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3-D measurement and visual characterisation of cylinder liner bore polishing

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Abstract

Wear in engine cylinder liners has long been a problem which has attracted considerable attention over the past 50 years. The surface of the liner is usually generated by a combination of base and plateau honing. The honed surface serves a dual function of providing good bearing capability as well as the ability to retain lubricant. Excessive wear can lead to the removal of the honing grooves and the formation of polished regions. These areas, known as bore polish, are detrimental to the overall performance of the engine and can lead to gas blow-by and scuffing. The engine testing industry, as part of their criteria for determining the performance of a lubricant, will inspect an engine liner for the size and frequency of these polished regions. The inspection of bore polish is a long and tedious process carried out by an inspector peering over the liner block with a torch and tracing the outline of polish regions onto an acetate sheet. There are numerous sources of errors and problems associated with this technique.

In order to provide to provide a better insight into bore polishing the School of Manufacturing and Mechanical Engineering, in collaboration with an independent engine testing laboratory, investigated this phenomenon. This paper will describe the current inspection technique and introduce a method of visually characterising the degree of bore polish. In an attempt to quantify the polish categories recently-developed 3-D surface characterisation techniques were employed.

Introduction

The problems of increased oil consumption, blowby, and scuffing have frequently been encountered and reported in heavy duty turbocharged diesel engines [1]. One cause, first reported in the 1960s [2] is a wear phenomenon known as *bore polishing* which entails the generation of a bright mirror-like appearance on the cylinder liner surface along with full or partial loss of the honing pattern. Bore polishing has been attributed to either hard carbonaceous deposits, formed on the top land of the piston or contaminates in the lubricating oil (or even both) [3].

Since the lubricating oil plays a major role in controlling these factors, bore polishing can be suppressed or even controlled by suitable oil formation. A number of engine tests have been developed for evaluation of the bore polishing tendency of lubricating oils. However, problems exist in the standardisation of testing due to design changes in engines and models becoming non-current or obsolete. Quantifying the amount of bore polish present on a liner has usually involved manual inspection of the engine. This can be either destructive with removal and splitting of the liner or non-destructive with the inspector peering inside the engine block.

Bore Polish and Bore Polish Rating

Bore polish involves the removal of the honed topography, by two- or three-body abrasive wear, to generate a mirror-like surface finish. There are varying levels of polish depending on how much of the original honed topography is remaining. The Co-ordinating European Council (CEC) [9] defined bore polish as being "*.... evidenced by clearly defined areas of bright mirror finish. It is caused by local mechanical wear of the surface.*" They went on further to define the visual rating of bore polishing as either light, medium, or heavy polish, the definitions are given in *table 1*. An engine which has developed bore polish will find lubrication oils and exhaust gases passing the rings (i.e. blowby). Where this occurs emission problems will transpire, i.e. a reduction in power output and increased oil consumption. As the bore polish progresses a very smooth surface is produced which leads to lubrication starvation. There is insufficient boundary lubrication to prevent solid contact and the surfaces will run together intimately. Local contact occurs which leads to welding and material transfer (i.e. scuffing) between the surfaces and ultimately complete engine failure.

As part of the comprehensive engine testing carried out when developing a new lubricant or new engine, a procedure is performed to encourage the generation of bore polish. *Table 2* lists the operating conditions of the more

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common tests employed. After the test the engine is stripped and the liners are assessed for bore polish.

Table 1 : Bore Polish Classifications [9]

POLISH TYPE	DEFINITION
Heavy	A mirror finish showing no traces of the original honing pattern.
Medium	A mirror finish showing faint original honing pattern.
Light	A mirror finish overlaid on the original honing pattern

Currently the most common method for detecting bore polish is by manual inspection, the bore polish being rated (by inspectors or qualified raters) as a percentage of the liner swept area (above bottom ring reversal). This technique [10] involves the inspector laying an acetate sheet on the bore face and, by the use of a mirror, pen and light source, determining where the polish occurs within a standard assessment area. The regions of polish are then traced around and, by calculating the areas of polish over the liner surface, a percentage polish value is calculated (*figure 1*). The advantage of this method is that a permanent record is made as well as the location of the polish being recorded. It should be noted that while there exists definitions to distinguish low, medium, and heavy polish, engine raters only specify if an area exhibits polish or not and doesn't consider the severity.

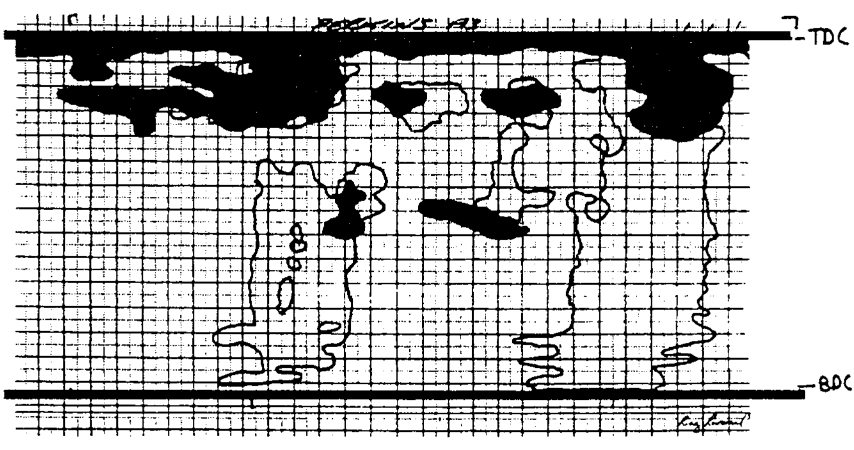

Figure 1 : Manual rating of polish after 400 hours (black is areas of polish viewed from the top while white are additional regions of polish detected after splitting the liner)

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The disadvantages are more numerous, the variations between inspectors on how much polish is present can be quite large and has been reported, by Pritchard and Palmer [**4**], to be as high as 20%. Lighting conditions are critical as too much reflectance and transmittance can make boundary definition very difficult. In addition, the whole nature of the rating is one that can not be performed on-line. It is also time-consuming, should only be carried out by qualified raters, and is dependant on the rater's perception of what constitutes polish.

An additional problem encountered by inspectors is the difficulty in determining the boundaries of the polished area which can lead to an overestimation [**11**]. The mechanism of polishing is a progressive phenomenon and can range from being indistinguishable from normal wear to a mirror finish without honing marks. Because of the graduation of polish it makes defining the boundaries difficult. With engine tests split between different laboratories such a variation could have a significant influence on whether a lubricant formulation is accepted or rejected, thus this error can no longer be tolerated. To reduce this subjective error a number of instruments have been proposed and developed [**5-8**]. However, it is the manual rating method which is still the only technique acceptable to the standards committees. Bore polish is an early indicator of imminent engine failure. Detecting and assessing bore polish as early as possible can result in considerable time and cost savings in engine testing. The problems associated with manual raters led to collaboration between the School and an independent engine testing laboratory to develop non-visual surface characterisation techniques.

Table 2 : Operating Conditions for the Main European Heavy Diesel Bore Polish Engine Tests

	Daimler Benz OM364A	Ford Tornado	MAN 2866 KSZ
Cylinders	4 in line	6 in line	6 in line
Displacement	4.0 litre	5.6 litre	12.0 litre
Aspiration	Turbocharged	Turbocharged	Turbocharged
Operation	Cyclic	Cyclic	Cyclic
Evaluation ◆ Piston Deposits ◆ Liner Polishing ◆ Oil consumption	 1st & 2nd groove Yes -	 - Yes -	 1st groove
Specifications	CCMC D3 DAF SHPD DB 227.0/1 DB 228.2/3	DAF SHPD RVI SHPD VOLVO VDS	MAN QC 13017

Bore Wear and Piston Motion

The wear patterns on the cylinder bore have been observed and mapped using 2-D stylus instruments by Ishizuki *et al* [12] as shown in *figure 2*. It can be seen in this figure that the greatest amount of wear occurs on the anti-thrust side and is concentrated at the position close to top dead centre (TDC).

For severe cylinder liner wear, heavy bore polish may appear at the positions as indicated in *figure 2*. These wear patterns can be related to the piston motion as shown by the piston traverse motion and tilting positions monitored by Ishizuki *et al* [12]. A diagrammatic layout of this motion is shown in *figure 3*.

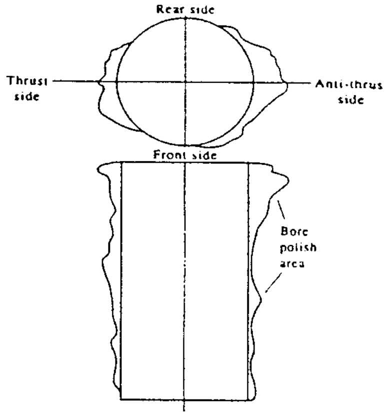

Figure 2 : Cylinder liner wear patterns (adapted from Ishizuki et al [12])

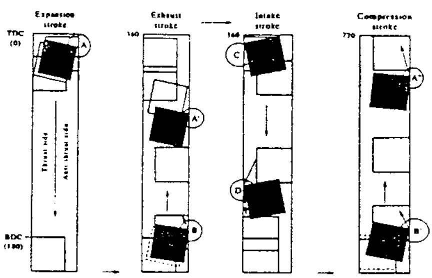

Figure 3 : Diagrammatic representation of piston motion (adapted from Ishizuki et al [12])

This indicates where contact occurs between the piston rings and cylinder wall during engine working strokes. From *figure 3* it can be seen that the major points of contact are on the anti-thrust side during the compression, expansion, and exhaust strokes. The action results in the wear pattern mentioned above and shown by Davis [13] and Dong *et al* [14].

3-D Measurement and Parameters

3-D surface measurement is a relatively new development which arose from the limitations which are inherent in 2-D stylus profilometry. There are a number of advantages to using 3-D measurements, these include:

- The information content of an areal measurement is greater than that from a profile, such as showing directional lay.
- 2-D profiles are more subject to erroneous features such as scratches. Parametric variation of up to 60% occurs along the same surface .
- 3-D measurement allows the surface to be easily visualised.
- Interactions between surfaces occurs in 3-D not two, therefore it makes more sense to measure in 3-D.

As a result of the largely uncoordinated development of 2-D surface metrology, well over 100 numerical roughness parameters were developed, with many of these having only limited significance [**15**]. To avoid the recurrence of this situation, a structured European Union (EU) based programme has been initiated for a new fundamental, 3-D surface measurement standard [**16**] and a minimum set of parameters deemed sufficient to characterise most surfaces.

The main differences between 3-D parameters and their 2-D counterparts are :

- The 3-D parameters use the least square plane as a reference plane. This levelling process has the shortcoming of introducing a 5% calculation error [**16**].
- National standards for 2-D characterisation evaluate the parameters over several sampling lengths, whereas 3-D parameters are determined within one sampling area.

It is worth noting that the parameter set has yet to be fully validated although this has not stopped instrument manufacturers from incorporating the parameters into their software [**17**].

For the analysis presented in this paper only a few of the parameters were selected. Three of the chosen parameters; S_q, S_{sk}, and S_{ku} are the direct 3-D counterparts of R_q, R_{sk}, and R_{ku} known as RMS roughness, skewness, and kurtosis respectively. The fourth parameters; the root mean square slope of the surface within the sampled area (S_{dq}), has some relevance to the reflectively of surfaces which is particularly important to optical mirrors. The lower the value the more reflective the surface is. The actual mathematical definitions for all 4 parameters is provided in the EU document [**16**].

Experimental background

Experimentation was carried out on a number of engine liners which had been subjected to the bore polishing tests described in *table 2*. For the first part of the analysis a liner was longitudinally spilt in half and a strip 20mm wide and 240mm long was cut from the anti-thrust face. The strip exhibited the varying degrees of wear ranging from the heavy polish at TDC to the unworn plataeu-honed surface below bottom ring reversal. The strip was further sectioned into 24 samples each 10mm long and these were then measured using

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a Taylor Hobson Form Talysurf, the measurement conditions are provided as an appendix. For the second half of the analysis the other liners were split in two and the severity of bore polish using the definitions presented in *Table 1* were assessed by a qualified manual rater. The regions of low, medium, and high polish were marked and then measured under the same conditions employed for the previous section over 80 measurements were taken.

Results

The parametric variation down the liner is presented in *figure 4 (a-d)* with the positions of TDC, Bottom Dead Centre (BDC), and mid-stroke marked on. *Figure 5(a-d)* presents the results for parametric variation in relation to the severity of bore polish. *Figure 5(a-d)* are topographic plots representing the 3 categories of liner polish as well as the unworn topography.

Discussion

The parameter S_q (*figures 4a)*, varies by a factor of 10 down the liner length. At position *5mm,* the parameter has a high value due to the carbon build-up which has occurred above TDC. At *TDC* the parameter drops towards a lower value suggesting a mirror-like finish is present. A slight variation in the parameter occurs until at *65mm* when a noticeable drop is observed - this region is mid-stroke where the piston moves from one face to the other causing additional contact (and thus wear) between the piston skirt and the liner. A gradual increase in the values occurs until *115mm* where the top ring in the piston pack begins to reverse at BDC. The zone *125 to 185mm* is where the piston begins to slow down as it approaches BDC. As the piston speed reduces the likelihood of interasperity contact increases and this is most prominent *185mm* down the bore where the bottom piston ring reverses direction. Below *185mm* is the unworn topography and this is substantiated by the increase in S_q.

Skewness and Kurtosis (*figures 4b* and *d)* have both been described as useful indicators of wear. As would be expected skewness remains negative throughout the liner length implying a valley-dominated surface. Significant changes in the parameter value (*figure 4b)* are produced at TDC, mid-stroke, and BDC. Kurtosis (*figures 4c)* varies from around 10 to highs at TDC, mid-stroke, and BDC. The S_{dq} value indicates the RMS value of the surface slope - as the topography approaches a mirror finish the parameter will tend towards zero. The unworn region of the liner registers a S_{dq} of 0.07 to 0.09 mm/mm which is quite typical for a plateau-honed surface [25]. Lower values are recorded near TDC, Mid-stroke, and BDC reiterating that the surface is becoming polished.

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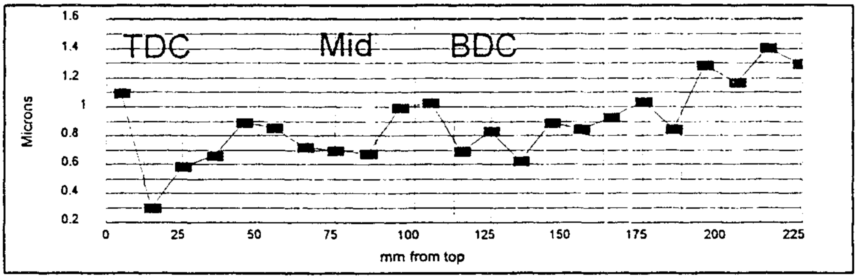
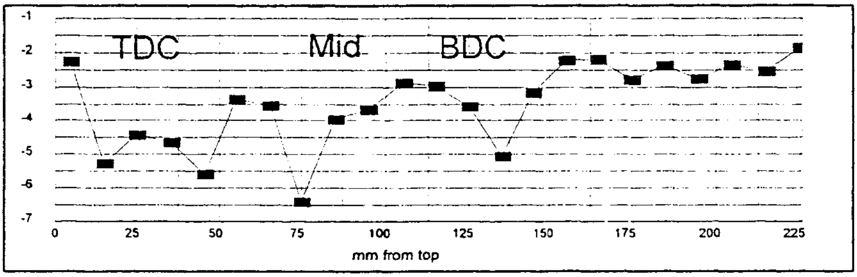
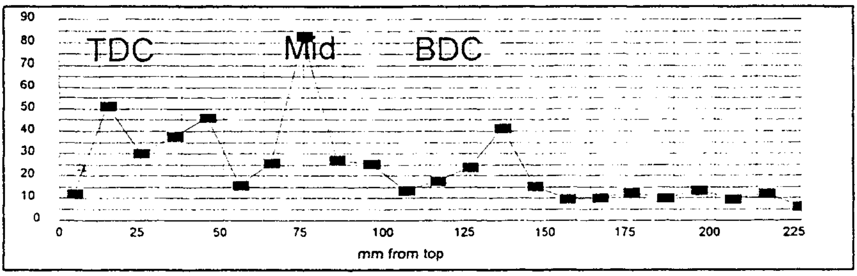


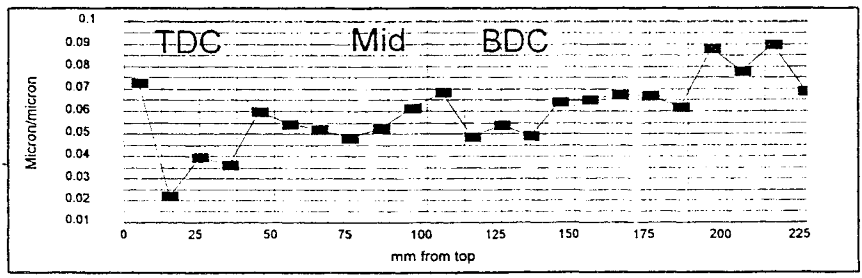
(a) S_q



(b) S_{sk}



(c) S_{ku}



(d) S_{dq}

Figure 4 : Parametric results down the liner

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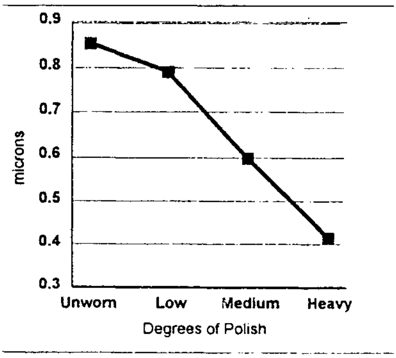
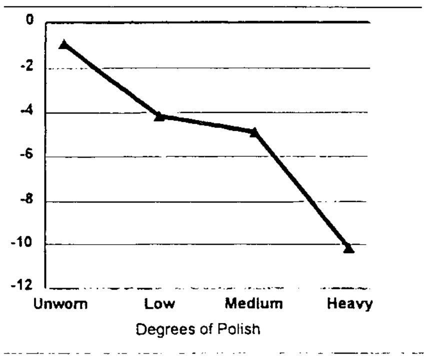
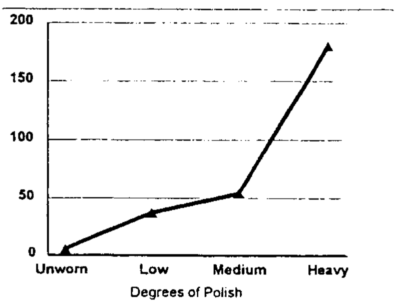


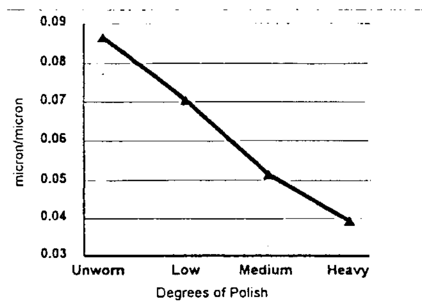
(a) S_q



(b) S_{sk}



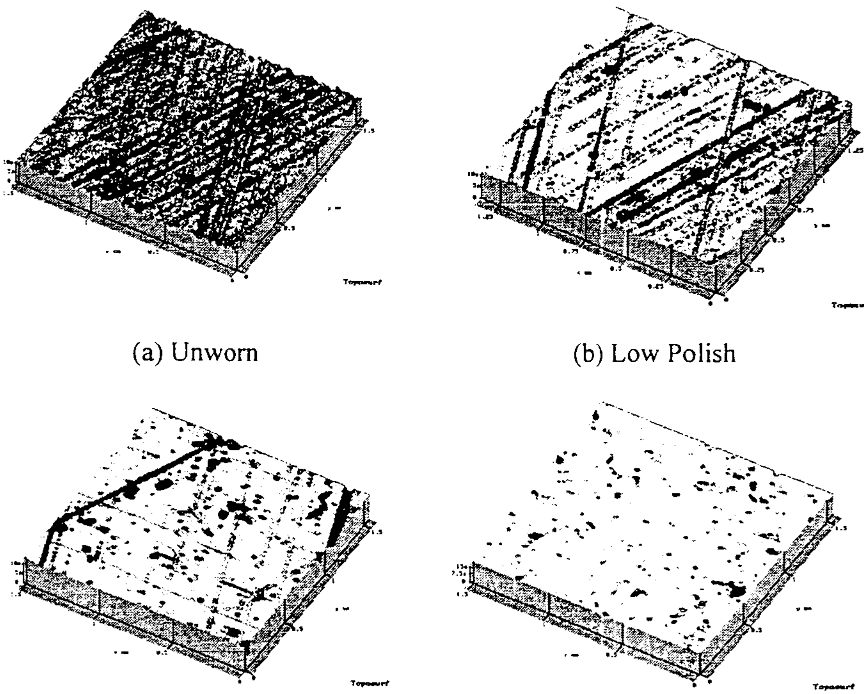
(c) S_{ku}



(d) S_{dq}

Figure 5 : Parametric variation and severity of polish

As the surface progresses through the various degrees of polish the overall RMS roughness (*figure 5a*) decreases. This can be attributed to the overall smoothing of the topography by the removal of the plateaux and the partial filling-in of the valleys (as illustrated in *figure 6a-d*). As the wear progresses skewness (*figures 5b*) becomes more negative denoting a surface which is more valley-dominant. This can be explained by the fact that the sliding motion present in the engine liners would remove the majority of peaks thus shifting the symmetry of the surface amplitude distribution. The rapid increase in kurtosis suggest that (coupled with skewness) the surface is being dominated by sharp deep valleys or pits. The large values of kurtosis (*figures 5c*) imply that the surface at *heavy polish* can no longer fulfil a suitable lubricant/ load bearing function. The RMS slope of the surface decreases significantly (*figure 5d*) as the surface becomes more polished. This is not surprising considering that the human detection/ classification of polish is dependent on the slopes of the surface strong correlation would be expected.



(a) Unworn (b) Low Polish

(c) Medium Polish (d) Heavy Polish

Figure 6 : Topographic Plots of Cylinder Liner Wear

Conclusion

The selected parameter set has demonstrated good correlation between stylus and visual techniques. The added advantages of the non-visual method is that the severity of bore polish can now be assessed.

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Appendix

Instrument	: Taylor Hobson Form Talysurf 120L
Measurement area	: 2mm by 2mm
Sample Spacing	: 12.26 by 12.26 microns