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Surface topography characterization of automotive cylinder liner surfaces using fractal methods

Deepak Lawrence K, B. Ramamoorthy*

Manufacturing Engineering Section, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai, India

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ABSTRACT

This paper explores the use of fractal approaches for the possible characterization of automotive cylinder bore surface topography by employing methods such as differential box counting method, power spectral method and structure function method. Three stage plateau honing experiments were conducted to manufacture sixteen cylinder liner surfaces with different surface topographies, for the study. The three fractal methods are applied on the image data obtained using a computer vision system and 3-D profile data obtained using vertical scanning white light interferometer from the cylinder liner surfaces. The computed fractal parameters (fractal dimension and topothesy) are compared and correlated with the measured 3-D Abbott-Firestone curve parameters (S_k, S_{pk}, S_{vk}, S_{r1} and S_{r2}) that are currently used for the surface topography characterization cylinder liner surfaces. The analyses of the results indicated that the fractal dimension (D) computed using the vision data as well as 3-D profile data by employing three different fractal methods consistantly showed a negative correlation with the functional surface topographical parameters that represents roughness at peak (S_{pk}),core (S_k) and valley (S_{vk}) regions and positive correlation with the upper bearing area (S_{r1}) and lower bearing area (S_{r2}) of the automotive of cylinder bore surface.

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1. Introduction

Surface topography of cylinder liner surface plays a major role in determining friction, wear, lubrication and sealing tightness of the piston assembly which in turn affects the running performance, emissions and longevity of the engines. The cylinder liner surfaces can be considered as engineered surfaces as they are manufactured using three-stage plateau honing process to generate different layers of surface geometric structure with deep valleys for oil retention and relatively smooth plateaux geometry on the top that serves as the bearing contact for the piston ring sliding. The cross hatched groove patterns generated on the surface as a consequence of the honing process mechanics is also tribologically significant. The resultant surfaces are currently characterized using multiple surface topographical parameters such as Abbott-Firestone curve parameters coupled with the cross-hatch angle [1,2].

A fractal is a fragmented geometric shape, which has same structure/statistical properties at all scales. The term fractal and the framework and techniques for its investigation are initiated by Benoit B. Mandelbrot to describe the degree of irregularity of objects of anomalous dimensions [3]. A self-similar fractal remains the same either statistically or literally if all their coordinates are scaled by the same factor. If different coordinates have to be scaled by different factor, the fractal is called self-affine. Over a period of time there were several techniques evolved to characterize the fractal nature of natural and man-made surfaces such as slit island method [4] reticular cell counting method [5], triangular prism method [6], compass method, variation method, Hurst orientation transform, power spectral method [7], differential box counting method [8], patchwork method [9], structure function method [10] and difference average law method [11]. These methods are developed for different scientific and engineering applications and differ in their computational efficiency and estimation boundary of fractal parameters, but are found to be useful for explaining different physical processes/phenomena involving different surface geometry.

Most of the processed component's surfaces have roughness that reaches out of ideal Euclidian geometry, and expressing that as a fractional value may be understood as a qualitative measure of the roughness. The surface roughness is generally characterized by the statistical parameters obtained from the 2-D or the 3-D profile data. However, as surface topography is a non-stationery random process, it is known that the variances of surface height and its derivative roughness parameters depend strongly on the resolution of the measuring instrument, sampling interval and the type of filter used for its processing. Hence, these parameters do not provide a unique characterization for a surface. This limitation imposes the

* Corresponding author. Tel.: +91 4422574674; fax: +91 44 22575705.
E-mail address: ramoo@iitm.ac.in (B. Ramamoorthy).

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use of many parameters for the better characterization of the same surface. The fractal parameters are believed to be intrinsic characteristic of surfaces and its utilization for the characterization of surface topographies can be as advantageous as these parameters are considered to be independent of scale, sampling and filtering. Stout et al. [12] stressed the need for more investigation on the variation of fractal parameters in terms of surfaces and the currently established characterization procedures, for the possibility of their use beyond the academia research.

There were several attempts in the past to characterize the surface topography of machined surfaces using different fractal methods. The works by earlier researchers that directly affects the course and direction of the present study are briefly mentioned here. In an earlier work, Brown and Savary [13], used compass method for the fractal analysis of ground surfaces using stylus profile data. Zhang and Gopalakrishnan [14], developed a functional calibration curve relating surface roughness and vision based areal fractal dimension for the roughness characterization of end-milled specimens. Rosen et al. [15], used the structure function based fractal method for the analysis of the cylinder bore surface wear using the wear region data obtained using stylus and atomic force microscopy. Thomas et al. [16], proposed the use of the structure function for the fractal characterization of the anisotropy of the grit-blasted, ground and plateau-honed surface. Jiang et al. [17], used the power spectral method for the fractal characterization of the surface roughness and anisotropy of ground surfaces using the atomic force microscope data obtained from ground specimens. Zhang et al. [18], described a relation between the roughness parameters Ra, Rq and Rsm and the fractal dimension computed by means of the reticular cell counting method. Mahovic Poljacek et al. [19], correlated the fractal parameter computed from the scanning electron microscope based grey scale micrographs of aluminium foil printing plates with that of the roughness parameters measured by means of stylus and laser scanning microscope. Risović et al. [20] investigated the correlation between fractal dimension inferred from electrochemical impedance spectroscopy measurements and the roughness parameters obtained by stylus and laser optical profilometric methods for lithographic printing plates of different surface topographies. Czifra et al. [21], used power spectral density based fractal dimension obtained using AFM data for the surface characterization of brake plunger manufactured using rolling process. Feng et al. [22] used the fractal method for the analysis of scan scale effect of AFM for the surface roughness characterization of Hastelloy substrates and amorphous alumina buffer layers in coated conductors.

Cylinder liner surfaces are stratified surfaces with multiple layers of micro geometry for meeting multi-functional requirements of the piston assembly system of automotive engines. Literature review indicates the deficiency of a parametric study that directly links the fractal parameters and the multiple surface topographical parameters that are used for the current characterization of plateau honed cylinder liners. The present work explores the use of box counting method, power spectral method and structure function method for the 3-D surface topography characterization of cylinder bores using two different type of surface data collected from cylinder liner surfaces manufactured with different surface topographies. 3-D profile data and surface image data obtained using the scanning white light interferometer and machine vision respectively are the two types of surface data used for the fractal analyses. The estimated fractal parameters namely fractal dimension and topothesy by employing three fractal approaches on two types of surface data are compared and correlated with the measured 3-D Abbott-Firestone curve based functional parameters namely, core roughness depth (S_k), reduced summit height (S_{pk}), reduced valley depth (S_{vk}), upper bearing area (S_{r1}) and lower bearing area (S_{r2}), and the results are analyzed.

2. Experimental procedures and measurements

Honing experiments were conducted on grey cast iron cylinder liners of 240 mm length and 106.8 mm inner diameter, using a vertical honing machine (Make: Nagel *VL*-05-120) in three different stages (rough, finish and plateau honing). The chemical composition of the grey cast iron liner material was C (3.2%), Si (2%), Cr (0.3%), Mn (0.8%), P (0.5%), Mo (0.4%) and S (0.06%) which is typically meant for heavy duty diesel engine trucks. Six metallic bonded diamond abrasive honing sticks with average grit sizes of D150, D75 and D15 (FEPA standard) were employed for rough, finish and plateau stages of honing process respectively. The honing process parameters namely, rotational speed (RS in m/min), oscillatory speed (OS in m/min), contact pressure (P in kPa), rough/finish honing time periods (HT (R/F) in s) and plateau honing time periods (HT (P) in s) were systematically varied at 4 levels as per L_{16} orthogonal array based design of experiment to generate 16 cylinder liners of different surface topographies (Table 1). The resultant plateau honed cylinder liners are sliced at the top dead centre using wire-EDM process to make 16 representative sample pieces of size 41 mm × 30 mm, for the 3-D surface measurements.

From the cylinder liner specimens, 3-D surface topographical parameters are measured using a vertical scanning white light interferometer (Make: Taylor Hobson CCI, HD). The surface is levelled by fitting a second order polynomial and a robust 3-D Gaussian filter with 0.08 mm cut-off is used for the computation of the 3-D Abbott-Firestone curve parameters [12]. Fig. 1 presents the plot

Table 1
Honing process parameters used for the plateau honing experimentation and the 3-D Abbott-Firestone parameters measured using vertical scanning white light interferometer for 16 cylinder liner specimens.

Exp. No.	RS (m/min)	OS (m/min)	*P* (kPa)	HT (R/F) (s)	HT (P) (s)	S_k (μm)	S_{pk} (μm)	S_{vk} (μm)	S_{r1} (%)	S_{r2} (%)
1	16	15	400	120	10	1.830	0.472	1.230	7.17	86.20
2	16	17	500	180	15	2.110	0.536	1.620	5.73	81.10
3	16	19	600	240	20	0.969	0.424	0.809	9.74	88.00
4	16	21	700	300	25	0.862	0.312	1.230	8.27	83.80
5	23	15	500	240	20	1.270	0.398	1.680	7.19	81.50
6	23	17	400	300	25	1.420	0.525	0.973	7.85	84.50
7	23	19	700	120	10	1.110	0.447	1.110	8.18	84.00
8	23	21	600	180	15	1.630	0.463	1.380	7.14	84.60
9	30	15	600	300	25	0.912	0.385	0.686	9.11	86.80
10	30	17	700	240	20	1.670	0.467	1.860	6.26	80.00
11	30	19	400	180	15	1.250	0.438	1.980	7.52	82.40
12	30	21	500	120	10	1.470	0.388	1.890	6.67	80.20
13	37	15	700	180	15	1.070	0.402	0.921	8.54	85.90
14	37	17	600	120	10	1.660	0.558	1.630	5.90	80.50
15	37	19	500	300	25	0.919	0.413	0.774	9.31	86.70
16	37	21	400	240	20	1.660	0.510	2.250	5.82	79.90

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