Article:

Koszela, W, Pawlus, P, Reizer, R et al. (1 more author) (2018) The combined effect of surface texturing and DLC coating on the functional properties of internal combustion engines. Tribology International, 127. pp. 470-477. ISSN 0301-679X

https://doi.org/10.1016/j.triboint.2018.06.034

The combined effect of surface texturing and DLC coating on the functional properties of internal combustion engines

Waldemar Koszela[a], Pawel Pawlus[a*], Rafal Reizer[b], Tomasz Liskiewicz[c]

[*] corresponding author, tel. +48-178651183, fax +48-178651183, email: ppawlus@prz.edu.pl

[a] Rzeszow University of Technology, 35-959 Rzeszow, Powstancow Warszawy 12, Poland

[b] University of Rzeszow, 35-959 Rzeszow, Tadeusza Rejtana 16 C, Poland

[c] University of Leeds, Leeds LS2 9JT, UK

Abstract

A reduction in frictional loss is an important aspect of efficiency in high-performance internal combustion engines. This can be achieved by the well-designed surface texturing of the cylinder bore, which can reduce friction at the ring/bore interface. In this work, dimples were created using plastic deformation on the cylinder surfaces of high-performance motorcycle engines. Prior to texturing, these cylinders had Nikasil coating. One cylinder was subjected to the deposition of DLC coating and then surface texturing. The results of the functional performance of internal combustion engines with textured cylinder surfaces were compared to untextured ones. The engine performance was analysed in terms of maximum power and maximum torque output. The results showed that cylinder surface texturing improved the functional properties of internal combustion engines. The maximum power increased by up to 5.8%. Best performance was achieved for internal combustion engines with textured cylinders and DLC coating. Such surface modification allows the powering of the motorbike with higher maximum speed and provides better vehicle dynamics at high speeds.

Keywords: cylinder, surface texturing, DLC coating, internal combustion engine

Nomenclature:
TDC – top dead centre
BDC – bottom dead centre
DLC – diamond-like carbon
PECVD – plasma enhanced chemical vapour deposition
PVD – physical vapour deposition
HP – horse power
IC – internal combustion
Ra – arithmetic mean deviation of roughness profile, µm
Spd – density of peaks, 1/mm^2
Sq – root mean square height of surface, µm
Str – texture–aspect ratio
Sz – maximum height of surface, µm

1. Introduction

The achievements of professional riders in motor sports depend primarily on their equipment. For riders of similar skills, a minor change in the operating parameters of their internal combustion engine (power and torque) can decide the outcome between winning and losing. The subjection of high-performance engines to extreme loadings decreases their useful life; therefore, the application of the best construction solutions, materials and machining methods is necessary. Most solutions applied in motor sports are eventually introduced in mass production.

A reduction in frictional loss is an important issue in order to meet the requirements of high efficiency in internal combustion (IC) engines. The application of surface texturing and advanced coatings is the main avenue towards minimising frictional losses in IC engines in passenger cars [1]. The piston ring–cylinder pack contributes significantly to the sum of frictional losses of the IC engine. Surface texturing can be used to reduce the friction between sliding elements. Dimples act as additional reservoirs for oil and traps for wear particles; therefore, their presence can improve the friction and wear resistance of tribological assemblies. The surface texturing of cylinder liners can cause the reduction of friction of the piston ring – cylinder assembly. Simulations have shown that cylinder liner texturing (contrary to piston ring texturing) can lead to a steady positive effect on friction under starved lubrication [2]. Starved lubrication occurs for the minimum supply of a lubricant to the contact zone, while under the fluid lubrication regime an oil film completely separates sliding surfaces. Textured cylinder liners can cause a decrease in fuel and oil consumption in IC engines. Zhou et al. [3] reported on the basis of theoretical models that circular dimple patterns between the top dead centres of the cylinder liner surface increased oil film thickness. The use of various laser surface texturing patterns to different cylinder liner regions could improve the functional properties of IC engines, like fuel and oil consumption [4]. An analytical model of the contact between a piston ring and a textured cylinder liner was developed [5]. It was found that for a barrel-shaped ring, the presence of dimples on the cylinder liner surface could generate additional load-carrying capacity. Tang et al. [6] used a flat steel surface of increased hardness over a textured steel surface under reciprocating sliding and reported a reduction in friction and wear due to the application of dimples with a pit-area ratio (the area occupied by the dimples) of 5%. Yin et al. [7] studied numerically the effect of cylinder liner texturing on lubrication in a diesel engine. The best results were obtained for a dimple density of 0.2–0.4 and for a depth to diameter ratio of 0.03–0.1. Usman and Park [8] developed a model of mixed lubrication in order to study the influence of liner texturing on the contact performance of the piston ring pack under warm engine conditions. Grooves normal to the sliding direction were found to improve the conditions for hydrodynamic lubrication, while micro-dimples were found to support the lubrication at the piston reversals. Vladescu et al. [9] investigated the effect of surface texturing on oil film thickness and friction force under conditions resembling those in the piston ring–cylinder liner pack. It was found that the presence of cavities led to an increase in the fluid film thickness and a decrease in the friction force (up to 41%) under the mixed lubrication regime. It has been shown that under full lubrication, the surface texture caused a reduction in film thickness and a small increase in friction force [9]. Grabon et al. achieved a large friction reduction under the fluid lubrication regime due to cylinder liner surface texturing; however, they showed that the effect of the presence of dimples on the coefficient of friction under the starved lubrication regime was negligible [10]. The numerical results indicated that the ring profile determined if cylinder surface texturing was beneficial or not. For quasi-conformal contact, a friction reduction of up to 70% is possible due to surface texturing. For non-conformal contact, however, the presence of cavities on the cylinder surface is harmful [11].

Laser texturing is the most common method for the creation of dimples [4, 7, 9]. This method is accessible, precise and easy. An increase in temperature observed in dimple areas is the biggest disadvantage of this method and limits its applicability to coated sliding elements. Following the laser texturing removal of burrs, further machining operation is required. Different methods of texturing, like burnishing (embossing) [10, 12, 13, 14], mechanical polishing, honing [15, 16, 14, 18], etching, abrasive jet machining [19, 20] or a combination of these methods, are also possible [21]. It is not difficult to create dimples of comparatively large dimensions, applied for example in the sleeves of slide bearings, contrary to the micro-dimples formed on thin-walled or coated elements.

A type of physical vapour deposition (PVD) coatings, which was applied successfully in motor vehicles, is called diamond-like carbon (DLC). DLC coating essentially consists of a mix of diamond and graphite. Different types of DLC coatings can be used, such as pure DLC, metal-doped and carbide-doped. Non-doped DLC coatings are divided into hydrogen-free and hydrogenated. The properties of doped hydrogenated DLC coatings depend on the dope material [22]. The introduction of DLC coatings opened additional possibilities in improving the functional performance of IC engines. DLC coatings have the following advantages: low friction, very good anti-wear properties, resistance to seizure, highly elastic modulus and hardness, good corrosion resistance, and high thermal and chemical stability [22, 23].

It was found that Me-C:H PVD coatings on the piston ring performed better than other solutions, particularly in regard to the wear rate of the cylinder liner [15]. Mobarak et al. [24] studied experimentally the tribological behaviour of hydrogenated amorphous carbon (a-C: H) DLC coating using a four-ball tribotester. It was found that wear and the coefficient friction was reduced after the application of DLC coating compared to the use of uncoated stainless steel.

The tribological performance of various coatings, including DLC coating, on nitrided and chrome-plated stainless steel piston rings was studied by Tung et al. [15]. The experimental results showed that DLC coating led to the lowest wear of the cast iron cylinder liner.

Boundary lubricated tribological tests were carried out under reciprocating sliding [26]. It was found that W-containing DLC coatings substantially improved the tribological performance.

Tribological tests were conducted using a reciprocating tester [27]. A detail of the cylinder block co-acted with a segment of the piston ring. Several coatings on the ring sample were applied (TiN, Cr-ceramic and TiAlN, and DLC). The results showed that the DLC coating led to the best tribological performance of the tested sliding pair.

The application of DLC coating for cylinder liners caused a reduction of the coefficient of friction by 19% during reciprocating laboratory tests. In addition, a substantial decrease in wear and a decrease in a the specific fuel consumption of an IC engine by 2.5% were found after DLC coating of cylinder liners compared with uncoated ones [28].

Nikasil coating was used first by Mahle in 1967 [29]. Nickel is the main component filling and binding the silicon carbide. This layer is characterised by considerably higher hardness and wear resistance than the substrate.

In this work, dimples were created on cylinders of high-performance motorcycle engines using the plastic deformation method. The combined effect of surface texturing and DLC coating on the functional properties of internal combustion engines was investigated.

2. Experimental details

2.1. Internal combustion engine cylinders

For the correct evaluation of the effect of texturing on operating parameters, the cylinders of a speedway motorcycle engine with honed Nikasil coating were modified. In a speedway, the track is composed of two straight sections connected by smooth oval curves. The starting region is divided into four equal portions. The length of the track must be between 260 and 425 meters, while the width should be not smaller than 10 meters. All heats, typically consisting of four laps, are run anti-clockwise [30]. Speed on the straight fragments of the track can exceed 100 km/h. The bike does not have brakes, and its weight should not be less than 77 kilograms. The motorcycle, fuelled by methanol, uses a four-stroke, single-cylinder engine of a capacity up to 500 cm^3.

The test object was a single-cylinder, four-stroke, spark-ignition engine. The tested engine was air-cooled, its capacity was 498 cm^3 with four valves on the cylinder head and an overhead camshaft. One complete engine with five different cylinders was used for this research in the engine test cell. Different engines with textured or untextured cylinders were used in motorcycles during races.

Three cylinders textured with different intensity 1, 2, 3, one cylinder following surface texturing and then DLC coating 4, and one reference untextured cylinder 0 were tested. The standard cylinder was denoted as 0, while the textured cylinders as 1, 2, 3 and 4 respectively.

2.2. Surface texturing

The creation of dimples on inner cylinder surfaces affects the co-action of the piston ring pack, which is responsible for mechanical losses in internal combustion engines.

Additional cavities were formed on plateau-honed cylinder bore surfaces. Plateau honing is a type of surface texturing. A cross-hatched surface texture created during plateau honing is a two-process texture resembling that obtained after the running in of an IC engine. It ensures good sliding properties of smooth surfaces with a great ability to maintain oil in valleys of the surface.

During the creation of dimples on the inner surface of the cylinder bore, plastic deformation of the machined surface was applied. The head for dimples creation was fitted to work in a vertical milling machine controlling the pressure of the forming roller and the change in the diameter of the machined cylinders [31]. The same pressure should be maintained along the whole bore surface should be maintained because any fluctuation may change cylinder bore diameters and the depth of the dimples. The proper setting of the head to the cylinder bore is a condition of the correct texturing process. This setting should be precisely controlled. Ceramic balls are the working element of the dimple formation. The design of the head allows for the creation of micro-dimples, the size of which depends on the adjustable pressure and diameters of the forming balls. The pattern of micro-dimples on the cylinder surface depends firstly on the design of the forming tool and secondly on the feed of the head. As a result of the change of the feed, which is the fundamental machining parameter, spacing between machining paths can be changed. Forming balls should be mounted to the roller with accuracy and precision. The method whereby dimples are burnished on the machined surface using the forming roller transforms the shapes of the forming balls and their array on the machining path. The textured surfaces were located in each cylinder bore between the top dead centre (TDC) and the bottom dead centre (BDC) of a piston.

It is possible to encounter difficulties in creating dimples for coated surfaces. Hard Nikasil coating on aluminum alloy surfaces causes changes in the concept of dimples creation in relation to homogeneous materials. During initial tests, these methods which caused coating damage or delamination were excluded. As a result, cavities were mechanically created on cylinders with Nikasil coating using forming elements of a spherical shape. Table 1 presents the types of tested cylinders.

Table 1. Types of tested cylinders

	Cylinder 0	**Cylinder 1**	**Cylinder 2**	**Cylinder 3**	**Cylinder 4**

Nikasil base layer	Yes				
Honing	Yes				
Texture	no	yes	yes	yes	yes
Distance between dimples in circumferential direction [mm]	–	1.0	1.0	1.0	1.0
Distance between dimples in axial direction [mm]	–	1.0	0.8	0.5	0.8
DLC coating	no	no	no	no	yes

Figure 1 presents the machining effect of dimple creation. The surface topographies of the cylinders were measured by white light interferometer Talysurf CCI Lite of 0.01 nm vertical resolution and stylus profilometer Hommelwerke T8000. In optical measurement, the objective 5× was used, and the measuring area 3.29 × 3.29 mm contained 1024 × 1024 points. During tactile measurement, the radius of the stylus tip was 2 µm, the measuring speed was 0.5 mm/s, the sampling interval was 5 µm and the measuring area was 4 × 5 mm. In both kinds of measurement, the form was removed using a polynomial of the 3rd degree. After optical measurement, spikes were excluded by truncation.

As a result of machining, micro-dimples of 0.25–0.35 mm in diameter and 4–6 µm in depth were obtained.

The obtained pits were mutually located at a distance of 1 mm in circumference and between subsequent paths: 1 mm for cylinder 1, 0.8 mm for cylinders 2 and 4, and 0.5 mm for cylinder 3.

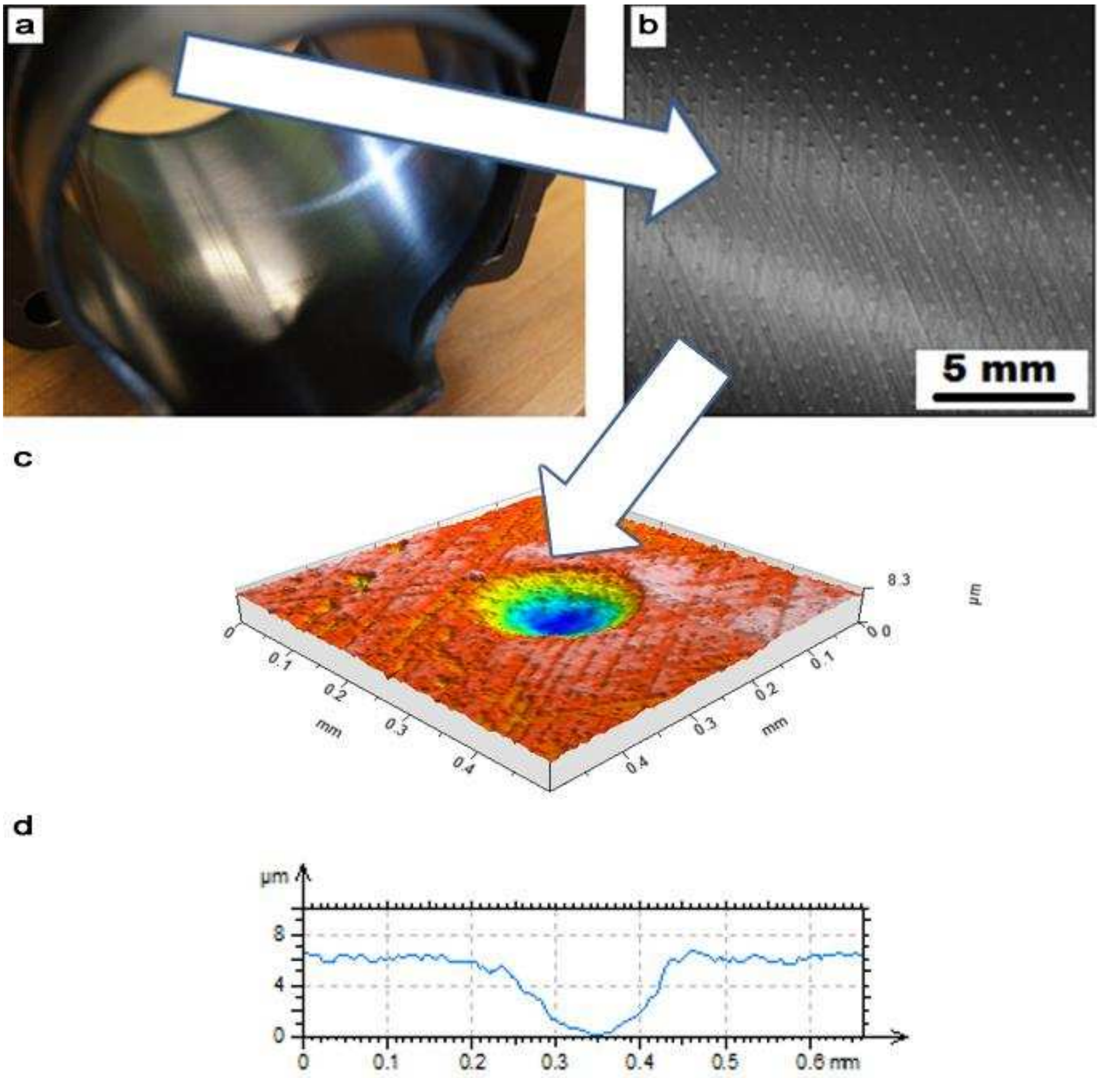

Figure 1. Textured cylinder: a) view of the cylinder; b) surface morphology; c) 3D representation of a single dimple; d) cross-section of a single dimple

Figure 2 presents the contour plots and texture directions of cylinders 1 and 4 before tests. It is evident from contour plots (Figures 2a and 2b) that the distance between dimples in the axial direction is smaller for the cylinder from engine 4. The main surface directions, shown in Figures 2c and 2d, resulted from honing. The honing angles were 32 and 36 degrees for cylinders from engines 1 and 4 respectively.

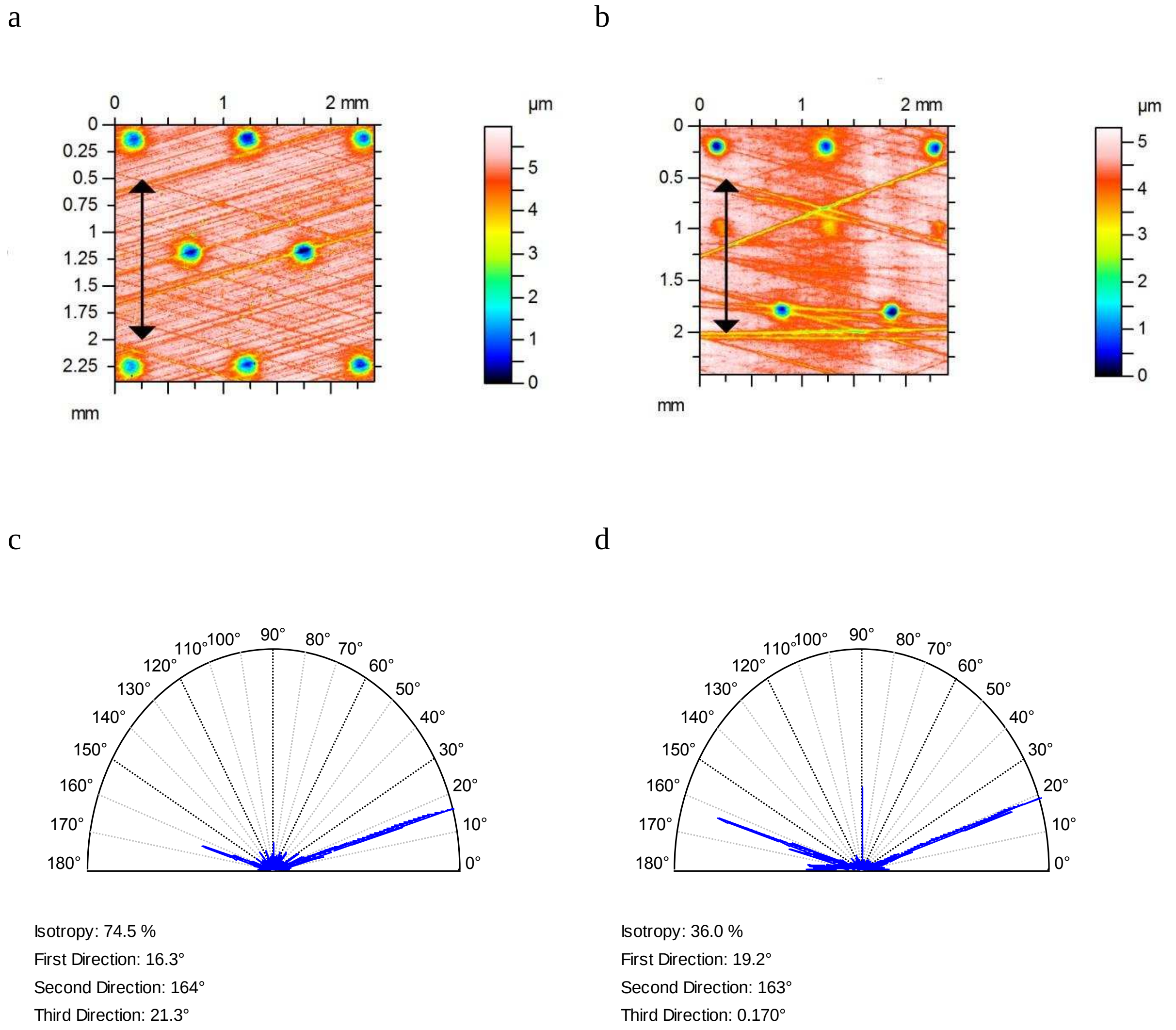

Figure 2. Contour plots (a, b) and main surface directions (c, d) of cylinders 1 (a, c) and 4 (b, d) prior to tests

The roughness height in the areas free of dimples was smaller in cylinders subjected to further deposition of DLC coating, as determined by the Ra parameter of 0.12 µm, and on average was smaller than 0.24 µm, as observed in the other cylinders. The honing angles on tested bores were similar: between 30 and 36 degrees within the set of cylinders.

2.3. DLC coating deposition

The DLC coating used in this study was deposited using the Plasma Enhanced Physical Vapour Deposition (PECVD) Flexicoat 850 system (Hauzer Techno Coating, the Netherlands). The cylinder was fixed in the middle of the process chamber to the bias table, rotating at 1 rpm with the cylinder bore facing the sputter targets. The coating architecture (Cr/Cr-WC/W:C-H/a:C-H) involved two interlayers below the top DLC coating layer: (i) chromium adhesion interlayer; and (ii) chromium/tungsten carbide/carbon graded interlayer. The coating recipe was automatically executed by the system software and the total coating process time was about 5 hours with the DLC coating top layer deposition step set to 150 min. The chromium interlayer was deposited by means of magnetron sputtering of a Cr target, while the tungsten carbide/carbon graded interlayer was deposited in one continuous deposition process using magnetron sputtering of the WC target with subsequent addition of acetylene as a source of carbon. A high pulsed bias voltage was set at 700 V during the DLC top layer deposition step. The obtained DLC coating deposited on top of the dimpled Nikasil layer had a uniform thickness of 1.5 µm.

2.4. Engine tests

Comparative measurements of engine parameters were carried out in a high-performance engine test home with wide experience in preparing engines for motor sports (speedway) and international riders. One engine was tested first with conventional and then with textured cylinders. The prepared engine was mounted on a special engine test bench and the measurement strategy carried out was typical for high-performance engines. The FRENELSA eddy-current dynamometer was used for measuring the torque and the speed. Eddy current dynamometers are currently the most common absorbers. A controlled acceleration test procedure was used. A microcontroller-based feedback control system with a closed-loop speed operation was useful towards the control of speed increase. The power was corrected using the DIN 70020 standard. Prior to each test, the engine was heated to 90^0 C. Measurements of engine characteristics were performed for the ignition system made by PVL for the following ignition advance angles: 20°, 25° and 30°. Other settings and operating fluids (oil, fuel) remained constant. The changes in engine characteristics with and without texturing were presented in graphs of torque and power versus the variable rotational speeds of the engine from 6,000 to 12,000 rpm. Each test was repeated twice. The difference between values of the maximum torque of the first and the second test with the same cylinder was smaller than 0.1 Nm. The compression pressure for each cylinder was very similar.

In order to analyse the effect of cylinder bore surface texturing on the performance and life of the engines, tests were carried out in two stages:

- comparative measurements of power and torque for the engine with conventional cylinder 0, and with textured cylinders 1, 2, 3 and 4,
- analysis of changes in the surface topographies of cylinders after the engines have been operating in comparable conditions.

3. Results and discussion

3.1. Engine tests

Table 2 presents the results of the investigation of internal combustion engines with all tested cylinders for different values of ignition advance angles. Ignition timing, in a spark ignition internal combustion engine, is the process of setting the ignition advance angle relative to the piston position. The correct ignition advance angle is important for the performance of an IC engine. This angle affects fuel economy and engine power.

Table 2. Maximum power and maximum torque for internal combustion engines with tested cylinders

		Cylinder 0	**Cylinder 1**	**Cylinder 2**	**Cylinder 3**	**Cylinder 4**
Ignition advance 20° before TDC	**Max power**	73.69 HP at 9.414 rpm	74.88 HP at 9.844 rpm	77.42 HP at 9.462 rpm	73.62 HP at 9.464 rpm	77.93 HP at 10.298 rpm
	Max torque	56.54 Nm at 8.401 rpm	58.25 Nm at 7.878 rpm	59.07 Nm at 8.402 rpm	56.97 Nm at 8.493 rpm	54.05 Nm at 9.915 rpm
Ignition advance 25° before TDC	**Max power**	74.93 HP at 9.881 rpm	76.53 HP at 9.619 rpm	76.29 HP at 9.764 rpm	75.29 HP at 9.342 rpm	77.27 HP at 10.784 rpm
	Max torque	56.36 Nm at 8.974 rpm	56.83 Nm at 7.446 rpm	56.32 Nm at 7.637 rpm	56.60 Nm at 9.362 rpm	52.30 Nm at 8.507 rpm
Ignition advance 30° before TDC	**Max power**	74.57 HP at 9.543 rpm	73.46 HP at 9.497 rpm	76.33 HP at 9.521 rpm	74.22 HP at 9.468 rpm	78.17 HP at 10.370 rpm
	Max torque	60.87 Nm at 7.568 rpm	55.76 Nm at 8.490 rpm	59.20 Nm at 8.542 rpm	55.05 Nm at 9.468 rpm	53.96 Nm at 10.128 rpm

It was observed that the second variant (2) of surface texturing without DLC coating was characterised by a high increase of power. For an ignition advance angle of 20°, this power increased by 3.74 brake horse power (HP), which is 5.1% of the power of the engine with the conventional cylinder. For the ignition advance angles of 25° and 30°, the relative increases were 1.8 and 2.4% respectively. This is a substantial change for high-performance engines. Textured cylinder 1 yielded smaller changes in engine characteristics. For the ignition advance angles of 20° and 25°, increases in maximum power ranged between 1.6% and 2.1% respectively. In the last measurement (ignition advance 30° before TDC) for this cylinder, power decreased by 1.5%. When engine with cylinder 3 was tested, no substantial changes of maximum power in relation to the conventional variant were observed, and a small decrease in the maximum power occurred. In this case, however, a high decrease (up to 16%) in torque for low rotational speeds was observed due to cylinder surface texturing for the middle and highest ignition advance angles. During lubrication of the piston – piston ring–cylinder assembly – with oil, an unprofitable situation may emerge when dimples are not completely filled with lubricant and where the hydrodynamic lubrication effect is limited. For textured surfaces, it is necessary to adjust the additional oil capacity to the amount of lubricant supplied by the lubrication system to the friction zone [32]. A distinct decrease in torque in the engine with cylinder 3, which has the highest density of dimples for low rotational speeds, is an example of the engine’s reaction when a limited amount of lubricant is present.

The largest increase in maximum power was found in the engine using a DLC-coated textured cylinder compared to the engine with cylinder 0. Similar to engines with other textured cylinders, for the ignition advance angle of 20°, this increase was the highest: 4.24 HP (5.8%). For the ignition advance angles of 25° and 30°, the relative increases of maximum power were 3.1 and 4.8% respectively. For this engine, the maximum power from all analysed engines was obtained for the highest rotational speeds.

An increase of power as a result of cylinder surface texturing was related to changes in torque runs. The torque curves were flattened in a wide range of rotational speeds of the engine. Figure 3 shows the characteristics of engines with cylinders 0 and 4.

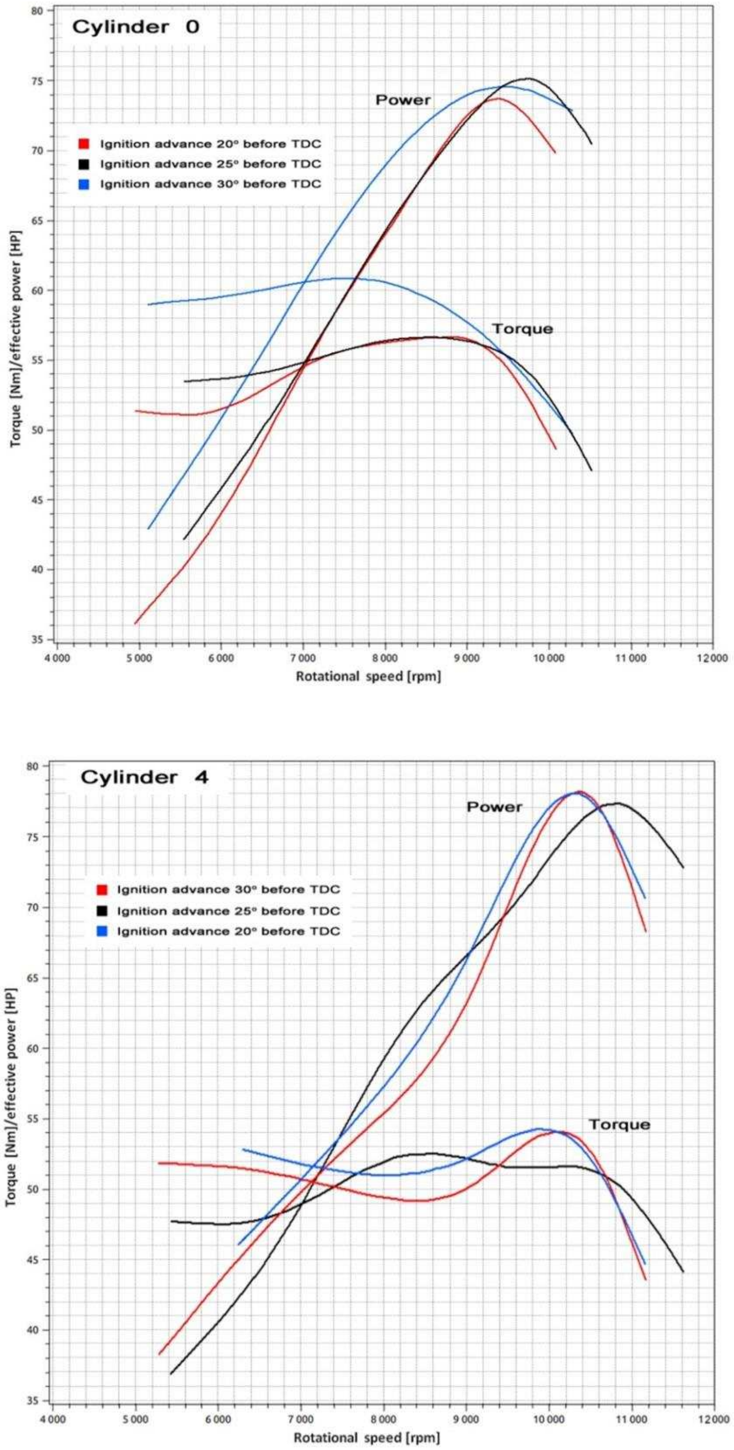

Figure 3. Torque and power as a function of the rotational speed of the test engine when equipped with cylinders 0 and 4

One can see from the analysis of Figure 3 that the engine with cylinder 4 generated more power at a distinctly higher rotational speed compared to the engine with untextured cylinder 0. The difference in brake power values was up to 4.8 HP, while in rotational speed it reached almost

1,000 rpm. This allows the powering of the motorbike with higher maximum speed. The values for torque rate were lowered smoothly, but the torque curves became more stable, especially near the upper speed limits. This would provide better vehicle dynamics at high driving speeds. Additionally, the engine with cylinder 4 showed that output parameters were less responsive to engine-tuning imperfections in terms of ignition advance angle sets.

In this work, the combined effect of surface texturing and DLC coating on the functional properties of high-performance engines used in speedway competition motorcycles has been studied. The obtained findings can be used in other internal combustion engines, and in particular competitions engines. For commercial applications, exhaust emissions should be taken into consideration.

3.2. Post-engine test surface characterisation

Figure 4 presents the contour plots and texture directions of cylinders 1 and 4 after the operation of internal combustion engines between 15–25 heats. As a result of wear, the surface topography of the cylinders has changed. For untextured surfaces after honing, surface height decreased with the creation of a new direction along the movement direction of the piston rings. A similar situation occurred for the surface topographies of textured cylinders. Surface amplitude decreased and a reduction in the depth of cavities occurred. A new direction, parallel to the piston–ring movement, was formed. The creation of this direction is related with a decrease in the texture–aspect ratio Str and an increase in the peak density Spd. Definitions of surface topography parameters from the ISO standard 25178 are given in Reference [33]. The Str parameter characterises the isotropy of the surface. If Str is close to 1, then the surface has the same properties regardless of direction, which means it is isotropic. Anisotropic surfaces with a dominant texture direction have Str parameters close to 0. The peak density is computed by dividing the number of peaks by unit area. This can be used in applications where contact is involved. Surface height was assessed by the Sq and Sz parameters. The Sq parameter is defined as the root mean-square value of the surface deviations within the sampling area. The Sz parameter is the sum of the largest peak height value and the largest valley depth value.

Surface change in cylinder 1 was smaller than that of cylinder 4. Since mileages were not the same, the analysis of the change of surface topographies was only quantitative. Dimple depth from cylinder 1 (Figure 2a and Figure 4a) changed from 5 µm to 3.5 µm on average. The root mean-square height Sq and maximum surface height Sz decreased from 0.7–0.75 µm to 0.52–

0.56 µm and from 5.9–6.1 µm to 4.3–4.7 µm respectively. Due to wear, a new direction, parallel to the direction of the piston ring movement (third direction – see Figure 4c), was created. As a result, the texture–aspect ratio Str decreased from 0.7–0.75 to 0.61–0.54, and peak density increased from 550–650 1/mm^2 to 850–1,300 1/mm^2.

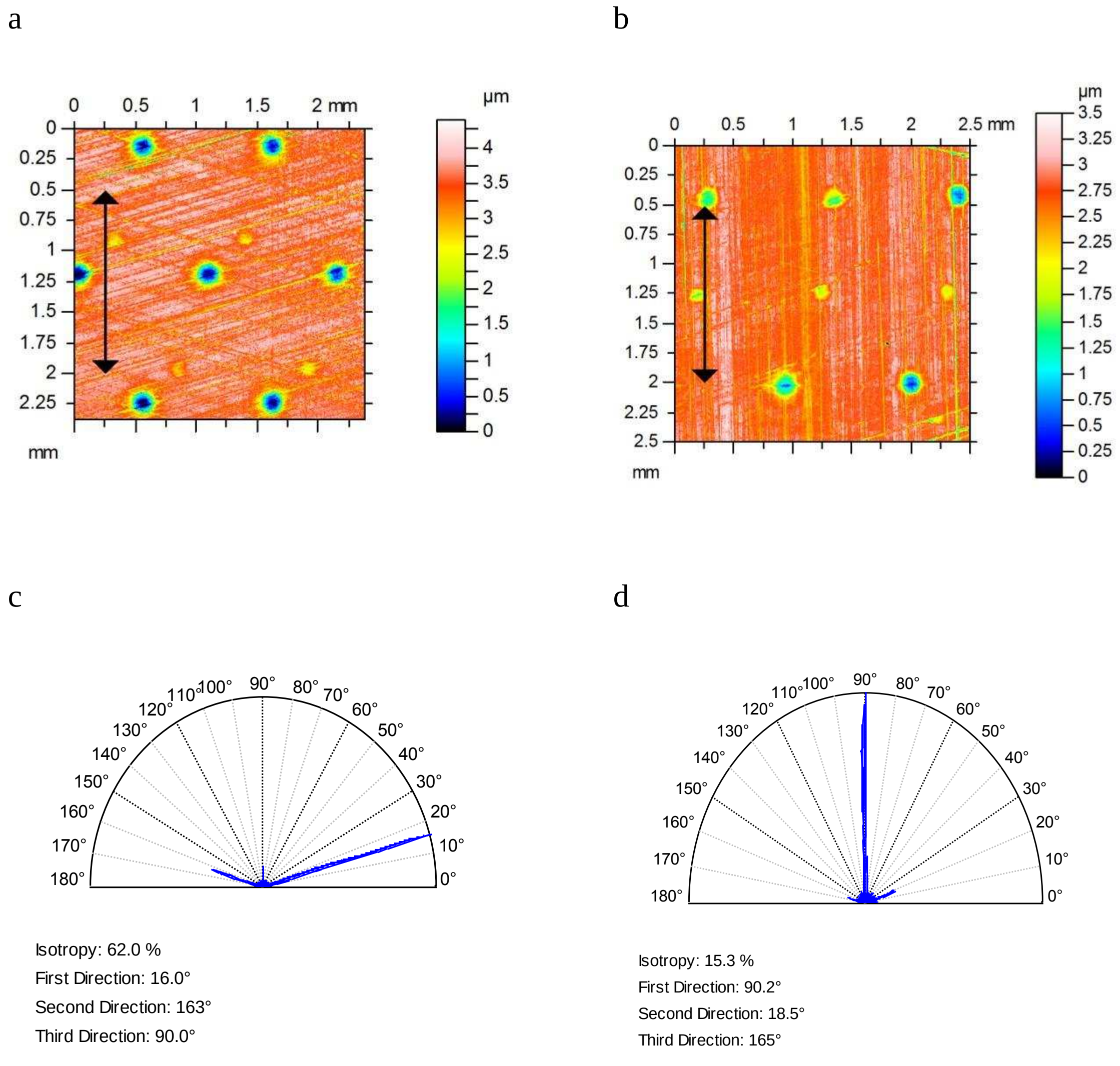

Figure 4. Contour plots (a, b) and main surface directions (c, d) of cylinders 1 (a, c) and 4 (b, d) after engine operation

The depth of dimples from cylinder 4 (Figure 2b and Figure 4b) decreased to 2–2.5 µm. Due to wear, the Sq and Sz parameters changed from 0.48–0.55 µm to 0.32–0.36 µm, and 5.3-5.6 µm to 3.2–3.4 µm respectively. As the wear was severe (the shallow honing valleys were erased), a new direction, which became the main direction, was formed (first direction – see Figure 4d). Due to the creation of this direction, the Str parameter decreased from 0.4–0.5

to 0.15–0.2, and the Spd parameter increased from 110–150 1/mm^2 to 550–600 1/mm^2. Cracks were not formed on the cylinder surface with deposited DLC coating. A similar tendency of parameter changes was also found to be the case for the other cylinders.

4. Conclusions

Dimples were successfully created on cylinder surfaces with Nikasil coating using the plastic deformation. One cylinder was subjected to deposition of DLC coating and then surface texturing. The results of the functional performance of high-performance internal combustion engines with textured and untextured cylinder surfaces were compared. It was found that cylinder texturing typically led to a decrease in resistance to sliding movement following an increase in the amount of lubricants in dimples. A decrease in the coefficient of friction caused an increase of power in a wide range of rotational speeds. It also led to a shift of engine characteristics towards higher rotational speeds.

The increase of power was the largest for the textured cylinder with a deposition of DLC coating. In this case, the increase of brake power values reached up to 4.8 HP (5.8%), while the increase in the rotational speed was about 1000 rpm as compared to the untextured bore. This allows powering the vehicle (motorbike) with a higher maximum speed, which would also provide better vehicle dynamics at high driving speeds. Good operational properties were also obtained for textured cylinders without DLC coating for the highest and medium dimples density.

For textured cylinders after engine operation, surface height decreased and a reduction in the depth of dimples was observed. A new direction, parallel to the piston ring movement was formed. The creation of this new direction is related to a decrease in the texture–aspect ratio Str and an increase of peak density Spd.

References

1. Holmberg K, Andersson P, Erdemir, A. Global energy consumption due to friction in passenger cars, Tribology International 47 (2012) 221-234
2. Gu C, Meng X, Xie Y, Yang Y. Effects of surface texturing on ring/liner friction under starved lubrication, Tribology International 94 (2016) 591–605

3. Zhou Y, Zhu H, Tang W, Ma C, Zhang W. Development of the theoretical model for the optimal design of surface texturing on cylinder liner, Tribology International 52 (2012) 1–6,
4. Hua X, Sun J, Zhang P, Ge H, Fu Y, Ji J, Yin B. Research on discriminating partition laser surface micro-texturing technology of engine cylinder, Tribology International 98 (2016)190–196
5. Biboulet N, Lubrecht AA. Analytical solution for textured piston ring – cylinder liner contacts (1D analysis), Tribology International 96 (2016) 269–278
6. Tang W, Zhou Y, Zhu H, Yang H. The effect of surface texturing on reducing the friction and wear of steel under lubricated sliding contact, Applied Surface Science 273 (2013) 199–204
7. Yin B, Li X, Fu Y, Yun W. Effect of laser textured dimples on the lubrication performance of cylinder liner in diesel engine, Lubrication Science 24 (2012) 293–312
8. Usman A, Park CW. Optimizing the tribological performance of textured piston ring–liner contact for reduced frictional losses in SI engine: Warm operating conditions, Tribology International 99 (2016) 224–236
9. Vlădescu S-C, Medina S, Olver AV, Pegg IG, Reddyhoff T. Lubricant film thickness and friction force measurements in a laser surface textured reciprocating line contact simulating the piston ring–liner pairing, Tribology International 98 (2016) 317–329
10. Grabon W, Koszela W, Pawlus P, Ochwat S. Improving tribological performance of piston ring – cylinder liner frictional pair by liner surface texturing, Tribology International 61 (2013)102-108
11. Checo HM, Ausas RF, Jai M, Cadalen J-P, Choukroun F, Buscaglia G-C. Moving textures: Simulation of a ring sliding on a textured liner, Tribology International 72 (2014) 131–142
12. Koszela W, Galda L, Dzierwa A, Pawlus P. The effect of surface texturing on seizure resistance of a steel-bronze assembly, Tribology International 43 (2010) 1933-1942
13. Koszela W, Pawlus P, Rejwer E, Ochwat S. Possibilities of oil pockets creation by the burnishing technique, Archives of Civil and Mechanical Engineering 13 (2013) 465-471
14. Koszela W, Dzierwa A, Galda L, Pawlus P. Experimental investigation of oil pockets effect on abrasive wear resistance, Tribology International 46 (2012) 145-153
15. Johansson S, Nilsson PH, Ohlsson R, Anderberg C, Rosen B-G. New cylinder liner surfaces for low oil consumption, Tribology International 41 (2008) 854-859
16. Mezghani S, Demirci I, Yousfi M, El Mansori M. Mutual influence of crosshatch angle and superficial roughness of honed surfaces on friction in ring-pack tribo-system, Tribology International 66 (2013) 54–59
17. Tomanik E, El Mansori M, Souza R, Profito F. Effect of waviness and roughness on cylinder liner friction, Tribology International 120 (2018) 547-555
18. Dimkovski Z, Tomanik E, Profito F. Influence of measurement and filtering type on friction predictions between cylinder liner and oil control ring, Tribology International 100 (2016)7-17
19. Wos S, Koszela W, Pawlus P, Drabik J, Rogos E. Effects of surface texturing and kind of lubricant on the coefficient of friction at ambient and elevated temperatures, Tribology International 117 (2018) 174-179

20. Wos S, Koszela W, Pawlus P. The effect of both surfaces textured on improvement of tribological properties of sliding elements, Tribology International 113 (2017) 182-188
21. Gachot C, Rosenkranz A, Hsu SM, Costa HL. A critical assessment of surface texturing for friction and wear improvement, Wear 372–373 (2017) 21–41
22. Gåhlin R, Larsson M, Hedenqvist P. ME-C:H coatings in motor vehicles, Wear 249 (2001) 302–309

23. Podgornik B, Jacobson S, Hogmark S. DLC coating of boundary lubricated components—advantages of coating one of the contact surfaces rather than both or none, Tribology International 36 (2003) 843-849
24. Mobarak HM, Masjuki HH, Mohamad EN, Rahman SMA, Al Mahmud KAH, Habibullah M, Salauddin S. Effect of DLC coating on tribological behavior of cylinder liner piston ring material combination when lubricated with Jatropha oil, Procedia Engineering 90 (2014) 733 – 739
25. Tung SC, Gao H. Tribological characteristics and surface interaction between piston ring coatings and a blend of energy-conserving oils and ethanol fuels, Wear 255 (2003) 1276-1285
26. Podgornik B, Hren D, Viˇzintin J, Jacobson S, Stavlid N, Hogmark S. Combination of DLC coatings and EP additives for improved tribological behaviour of boundary lubricated surfaces Wear 261 (2006) 32–40
27. Cho D-H, Lee Y-Z, Evaluation of ring surfaces with several coatings for friction, wear and scuffing life, Transactions of the Nonferrous Metals Society of China 19 (2009) 992-996
28. Rejowski E, Mordente S, Pillis M, Casserly T. Application of DLC coating in cylinder liners for friction reduction, SAE Technical Paper 2012-01-1329 (2012)
29. J, Goodman, Nikasil and Alusil. Engine Professional (2008) 18-22
30. Speedway FAQ: Main rules http://www.speedway-faq.org/mainrule.html last visited 1st May 2018
31. W, Koszela, Polish Patent No, 217855 (2014), Head for oil pockets creation on cylinder liner surface
32. Wos S, Koszela W, Pawlus P. Determination of oil demand for textured surfaces under conformal contact conditions. Tribology International 93 (2016) 602-613
33. Leach R. (Ed,), Characterisation of Areal Surface Texture, Springer-Verlag, Berlin, Heidelberg (2013)