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Identifying Cylinder Liner Wear using Precise Coordinate Measurements

Salah Hamed Ramadan Ali[1,#], Hassan Hassan Mohamed[2] and Mohamed Kamal Bedewy[3]

1 Precision Engineering Division, National Institute for Standards (NIS), Giza, Egypt, 12211-136
2 Automotive Eng. Dept., Faculty of Engineering, Helwan University, Mataria, Cairo, Egypt, 11718
3 Dean of Engineering, Misr Univ. for Science and Technology, 6th of October City, Egypt, 12568
Corresponding Author / E-mail: SalahAli20@yahoo.com, TEL: +20-1-2625-2561, FAX: +20-2-3386-7451

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This paper aims at exploiting the accurate precise measurements of CMM machine in exploring and investigating the wear happening between contacting solid surfaces. For instance, excessive wear, if detected by the CMM measurements, in a cylinder bore of an internal combustion engine can dramatically affect its performance quality, sealing function, scheme of lubrication, and eventually its service life span. In such case, the finger print would be the original design GD&T tolerances. Widely spread availability of CMM machines at a reasonable cost may make the applicability of this novel technique of wear detection feasible. In this work, precise and accurate measurements of deviations in roundness, straightness, and concentricity in a cylinder bore of an air cooled Automotive Diesel Engine dismantled for an overhaul using a CMM machine have been executed and analyzed to validate this technique. Thus, the results have been presented, discussed, analyzed and interpreted in order to evaluate the status of the engine during operation. Locations of remarkable deviations representing aggressive wear happenings in the cylinder bore are detected and investigated. The measurements, within the limits of uncertainty attributes, could reflect the performance quality of the engine, the suitability of the applied scheduled maintenance plan, and may also point at possible adverse operating conditions contributed to this wear. In the light of the findings, recommendations may thus be drawn and offered to the engine designer to improve his design. For instance, surface treatments and coatings could be preferably changed, or an innovative constructional modification may be suggested to homogenize the wear occurrence in the cylinder bore during operation. This may extend the operating life span of the cylinder and in turn reduces the maintenance expenses. This novel technique for the wear development recalling proved to be successful and reliable tool to diagnose the root causes of the wear aggression occurrence.

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NOMENCLATURE

TDC = top deed center
BDC = bottom deed center
F_n = normal acting force on piston pin
F_s = axial transmitted force
F_a = crankshaft force due to clutch engagement
F_f = relative motion of piston rings
OOR = out of roundness
OOS = out of straightness
MPE_E = maximum permissible specific error value
L = measured length
M_{AV} = mean value of five repeated test measurements
S_D = standard deviation
n = number of repeated measurement tests
U_c= combined standard uncertainty due to reputability
S_a = averaged of straightness measurements
R_a =averaged of roundness measurements

1. Introduction

Geometrical and dimensional measurements using precision measuring devices are crucial during the manufacturing processes of parts to insure their compliance with the design requirements.[1] In addition, those accurate measurements may also be employed with reference to their benchmark values to monitor the extent and severity of functional deterioration of the parts, especially those working with their surfaces during service. This helps the maintenance engineer take proper decisions regarding his forthcoming maintenance plan and/or repair actions. Thus, the durability and reliability of the parts and the assembly would be favorably affected.

Air-cooled Diesel engine, for instance, is commonly used in heavy-duty transport fleets applications due to their high performance, efficiency, and low fuel consumption. The surface contact problems between cylinders and pistons through their rings are vital to the engine performance within the adverse operating conditions of high pressure, temperature rise, and high relative velocity of the contacting surfaces.[2,3,4] Fine finish and surface treatment together with proper geometrical and dimensional tolerances standards implementation are required in order to ensure good sealing between cylinder wall and piston rings, good load-carrying capacity, good lubrication conditions, less friction, suitable wear resistance, low translated vibration levels, high engine efficiency, and longer service life span.[5,6] The main function of the piston rings assembly is to provide a good dynamic sealing between combustion chamber and crankcase during compression and power strokes. Reasonable sealing minimizes power loss due to charge escape from the combustion chamber within suitable ring expansion gap and limited friction force. For long sealing service life, friction and wear between piston rings and cylinder wall have to be properly controlled.[7,8] They are controlled by lubrication of the interface with dry lubrication of cylinder bore material composition besides an oil film thick enough to separate the asperities of piston rings and cylinder surface.[3,7] The friction loss varies according to piston velocity between top dead center (TDC) and bottom dead center (BDC), where the oil film thickness depends on the instantaneous relative velocity of the piston ring, which varies from zero at TDC and BDC to a maximum in the middle section. This means that wear conditions will vary along the piston ring traveling distance, from mild to severe.[9]

Normally the cylinder bore is not cylindrical along its entire length. Practically, the bore distortion causes loss of conformity between piston rings and cylinder wall, which in turn produces some troubles to oil film distribution. Variation in the oil film thickness exposes piston rings and cylinder to the whole spectrum of lubrication regimes, from mixed and probably elastohydrodynamic to full film hydrodynamic lubrication.[5,7,10] Consequently, different wear mechanisms will develop geometrical departures in transverse sections along the cylinder bore.[9]

TDC location on the bore suffers heavily from oil starvation more than that at the BDC and its vicinity. Although the piston at both locations are kinematically characterized by marginal inversion velocity situations where it reaches zero before starting to get inverted, the most severe wear is expected to appear at the TDC due to the oil shortage while at the BDC the oil is available either from the source or due to gravity. However, the BDC may also experience high wear rate due to the existence of hard grit and wear debris accumulated by the gravity at this location and the neighboring area. The middle location and the nearby zone, where the piston velocity reaches its maximum value, mild wear only is expected because the oil film becomes dynamically thick enough to separate the mating solid surfaces and prevent metal-to-metal contact.[11]

Although there are many new advanced inspection equipment such as CMM machines of which their use is so far only monopolized to the manufacturing fields,[12,13] rare published research work yet exists in the use of such advanced CMM metrology utilities in the field of engine health monitoring through geometrical departure measurements and analysis.

Characterization of engine cylinder bore geometry and dimensions is a two manifold problem. The first is related to the applied techniques and quality standards adopted during manufacturing inspection process. This concerns the prescribed surface design parameters such as dimensional and geometrical tolerances, and surface roughness. The second is related to processing such data with the purpose of monitoring the changes that happened to the surface geometry and dimensions during engine service life span. This would help in two aspects: the first is related to maintenance decisions, while the second is related to design modifications. Research work has been done on surfaces with Gaussian distribution roughness, but cylinder wall fine finished surface with specified geometrical features and properties participate simultaneously together to controlling the environment that critically affects the engine functional performance and life.[14-17] Although the specified surface parameters represent advanced features, their definition is generally unrelated to any physical or mathematical properties of the surface topography.[18] The plotted accumulation of surface asperities heights according to the Gaussian distribution appears as straight-line scales. For transitional surface topography, such a scale appears as two intersecting straight lines. The slopes of the lines are proportional to the standard deviations of the two distributions, while the point of intersection represents the depth of transition from one finish to another. Difficulties encountered using this technique to apply, has recently solved with developing advanced calculations software.[12]

On the other hand, the numerical description of the changes in the operating surface geometry during service life span necessitates detecting and follow up the surface geometrical deviations. However, some changes occur in such a way that a band of surface fine wavelength may disappear. Hence, Fourier Transformation Analysis is needed in this case to determine the surface power spectrum using special software to characterize the changes in the surface straightness and roundness relevant to operation environment changes.[11] Statistical calculation analysis of combined standard uncertainty (type A) is also needed for CMM measurements.[20]

The purpose of this work is to demonstrate employing the accurate precise surface geometrical and dimensional measurements to monitor and follow up the extent of severity of wear changes in a worn out cylinder of an Automotive Diesel Engine as related to the resulted geometrical distortions in both transverse directions (out-of-roundness, and derived concentricity), and longitudinal directions (out-of-straightness). Thus, design improvements and/or correction actions to the scheduled maintenance plan could be suggested in the light of the analysis of the obtained measurements within the relevant uncertainties. Innovative design modification and inspired ideas may also be pointed at for the sake of extending the engine service life span and minimizing the running operational and maintenance expenses.

2. Cylinder forces and surface measurements

2.1 Dynamic friction force

Gas pressure due to combustion represents the essential axial force acting on the piston crown area to move it downwards against reciprocating mass inertia. F_n is the instantaneous sum of the normal acting forces on piston pin, Fig. 1. Reciprocating piston motion on angular movable connecting rod generates a variable piston side force F_s. An axial transmitted force F_a of the crankshaft due to clutch engagement force and gear force components affect the cylinder wall. The resultant of piston forces F_s and F_a attacks the wall at an angle with F_s. The angle value varies as a function of the force amplitude to generate a resultant force causing rotation around the cylinder axis. Dynamic friction force F_f has been produced due to relative motion of piston rings with respect to the cylinder wall under the effect of the resultant force in a spiral like motion. This causes the cylinder bore to wear at rates corresponding to the resultant force amplitude and direction to generate eventually a cylinder out-of-roundness (OOR) and out-of-straightness (OOS).

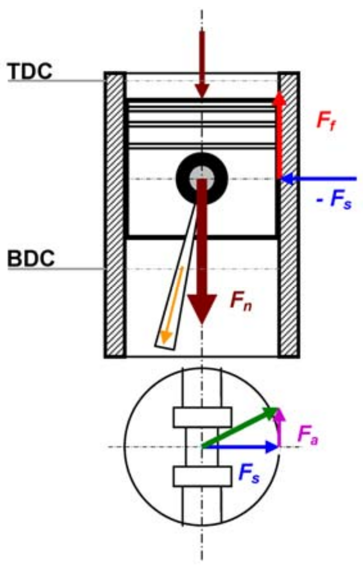


Fig. 1 Forces acting on the cylinder bore

2.2. Surface geometry measurements

Geometrical and dimensional characteristics of the cylinder bore surface have been measured using a computerized Coordinate Measuring Machine (CMM) equipped with a contact-scanning probe and a Least Square (LSQ) computing algorithm.

The CMM used throughout this work was Carl Ziess bridge model available at the Engineering and Surface Metrology Lab, Precision Engineering Division, National Institute for Standards (NIS) at Egypt. It is capable of producing accurate results with a reasonable repeatability and reproducibility for the surface geometrical departure features. The maximum permissible specific error value of the used CMM machine can be judged using the following equation:

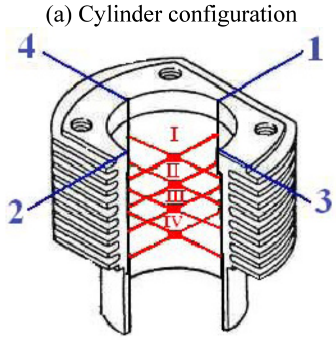
$$MPE_E = \pm (0.9\ \mu m + (L/350)),\ \mu m \qquad (1)$$

Where L is the measured length in mm.

Table 1 Cylinder material specifications

Chemical analysis, wt. %							Mechanical properties	
C	Si	Mn	P	S_{Max}	Cr	Ni	HB	σ_t, MPa
3.10	2.10	0.65	0.30	0.10	0.20	0.32	220	Min. 220

(a) Cylinder configuration



(b) Locations for roundness and straightness measurements

Fig. 2 Engine cylinder configuration and locations of measurements

The CMM measurement performance was verified according to ISO-10360.[19] An experimental investigation has been conducted on an air-cooled Diesel engine cylinder made of high quality grey cast iron (GG 25) having initially a design diameter of 110 mm and configuration shown in Fig. 2(a). The chemical analysis and mechanical properties of the cylinder material are presented in Table 1, where HB is the Brinell hardness and σ_t is the tensile strength. The piston stroke is 140 mm.

A straight Stylus tungsten carbide shaft probe with a ruby tip attached to PRISMO CMM machine was used to quantify the surface geometric and dimension departure characteristics of the cylinder bore. The CMM traveling speed was 40 mm/s and the probe scanning speed was 10 mm/s during measurements. The straightness measurements were carried out along four longitudinal equispaced locations, 90^o apart around the circumference, at 1, 2, 3, and 4 as indicated in Fig. 2(b). Cylinder bore roundness quantification was conducted at sections I, II, III and IV nearby TDC, midway, and BDC planes as shown in Fig. 2(b). The surface geometrical and dimensional features were represented by mean average values of five repeated test measurements.

3. Uncertainty assessment of measurements

Mean average values and combined uncertainty of roundness and straightness measurements for the engine cylinder bore have been presented in Table 2. Where M_{AV} is the mean value of five repeated test measurements, S_D is the standard deviation, and U_C is the combined standard uncertainty due to measurement repeatability ($U_C=S_D/\sqrt{n}$), where n is the number of repeated tests for each target measurement.[19] It worth mentioning that type B source of uncertainty is not accounted for by U_C values because of its relative insignificance to the OOR and OOS. The accuracy and uncertainty of these measurements have been determined and found to be within the acceptable standard limits.

The roundness and straightness results of five repeated laboratory tests conducted on each one of the adopted four transverse sections I, II, III, and IV, and the four longitudinal profiles 1, 2, 3, and 4, have been processed and presented in Figs. 3 and 4, respectively. The results are also tabulated in table 2 and the calculated values of the relevant uncertainty are plotted in Fig. 5.

Table 2 Measurements of both roundness and straightness together with the uncertainty assessment

Tests / Positions	Test 1	Test 2	Test 3	Test 4	Test 5	M_{AV}	S_D	U_C
1. Roundness, μm								
@ circle I	91.0	90.9	90.9	90.9	91.0	90.94	0.0548	0.0245
@ circle II	32.1	31.8	32.1	31.9	31.8	31.94	0.1152	0.0678
@ circle III	23.0	23.5	24.2	24.0	24.3	23.80	0.5431	0.2429
@ circle IV	18.2	18.3	18.3	18.5	18.9	18.44	0.2793	0.1249
2. Straightness, μm								
@ line 1	71.0	71.0	70.3	70.5	70.1	70.58	0.4087	0.1828
@ line 2	54.4	54.1	54.3	54.5	54.5	54.36	0.1673	0.0748
@ line 3	13.6	13.8	13.7	13.6	13.7	13.68	0.0837	0.0347
@ line 4	34.6	34.7	34.8	34.8	34.9	34.76	0.1140	0.0510

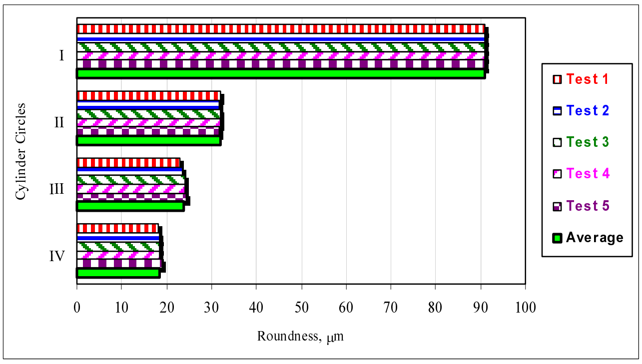


Fig. 3 Bore roundness measurements at four transverse sections along piston stroke

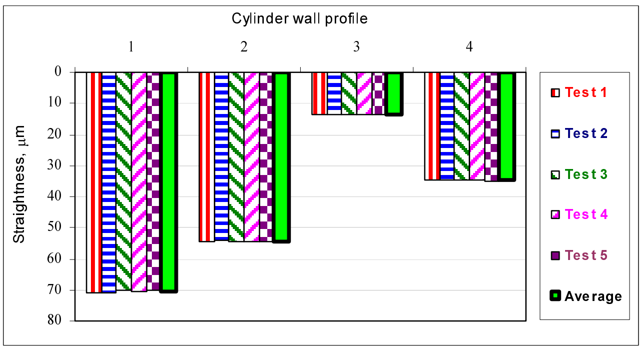


Fig. 4 Bore straightness measurements at four longitudinal equispaced locations

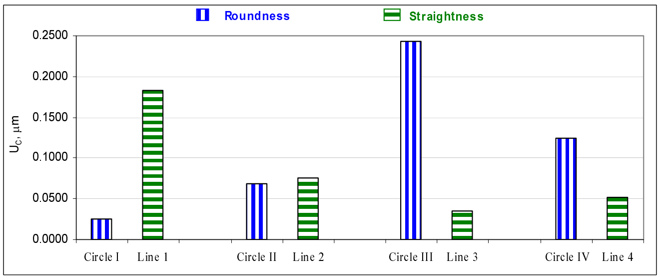


Fig. 5 Uncertainty values of five repeatable tests of OOR and OOS

4. Results and discussion

Roundness, straightness, and concentricity averages for cleaned up worn cylinder bore have been measured using accurate stylus surface scanning technique on a programmable CMM machine. The concentricity is represented by the relative roundness run out at the selected transverse sections I, II, III, and IV with respect to circle I taken as a datum as shown in Fig. 2(b). RMS averaged values of five similar arrays of measurements have been considered. The results have been presented, discussed, and interpreted.

4.1 Out-Of-Roundness measurement results

Average out-of-roundness results (R_a values) have been processed for each measured circle on the bore surface and presented in figure 6 with reference to the nominal diameter, which is numerically computed and found equal 111 mm. The roundness is represented at each transverse section by the domain between the two virtual enveloping circles tangent to the distorted shape processed using LSQ fitting technique built in the machine as indicated in figure 6.

Analysis of the roundness patterns of the cylinder bore, illustrated in Fig. 6, indicates the following points:

- The CMM machine software establishes a reference geometric feature of ideal regular form, deduced numerically from one or more realistic irregular scanned shapes. The established reference datum can be used in the assessment process of the run out values of the geometric features of the object under investigation.
- Circle I nearby the TDC, as expected due to lubricant starvation, depicted the highest average distorted dimension of D_I=111.1779 mm and the largest average out-of-roundness (R_a=90.8 μm). Whereas, the smallest distorted dimension was depicted at section III (D_{III}=111.0204 mm) in the vicinity of the

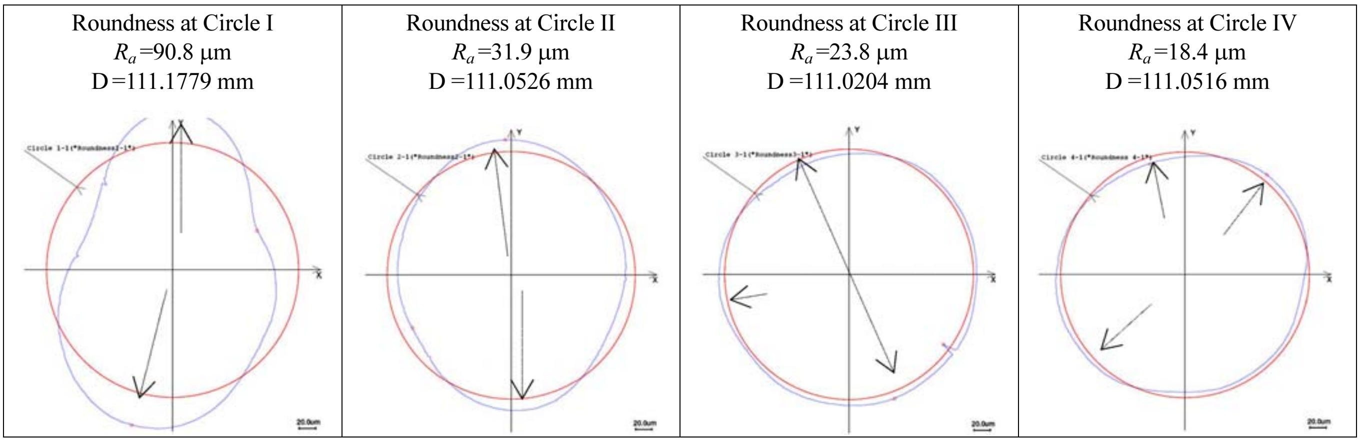


Fig. 6 Roundness sample measurement records of engine cylinder bore (··· maximum amplitudes)

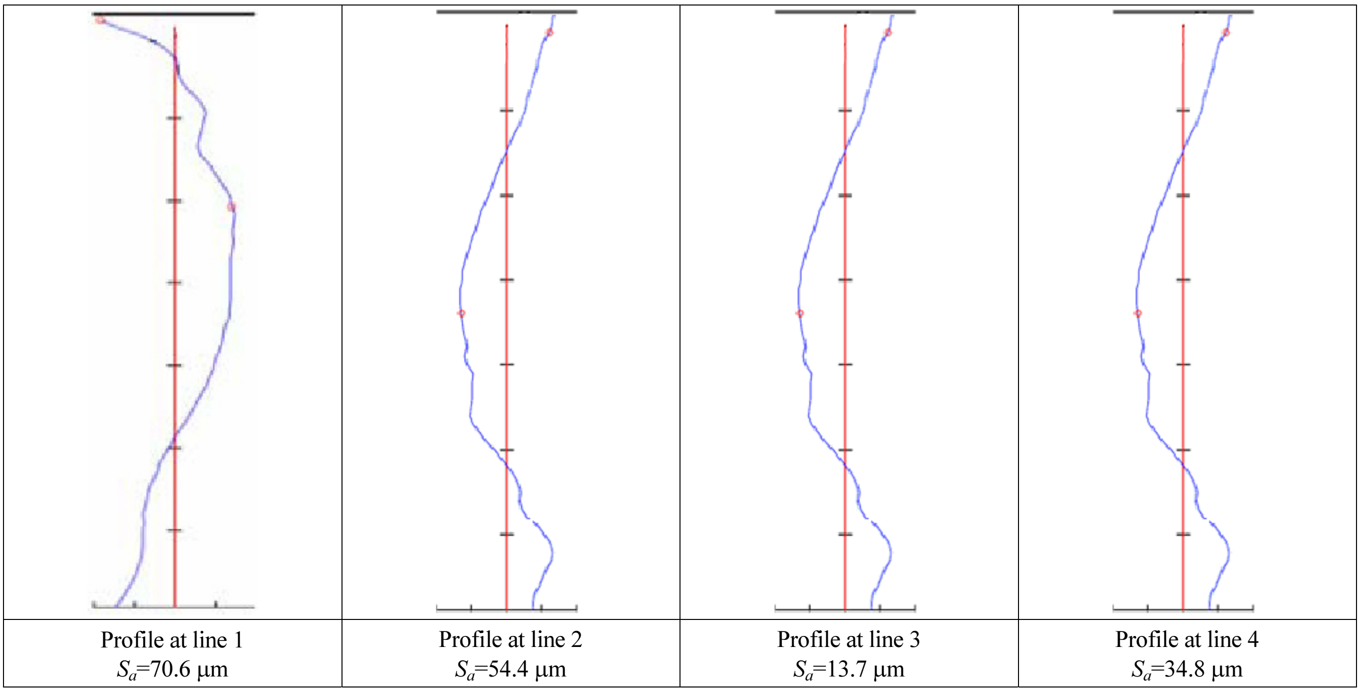


Fig. 7 Longitudinal sample profiles of cylinder straightness (Sa is the averaged straightness of the profile)

mid-stroke point of the piston crown ring with average OOR value R_a=23.8 µm, while the smallest out of roundness value was found nearby the BDC at circle IV (R_a=18.4 µm).

- Roundness of circle I have two maximum amplitudes (arrow tips in Fig. 6) at points corresponding to location of resultant surface reaction $\sqrt{F_s^2+F_a^2}$ of piston side force F_s and crankshaft axial force F_a. The side force amplitude and direction vary according to the nature of piston traveling displacement especially at compression and power strokes.
- Amplitudes of circle III have the smallest wear variation rate with relatively small out of roundness, which may be due to good lubrication conditions and light side forces at that location. Whilst, roundness nearby the BDC (circle IV) has different directions of peak amplitude going with the indicated direction of cylinder distorted shape. This may be attributed to the stud clamping force situation (magnitude and direction) when the piston passes by this location. At both BDC and TDC marginal inversion locations, the loads on the piston generates a stringent translated piston dynamics.

4.2 Concentricity measurements

Experimentally measured values of the relative roundness on the bore at different transverse locations (concentricity) have been found 39.1, 44.4, and 61.2 µm between circles I and II, circles I and III, and circles I and IV, respectively with the axial center line of round profile I as reference datum as shown in Figs 2, 6. This would reflect the distortion resulted from the extremely severe wear mechanisms to which the engine cylinder bore was being experienced during service.

4.3 Out-Of-Straightness measurement results

Figure 7 shows sample record of four averaged longitudinal profiles at equispaced locations 1, 2, 3, and 4 along the cylinder inner wall as indicated in Fig. 2 above. The maximum out of straightness value (S_a) processed from the measurements along each longitudinal profile represents the deviation domain around the relevant reference line obtained by applying LSQ fitting technique.

Straightness profile sample records shown in Fig. 7 disclose the following points:

- Non-uniform wear rates are exposed along all averaged longitudinal profiles. It is clear that every point on the cylinder bore is subjected to different concurrent dynamic and environmental conditions of pressure, friction, lubrication scheme, sliding velocity, contact temperature, and contact force (orientation and magnitude). Thus, frequent evaluation of bore surface geometrical status is needed whenever possible to help monitoring the functional degradation and diagnosing the surface failure symptoms in anticipation. So that, reasonable decisions can be taken regarding surface treatment implementation and/or constructional design improvement inspiration.
- Maximum wear rates have been found to consistently lie within the TDC of the first pressure ring contact area for all averaged profile measurements of 70.6, 54.4, 13.8 and 34.8 μm. This may be explained by the bad tribological conditions at the TDC location as aforementioned. The largest value of straightness departure (70.6 μm) which lies on profile 1 was formed during power strokes as a direct response to large side force reaction at high combustion temperatures. These findings agree with a study carried out by Schneider et al.[5]
- Wear valleys of bore straightness has large values for profile at points 1 and 2 of power and compression stroke ends (nearby BDC) due to side force reaction of concentrated piston inertia, while profile of points 4 and 3 have shown the smallest amplitude valleys, respectively.
- An extended valley of straightness has the first profile of power stroke until 70 mm long; it may be produced of piston-skirt stringent side pressure and combustion gas high temperature beside piston rotation around its pins under the effect of the friction force moment. Strong piston skirt dynamics accelerates the wear of the crankshaft axial movement control washers.

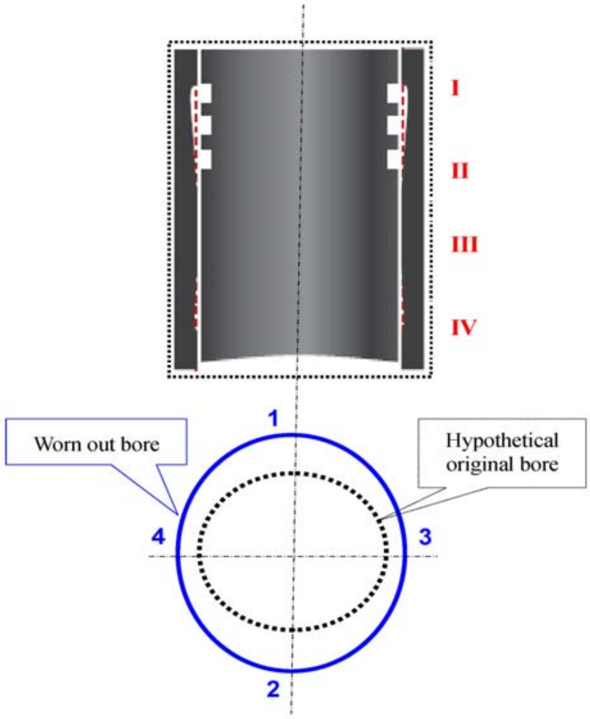


Fig. 8 Illustration of geometric deviations in the cylinder liner

5. Conclusions

- Geometrical and dimensional micro scale precision measurements of straightness, roundness, bore diameter, and concentricity of the internal surface of a worn out engine cylinder have been executed using CMM machine. Compared to its original design GT&D tolerance limits, these measurements proved to represent a novel reliable diagnostic tool for the wear development and aggression monitoring. Scenarios of the probable adverse operating conditions during service may also be drawn. The dimensional measurements of the bore diameter at different transverse locations along the traveling stroke have assured previous findings using other different complicated measuring techniques. In turn, this may provide feedbacks to both the engine designer for modifications and the maintenance engineer for his forthcoming preventive and corrective maintenance plans layouts.
- Wear at the TDC and BDC transverse sections have been found much larger than the wear occurred at the middle of the stroke and near the BDC. This phenomenon is attributed to the continuous existence of lubricating oil film dynamically preserved at that location.
- Precision CMM measurements may also provide an insight in the engine dynamics that may contribute to the excessive wear occurrence in the engine cylinder. The geometric deviation due to inhomogeneous wear has caused ovality in the bore where ($S_{a1}>S_{a2}>S_{a4}>S_{a3}$), as depicted in Fig. 8. This may inspire the engine designer to introduce an innovative modification to the engine by developing a controllable cylinder-rotating device about its axis probably without having to dismantle the engine parts, so that the wear can be homogenized. Thus, the power loss due to friction and wear in the cylinder may be minimized and the engine operating life span may be rather prolonged. In addition, the maintenance expenses may be also reduced.

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