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Research Article

DETERMINING SURFACE TOPOGRAPHY FOR CYLINDER LINER SURFACES USING 2D FAST FOURIER TRANSFORM

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ABSTRACT

In this study, roughness measurement verification using acquired images from the cylinder liner surfaces was conducted using Fast Fourier Transform (FFT). Cylinder liners that worked at specific times were used in the measurements. The surface images of the cylinder liners from two different tractor models were captured and inspected by a rotating (Nipkow disc) confocal microscope. The captured images were then preprocessed using high pass filter in order to enhance the image before further image analyses conducted. This study indicated that determination of surface roughness is possible using the image analysis techniques. 2 dimensional (2D) FFT image transformation techniques will be used in the near future extensively to determine the surface characterization of cylinder liners of engines used in tractors over time. In all cylinder liners used this study, the smoother appearance of the lower-middle parts suggested that the piston worked mostly in this region.
Keywords: Fast fourier transform, roughness measurement, surface finish quality.

1. INTRODUCTION

According to researches in all over the world, wear is the main reason of the 70% of the machinery parts to become inconsumable. Moreover, energy loss due to wearing causes high amount of expense. In this context, even increase on efficiency of lubrication system cannot eliminate the wear.

Cylinder liner, piston skirt, piston rings, valve train, crankshaft and its bearings are the major lubricated components in internal combustion engines. Friction in the piston-cylinder liner system causes mechanical power loss in the engine. The piston-cylinder liner system is investigated by both the manufacturers and customers in optimizing. Surface roughness of cylinder liners plays an important role in the control of tribological properties in the cylinder liner-piston ring system. Running-in duration, oil consumption, exhaust gases emission and engine performance are affected through cylinder liner surface topography.

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Precision measuring devices are used during the manufacturing processes of cylinder liners for geometrical and dimensional measurements due to their crucial role to insure their compliance with the design requirements. Typically the cylinder bore is not cylindrical along its whole length. Loss of conformity between piston rings and cylinder liner, as well as troubles to oil film distribution, is caused by through the bore distortion. Accordingly, in transverse sections along the cylinder bore will be occurred by different wear mechanism [1].

Surface characterization is understood as the analysis of the surface geometry into basic components based usually on some functional requirement. These components can have various shapes, scales of size, distribution in space and can be constrained by a multiplicity of boundaries in height and position [2]. Issues like the establishment of reference lines can be viewed from their ability to separate geometrical features or merely as a statement of the limit of instrument capability. Ease of measurement can influence the parameter or feature [3].

For the description of the workpieces, the Geometrical Product Specifications and Verification (GPS) defines on a technical drawing the shape (geometry), dimensions and surface characteristics of a workpiece. In this way the optimal function of the respective part is supposed to be guaranteed considering a certain manufacturing tolerance [4].

Developing from the need to machine as the demands grew in the last thirty years and there came some new methods of fabrication with different materials. Hand by hand with this development the need came to make very accurate machine constructions and to miniaturize sensors and actuators in order to enable the nonintrusive ultra-precise control of instruments and production equipment. Also a special demand for quality management is in the point of view in this field [5].

Surface profile is consisting of roughness, waviness and profile. The roughness profile can be described as the profile derived from the primary profile by using a long-wavelength filter with a cut-off λc. This profile is for the evaluation of surface roughness of workpiece. The roughness average (R_a), the most commonly used roughness parameter, is used to assess the surface roughness by the non-contact, non-destructive, optical measurement technique making a significant contribution to the development of dimensional measurement field.

Computational methods such as image analyses are powerful tools to investigate, assess and characterize the surfaces. Therefore, this paper investigated the surface characteristics of the micro-scaled manufactured samples not only in measuring their surface roughness but also analyzing their surfaces using an image processing technique called as fast Fourier transform (FFT).

Figure 1 represents the evaluation process flow called as iGrafx (the professional process management software toolbox) consisting of two main phases, namely the measurement of roughness parameters and computational phases. The flowchart of the measurement process indicate the roughness result for a certain measurement point of a given sample and to disclose digital image processing know-hows to analyze and estimate the roughness of cylinder liner's surfaces [6].

2. MATERIAL AND METHOD

The purpose of this study is to investigate the surface characterization of cylinder liners of engines used in tractors over time. Two different used cylinder liners having different textures after a certain operating time were inspected by means of the evaluation of the roughness measurements.

The cylinder liners from two different tractor models were prepared for preliminary sample preparation. The CAD drawing of cylinder liner (Figure 2a), cylinder liner used in this experimental study (Figure 2b) are cut vertically in eight (8) sections shown in Figure 2c. Each section was marked as three (3) equal parts (upper-middle-lower), and the measurements were repeated ten (10) times scans from each section.

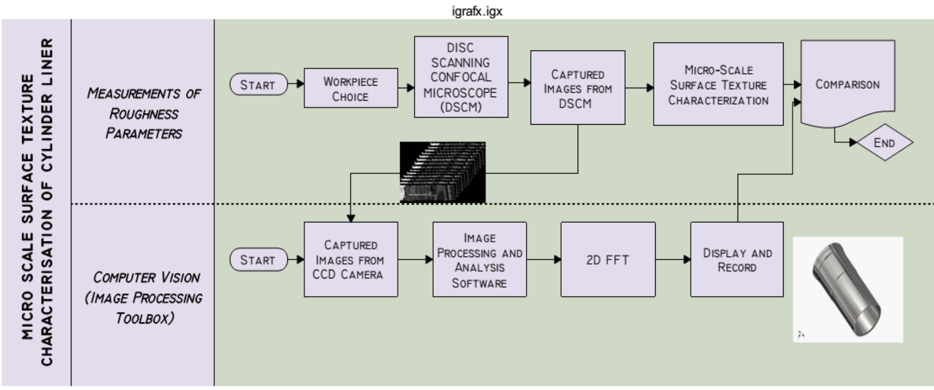


Figure 1. The evaluation process flow for surface roughness characterization

(a) (b) (c)

Figure 2. CAD drawing of cylinder liner (a), cylinder liner used in this experimental study (b) and three (3) equal parts (upper-middle-lower) on each section of the cylinder liner used in this experimental study (c).

For surface roughness measurements, a rotating (Nipkow disc) confocal microscope (NanoFocus - µsurf) [5] was used (Figure 3). Cylinder liners working at specific times were used in the measurements.

For all samples, the surfaces were measured at several different positions on the measuring area in terms of eleven (11) different surface roughness parameters like R_a, R_z, R_{sk}, S_a, S_z, etc., but the most commonly used roughness parameters R_a and S_a.

2D surface profile parameter R_a as amplitude parameter (average of ordinates) and 3D surface profile parameter S_a as average deviation of the surface are calculated in Table 1 as below:

The surface roughness and wear behaviors of cylinder liners of two different tractor models were investigated by using a rotating (Nipkow disc) confocal microscope (NanoFocus - µsurf) [11].

3. EXPERIMENTAL PROCEDURE

3.1. Measurements of Roughness Parameters

In this study, surface roughness of selected cylinder liners was measured in micro-scale. The surface investigations were performed with a rotating (Nipkow disc) confocal microscope (NanoFocus - µsurf) (Figures 3b) [11].

In disc scanning confocal microscopy (DSCM), the motorized disc called as Nipkow disc turns and captures light representing a slice of image from sample surface (Figures 3a). The specifications of DSCM (800S - 20x) used in this study are given in Table 2. Figure 4 shows 3D image of cylinder liner sample taken with high dynamic picture option.

Table 1. 2D/3D Surface Profile Parameters [7, 8, 9, 10]

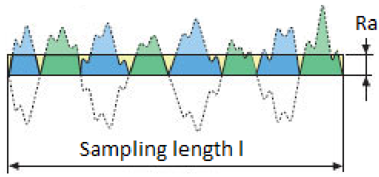
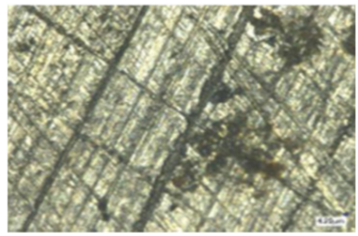
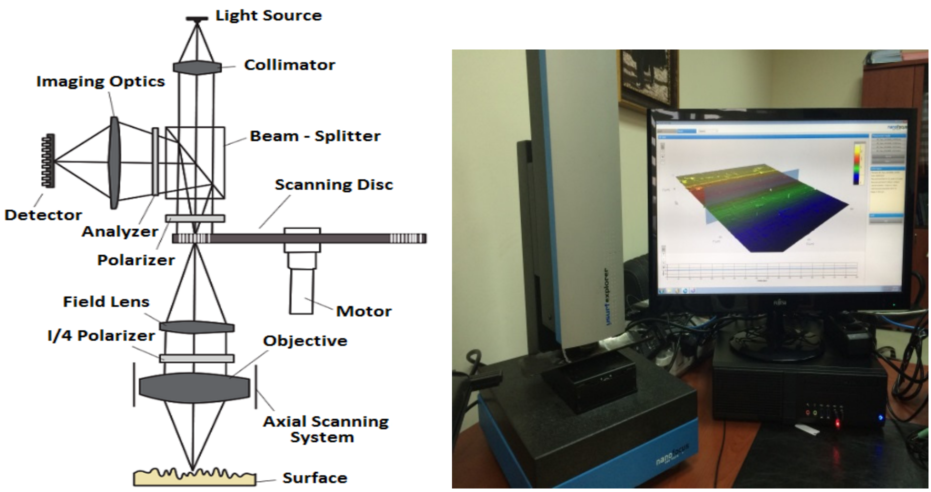
Equation with description	Graphical/Schematical Representation
Arithmetical mean deviation of the assessed profile R_a $$Ra = \frac{1}{l}\int_0^l \lvert Z(x)\rvert dx$$ Arithmetic mean of the absolute ordinate values *Z(x)* within a sampling length.	
$$Sa = \iint_a \lvert Z(x,y)\rvert\, dx\, dy$$ S_a: The average deviation of the surface	

Table 2. The specifications of Disc scanning confocal microscopy (DSCM) [11]

Measurement Methods	Spatial resolution	Z Resolution	Range Z
Disc scanning confocal microscopy (DSCM)	1,6 µm	0,04 nm	3,1 mm



(a) (b)

Figure 3. Schematic diagram illustrating of the working principle of DSCM (a) and a rotating (Nipkow disc) confocal microscope (NanoFocus - µsurf) during the roughness measurements of the cylinder liner surface (b) [11]

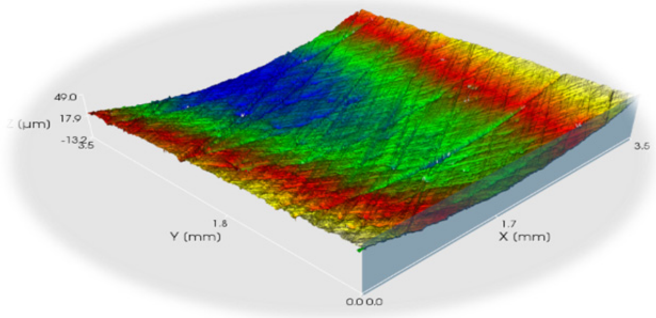


Figure 4. A 3D image of cylinder liner sample taken with high dynamic picture option [11]

The experiments were carried out by preparing the cylinder liner specimens. Each section was marked as three (3) equal parts (upper-middle-lower). The captured images having three different roughness values of (R_a) 0,155, 0,135 and 0,132 µm are given in Figure 5.

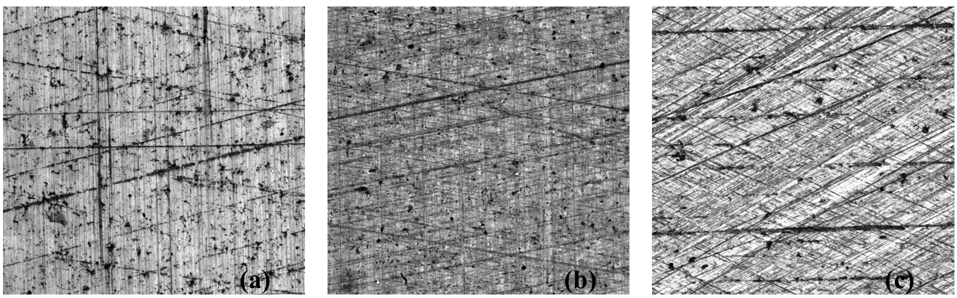


Figure 5. The captured images taken from the workpieces (a) Coarse surface (R_a = 0,155µm), (b) Medium surface (R_a = 0,135µm) and (c) Fine surface (R_a = 0,132µm)

The size of workpieces was 220x40 mm. The field view of instruments was 800x800 µm. Each measurement is the average of ten scans. 11 roughness parameters were obtained during each measurement and R_a values were used in this study.

3.2. Image Processing and Analysis

Several investigations have been performed to inspect surface roughness of a workpiece by using image processing techniques. The same location of each captured image as shown was processed and analyzed using Matlab image processing toolbox. The name of the technique carried out in this study was 2D Fast Fourier Transform (FFT) image processing technique [6].

The Fourier Transform is used if the geometric characteristics of a spatial domain image are desired, since the image in the Fourier domain is decomposed into its sinusoidal components. Therefore, it is easy to process certain frequencies of the image. The 2D FFT function in Matlab software transforms the spatial-domain image into the frequency domain image to identify the major influencing factors. The captured color images of cylinder liner samples were transformed into gray level 8 bit images. Eight bit gray images were binarised using 0.2 threshold level. Binarised images were analysed using Fast Fourier Transform. The percentages of black and white pixel numbers of the transformed images were computed [6].

Calculation of the percentage of black pixels (PBP) is presented below:

$$PBP = \frac{TNBP}{TNP} \times 100 \tag{3.1}$$

where;
PBP is the percentage of black pixels (%);
TNBP is the total number of black pixels in the image; and
TNP is the total number of pixels in the image.
Calculation of the percentage of white pixels (PWP) is presented as follows:

$$PWP = \frac{TNWP}{TNP} \times 100 \tag{3.2}$$

where;
PWP is the percentage of white pixels (%);
TNWP is the total number of white pixels in the image; and
TNP is the total number of pixels in the image.

4. RESULTS AND DISCUSSION

Cylinder liner surfaces of two different tractor models were compared. R_a and S_a values of measured surface roughness were compared and depicted. RMSE values from the surface roughness for both R_a and S_a values for the cylinder liners belonging to Massey Ferguson and Ford, respectively were computed. Then, RMSE values were compared to investigate the effect of working time on surface topography.

The error between the measured values from the surfaces of the cylinder liners belonging to Massey Ferguson and Ford was calculated respectively in terms of R_a with different sampling position and S_a represented in Table 3.

In terms of R_a, RMSE for the cylinder liners belonging to Massey Ferguson and Ford respectively,

- Lower part (Massey Ferguson): 0,035 µm (vertically) and 0,038 µm (horizontally).
- Lower part (Ford): 0,090 µm (vertically) and 0,108 µm (horizontally).
- Medium part (Massey Ferguson): 0,023 µm (vertically) and 0,042 µm (horizontally).
- Medium part (Ford): 0,101 µm (vertically) and 0,050 µm (horizontally).
- Upper part (Massey Ferguson): 0,043 µm (vertically) and 0,077 µm (horizontally).
- Upper part (Ford): 0,092 µm (vertically) and 0,089 µm (horizontally).

In terms of S_a, RMSE for the cylinder liners belonging to Massey Ferguson and Ford respectively,

- Lower part: 5,892 µm (Massey Ferguson) and 2,791µm (Ford)
- Medium part: 3,660 µm (Massey Ferguson) and 2,124 µm (Ford)
- Upper part: 6,021 µm (Massey Ferguson) and 4,130 µm (Ford)

For the surface roughness parameter of cylinder liner (R_a), the values were varied between 0,080 µm and 0,400 µm. Generally, the optimum value of R_a for cylinder liner manufacturer, which is obtained from engine maintenance companies and experimental application, is found approximately as 0,650 µm.

The surface roughness measurements results taken from the vertical position and horizontal position showed that a maximum difference of about 30% in terms of R_a was observed. Surface roughness values for horizontal measurements were higher than those for vertical measurements.

In terms of S_a parameter, the surfaces of cylinder liner belonging to Ford were smoother than those belonging to Massey Ferguson.

Table 3. Roughness measurement results taken from three different surfaces of the cylinder liners for two different tractor models in terms of R_a (vertically and horizontally) and S_a in µm.

#no measurement	***LOWER***			***MEDIUM***			***UPPER***		
	Sa	***Rav***	***Rah***	***Sa***	***Rav***	***Rah***	***Sa***	***Rav***	***Rah***
1	10,964	0,152	0,119	18,780	0,120	0,146	11,480	0,151	0,142
2	11,050	0,151	0,121	9,698	0,110	0,142	10,400	0,090	0,132
3	9,676	0,101	0,123	17,440	0,175	0,143	9,272	0,162	0,139
4	9,610	0,111	0,153	17,600	0,163	0,235	13,400	0,144	0,113
5	8,732	0,110	0,103	14,480	0,159	0,203	14,460	0,210	0,344
6	10,016	0,191	0,086	17,882	0,119	0,127	20,680	0,196	0,167
7	28,480	0,090	0,106	15,380	0,113	0,148	24,860	0,112	0,172
8	14,120	0,095	0,153	9,548	0,129	0,251	26,180	0,217	0,309
9	8,838	0,173	0,223	9,580	0,131	0,174	11,972	0,116	0,160
Average	12,387	0,130	0,132	14,488	0,135	0,174	15,856	0,155	0,186
Std Dev	6,249	0,037	0,040	3,882	0,024	0,045	6,386	0,045	0,082
RMSE	**5,892**	**0,035**	**0,038**	**3,660**	**0,023**	**0,042**	**6,021**	**0,043**	**0,077**
10	12,846	0,244	0,279	11,320	0,323	0,283	12,520	0,333	0,371
11	9,522	0,158	0,186	11,884	0,308	0,258	14,080	0,398	0,302
12	9,780	0,200	0,196	11,060	0,182	0,212	9,848	0,240	0,235
13	15,140	0,247	0,154	13,260	0,241	0,169	22,000	0,262	0,219
14	17,870	0,221	0,372	14,120	0,424	0,294	19,100	0,332	0,376
15	14,620	0,119	0,110	17,800	0,084	0,161	10,332	0,136	0,151
16	13,820	0,089	0,089	11,980	0,114	0,226	12,400	0,091	0,093
17	10,760	0,374	0,376	10,200	0,285	0,313	9,892	0,211	0,291
18	9,521	0,345	0,367	13,200	0,217	0,221	10,160	0,217	0,256
Average	12,653	0,222	0,236	12,758	0,242	0,237	13,370	0,246	0,255
Std Dev	2,961	0,095	0,115	2,252	0,107	0,054	4,381	0,098	0,094
RMSE	**2,791**	**0,090**	**0,108**	**2,124**	**0,101**	**0,050**	**4,130**	**0,092**	**0,089**

4.1 2D Surface Measurement Results

Figures 6 and 7 represent roughness measurement results taken from three different surfaces of the cylinder liners from Massey Ferguson and Ford respectively in terms of R_a (vertically and horizontally).

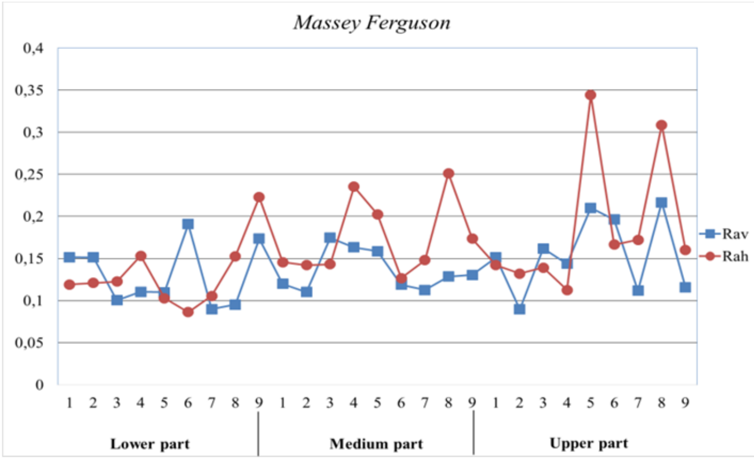


Figure 6. Roughness measurement results taken from three different surfaces of the cylinder liners from Massey Ferguson in terms of R_a (vertically and horizontally)

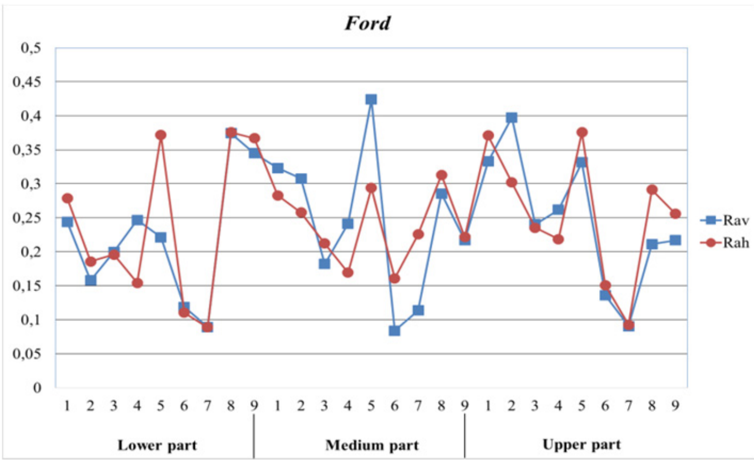


Figure 7. Roughness measurement results taken from three different surfaces of the cylinder liners from Ford in terms of R_a (vertically and horizontally)

4.2 3D Surface Measurements Results

In this study, the analyses of the surfaces of the cylinder liners with the same geometry and material counterparts were examined. Nine consecutive roughness measurements (repetition of ten scans) were performed for the cylinder liners' surfaces belonging to tractor models of Massey Ferguson and Ford.

Figures 8 and 9 indicate roughness measurement results taken from three different surfaces of the cylinder liners from Massey Ferguson and Ford in terms of S_a.

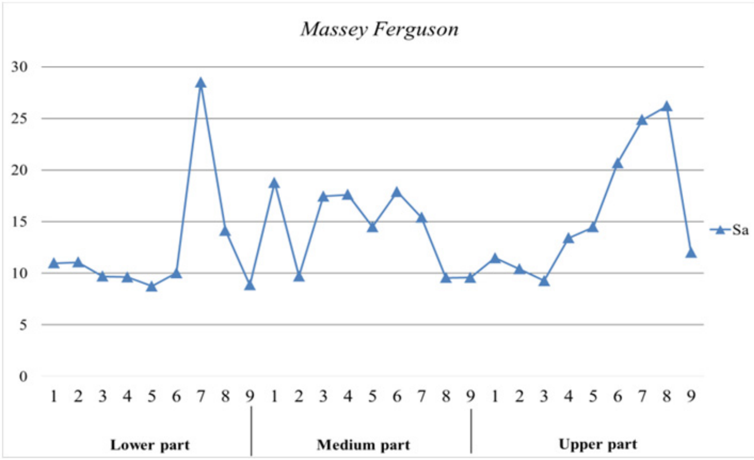


Figure 8. Roughness measurement results taken from three different surfaces of the cylinder liners from Massey Ferguson in terms of S_a

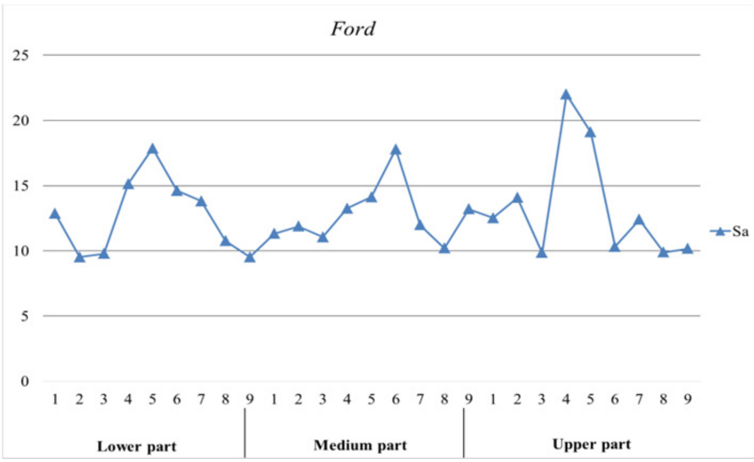


Figure 9. Roughness measurement results taken from three different surfaces of the cylinder liners from Ford in terms of S_a

4.3 2D Fast Fourier Transform Image Processing Results

Figure 10 illustrates the results of 2D Fast Fourier Transform analyses. Figures 10a, 10b and 10c clearly indicate that as the roughness increases the diameter of white pixels blob decreases. Additionally, the number of black pixels increases as the roughness of surface increases.

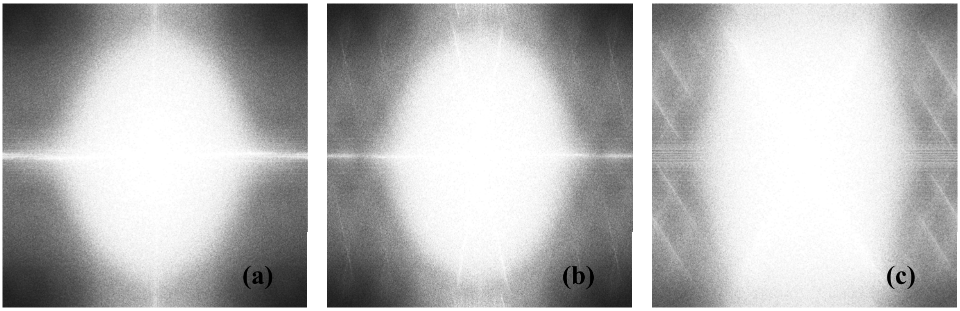


Figure 10. The FFT images taken from the workpieces (a) Coarse surface (R_a = 0,155μm), (b) Medium surface (R_a = 0,135μm) and (c) Fine surface (R_a = 0,132μm)

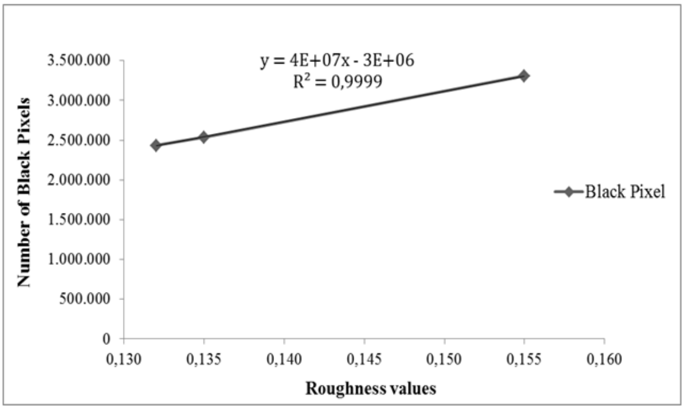


Figure 11. The number of Black (Dark) pixels from FFT images taken from images of workpieces a) Coarse (R_a = 0.155μm), b) Medium (R_a = 0.135μm) and c) Fine (R_a = 0.132μm) surfaces

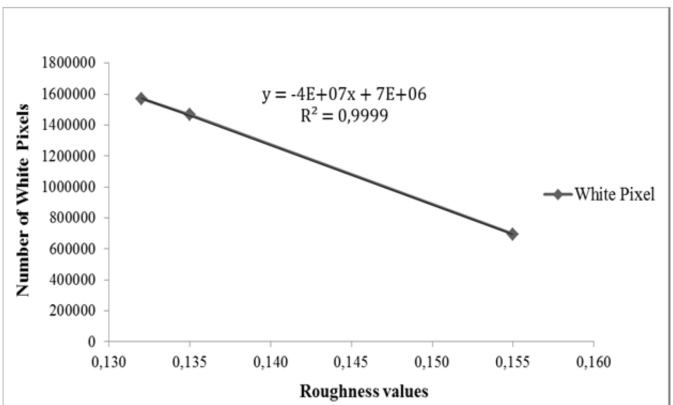


Figure 12. The number of White (Bright) pixels from FFT images taken from images of workpieces a) Coarse (R_a = 0,155μm), b) Medium (R_a = 0,135μm) and c) Fine (R_a = 0,132μm) surfaces

Figures 11 and 12 respectively shows the relationship between the number of black and white pixels and surface roughness. The number of black pixels in the image increases with increase in surface roughness (Figure 11). The regression equation and the coefficient of determination for the relationship between black pixels and surface roughness are given at equation [4.1] [6].

$$Y_{bp} = 4E{+}07{*}R_a - 3E{+}06 \qquad (R^2 = 0{,}99) \qquad (4.1)$$

where;
y_{bp} is the number of black pixels
R_a is surface roughness

Also, as the surface roughness increases, the number of white pixels in the image decreases. Therefore, the decrease in the number of white pixels agrees with the results from Figure 12. The regression equation and the coefficient of determination for the relationship between white pixels and surface roughness are presented at equation [4.2] [6].

$$Y_{wp} = -4E{+}07{*}R_a + 7E{+}06 \qquad (R^2 = 0{,}99) \qquad (4.2)$$

where;
y_{wp} is the number of white pixels
R_a is surface roughness

5. CONCLUSIONS AND RECOMMENDATIONS

Generally, in experimental studies, 2D results are obtained through measurement of surface roughness devices. These measurements give information about only one profile over the surface of sample which is depends on selected cut off value. By consideration on working condition of samples and surface texture, accuracy of 2D measurement results is predicted. According to tables of measurement results, the differences between measured surface roughness values support the theory. Due to that, in this study, 3D surface measurement system is also used for the evaluation of the surface quality. With this 3D evaluation, numeric evaluation of surface texture under abrasive working condition is more reliable and gives more accurate results.

The aim of this application was to recognize the differences between the surfaces of the cylinder liners from two different tractor models, Massey Ferguson and Ford, after a certain operating time. This study highlighted the initial conditions when measuring roughness of the cylinder liners' surfaces. The results from the surface roughness measurement ascertained that the direct sliding motion affected by the surface finish quality.

As a result, the roughness values at the upper parts of the cylinder liners were found to be lower than those in the middle and lower parts. The smoother appearance of the lower-middle parts in all cylinder liners suggest that the piston worked mostly in this region and the wear was quite much here. When the lower, middle and upper parts of the cylinder liners were compared, it was concluded that the roughness values obtained from the upper parts were higher than those from the lower-middle parts.

In this study, roughness measurement verification using captured images from the cylinder liner surfaces was conducted using 2D Fast Fourier Transform (FFT). The captured images were then preprocessed using high pass filter in order to enhance the image before further image analyses conducted. This study showed that 2D FFT image processing technique was useful in the determination of surface roughness. 2 dimensional (2D) FFT image transformation techniques will be used in the near future extensively to determine the surface characterization of cylinder liners of engines used in tractors over time.

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