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Advanced Low Friction Engine Coating Applied to a 70cc High Performance Chainsaw

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Abstract

Present two stroke engines used for hand held power tools must confirm to prevailing emission legislation. A fact is that today the engines have to be run at leaner air fuel setting resulting in less amount of lubrication oil passing through the engine. This lean mixture combined with high mixture trapping efficiency also affects the combustion, raising the overall working temperature of the engine. So to gain more robustness out of these air-cooled power heads one viable route is to use different coatings to take control of tribology and heat management within the two stroke power head.

In this paper a first discussion and description of the different coatings and their merits to the air cooled two stroke engine is conducted. Furthermore engine data for the test engine, in this case a 70cc professional chainsaw are presented. The outcome of engine dyno testing of the different coatings are presented and analyzed for further discussion.

Conclusion, there are positive effects on the two-stroke power head by introducing new advanced engine coatings, to achieve the most out of the coatings this must be taken into account during the first design of the engine. Also the economic impact on the final products has to be considered for market competitiveness.

Introduction

Husqvarna - as a member of a group of European SMEs, surface coating technology providers and engine manufacturers - wish to develop and demonstrate a second-to-none advanced low-friction coating tailored for engine applications. Contrary to existing approaches this is based on a holistic approach combining coating technologies, substrate alloys and well known large-scale second-to-none production technologies.

The implementation of the Advanced low friction Engine Coating (AdEC) project will significantly contribute to upgrading state-of-the-art surface technologies and improve existing advanced coating processes through investigation within the field of material science, especially in the area of complex materials focusing on Ni-Co based dispersion coatings containing a mixture of nano-diamonds and hexa-boron nitride (BN).

The latest development in the use of advanced coating materials was introduced when NSU invented the Wankel engine in the late 60s. For that purpose, an electrochemical deposit coating (Nikasil) was invented. The most promising surface coatings largely available today also include CrN and different types of diamond-like carbon coatings - the so-called DLC-coatings. All these currently applied coatings, as well as R&D based alternatives are failing in the long term due to low wear-resistance, too high prices and the lack of facilitating low friction, due to a non-existing affinity to lubricating molecules, aggravated by lack of thermal stability, a limited oxidation resistance at elevated temperatures and sensitivity to sulphur contaminated fuel. Furthermore, none of the existing solutions have been optimized in a holistic manner which is one of the major success criteria of the present project. Whereas the AdEC project likewise addresses coatings for internal cylinder walls, the present paper is focused on DLC coatings for pistons and piston rings.

Diamond-like carbon (DLC) comprises a large family of self-lubricating coatings. DLC consists of an amorphous network of carbon atoms which predominantly form sp^2 and sp^3 hybridizations. DLC is also referred to as amorphous carbon (a-C) and may in addition to carbon contain an amount of hydrogen (a-C:H). The microstructure, chemical composition and mechanical and tribological properties of DLC coatings can be widely tuned depending on the deposition conditions and their doping with metallic and non-metallic elements (a-C:H:X or a-C:X, where X denotes the doping element) [1]. DLC is widely employed under non-lubricated conditions. However, under boundary lubrication conditions, DLC may likewise provide valuable wear protection and friction reduction. Depending on the type of oil and the type and concentration of additives, it has been found that DLC can be optimized to perform very well in oil lubricated contacts as well [2]. Extreme pressure (EP) and anti-wear (AW) additives are known to reduce friction and wear in metallic contacts. However, when one or more of the contacting surfaces is coated with DLC, the mechanism is changed. Nevertheless, friction reduction may still be obtained due to the formation of new types of tribofilms [3]. In tribological contacts, DLC coatings often undergo a local graphitization process at the surface, resulting in the formation of friction reducing tribofilms. Furthermore, new types of tribofilms may be formed when doped DLC coatings interact with oil additives under conditions of elevated temperatures and high contact pressures. As an example, under certain conditions, tungsten-doped DLC (a-C:H:W) coatings have been found to interact with extreme pressure (EP) additives in oils. In the presence of sulphur-based additives, WS_2-type low-friction tribofilms may thus be formed in contacts involving a-C:H:W parts. However, often the resulting friction reduction is accompanied by an increased wear rate due to the formation of the tribofilm [4,5,6].

The development of a DLC coating for engine applications requires an optimization of the microstructural and mechanical properties of the coating along with an adaption of the coating to the oil lubricant and its additives. In this paper, pistons and piston rings coated with both un-doped (a-C:H) and tungsten-doped (a-C:H:W) DLC have been investigated in a 70cc high performance chainsaw.

Experimental

The test engine, HUSQVARNA 372XP X-TORQ, is a 70cc professional chainsaw in the larger mid-size class, see Figure 1 and Table 1, built for very demanding applications. The chainsaw is equipped with a stratified scavenged two stroke engine for reduced fuel consumption and exhaust emissions. For further descriptions on the stratified scavenging operational principle, see ref [7,8,9].

Figure 1. Test object, all engine tests were performed on a Husqvarna H372 XP X-TORQ

Table 1. Engine specification

Type	Stratified scavenged air cooled two stroke
Displacement [cc]	70.7
Bore [mm]	50
Stroke [mm]	36
Connecting rod [mm]	65
Compression ratio	10.3:1

The DLC coatings were deposited using a CC 800/9 magnetron sputtering system manufactured by CemeCon AG. The a-C:H coatings were sputtered from two graphite targets operated in DC mode in a combined Ar and C_2H_2 atmosphere. In addition, for the a-C:H:W coating, a tungsten target was employed. The tungsten target was operated in high power impulse magnetron sputtering (HiPIMS) mode. During deposition, either a DC or a pulsed bias was applied to the substrates. A summary of the deposition conditions is presented in Table 2. The films were deposited onto Mahle aluminum (M145) pistons and phosphatized cast iron piston rings. Prior to deposition, a thin Sn coating was removed from the piston by chemical etching in HNO_3, whereupon they were ultrasonically cleaned in Eskaphor. The piston rings were ultrasonically cleaned in Tikapur. In addition, Si(100) substrates were included in the deposition process for subsequent analysis by nanoindentation and Raman spectroscopy. During deposition, the pistons were subjected to a three-fold rotation, whereas the piston rings and the Si substrates were subjected to a two-fold rotation. A mild, *in-situ* plasma etch was performed on the substrates. Prior to the deposition of the DLC top-coating, a CrN interlayer was deposited in order to improve the film to substrate adhesion and to provide load support.

Table 2. Summary of the deposition conditions.

	Coating	Bias type	C_2H_2 flow (sccm)	Targets
DLC-1	a-C:H	DC	30	Graphite
DLC-2	a-C:H	MF	60	Graphite
DLC-3	a-C:H	MF	35	Graphite
W-DLC	a-C:H:W	HiPIMS	5	Graphite + tungsten

Cross-sectional images were obtained by scanning electron microscopy (SEM) using a Nova 600 nanoSEM (FEGSEM) manufactured by FEI.

The hardness (H) and reduced elastic modulus (E_r) of the films were evaluated by nanoindentation. A nanoindenter of the type TI-900 TriboIndenter manufactured by Hysitron Inc was employed. Indentations in a fused quartz standard were performed to calibrate the area function of the Berkovich tip. H and E_r were extracted from the indentation curves using the Oliver-Pharr approach [10].

Raman spectroscopy was performed with a Renishaw inVia Raman microscope equipped with an argon laser of wavelength 514.5 nm. Care was taken to avoid sample damage from exposure to the laser beam.

The thermal stability of the coatings was tested by annealing the coatings at 300 °C for approximately two hours under atmospheric conditions. Nanoindentation and Raman spectroscopy were performed both before and after the annealing process in order to evaluate the structural and mechanical changes.

Dyno testing of performance (80-180rps) and emissions at rated speed (170rps) has been made. Each sample was tested in a new cylinder, enabling also the Nikasil plating of the cylinder to be examined after testing. The cylinder/piston assemblies were given a 1.5h break in before testing, accumulating a total run time of just over 2h.

Following the engine test, the coated pistons and piston rings were investigated using SEM and energy dispersive X-ray spectroscopy (EDX). Either a Bruker TM3000 table-top instrument or an EVO LS25 instrument manufactured by Zeiss was employed. The pistons were wiped with a clean cloth prior to the EDX analysis, whereas the piston rings were wiped with ethanol.

In addition to the power and emission tests, the DLC coatings were applied to pistons for cylinder pressure measurements using a Kistler 6052C27 cylinder pressure transducer to measure the Pmax, Pmax angle and enable calculation of FMEP. The measurements were made over 100 revolutions with 0.2° resolution at 170rps/lambda0.80 and are presented as mean values of each point.

Results and Discussion

Four different DLC coatings were investigated in this study. The properties of the coatings are summarized in Table 3, while examples of coated pistons are shown in Figure 2. The color of the DLC coatings depends on the microstructure of the coating along with the presence of doping elements.

Table 3. Summary of the properties of the coatings investigated in this paper.

	H (GPa)	E_r (GPa)	Estimated H concentration (at. %)	Temperature stability
DLC-1	12	104	27	Poor
DLC-2	12	95	28	Poor
DLC-3	18	144	21	Good
W-DLC	17	180	-	Good

Figure 2. Images of pistons coated with DLC-1 (left) and W-DLC (right).

For all of the coatings investigated in this study, Raman spectroscopy revealed a signal in the range of 1000 cm^{-1} to 1700 cm^{-1} typical of DLC [11]. For the un-doped DLC coatings, the hydrogen concentration could be estimated from the Raman spectra using the empirical equation in ref. [12]. The estimated hydrogen concentrations are provided in Table 3. The W-DLC coating likewise contains hydrogen since it was deposited in a C_2H_2-containing atmosphere. However, the aforementioned empirical equation does not apply to doped DLC, and hence, no estimated hydrogen concentration is reported for the W-DLC coating in Table 3.

X-ray diffraction indicated the presence of W-C crystallites. The W-DLC coating is thus a composite coating consisting of tungsten carbide nanocrystallites embedded in a DLC matrix.

Figure 3 shows cross-sectional images of the different DLC coatings deposited onto flat and smooth Si substrates. It is evident from the images that the morphology of the coatings changed as a consequence of the different deposition conditions (see Table 2). The DLC-2 and DLC-3 coatings, which were deposited using MF bias, had a smoother and finer columnar structure as compared to the DLC-1 and W-DLC coatings. However, as evident from the examples in Figure, the coating roughness increased significantly when the coatings were deposited onto pistons and piston rings.

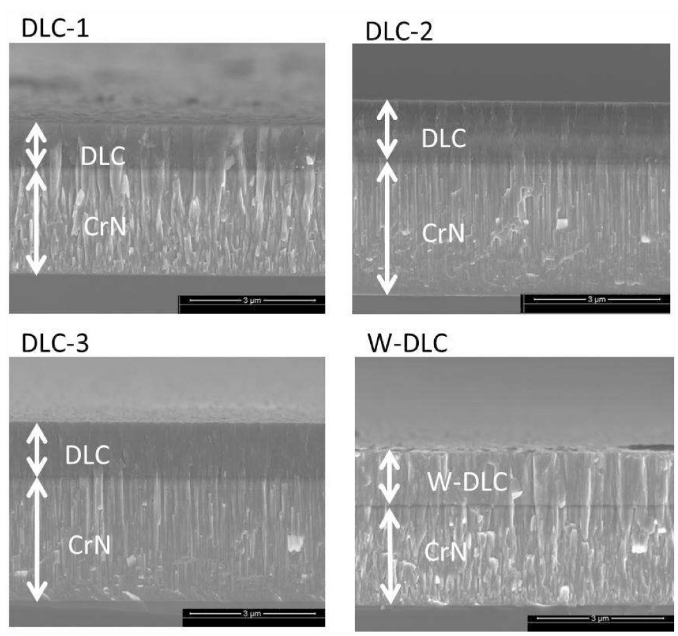

Figure 3. Cross-sectional SEM images of the DLC coatings on Si substrates.

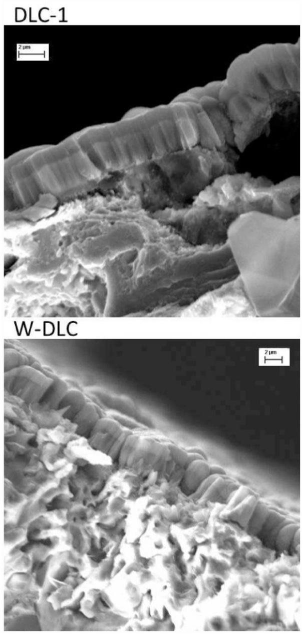

Figure 4. Cross-sectional SEM images of the DLC-1 (top) and W-DLC (bottom) coating deposited onto grey cast iron piston rings.

In Figure 5 the Raman spectra obtained from the DLC-1 and DLC-3 coatings before and after annealing are shown. Before annealing, the Raman spectra of both coatings showed a signal in the range of 1000 cm^{-1} to 1700 cm^{-1} typical of DLC [11]. For DLC-1 it is evident from the figure that the Raman signal after annealing was significantly altered, indicating that the film structure had decomposed. Changes in the mechanical properties of the DLC-1 coatings were likewise observed after annealing. This coating thus had poor temperature stability. On the other hand, for the DLC-3 coating, only minor changes corresponding to a slight structural ordering were observed as a consequence of annealing. Furthermore, no significant changes in the mechanical properties were observed for the DLC-3 coating after annealing. Hence, it is suggested that this coating has good temperature stability. The temperature stabilities of the remainder of the investigated coatings are presented in Table 3.

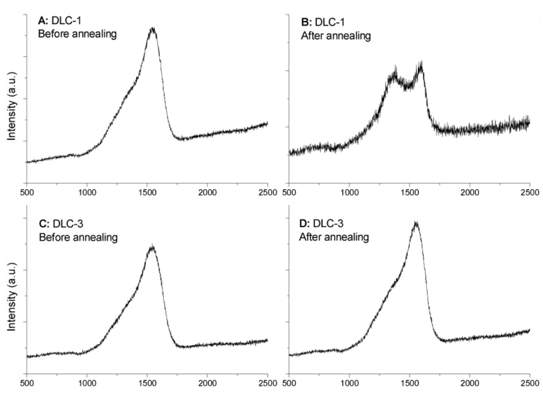

Figure 5. Raman spectra of DLC-1 and DLC-3 before and after annealing at 300 °C for approximately two hours.

Table 4. Engine test combination assemblies.

Test No.	Piston	Piston rings
1	Standard	Standard
2	Standard	DLC-1
3	Standard	W-DLC
4	DLC-1	Standard
5	W-DLC	W-DLC

The results from engine tests of the five combinations are presented in Figure 6 as the brake power as a function of the charging efficiency with the reference assembly from test 1 set to 100%. All coatings indicate higher friction loss than the reference. However, since the cylinder to piston clearance was tighter with the coated pistons (as the main focus was to examine the coating to piston adhesion) this can be expected. The coated rings had very little effect on the indicated friction. The test combinations are summarized in Table 4.

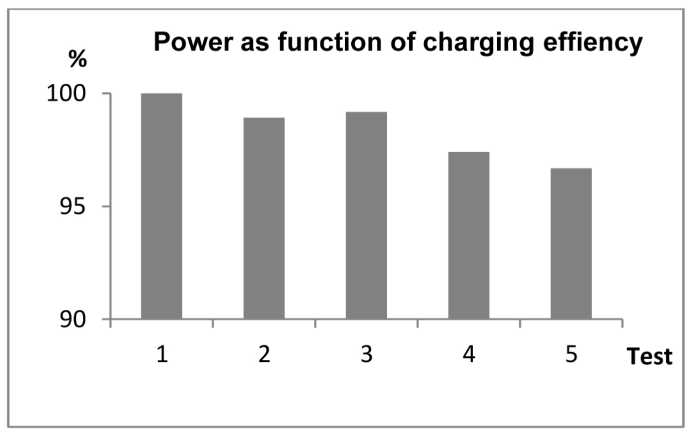

Figure 6. Indication of friction loss based on power output as function of charging efficiency from test 1-5.

Figure 7 shows EDX maps of the distribution of Cr and Fe on the DLC-1 coated piston rings after engine test 2. Prior to engine test 2, an essentially even distribution of Cr was observed, whereas no Fe signal was found. The appearance of areas of decreased Cr signal (from the CrN interlayer) and corresponding increased Fe signal (from the grey cast iron substrate) suggests that the DLC-1 coating was at least partially worn off during the engine test. The stripes arise due to the higher wear on the tops of the machining marks in the piston rings as compared to the valleys.

The W-DLC coated piston rings investigated in engine test 3 were likewise examined by EDX. Prior to the engine test, EDX revealed an even distribution of W and Cr on the outer face of the W-DLC coated piston rings. However, as shown in Figure 8, some of the W-DLC coating was worn off during the engine test, as indicated by the areas with decreased W signal and corresponding increased Cr (from the CrN interlayer) and Fe (from the grey cast iron substrate) signals. A similar observation was made for the W-DLC coated piston rings after engine test 5. Since small S signals were observed on the piston rings both before and after the tests, no clear evidence of a WS_2-type of tribofilm was found. Thus, either the tribofilm was removed when wiping the piston rings with ethanol, or it was never formed. Since both engine test 3 and 5 suggested higher friction levels as compared to engine test 1, this indicates the absence of a friction-reducing WS_2 tribofilm.

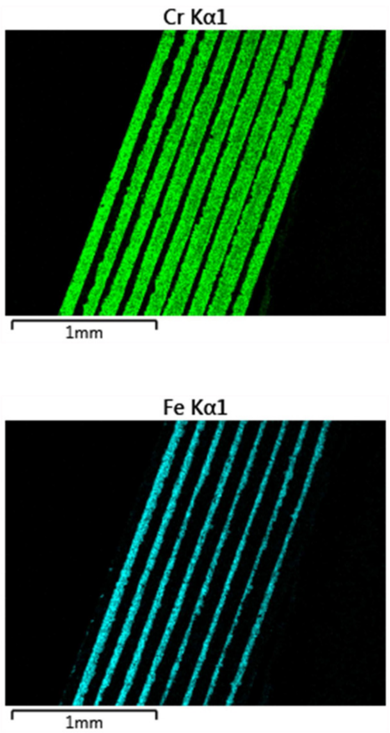

Figure 7. EDX maps showing the distribution of Cr (left) and Fe (right) on the DLC-1 coated piston ring after engine test 2.

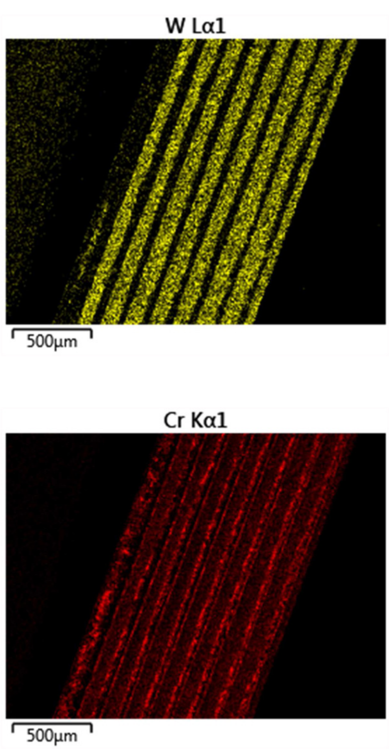

Figure 8.

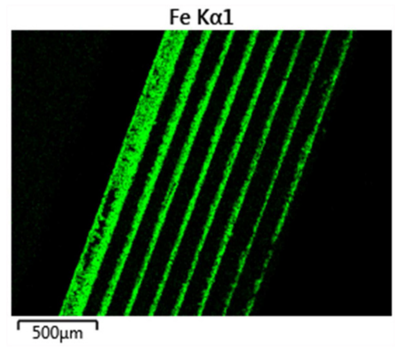

Figure 8. (cont.) EDX maps showing the distribution of W (left), Cr (middle) and Fe (right) on the W-DLC coated piston ring after engine test 3.

Figure 9 and Figure 10 show the exhaust and intake side, respectively, of the standard, DLC-1 coated and W-DLC coated pistons after engine tests. It appears from the images that the coated pistons were subjected to less wear as compared to the standard piston. EDX revealed no P or S signals on the exhaust side of either of the pistons in the images, suggesting the absence of additive-induced tribofilms. It is not straightforward to detect potential carbon-based tribofilms in the present study. However, as shown in figure 6, the indications of higher friction (engine test 2, 3, 4 and 5) suggest that no advantageous tribofilm formation occurred during the engine tests. The general impression is that the coatings stick well to the parts they are applied to during engine tests, and show less wear than stock parts.

Figure 9. Exhaust side of the standard piston (left) after engine test 1, the DLC-1 coated piston (middle) after engine test 4 and the W-DLC coated piston (right) after engine test 5.

Figure 10. Intake side of the standard piston (left) after engine test 1, the DLC-1 coated piston (middle) after engine test 4 and the W-DLC coated piston (right) after engine test 5.

In the previous discussion it was concluded that the coating adhesion was sufficient for engine tests. An evaluation of the tribological properties was subsequently made using cylinder pressure measurements on the coatings in Table 3. For these tests, only the pistons were coated and run with standard piston rings. The coated pistons and the reference piston were matched with cylinders to achieve 50 µm clearances to avoid seizure or increased friction due to coating thickness.

Figure 11 shows the cylinder pressure traces at 170rps/ lambda0.80. Variations of angle Pmax were found ranging from 14°atdc to 13.2°atdc, and the corresponding variations of Pmax ranged from 26 to almost 28 bar (see Table 5).

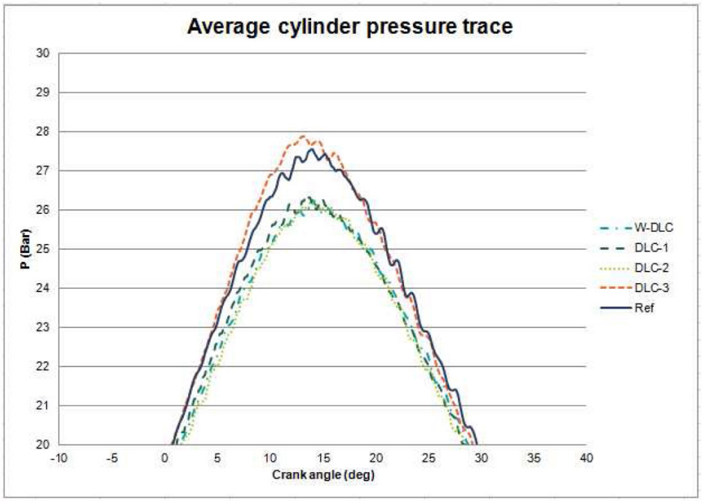

Figure 11. Pressure trace with different coatings.

The angle Pmax variation shown in Table 5 is likely due to thermal insulation of the DLC-coatings. Furthermore, the Pmax variations may be a result of different ring to piston clearances due to varying thickness of the different coatings, as the ring grooves was not masked when applying the coatings.

Table 5. Cylinder pressure max and angle.

Coating	Pmax (Bar)	Angle Pmax (°atdc)
reference	27.55	14
W-DLC	26.25	14
DLC-1	26.38	13.4
DLC-2	26.23	14.2
DLC-3	27.88	13.2

Table 6 shows the mean effective pressures measured and calculated from the tests. The W-DLC coated piston showed a more than 3% reduction in Fmep compared to the reference piston and over 10% reduction compared to the other DLC-coatings tested. The finding suggests that the W-DLC coating is a promising candidate for providing friction reduction in a two-stroke engine.

Table 6. Mean effective pressures.

Coating	IMEP (Bar)	BMEP (Bar)	FMEP (Bar)	Loss (%)
reference	4.256	3.34	0.916	21.5
W-DLC	4.157	3.271	0.886	21.3
DLC-1	4.095	3.019	1.076	26.3
DLC-2	4.056	3.035	1.021	25.2
DLC-3	4.152	3.096	1.056	25.4

Conclusion and Outlook

From a visual inspection, it appeared that the investigated coatings provided improved wear protection. In the present study, no evidence of the formation of WS_2-type of tribofilms was found.

The tests show that the W-DLC coating may give lower friction in an air-cooled two-stroke engine. However, further testing has to be made with actions taken to ensure that the ring is functioning properly followed by an evaluation of long time wear properties and the ability to withstand seizure.

A further optimization of the DLC coatings and their interaction with the oil additives may provide improved tribological performance. Another possible candidate worth investigating as an engine coating is silicon-doped DLC. In the literature, it has been found that this type of DLC has high temperature stability and may form protective tribofilms due to its interaction with oil additives [6,13].

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Definitions/Abbreviations

AdEC - Advanced Engine Coating

DLC - Diamond-like carbon

W-DLC - Tungsten-doped diamond-like carbon

SME - Small Enterprices

EDX - Energy dispersive X-ray spectroscopy

NSU - NSU Motorenwerkemn

atdc - After top dead centre

IMEP - Indicated Mean Effective Pressure

BMEP - Brake Mean Effective Pressure

FMEP - Friction Mean Effective Pressure.

EP - Extreme pressure additives

AW - Anti-wear additives

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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