Wear analysis of pin and roller surfaces

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Abstract. In this paper, three different combinations were evaluated: (i) steel pin vs steel roller, (ii) steel pin vs tungsten disulfide (WS₂) coated roller and (iii) PVD pin vs steel roller. The aim of this paper is to properly quantify the topographical variations of the pin/roller surfaces and assess the appropriateness of the measuring technique before and after the tribological tests performed for friction reduction. An in-house tribometer was used to test the friction/wear performance of the three different combinations. Surface topographies were measured by white light interferometer (3D) and mechanical stylus (2D). To enable fast relocation on the stylus and interferometer, a 3D printed mask was used. Regarding the pins, Sa, Sk and Svk have been found to follow the wear changes; the lowest wear change for the combination (ii) and highest for the combination (i) but less for the combination (iii). Regarding the changes of Ra on the pin locations where edge contact occurs, the largest changes were found to be for combination (i), followed by combination (ii) and (iii). Ra and Rk change less significantly for the roller surfaces. Good correlations among the friction, initial/final roughness and radial displacements were also found.

1. Introduction
Over the last decades, the government has imposed new regulations and standards requiring better fuel economy and lower emissions for heavy-duty diesel engines. At low engine speeds, valve train friction makes a significant contribution to the engine friction [1], especially in the pin-roller assembly, which adversely affects the durability of these components [2]. These regulations became a necessity to drive the product development. Some of these demands are directly related to friction, wear and lubrication of these mechanical components depending on the operating conditions and the original surface topography [3, 4]. Wear plays an important role in determining life span of products of machine elements. By using wear resistance materials, the wear becomes smaller and down to nanometer scale. Roughness has a strong impact on wear in valvetrain components [5]. The usage of coatings is growing strongly; a huge progress has been achieved in the development of surface treatments. It has been found that the tungsten disulphide (WS₂) coating materials have reduced the friction wear operating at low speeds and high loads. The main reason for using the WS₂ coating is the cost efficiency of the process called “triboconditioning” introduced by Applied Nano Surfaces Sweden AB. It combines burnishing with deposition of a low-friction film of tungsten disulphide on the surface compared to the uncoated materials WS₂ shows higher temperature [6-10]. The PVD has been used very successfully to improve fatigue resistance [11] and improving the lifetime with larger friction reduction of rolling contacts under high contact pressure [12, 13]. But it has found that at low speed
and low pressure of the sliding contact, the WS$_2$ soft coating also improves the performance instead of more expensive PVD hard coating. This is probably because: (i) a better surface finish with flatter asperities, (ii) a low-friction tribofilm and (iii) a low wear-reduction, especially in lubricated sliding contacts at the boundary and mixed regime [6-10]. There are other di-sulphide coatings like MoS$_2$ also governing the tribological performance, but at low sliding speed the WS$_2$ coating improves the performance because of its thermal stability and less sensitivity to humidity compared to the MoS$_2$ coating [10]. Nowadays, there are still attempts to improve tribological properties through the methods of surface engineering and better understanding of wear mechanisms in relation to the evaluation of the surface condition [14]. Surface topography measurement can be used for characterization of types of wear and for microscopic wear measurement. There are many ways to measure and evaluate wear. In some cases, wear amount can be obtained after the measurement of worn surface by using relocation techniques [15, 16]. A commonly used technique is to measure wear tracks by using 2D stylus profilometer [17] or 3D interferometer [18].

The aim of this paper is to properly analyze the topographical variations of the pin/roller surfaces before and after the tribological tests primarily performed for evaluation of friction reduction. Another goal is to analyze the wear scratches with a proper relocation technique [19].

2. Materials and Methods

2.1. Surface samples
The coated samples are considered to have the same macro geometry before and after surface treatment. The initial profile analysis is performed and presented in table 1. Each combination consists of five samples of pins/rollers. All pins have the same dimension with 25 mm in diameter and 55 mm in length. Roller has standard dimension of 35 mm in diameter and 25 mm in length.

| Combinations | (i) steel pin vs steel roller | (ii) steel pin vs tungsten disulfide (WS$_2$) coated roller | (iii) PVD coated pin vs steel roller |
|--------------|------------------------------|--------------------------------------------------------|----------------------------------|
| Pins         |                              |                                                        |                                  |
| Initial profile |                              |                                                        |                                  |
| Ra and Rvk   | Ra=0.031µm, Rvk=0.052µm      | Ra=0.028µm, Rvk=0.047µm                                | Ra=0.037µm, Rvk=0.08µm           |
| Rollers      |                              |                                                        |                                  |
| Initial profile |                              |                                                        |                                  |
| Average of Ra and Rvk | Ra=0.058µm, Rvk=0.085µm       | Ra=0.031µm, Rvk=0.06µm                                 | Ra=0.06µm, Rvk=0.088µm           |

2.2. In house tribometer
A dedicated test rig for pin-roller contact testing has been developed in-house (see figure1.a) in order...
to test the standard size components under controlled conditions. The experimental setup and schematic of tribometer illustrated in figure 2.b. Instead of an eccentric cam as in a real engine, a cylindrical cam driven by the electric motor-A is used to drive the roller under a constant load in order to stabilize the load, increase the accuracy and repeatability, a suspension with flexible steel sheets between the pin-roller assembly and the load sensor was used. The load is adjusted by moving the whole table vertically by the electric motor-B. Electrical heating elements connected to a control system maintain the oil at a stable temperature and an oil recirculation system keeps the oil pressure at a correct level. Data-acquisition and speed control of motor-A is achieved by LabView [20].

**Figure 1a.** Tribometer set up used at Halmstad University.
2.3. Running conditions and procedure

Before performing any test, an alignment had been performed and discussed in [21]. A summary of the initial conditions/parameters for the tests is presented in table 2.

| Test Conditions                      | Value                   |
|--------------------------------------|-------------------------|
| Load                                 | 5 kN                    |
| Oil. Temperature in path/inlet to contact | 38°C                   |
| Oil viscosity/pressure                | SAE 0W-20 at 1 bar      |
| Rotational speed                     | 20-1130 rpm             |

2.4. Measuring methodology and Surface characterization

Before conducting the roughness measurements, a contact configuration performed to predict the zone area of contacts between pin/roller and the driving cam, the configuration will help to relocate the area of the contact between the mating surfaces. A measuring methodology used for evaluating changes between unworn and relocated worn surface, 3d printed mask was used to enable fast relocation for the pins and rollers. This measuring method can be used typically for all the testing samples. Due to the limitations only the 2D measurements were conducted in the inner surface of the roller.

The 2D measurements were taken at three angular positions: 72°, 90°, and 108° each cylinder from of each pin and four angular sectors (0°, 90°, 180°, 270°) on the roller surfaces as shown by the figure 2b. Measurements taken with the help of Somicronic Surf scan 3CS mechanical stylus system (resolution of 1 μm in x, 6 nm in z-direction). A probe with 2 um tip radius and 90° tip angle were used for measuring pin/roller surfaces running with a speed of 0.3 mm/s.
The 3D measurements were taken directly on the surfaces 6 positions (11, 12, 13, 36, 37, 38 mm) from the left side of each pin direction) in the axial direction of the pin as shown by the figure 2a. Six positions/regions were measured with 10X magnifications (600 μm x 800 μm measurement area, 0.1 nm vertical resolution) with non-contact white light interferometer Phase shift MicroXam. The data were analyzed in the Mountainsmap v7 software, removing the second order polynomial, and then filtered with 3D high pass Gaussian filtering with a cut-off length of 0.25 mm, the 3D standard parameters are included in this study from are height parameter and functional
parameters according to ISO 25178-2.

3. Results
The results will be presented in two parts, surface measurements techniques and correlation study the result of the friction behaviour presented in [21]

3.1. Relocation
Figure 3 shows the surface topographies of the three different combinations before and after the test. The roughness calculated from the extracted profile and results show that steel pins run against the tungsten disulfide (WS2) coated roller (Sa=0.48μm. Sk=0.099μm. Svk=0.98μm) have lower wear than pins run versus the steel roller (Sa=0.53μm. Sk=0.161μm. Svk=0.101μm).
Figure 3 3D surface topographies 2D profile of wear tracks of the three combinations before and after the test (a) combination (i) steel pin vs steel roller showing higher peak and valley before the test, (b) combination (ii) steel pin vs tungsten disulfide showing less peak and valley before the test,(c) combination (iii) PVD pin vs steel roller show more roughness and more valley before the test.

3.2. 2D Roughness parameters
Figure 4 (left) shows the Ra of the relocated surfaces evaluated separately on the left and right side of the pin (averages of 40 measurements). For the steel pin combination, Ra on the left side is higher than of the left side after the test while the WS$_2$ combinations show lower values of right side rather than the left side.

Figure 4. (a) Ra of pins evaluated at the left and right locations. (b) Percentage of Ra and Rk changes for the rollers and pins. The parameters are averages evaluated at the left/right locations on the pins and at four angular positions on the rollers.
Figure 4 right shows the Ra and Rk changes for the rollers and pins because Ra and Rk were the most stable parameters. 60 measurements were evaluated for the roller. Ra and Rk change less significantly for the roller surfaces. The Ra and Rk for the pin surfaces show that the steel pin vs WS$_2$ has the lowest changes while the steel pin vs steel roller has the highest one. The PVD pins do not change much on the right side after the test.

### 3.3. 3D Roughness parameters analysis

Figure 5 left show the variation of Sa, Sk and Svk which are the averages of five 10x interference measurements of the three different combinations. The total percentage of increase after the test is calculated by: Percentage of increase (%) = (Sx before − Sx after)/ Sx before * 100. where Sx = Sa, Sk or Svk. It can be noticed that the parameters seem more stable and clearly show that WS$_2$ type changes less (Sa=7%, Sk=10% and Svk=16%) and steel type changes more (Sa=25%, Sk=12% and Svk=41%).

![Figure 5](image)

**Figure 5.** Left: the variations of Sa, Sk and Svk for the three different pin types. Right: Percentage of Sa, Sk and Svk changes for the pins.

The figure 5 right shows the variation of Sa, Sk and Svk for the three different pin types (Sk and Svk show more clear differences).

### 3.4. Correlation

The linear correlation coefficients among the rollers 2D roughness parameters, coefficient of friction-COF and radial displacement (total radial displacement Y and local radial displacement amplitude y) were calculated (see table 3). Values only over 0.9 are considered significant. Strong correlation exists among the radial displacement, COF and the parameters: Ra, Rq, Rp, Rz, Rdc, Rku, Rdc, Rk and Rvk. Figure 6 shows the radial displacement of the three different combinations which were tested under same conditions which is the average of 50 readings of each combinations.

The steel type combinations (i) had the largest total radial displacement (Y) and the largest local radial displacement amplitude (y) followed by the PVD and WS$_2$ type. Vertical displacement amplitudes were measured by using linear gage Mitutoyo LGB2 and recorded with SENSOPARK software.
Figure 6. The displacement amplitude of three combinations with global(Y) and local(y) measurement.

Table 3 the correlation coefficient matrix among the rollers 2D roughness parameters, radial displacement, and coefficient of friction-COF at three different speeds (20 rpm, 40 rpm and 60 rpm). The 2D roughness parameters of pins are the average of 15 readings and for roller 20 readings. COF friction calculated from the average of 50 readings and radial displacement mentioned in average of 50 readings.

Values only over 0.9 are significant. Only the significant values are shown in the tables. The positive values mean the parameter and the response have the same variation.
Table 3. The correlation coefficients matrix among the rollers 2D roughness parameters, radial displacement, and coefficient of friction-COF at three different speeds (20 rpm, 40 rpm and 60 rpm).

| Coefficient of Friction | COF 20rpm | COF 40rpm | COF 60rpm | Global vertical displacement | Local vertical displacement |
|-------------------------|-----------|-----------|-----------|-----------------------------|-----------------------------|
| COF 20rpm               |           |           |           |                             |                             |
| COF 40rpm               | 0.99      |           |           |                             |                             |
| COF 60rpm               | 1         | 0.98      |           |                             |                             |
| Global vertical displacement | 0.99   | 1         | 0.97      |                             |                             |
| local vertical displacement | 1       | 0.99      | 1         | 0.98                        |                             |
| Rq                      | 0.88      | 0.93      | 0.85      | 0.95                        | 0.86                        |
| Rp                      | 0.89      | 0.94      | 0.86      | 0.95                        | 0.87                        |
| Rv                      | 0.85      | 0.90      | 0.81      | 0.93                        | 0.83                        |
| Rz                      | 0.88      | 0.92      | 0.84      | 0.94                        | 0.85                        |
| Rdc                     | 0.88      | 0.93      | 0.85      | 0.95                        | 0.86                        |
| Rk                      | 0.88      | 0.93      | 0.85      | 0.95                        | 0.86                        |
| Rpk                     | 0.89      | 0.94      | 0.86      | 0.96                        | 0.87                        |
| Rvk                     | 0.86      | 0.91      | 0.82      | 0.93                        | 0.83                        |
| Ra                      | 0.99      | 1         | 0.99      | 1                           | 0.99                        |
| Rq                      | 1         | 1         | 0.99      | 0.99                        | 0.99                        |
| Rp                      | 0.96      | 0.92      | 0.98      | 0.9                         | 0.97                        |
| Rv                      | 0.98      | 0.99      | 0.96      | 1                           | 0.97                        |
| Rz                      | 1         | 0.98      | 1         | 0.97                        | 1                           |
| Rdc                     | 0.99      | 1         | 0.98      | 1                           | 0.98                        |
| Rk                      | 0.99      | 1         | 0.98      | 1                           | 0.98                        |
| Rpk                     | 0.93      | 0.89      | 0.96      | 0.86                        | 0.95                        |
| Rvk                     | 0.99      | 1         | 0.98      | 1                           | 0.99                        |

Table 4 shows the correlation coefficients matrix among the pins 2D/3D roughness parameters, radial displacement, and coefficient of friction-COF at three different speeds. The 2D roughness parameters of pins are the average of 15 readings and 20 readings for roller. The 3D parameters which are the average of 10 readings show significant correlation after the test. Rk has strong correlation with COF for the unworn surfaces while Sk and Sv correlate well with COF and radial displacement before and after test. Values only over 0.9 are significant. Only the significant values are shown in the
tables. The positive values mean the parameter and the response have the same variation. While the negative sign means the parameter and the response have the different variation.

**Table 4.** The correlation coefficients matrix among the pins 2D/3D roughness parameters, radial displacement and coefficient of friction-COF at three different speeds (20 rpm 40 rpm and 60 rpm).

| Pin | COF 20rpm | COF 40rpm | COF 60rpm | Global vertical displacement | Local vertical displacement |
|-----|-----------|-----------|-----------|----------------------------|----------------------------|
| COF |           |           |           |                            |                            |
| COF 20rpm | 0.99     |           |           |                            |                            |
| COF 40rpm | 0.98     | 1         |           |                            |                            |
| COF 60rpm | 1        | 0.99      | 0.97      |                            |                            |
| Global vertical displacement | 0.99 | 1 | 0.97 | | |
| Local radial displacement Amplitude | 1 | 0.99 | 1 | 0.98 | |
| Pin 2D parameter Unworn |         |           |           |                            |                            |
| Ra | 0.47 | 0.56 | 0.40 | 0.60 | 0.43 |
| Rz | 0.32 | 0.42 | 0.25 | 0.47 | 0.27 |
| Rc | 0.39 | 0.49 | 0.32 | 0.53 | 0.35 |
| Rku | 0.12 | 0.22 | 0.05 | 0.28 | 0.07 |
| Rdc | 0.47 | 0.56 | 0.41 | 0.61 | 0.43 |
| RPc | -0.12 | -0.22 | -0.05 | -0.28 | -0.07 |
| Rk | 0.99 | 0.96 | 1.00 | 0.94 | 0.99 |
| Rvk | 0.12 | 0.22 | 0.05 | 0.28 | 0.07 |
| Pin 2D parameter Worn |         |           |           |                            |                            |
| Ra | 0.97 | 0.94 | 0.98 | 0.91 | 0.98 |
| Rz | 0.96 | 0.93 | 0.98 | 0.91 | 0.97 |
| Rc | 0.98 | 0.96 | 0.99 | 0.94 | 0.99 |
| Rku | 0.97 | 0.94 | 0.99 | 0.92 | 0.98 |
| Rdq | 0.96 | 0.92 | 0.98 | 0.9 | 0.97 |
| Rdc | 0.99 | 1 | 0.98 | 1 | 0.99 |
| RPc | -0.94 | -0.9 | -0.96 | -0.87 | -0.95 |
| Rk | 0.96 | 0.99 | 0.94 | 0.99 | 0.95 |
| Rvk | 0.81 | 0.87 | 0.85 | 0.87 | 0.84 |
| Pin 3D Parameter Unworn |         |           |           |                            |                            |
| Sa | 0.62 | 0.70 | 0.57 | 0.74 | 0.59 |
| Sq | 0.34 | 0.44 | 0.27 | 0.49 | 0.29 |
| Sz | 0.74 | 0.66 | 0.78 | 0.62 | 0.77 |
| Sk | 0.97 | 0.99 | 0.95 | 1.00 | 0.95 |
| Svk | 0.92 | 0.87 | 0.94 | 0.84 | 0.93 |
| Pin 3D Parameter Worn |         |           |           |                            |                            |
| Sa | 1.00 | 0.98 | 1.00 | 0.97 | 1.00 |
| Sq | 1.00 | 0.99 | 1.00 | 0.98 | 1.00 |
| Sz | 1.00 | 0.98 | 1.00 | 0.97 | 1.00 |
| Sk | 1.00 | 1.00 | 0.99 | 0.99 | 0.99 |
| Svk | 0.95 | 0.98 | 0.93 | 0.99 | 0.94 |

4. **Discussion**

The roughness analysis of pin and roller were measured by stylus and interferometer. 2D measurements were significant while measuring inner surfaces of the roller. 3D measurements were
significant to trace the wear scratches over the pin surface. To enable fast relocation on the stylus and interferometer, a 3D printed mask was used. The roughness parameters were selected for this study according to the significant changes in the correlation matrix see table 3 and 4. WS2 coated roller surfaces showing lower roughness than than both the PVD type and steel type (see figure 4 and 5). 60 measurements were evaluated for the roller. 45 measurements were evaluated for the pin. Ra, Rk and Rvk in 2D and Sa, Sk and Svk in 3D change more significantly for the roller and pin surface.

The results of combination (ii) samples reduce the rolling wear; it can be seen in (figure 3.b). The Tungsten disulphide (WS₂) roller coatings and the burnishing effect enabled smoother surface and enhances the wear resistance. On other hand vertical displacement behavior of each combination follow the trend of friction and roughness. Indeed, the relation of initial roughness with friction behaviour and vertical displacement behaviour illustrated in table 3 and table 4. The roughness of pin/roller surfaces are highly correlated with the coefficient of friction.

5. Conclusion

- The roughness increase after test and the pin surface shows more significant change than the roller surface. The Ra of the pin surfaces increase in the following order WS₂ (20%), PVD (22%) and steel type (35%). Ra of the roller surfaces increase as: WS2 by 2%, PVD by 4% and steel type by 7%.
- The roughness value Ra of pin over left side of measurements is higher than right side. The trend has the following decreasing order: WS₂ coated type < PVD type < steel type. Another fact is that the initial roughness of PVD pin (Ra) is higher than WS₂ pins (Ra = 0.026 μm).
- Ra, Rk, Rvk, Sa, Sk and Svk parameters are more stable for evaluation.
- Strong linear correlation exists between the radial displacement, COF and the 2D parameters Ra, Rq,Rp Rz, Rdc, Rku, Rdc, Rk and Rvk for the roller surfaces. While for the pin surfaces Rk has strong correlation with COF for the unworn surfaces. Sk and Svk show significant correlation with COF and radial displacement before and after test.
- In [21] was found out that the friction was highest for the steel combination, medium for the PVD combination and lowest for the WS₂ combination. The wear manifested in Sa and Svk changes of the pins follow this trend of the coefficient of friction.

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