Surface Texture Evaluation of Cylinder Liners Using Machine Vision

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Abstract: - Roughness of cylinder bore surfaces is significant with regard to the friction, wear, contact mechanics and lubrication flow inside the internal combustion engine blocks. In addition to the conventional surface roughness parameters like Ra, Rz JIS and Rz DIN, parameters derived from the material ratio curve and honing angle are used for the functional performance prediction and quality control of cylinder liners. This work presents a method for the description and evaluation of the surface topography of cylinder liner surfaces using machine vision. Images of the cylinder liner surfaces manufactured with different roughness values are captured using a charge coupled device (CCD) camera attached with a miniature microscopic probe in a non-destructive manner .The captured images of the cylinder liners are pre-processed to evaluate image based texture parameters based on the statistical properties of the image intensity histograms and box counting fractal method. The developed image based texture parameters are compared and correlated with stylus based roughness parameters. The internal surface image capturing method, the image processing procedure and the results are presented and analyzed in this paper.

Key-Words: - cylinder bore, surface topography, machine vision, honing, image texture parameters, roughness

1 Introduction

Cylinder liner –piston ring system is a major contributor for the mechanical losses in an engine. A major portion of oil consumption arises from bore distortion and poor piston ring sealing resulting from the piston ring and/or cylinder bore wear. Controlling the surface finish and texture of cylinder liner surface plays an important role with respect to friction (fuel efficiency), wear (durability and running performance) and oil consumption (noxious emissions) of an engine. For the surface characterization of cylinder bore surfaces, conventional surface roughness parameters like Ra, Rz JIS or Rz DIN/ISO and parameters derived from the material ratio curve and honing angle are typically used by the engine manufactures.

Cylinder liners of internal combustion engines are finished using multi stage honing process, which is popularly known as plateau honing. This three stage honing process give cylinder liner, the desired finish and a surface texture with the characteristic cross-hatch groove pattern. Plateau honing was developed to generate surfaces that resemble 'run-in' surfaces. The required surface is generated using three stage-honing processes; the first process is a base honing process using a coarser honing stick aiming to generate deep valleys for lubrication retention. The second process is the finish honing process, which is accomplished using a medium size abrasive grit on honing stick. Finally, plateau honing is carried out with very fine abrasive grits to generate plateau kind of surface with very fine finish for reduced friction and proper bearing during piston ring travel [1]. In addition to creating a plateau surface, crosshatched groove patterns are generated on the liner surface as a consequence of the simultaneous rotational and the reciprocating movement of honing abrasive stick inside the cylinder bore. Typical honing process for cylinder liner surface production and the resulting surface texture are shown in Fig 1.

With growing demand of industrial automation in manufacturing, machine vision plays an important role in quality inspection and process monitoring. Many researchers in the past have used machine vision technique for the evaluation of surface texture parameters from ground, shaped, turned and milled work specimens. Luk et al. [2] utilized statistical parameters such as mean and standard deviation derived from the grey level distribution and correlated them with the Ra value determined from the stylus method. Ramamoorthy et al. [3] [4] [5], presented machine vision based image analysis for surface roughness analysis and classification of machined surfaces. Younus [6] suggested a method for the adaptive control of machining based on the

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grey level coefficient derived from a pixel and its eight neighbouring pixels.

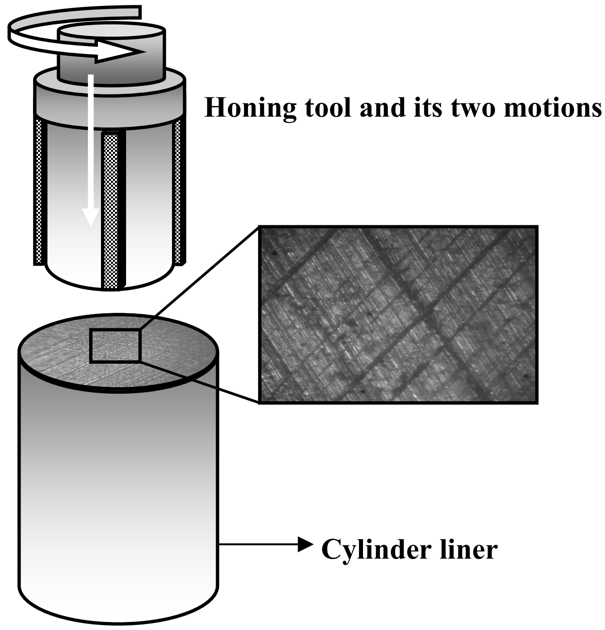

Fig1: Honing process and the resultant surface image

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This paper presents a method for the surface characterization of cylinder bores using image histogram based texture parameters and box-counting based fractal dimension. The evaluated image based surface descriptors are compared and correlated with stylus based roughness parameters measured from the cylinder liners.

2 Materials and methods

Plateau honing experiments are conducted for manufacturing nine grey cast iron based cylinder liners with different roughness values. The cylinder liners are having a diameter of 106.85 mm and a length of 240 mm that are meant for commercial trucks. The 3 stages of honing process are carried out in Nagel honing machine by varying the rotational speed between 16-30 m/min, oscillatory speed between 13-19 m/min, honing pressure between 400-700 kPa, Rough/finish operation time between 120-300 seconds and plateau honing time between 10-25 seconds. Diamond abrasive sticks with an average grit size of 150, 75 and 15 are used for rough, finish and plateau honing stages respectively.

Currently, 2D surface profile parameters based on material ratio curve (ISO 13565-2 - R_{vk}, R_{pk}, R_k, M_{r1} and M_{r2} parameters) coupled with a conventional roughness parameters (Ra or Rz ISO or Rz JIS) and honing angle are used as the specification for the surfaces of cylinder liners. The roughness values are measured at different sections of the cylinder liner using a stylus instrument (Mahr Surf 20) by using a cut of length of 2.5 mm and evaluation length of 12.5 mm, which are given in Table1.

Table1: Measured surface roughness values using stylus instrument of plateau honed surfaces

Ex.No	Ra	Rz JIS	Rz ISO	Rk	Rpk	Rvk
1	0.787	3.109	5.988	1.640	0.370	1.767
2	0.361	1.789	3.953	0.733	0.230	1.310
3	0.280	1.397	2.958	0.583	0.213	1.017
4	0.338	1.647	3.622	0.730	0.260	1.437
5	0.298	1.307	2.624	0.877	0.287	1.610
6	0.242	1.518	3.036	0.757	0.297	1.163
7	0.261	1.312	3.096	0.900	0.270	1.307
8	0.305	1.927	3.444	0.543	0.190	1.033
9	0.351	1.818	3.526	0.557	0.177	1.273

The images are captured from the internal surfaces of the plateau finished grey cast iron cylinder liners of varying roughness values using a miniature microscopic vision system without destroying/damaging the liners. This vision system consists of a moveable microscopic probe with a white light emitting diode (LED) attached on the probe holder near the objective as lighting source.

The output of this probe is connected through an optical coupler to a miniature CCD camera (Basler, *make*) which is interfaced to a computer to visualize and store the cylinder liner surface images (See Fig.2) The probe and the CCD camera can be moved horizontally and vertically inside the cylinder liner and the equipment is having capability for a total system magnification of approximately 100X. The camera pixels are calibrated by measuring 1/100 mm optical grating and each pixel size is determined as 1.33 µm.

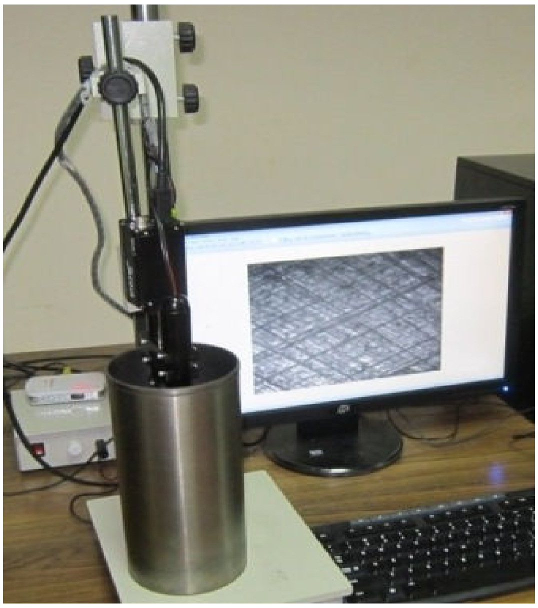


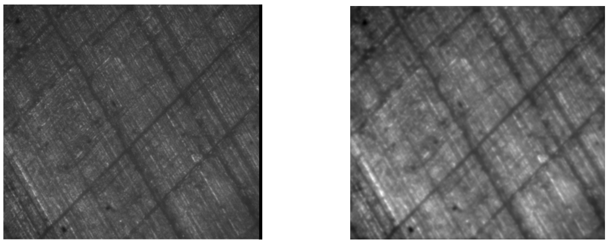
Fig 2: Set-up used for the internal image capturing of cylinder bore surface.

3 Image processing and computation of surface descriptors

The captured images from the cylinder liners were originally of size 1392 pixels (width) X 1040 pixels (height) which are cropped to 512 pixelsX512 pixels for the subsequent image operations. All the images are pre-processed by applying a Butterworth low pass in the frequency domain with a cut off frequency of 0.06 and order 1 followed by a normalization based on the maximum and minimum intensity values to enhance the contrast and quality. A typical captured image and the resulting image after pre-processing are shown in Fig. 3.

3.1 Texture parameters

Texture is an intrinsic property of all the surfaces. It carries important information regarding the structural arrangement of grains or particles on the surfaces. The pattern of intensity distribution of the captured images represents the texture of the image.



a) Original image b) Pre-processed image

Fig 3: Images of plateau honed surfaces

3.1 Texture parameters

Texture is an intrinsic property of all the surfaces. It carries important information regarding the structural arrangement of grains or particles on the surfaces. The pattern of intensity distribution of the captured images represents the texture of the image.
In this work an approach based on the statistical properties of the intensity histograms are used for the texture analysis of cylinder bore images to correlate with three material ratio roughness parameters. Based on numerous preliminary studies, the following three texture descriptors are observed to be correlating with the three roughness parameters (Rk, Rpk and Rvk) derived from the material ratio curve.

a) Uniformity= $U = \sum_{i=0}^{L-1} p^2(z_i)$ -------------- (1)

b) Average contrast $\sigma = \sqrt{\mu_2}(z)$ ------------ (2)

c) Smoothness= $R = 1 - 1/(1+\sigma^2)$ -------- (3)

Where,
z_i is a random variable indicating intensity,(z) is the histogram of the intensity levels in a region and σ^2 is the variance.

3.2 Grey level average value (Ga)

In this study, another image feature used is the arithmetic grey level average value, which is defined as

$$Ga = \sum |g_1 - g_m| + |g_2 - g_m| + ... + |g_n - g_m| \Big/ n$$

where

$$gm = \sum (g_1 + g_2 + ... + g_n)/n - - - - - -(4)$$

3.3 Box counting approach based fractal dimension

Fractal geometry, as an extension of classical Euclidean geometry, characterizes the average slope of a profile in the two-dimensional space and reflects the space-filling ability in the three-dimensional space. Fractals are identified by their property of appearing similar to the original image under a range of magnification scales. In broad terms, a fractal is a rough or fragmented geometric shape that can be subdivided in parts, each of which is nearly a reduced copy of the whole. Fractals can be described by a scale invariant parameter called a fractal dimension denoted by D. The fractal dimension is a measure of how densely the fractal occupies the space in which it lies.

In this paper, box counting method suggested by Sarkar and Chaudhuri [7] is used for calculating the fractal dimension of the cylinder bore image. Arunachalam and Ramamoorthy [8] used box counting method of fractal dimension for the grinding wheel wear monitoring. This method counts the number of boxes that cover the image intensity surface at particular grid size. The surface can be considered as a 3D space, in which the two coordinates (x, y) represent the 2D position and the third coordinate I represents the image grey level intensity. For a given image of size Nx x Ny, the image is portioned in to grids of size S X S. The grids are numbered as (u, v), where $0 \leq u, v < r$ and r = Nx/S. Each grid is stacked with a column of boxes of size SxSxS'. If the maximum grey level intensity is G, then G/S' = I/S. If the minimum and maximum number of grey levels of the image in the (u, v) grid fall in the boxes numbered *k* and *l* respectively, then the number of boxes covering the image intensity surface over the (u, v) grid is Nr (u, v) = *l*-*k* +1. With different grid size S, different values of r and Nr can be obtained. The fractal dimension can be estimated from the least square linear fit of log (Nr) versus log (1/r). The slope of the linear fit represents the fractal dimension of the image.

4) Results and Discussions

The surface texture parameters are computed from the cylinder liner surface images based on the above three methods using MATLAB™ and are given in Table 2

Table 2: Image based surface descriptors obtained for honed surface images

Ex.No	FD	Ga	Contrast	Smoothness	Uniformity
1	2.1808	18.5978	26.532	0.00844	0.01218
2	2.2013	24.9312	30.311	0.01393	0.00922
3	2.2154	25.5349	31.504	0.01503	0.00877
4	2.2071	23.7853	29.967	0.01362	0.00958
5	2.2157	23.5277	29.77	0.01344	0.01003
6	2.2005	25.3227	32.199	0.01569	0.00897
7	2.2168	24.6057	31.198	0.01474	0.00950
8	2.1960	26.1352	32.505	0.01598	0.00915
9	2.2099	23.697	30.324	0.01394	0.00967

The evaluated image based surface descriptors are plotted against Stylus based roughness values. The fractal dimension obtained from the surface images are well correlated with Rz JIS and Rz DIN/ISO with a coefficient of determination of 0.824 and 0.726 respectively as shown in Fig 4 and Fig 5.

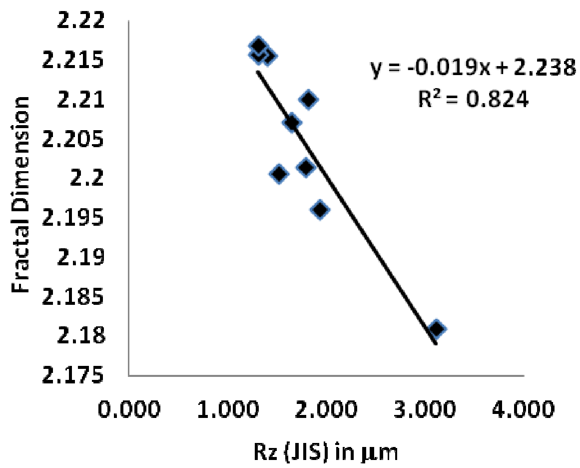


Fig 4: Correlation of Image based fractal dimension with Rz JIS based on stylus profilometer

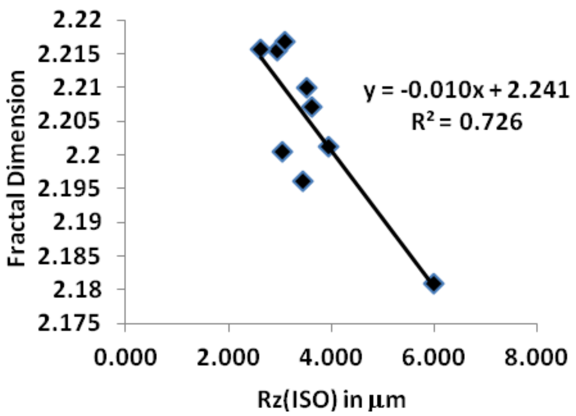


Fig 5: Correlation of Rz DIN/ISO based on stylus profilometer with Image based fractal dimension

The Ga value which is defined in the same way as Ra is defined for a 2D profile shows good correlation with stylus based Ra value with a coefficient of determination (R^2) above 0.85 as shown in Fig 6.

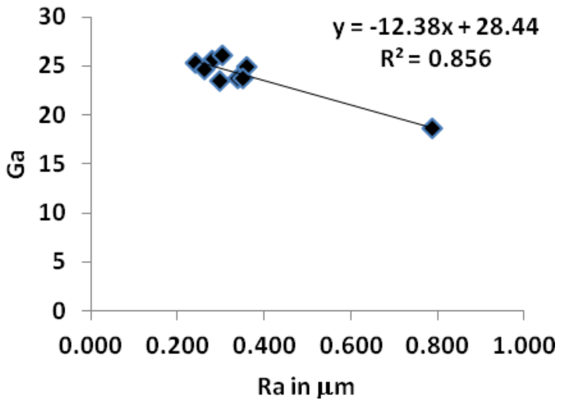


Fig 6: Correlation of Ga values computed from image with Ra values based on stylus profilometer

The three roughness parameters (Rk, Rpk and Rvk) derived from the material ratio curve are plotted against the three image texture parameters, smoothness, uniformity and contrast respectively.

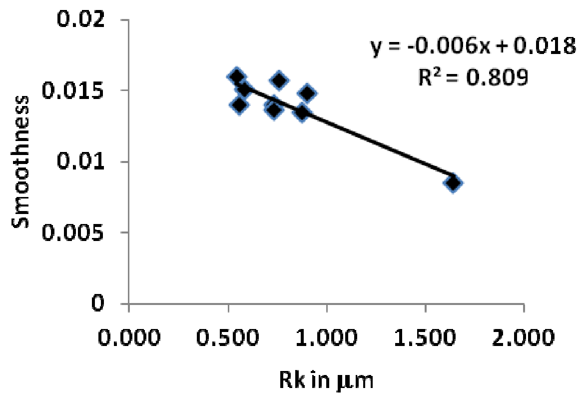


Fig 7: Correlation of texture parameter 'Smoothness' computed from image with Rk value derived from the bearing ratio curve.

In Fig 8, it is to be noted that the fitting between uniformity and Rpk is carried out using a 2nd order polynomial (with R^2 =0.853) and not using linear least square technique as in other cases. Among all image based parameters Rpk showed best fit with the parameter uniformity with a R^2 =0.5154 for linear fit.

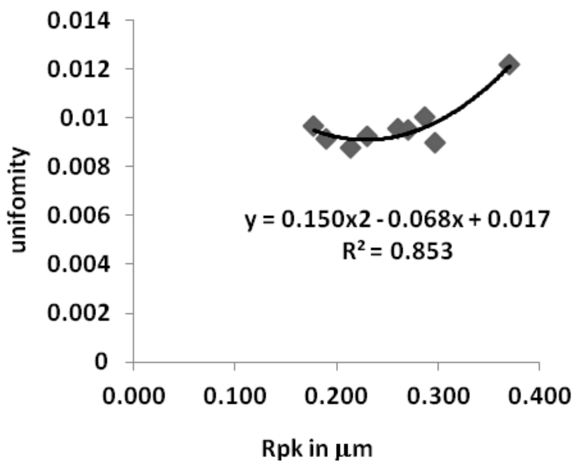


Fig 8: Correlation of texture parameter 'Uniformity' computed from image with Rpk value derived from the bearing ratio curve.

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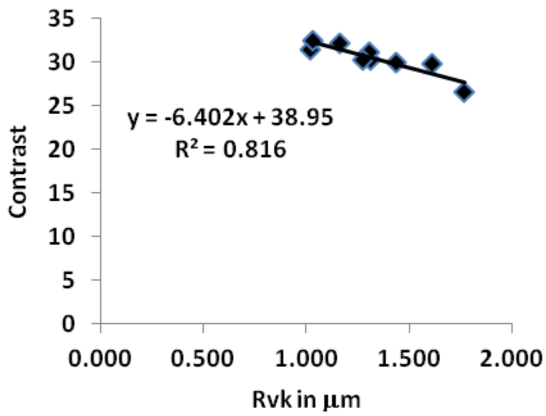

Fig 9: Correlation of texture parameter 'Contrast' computed from image with Rvk value derived from the bearing ratio curve.

5 Conclusion

This paper has explained the use of machine vision technique for the evaluation and inspection of cylinder liner surfaces topography that are tribologically significant for the successful performance of internal combustion engine. Pre-processing of internal images grabbed from cylinder liners is necessary for removing noise and achieving uniform illumination. Image texture parameters, smoothness and contrast are observed to be having linear correlation with bearing ratio parameters Rk and Rvk with a coefficient of determination above 0.8.Arithamatic grey level average (Ga) and Fractal Dimension based on box counting method have well correlated with conventional roughness parameters such as Ra,Rz (JIS) and Rz (DIN). CCD camera aided image capturing and personal computer (PC) based image processing approach proposed in this work for the surface topography evaluation of cylinder liners is cost effective and has the potential for the in situ inspection/automation .

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