hardness compared to the original piston ring due to its resistance toward wear. The hardness depends on the time maintained during heating. Furthermore, it was also shown that the modified piston ring led to better reduction in coefficient of friction as well as less weight loss due to wear. These characteristics can result in better endurance during engine operation and prevent damage due to lubrication failure.

Key words: Diffusion coating, piston ring, friction, wear, boundary lubrication, chromium coating

INTRODUCTION

In internal combustion engines, coatings and surface treatments are commonly used on components such as piston, piston rings and cylinder liner in order to reduce friction and wear inside the combustion chamber. Functional coatings and surface treatments offer several possibilities to improve the sliding properties of metal-to-metal contact surfaces. The range of coatings and surface treatments currently used in the reciprocating system covers a variety of different compositions and deposition techniques.

In general, there are several coating techniques that are currently being used for deposition of wear-resistant coatings on piston rings, namely galvanic coatings and thermal spraying (Barbezat, 2005). Another surface treatment method also commonly used for piston rings is surface nitriding (Pinedo, 2003) which combines hardening and coating processes to produce a graded iron nitride structure on the ring surface region. In addition, soft coatings for friction reduction can also be applied (Tarasov *et al*., 2002). However, coated ring faces may be susceptible to edge flaking, hence, precautions like edge radius before or after the coating deposition and use of inlays or semi-inlays covering only part of the ring face is used.

A piston ring material is chosen to meet the demands set by the running conditions. The material should be elastic and resistant against wear and damage even in hostile conditions. The ring coating, if applied, needs to work well together with both the ring and the liner materials, as well as with the lubricant. Since one task of the rings is to conduct heat to the liner wall, good thermal conductivity is also required. As a result, grey cast iron was commonly used as the main material for piston rings (Mogul, 1998). From a tribological perspective, the grey cast iron is beneficial as it consists of the graphite phase which is preferred for dry lubrication in the conditions of cold-start and oil starvation as it can also oil reservoir (Glaeser, 1992). To improve its resistance to wear and

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damage, the base material is coated with some materials, usually chromium which is suitable for abrasive, corrosive and hostile conditions. Hard chrome plating is commonly used for the compression ring, where as other piston ring surfaces can be thermally (plasma) sprayed with molybdenum, metal composites, metal-ceramic composites or ceramic composites, as a uniform coating or an inlay coating material. According to Rastegar and Richardson (1997) hard chromium layers can be improved by plasma spraying chromium ceramic on the ring face, thus, increasing the thermal load capacity.

As for any tribological surface, surface finish is important for lubrication condition and frictional behavior. For decades, piston rings have been coated both for suppressing wear and also for reducing friction and thus fuel consumption, especially during the running-in stage of the engine operation (Ma *et al*., 1998; Priest and Taylor, 2000). Takumi ***et al.*** (2003) analyzed the mixture of penetrating layer on a TiAl alloy and found that alloy TiAl coated by Cr and Al has good oxidizing prevention on high temperature. King ***et al.*** (2004) also modified coating by means of penetrating on steel of pre-nitro carbon H13 and found that holes on the micro carbon H13 can be reduced to have good microstructure. Ortmann ***et al.*** (2003) studied on structuring process of CrN coating in dry and lubricated sliding conditions and found that CrN coated material has better sliding wear endurance and lower friction coefficient. Shyrokov ***et al.*** (2005) performed test and mathematical modeling to predict friction and wear resistance of thin chromium-based coating applied for carbon steels and later found that thin chromium based coating can exhibit higher resistance to wear, friction and abrasion. Truetler (2005) studied plasma-deposited coating for gas direct injection engine of automotive components and noted its capability in reducing friction and wear under well lubricated components. Vetter ***et al.*** (2005) analyzed selections of surface treatment methods for automotive engine piston rings which can increase mechanical and thermal loading capacity, longer lifetime, weight reduction, friction reduction and corrosion resistance as demanded for modern automotive systems and concluded that piston ring with chromium-based coating provided corrosion protection, higher wear resistance and good lubrication performance of the engine as well as improved material strength for applications on high temperature load. Skopp ***et al.*** (2007) used thermally sprayed titanium sub oxide coatings for piston ring and cylinder liners of grey cast iron under mixed lubrication and dry-running conditions and found that piston ring and cylinder liner with titanium sub oxide coatings possessed high wear resistance. Furthermore, the combination of good lubrication and grey cast iron with titanium sub oxide coatings indicated high endurance to wear resistance than those for coating.

As a summary on the brief literature review, chroming process can be utilized to improve boundary lubrication characteristics for the piston ring using certain material that can provide interface between piston ring and cylinder liner. Proper lubrication and good condition of piston ring surface would increase the engine performance and reduce the exhaust emission. Hence, this study focused on the surface integrity and strength of newly produced piston ring after undergone boundary lubrication between piston ring and cylinder liner as compared with the original piston ring for CNG fuelled engine.

MATERIALS AND METHODS

Preparation of samples: In this study, several mixtures of materials on the chromium coating, also referred to as chroming, were used to determine suitability of the piston ring surface for engine application. The study was conduced at the Material Processing Laboratory and the CNGDI Engine Laboratory at the Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia in 2007-2008.

The material for the new piston ring was the ASSAB DF-3 steel with several other substances such as 0.9% carbon (C), 0.85% chromium (Cr), 96.6% ferric (Fe), 1.2% manganese (Mn) and 0.55% titanium (W) (Boyer and Gall, 1995). The chemical compound required for the chroming process is a mixture of three substances, namely chromium (Cr 99.5%), ammonium chloride (NH_4Cl 99.8%) and aluminum oxide (Al_2O_3 99.0%). The percentages of these substances represent purity level of the compounds for the coating process. The addition of NH_4Cl was to facilitate diffusion of chromium onto the base metal as it can be a catalyst for the chroming process, while Al_2O_3 was added to enhance hardness and structural integrity of the piston ring. A furnace (model: CMTS L16) was then used to heat the piston ring and chromium on certain temperature and period of time. A crock was used to mix chemical substance and piston ring. The chromium crock is made of conventional steel meanwhile the specimen which were to be chromed were dipped into the crock.

The piston ring depicted in Fig. 1 was manufactured using a CNC machine which was then undergone the chroming process. The dimension for the piston ring followed exactly the current production piston ring dimension which is to be fitted onto a piston of 78 mm bore diameter so that the expected result meets the requirement for the engine. In this experiment, four piston

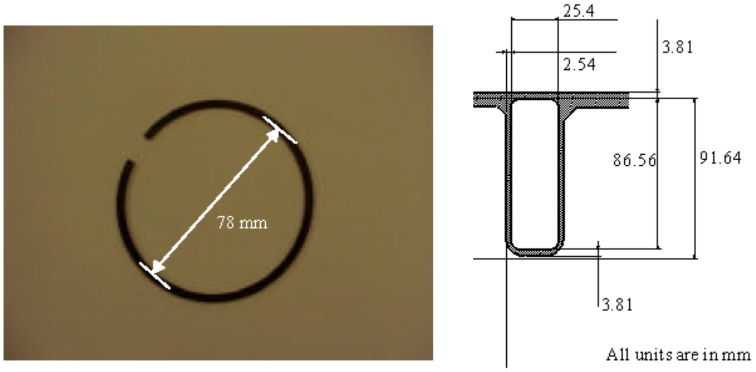

Fig. 1: Dimension of the piston ring and its cross-section

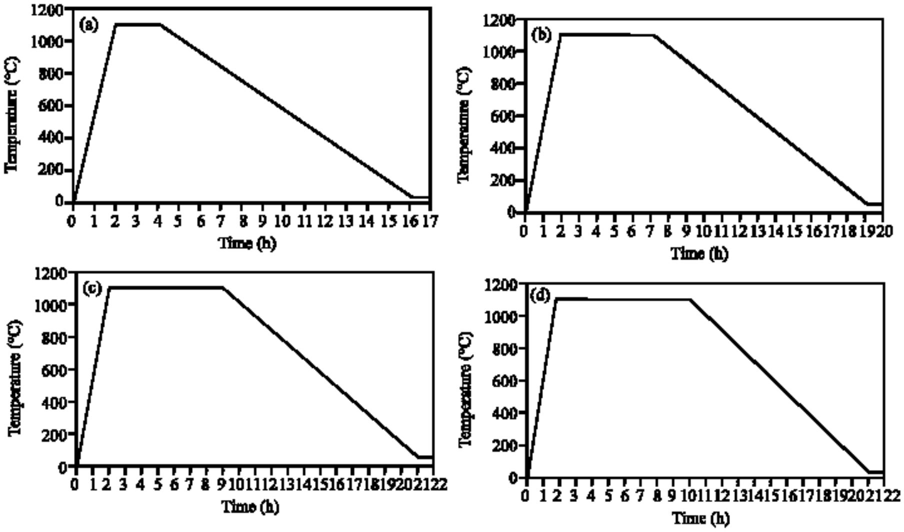

Fig. 2: The temperature profile during (a) 2 h maintenance for the first piston ring chroming process; (b) 5 h maintenance for the second piston ring chroming process; (c) 7 h maintenance for the third piston ring chroming process and (d) 9 h maintenance for the fourth piston ring chroming process

ring samples were fabricated using the same material (ASSAB DF-3 steel) with different heating process in order to obtain different hardness values. The piston ring was dipped into chromium tube containing of mixtures of 5-15% chromium, 1-5% ammonium chloride (NH_4CL) and approximately 80-94% aluminum oxide (Al_2O_3).

Next, the chromium tube together with the piston ring inside and the chromium compound was heated in the furnace. The heating requirement for each chroming process was summarized in Fig. 2a-d. For the first sample, the furnace was heated for 2 h until the inner temperature reached 1100°C. Then, the temperature was maintained for 2 h (referred to as 'maintenance time') followed by another 12 h of constant temperature drop to reach 36°C (Fig. 2a). Then, the chromium tube with piston ring was cleaned using a sand paper (320 grit silicon carbide) in order to remove the remaining chromium dust and to make its surface smooth. For the second sample, the furnace temperature had been maintained at 1100°C for 5 h (Fig. 2b). Similarly, for the third and fourth samples, the furnace temperatures had been maintained at 1100°C during 7 h (Fig. 2c) and 9 h (Fig. 2d), respectively. Then, all the samples including the original piston ring and the cylinder liner underwent the hardness test.

Hardness test: The hardness test was conducted using the Shimadzu HMV 2000 Micro-hardness Tester, which had been standardized for Vickers hardness (HV) test according to the manufacturer's instructions. The purpose of this test was to determine the hardness of all the piston ring samples as well as to ensure the microstructure formed after the coating was applied to the samples. For this test, the original piston ring and four chromed piston ring samples were subject to loading of

5 N for 10 sec. The loads were applied at 10 points of different locations on the piston ring and the averages of the readings are calculated for all the samples.

Friction and wear test: Apart from the hardness test, the test for friction coefficient was also carried out using the Reciprocating Friction Test (TR-281M8) which conforms to the ASTM D6079 standard. The test was performed at a certain speed emulating an engine operation of 1500 rpm without combustion. In addition, a digital scale (Scaltel SBA 31) was used to measure the weight of each sample before and after the test. For this scope of study, combustion was excluded since the instrumentation used to measure friction coefficient cannot function under extreme temperature condition.

The experiment was carried out using two sets of piston ring samples, the first sample was with the original piston ring which was made of grey cast iron while the second sample for the friction and wear test was taken as the third sample in the hardness test, i.e., the piston ring which underwent 7 h at 1100°C inside the furnace after comparing the hardness of the samples after undergone the chromisation process with that of the cylinder liner. Each set of experiments was performed on three types of lubricant, namely the 15W50 and 20W50 mineral oils as well as the 10W40 semi-synthetic oil. The codes for these oils are according to the ratings by the SAE (Society of Automotive Engineers) which provides standards to the range of viscosities for a multi-grade mineral oil in centistokes. By using this categorization, the viscosity range of oils having the same SAE rating is similar regardless the commercial brand. Moreover, these lubricant were chosen to maintain continuity with the previous work carried out by Adril *et al*. (2009) which use similar lubricants in identification of a suitable lubricant for a compressed natural gas direct injection engine.

The selected samples were then tested under a reciprocal and sliding movement on a cast iron platform which mimics the real interaction in the engine between the piston ring and the cast iron cylinder liner with a load of 30 N for 5 h with the surrounding temperature set at 100°C. After the coefficients of friction were determined for all cases, the wear for each ring were assessed by measuring the weight difference before and after the test and the weight loss were calculated.

RESULTS AND DISCUSSION

Discussion on hardness test: After undergone a series of heat treatment as specified in Fig. 2, the ASSAB DF-3 piston ring have been coated with chromium with different degrees of material diffusion depending on the type of heat treatment used. The magnified view of the original piston ring material is shown in Fig. 3, which was made of grey cast iron with chromium coating in order to reduce wear and friction. However, an unsmooth surface is visible from the figure where the coated materials do not penetrate into the base material and this leads to increased friction and wear after in use.

On the other hand, Fig. 4a showed the structure of piston ring material, which have been chromed at 1100°C for 2 h and undergone gradual cooling process for 12 h in the furnace. It was observed that this chroming process was incomplete with a measured 53 HRc material hardness which is slight higher than the hardness of the original base material (without chroming), i.e., 42.7 HRc, but lower than the production piston ring which was measured at 61.8 HRc.

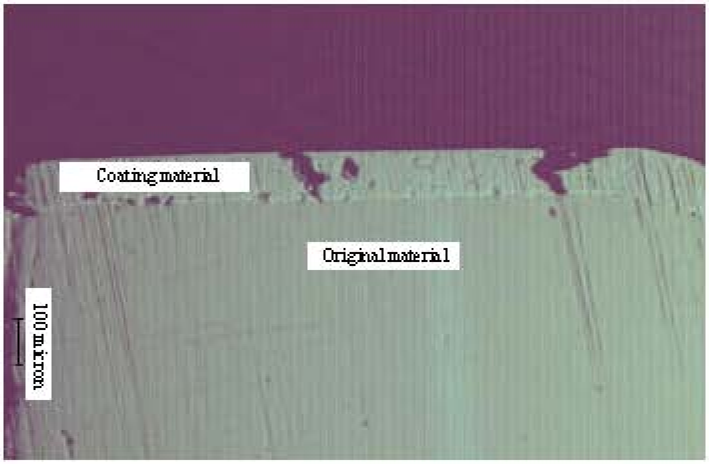

Fig. 3: Magnified view of the original piston ring surface

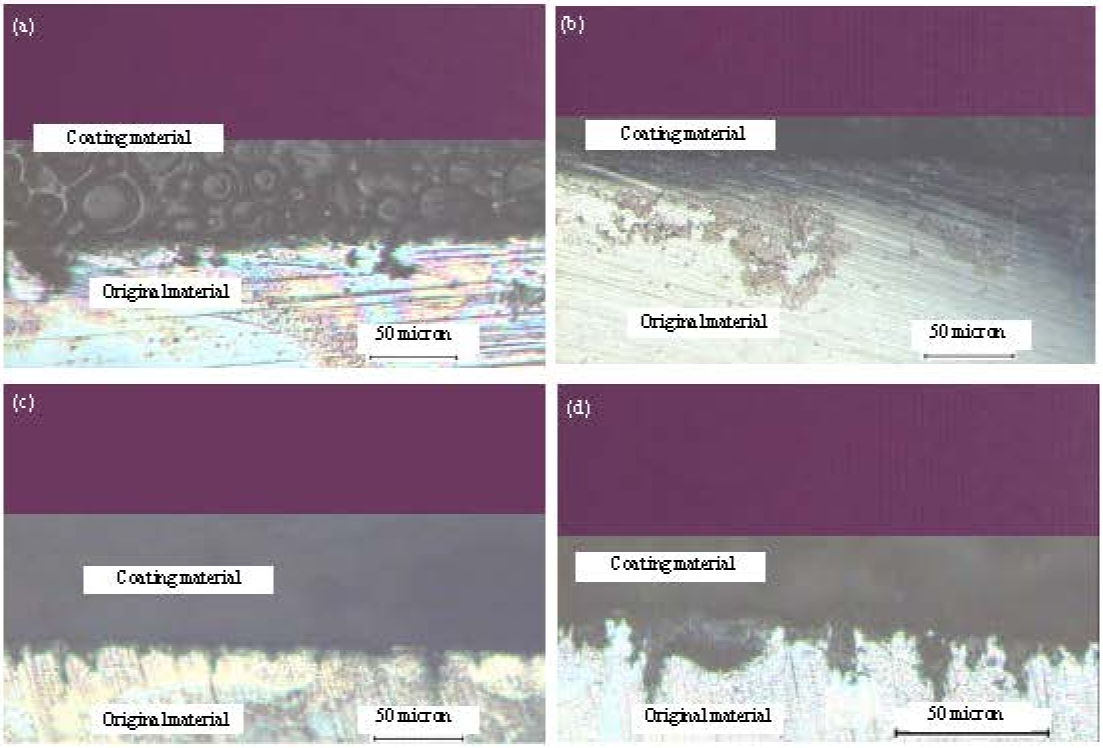

Fig. 4: Micro structure of piston ring surface material ASSAB DF-3-chroming on 1100°C furnace temperature during (a) 2 h of maintenance and 12 h of cooling; (b) 5 h of maintenance and 12 h of cooling; (c) 7 h of maintenance and 12 h of cooling and (d) 9 h of maintenance and 12 h of cooling

The diffusion of the chromium mixture into the base material can be further improved by using longer hour of heat treatment at 1100°C followed by similar rate of temperature drop during gradual cooling. The microstructure of the surface material of the piston ring with diffusion coating was shown in Fig. 4b. It is visible that the coat mixture (Cr 99.5%) integrated itself into the original material which results into a hardness of 53.6 HRc. Thus, sustaining the temperature for 5 h slightly increase the material hardness by 0.6 HRc since, by maintaining the piston ring heating temperature, more coating materials can penetrate into the base material to improve its hardness. Furthermore, the hardness was further improved to 65.3 HRc (Fig. 4c) as the temperature was maintained for 7 h followed by 12 h of gradual cooling. As the time for sustaining the temperature at 1100°C was increased (Fig. 4d) to 9 h followed by 12 h gradual cooling, the material hardness had increased to 68 HRc (Table 1) which exceeded the hardness of the cylinder liner (66 HRc) as shown in Table 2. The original piston ring from grey cast iron having the hardness averages 61.8 HRc after 10 time repetition as summarized in Table 1 compared to the original piston ring hardness of 42.7 HRc before chroming (Table 2). A graph for the relation between the maintenance time and the resulting hardness is shown in Fig. 5.

From observation through the images displayed in Fig. 4, it is obvious that the quality of the penetration is proportional to the resulted hardness. However, the selection of the fourth samples may cause scoring to the cylinder liner since the hardness of piston ring is higher than that of the cylinder liner, while the first and second sample is even softer than the original piston ring. Therefore, the third sample was chosen for a good choice to be fitted into the engine. The selection can be justified by looking at Fig. 5 where the hardness for the sample should not exceed the limit set by the material for cylinder liner.

Discussion on coating microstructure: To see whether or not the microstructure produced by the chroming process is comparable with the outcomes produced by other researcher, the coating profile obtained from the study were then compared with works performed by other researchers as reported here. However, the scope of comparison is limited to the microstructure profile since, all the cases chosen used different compound to strengthen the surface as well as were applied for different components and applications.

Table 1: The results of piston ring hardness testing after chroming

	Piston ring using ASSAB DF-3 after chroming (HV) (Temperature = 1100°C)				
No.	Piston ring before chroming (ASSAB DF-3)	Constant temperature for 2 h	Constant temperature for 5 h	Constant temperature for 7 h	Constant temperature for 9 h
1	457	639	562	852	1254
2	337	538	554	852	1036
3	468	521	601	837	1361
4	369	542	572	879	1470
5	352	612	561	831	1505
6	361	539	543	864	1302
7	378	576	581	796	1451
8	462	516	575	801	1276
9	531	561	632	834	1348
10	472	590	547	863	1379
Avg.	418.7HV = 42.7 HRc	563.4 HV = 53.0 HRc	572.8 HV = 53.6 HRc	840.9 HV = 65.3 HRc	1338 HV = 68 HRc
SD	66.5	40.4	26.9	26.9	134.9

Table 2: The test results of original piston ring hardness and cylinder liner

No. of tests	Hardness of piston ring (grey cast iron) (HV)	Hardness of cylinder liner (HV)
1	821	863
2	769	872
3	724	844
4	693	890
5	802	893
6	716	895
7	733	870
8	678	831
9	691	831
10	721	842
Avg.	735 HV = 61.8 HRc	863 HV = 65.8 HRc
SD	47.9	20.3

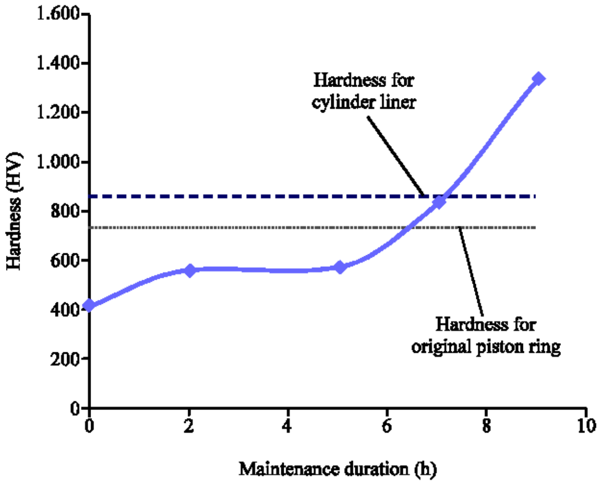

Fig. 5: Relation between maintenance duration during the chroming process and the resulting hardness

The first comparison was made with the work by Vetter *et al.* (2005), who used a similar coating process for connecting rod using the CuAlSn compound on a copper substrate as depicted in Fig. 8a. From the microstructure shown in the figure, the PVD coating form a visible interface with the base material in which flake-debris can be formed under certain loading and speed. On the other hand, Truhan *et al.* (2005) used the chromium-plated piston ring and performed a test on the coefficient of friction produced at different engine speeds. The microstructure profile of his specimen clearly shows a visible parting line between the coating and the base materials which is the cast iron (Fig. 8b). A better coating was produced by Nolan *et al.* (2006), who studied the sliding wear for a TiN coating on a Ti-6Al-4V alloy produced through the PVD coating process (Fig. 8c). While this give a better coating quality and thus superior wear resistance, the technology is not affordable to be adopted for automakers for production automotive engines. Another type of coating was presented by Picas *et al.* (2006) which used the Cr_3C_2-NiCr powders as depicted in Fig. 8d. From the microscopic observation, the coating layer is seen to form a good bonding with the base material. However, there may be an issue of surface integrity due to the quality of its surface finish which makes it unsuitable for automotive. From the comparison made on physical observation for the micro-structure patterns, it can be summarized that the coating layer (chromium) laying on the surface of the base material with certain degrees of penetration into the base material can provide better resistance to wear as a result of increase in surface hardness.

Discussion on friction and wear test: After performing the friction test, coefficients of friction of the original piston rings as well as the modified (chromed) piston rings are listed, respectively in Fig. 6 and 7. From the figures, it is evident that, under the same condition, diffusion coating can reduce friction by almost 14-39% as indicated in Table 3 depending on the lubricant used. This is due to the capability of the chromium coating in separating both the contacting surfaces while maintaining low friction. This is similar to having a layer of solid lubricant in between the oil film and the base material which in turn can also protect the base material from wear.

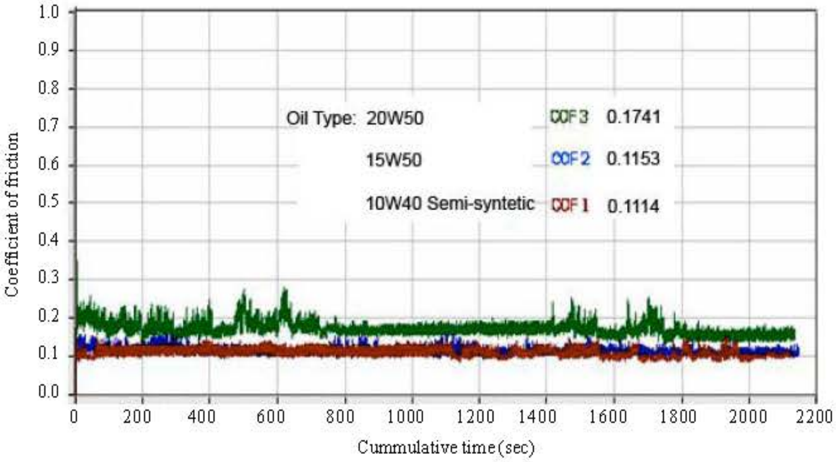

Fig. 6: Coefficient of friction for the original piston ring made of grey cast iron for the tested lubricants

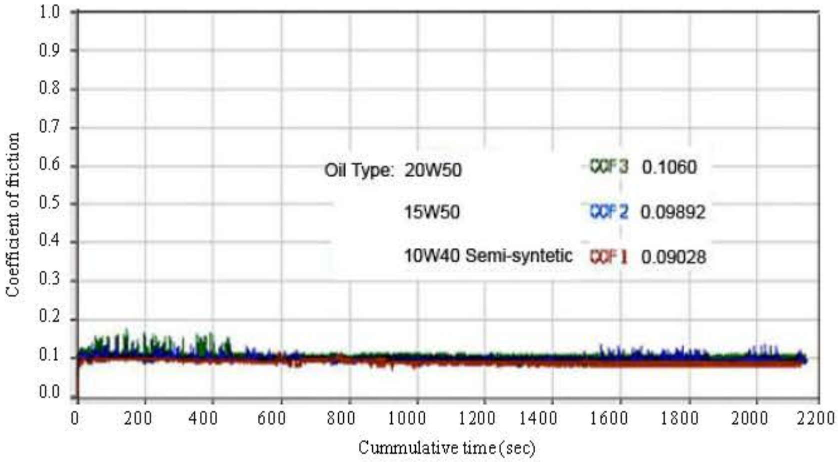

Fig. 7: Coefficient of friction for the chromed ASSAB DF-3 piston ring for the tested lubricants

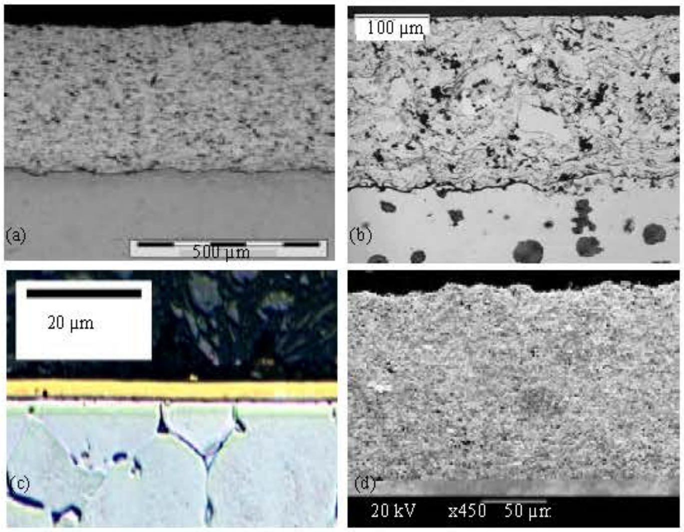

Fig. 8: Micro-structure of the surface for several materials occupied by the previous studies by (a) Vetter *et al.* (2005); (b) Truhan *et al.* (2005); (c) Nolan *et al.* (2006) and (d) Picas *et al.* (2006)

Table 3: Comparison of coefficient of friction for the original and modified piston ring

Types of lubricant	Original piston ring	ASSAB DF-3 chromed piston ring	Friction reduction
10W40 Semi-synthetic	0.1114	0.09028	18.9
15W50	0.1153	0.09892	14.2
20W50	0.1741	0.1060	39.1

Table 4: Comparison of weight loss for the original and modified piston ring

Types of lubricant	Original piston ring (mg)	ASSAB DF-3 Chromed piston ring (mg)
10W40 Semi-synthetic	0.5	0.4
15W50	0.4	0.3
20W50	0.3	0.1

Overall, based on the test outcomes from Fig. 6 and 7, the 10W40 semi-synthetic oil gave the lowest coefficient of friction among the three oils used. However, the significant reduction was given by the test using the 20W50 oil as can be seen Table 3 since, the original piston ring yielded a relatively higher friction. Hence, this test proved the effectiveness of the modified chromed ring via the diffusion coating process in reducing the friction.

In terms of wear, its assessment can be made by simply measuring the weight loss due to the test. The weight loss for all cases is tabulated in Table 4. From the Table 4, it was found that the weight loss for the modified chromed piston ring was less than the original piston ring. This also showed the capability of the modified chromed piston ring in minimizing wear thus increasing the endurance of the engine.

CONCLUSIONS

As a way to overcome boundary lubrication during gaseous fuel combustion, coated piston ring can play an important role to ensure smooth sliding and reciprocal motion of piston ring along the cylinder liner, thus, preventing damage on material structure. This situation caused high frictional resistance between piston ring and cylinder liner at high temperature, which can lead to scoring and scuffing inside the cylinder liner. However, piston ring with diffusion chromium coating at a controlled temperature and duration is capable of minimizing the debris produced which can consolidate as much as the base material during the engine operation. The piston ring with 99.5% chromium coating with 7 h maintenance in the furnace is found to be suitable for engine operation since it yielded a better hardness of 65.3 Hrc compared to the original piston ring with 61.8 HRc due to the effect of chroming process that provide the resistance toward wear while maintaining less than the hardness for the cylinder liner. Further test on friction and wear showed that the modified piston ring led to better reduction in coefficient of friction for all different oil tested as well as less weight loss due as a result of wear. Among the three oil tested, the 20W50 is seen to gain the most from the proposed chroming process since it gained the highest friction reduction (39.1%) as well as the lowest weight loss (0.1 mg). Nevertheless, in general, the proposed chroming result in reduced friction regardless the oil type.

REFERENCES

Adril, E., S. Abdullah, A.K. Ariffin, A. Muchtar and K. Omar, 2009. Comparative study of characteristic of lubricant oils in gasoline and compressed natural gas engines. Eur. J. Sci. Res., 30: 282-293.

Barbezat, G., 2005. Advanced thermal spray technology and coating for lightweight engine blocks for the automotive industry. Surf. Coat. Technol., 200: 1990-1993.

Boyer, H.E. and T.L. Gall, 1995. Metals Handbook. 8th Edn., American Society for Metals, Metal Park, Ohio, ISBN: 087170188X.

Glaeser, W.A., 1992. Material for Tribology, Tribology Series 20. Elsevier Science Publisher BV. Amsterdam, The Netherlands.

King, P.C., R.W. Reynoldson, A. Brownrigg and J.M. Long, 2004. Cr(N,C) diffusion coating formation on pre-nitrocarburised H13 tool steel. Surf. Coat. Technol., 179: 18-26.

Ma, Z., N.A. Henein, W. Bryzik and J. Glidewell, 1998. Break-in liner wear and piston ring assembly friction in a spark ignited engine. Tribol. Trans., 41: 497-504.

Mogul, F., 1998. Supplement Shell Lexicon Verbrennungsmotor (Piston Ring and Crankcases). Federal-Mogul Powertrain Systems (International) Ltd., Germany.

Nolan, D., S.W. Huang, V. Leskovsek and S. Braun, 2006. Sliding wear of titanium nitride thin films deposited on Ti–6Al–4V alloy by PVD and plasma nitriding processes. Surf. Coat. Technol., 200: 5698-5705.

Ortmann, S., A. Savan, Y. Gerbig and H. Haefke, 2003. In-process structuring of CrN coating and its influence on friction in dry and lubricated sliding. Wear, 254: 1099-1105.

Picas, J.A., A. Forn and G. Matthäus, 2006. HVOF coatings as an alternative to hard chrome for pistons and valves. Wear, 261: 477-484.

Pinedo, C.E., 2003. The use of selective plasma nitriding on piston rings for performance improvement. Mater. Des., 24: 131-135.

Priest, M. and C.M. Taylor, 2000. Automobile engine tribology-approaching the surface. Wear, 241: 193-203.

Rastegar, F. and D.E. Richardson, 1997. Alternative to chrome: HVOF cermet coatings for high horse power diesel engines. Surf. Coat. Technol., 90: 156-163.

Shyrokov, V., A. Maksymuk and C. Vasyliv, 2005. Prediction of wear-resistant thin diffusive coatings. Tribol. Int., 38: 179-185.

Skopp, A., N. Kelling, M. Woydt and L.M. Berger, 2007. Thermally sprayed titanium sub oxide coatings for piston ring/cylinder liners under mixed lubrication and dry-running conditions. Wear, 262: 1061-1070.

Takumi, N., T. Izumi, S. Hayasi and T. Narita, 2003. Two-step Cr and Al diffusion coating on TiAl at high temperatures. Intermetallics, 11: 225-235.

Tarasov, S., A. Kolubaeva, S. Belyaeva, M. Lernerb and F. Tepper, 2002. Study of friction reduction by nanocopper additives to motor oil. Wear, 252: 63-69.

Truetler, C.P.O., 2005. Industrial use of plasma-deposited coatings for components of automotive fuel injection systems. Surf. Coat. Technol., 200: 1969-1975.

Truhan, J.J., J. Qu and P.J. Blau, 2005. The effect of lubricating oil condition on the friction and wear of piston ring and cylinder liner materials in a reciprocating bench test. Wear, 259: 1048-1055.

Vetter, J., G. Barbezat, J. Crummenauer and J. Avissar, 2005. Surface treatment selections for automotive applications. Surf. Coat. Technol., 200: 1962-1968.