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Wear measurement of the cylinder liner of a single cylinder diesel engine using a replication method

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ABSTRACT

Published data on piston ring and cylinder bore wear in engines is very limited because of the technical difficulties involved in performing the measurements. Moreover, cylinder bore wear is more difficult to measure than ring wear because it occurs over a much larger surface area, and the wear rates vary widely at different locations on the bore. In this paper, cylinder liner surface roughness and wear measurements were performed through an experimental study of a single cylinder diesel engine operating at a steady-state. A replication method was used to evaluate wear and surface roughness on a cylinder liner, where measurements were made at different locations on the cylinder liner before and after each test. Replicated surface profiles were measured by a WYKO NT 1100 optical surface profilometer. It was found that surface roughness decreased with time and the rate of decrease was higher during the run-in period. A unique wear volume calculation method that includes bearing ratio parameters was proposed, and reasonable results for wear volume were obtained. Cylinder bore wear rates measured by this replication method were consistent with long-term wear observed in different tests of diesel engines.

1. Introduction

In an internal combustion engine, piston rings and cylinder bore play very important roles in achieving desired engine performance and durability. A higher ring tension results in better sealing, but increases friction and may also increase wear of rings and cylinder bore. Wear in most cases occurs through surface interaction at asperities and is a complex process influenced by a number of factors including the metallurgy of contacting materials, surface texture, operating conditions of the components, load, speed, temperature, environment, and lubricant formulations [1]. The wear process is generally quantified by wear rate, which is defined as the volume or mass of material removed per unit time or per unit sliding distance.

Published data on ring and bore wear in engines is very limited because of the technical difficulties involved in performing the measurements. Cylinder bore wear is even more difficult to measure than ring wear because it occurs over a much larger surface area, and the wear rates vary widely at different locations on the bore. Ring wear can be determined by simply measuring mass loss, but bore wear must be determined by careful dimensional measurements at different locations. Bore wear is generally reported as a dimensional change at the maximum point of wear, e.g. at top ring reversal, rather than as weight loss.

Several experimental methods, bench tests and wear models have been developed to collect data on piston ring and cylinder bore wear rates in diesel and spark-ignition engines. Schneider and Blossfeld [2] developed a radiotracer method to measure piston ring and cylinder liner bore wear rates in a spark-ignition engine, where rings and cylinder bore were made radioactive by surface layer activation, and both ring and bore wear data were obtained by measuring the accumulation of radioactive wear debris in the lubricating oil. Cylinder bore steady-state wear rates were very low compared to the wear generated during initial break-in and when changing from one operating condition to another. Radil [3] also developed bench tests that simulated top ring reversal (TRR) conditions to investigate lubricants and piston ring/cylinder liner materials for advanced diesel engines. To better evaluate the effectiveness of the test method in simulating the wear at TRR, a top compression ring and a cylinder liner were obtained from a real engine that operated in the engine for almost 400,000 miles. It was shown that the ring and liner specimen wear surface morphologies were quite similar to real engine experience near TRR. Wear results for the laboratory test liner specimens were an order of magnitude greater than the wear on the engine liner.

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Nomenclature

A	base area of a pyramid
A_k	bearing surface area at the interface of the core and the valley
A_M	surface area measured by WYKO profilometer
A_p	bearing surface area at the interface of the peak and the core
A_1 and A_2	top and base areas for a frustum
h	height of pyramid or frustum
H_{tp}	height difference between bearing surfaces
M_{r1}	material component relative to peaks
M_{r2}	material component relative to valleys
R_a	roughness average
R_q	root-mean-square roughness
R_z	10-point height parameter
R_t	roughness total
R_k	core roughness depth
R_{pk}	reduced peak height
R_{vk}	reduced valley depth
t_p	bearing ratio
TRR	top ring reversal
V_1	the volume of material that will be removed during run-in period
V_2	the potential volume of retained lubricant
V_K	volume relative to core
V_p	volume relative to peaks
V_v	volume relative to valleys
V_{tot}	total volume
$V_{\text{tot.after}}$	volume after the test
$V_{\text{tot.before}}$	volume before the test
W_{vol}	wear volume

A laboratory bench test to evaluate piston ring and cylinder liner materials for their friction and wear behaviors in real engine oils was also presented by Truhan et al. [4]. Ring segments were tested against flat specimens of gray cast iron typical for cylinder liners. A geometric model was developed to calculate the wear volume of both the ring segment and the cast iron flat that takes into account the compound curvature of the ring segment and the curvature of both wear scars. It was found that wear testing at fixed load accelerated the wear rates of the ring and cast iron flat by at least an order of magnitude over that observed in an operating engine.

In addition to experimental investigations, wear processes have been simulated by modeling. An abrasive wear model for both cylinder bore and piston ring for the steady-state period, based on Archard's wear equation was developed by Gangopadhyay [1]. The model took into account ring geometry, ring tension and lubricant properties, but did not take into account the effect of bore distortion, transients, fuel dilution, corrosive wear, etc. According to this model, the wear depth decreased below the second ring position due to the decrease in gas pressure. The top ring reversal location showed more wear than the second ring as a result of the higher gas pressure. Qiu et al. [5] developed a new wear model for piston ring and cylinder bore systems based on contact mechanics. It was found that the accumulated wear of the ring and the bore surface increased with running time, and the wear distributions of the ring and the bore coincided with trends seen in real engine applications. The wear of the two ends of the cylinder bore, especially at the top ring reversal area, was higher than that of the mid-stroke portion of the cylinder bore.

Direct and real time measurement of surface parameters and wear on an engine cylinder bores are still very limited, and it appears that there are no published papers that present the evolution of surface parameters at a certain location on the cylinder bore. The purpose of this work is to measure the cylinder liner surface roughness and wear that occur in a single cylinder diesel engine using a replication method. Surface profiles on a replicate were measured using a WYKO NT 1100$^{\text{TM}}$ optical surface profilometer. Using the replicate data, a unique method was developed to calculate wear volume and wear rate of the cylinder liner. The evolution of roughness average and wear volume are shown for different locations on the cylinder liner, and average wear depth is compared to published results from other methods.

2. Experimental apparatus

2.1. Engine and generator apparatus

A single cylinder, air cooled, direct-injected Yanmar L100EE diesel engine was coupled to a PRAMAC ES5500C generator set to provide load control. The generator set has a nominal 5.5 kVA peak output and was connected to a variable load-bank of resistance heaters, which enabled the engine load to be incrementally applied for warm-ups and cool-downs. The engine has an aluminum engine block and a cast iron cylinder liner, and was operated at the nominal full speed of 3600 rpm. The engine crankcase was modified to facilitate the removal and reinstallation of the piston and the connecting rod in order to install the piston and rings into the engine and perform bore measurements at the start of each test. This modification greatly reduced the time needed to measure and document all of the cylinder kit parameters prior to each test. The engine was mounted in a way that facilitated access to the underside of the engine for the removal of the piston assembly.

2.2. Replica preparation and wear measurement

Since it is very difficult to measure the surface of the cylinder bore surface directly, a replication method was applied to obtain the surface profile of the bore before and after each test. A fixture, designed by CK Technology (patent pending), was to ensure an accurate, repeatable replication process. The fixture included a 16 mm diameter rod that had an indexing feature and a channel to hold the replicating material. The replicating material used was Struers Repliset®. Repliset is a silicon rubber which is a liquid before curing. When mixed with a curing agent, it will cure in 10–15 min. Repliset can replicate surface details over the entire replica surface with a resolution down to 0.1 μm. The uncured liquid Repliset was dispersed in the channel of the rod and held against the cylinder bore surface by the fixture. Once cured, the Repliset was carefully peeled away from the cylinder bore, and then measured by the WYKO NT1100 optical surface profilometer. The replicas were produced at four circumferential locations, 90 degree apart, around the bore: i.e. thrust side, anti-thrust side, front side and back side. For each replica, surface profiles were measured at four locations along the axial direction of the bore: i.e. the top ring reversal, the second ring reversal, the middle of the stroke and the bottom dead center of the oil ring reversal, as shown in Fig. 1. Therefore, data were collected at 16 locations of the cylinder bore for each measurement.

2.3. Wear test procedure

Before each test, the cylinder head was removed from the engine and the piston was removed from the cylinder bore and the cylinder bore was honed using a FLEX-HONE$^{\text{TM}}$ in order to obtain a new surface profile. The Flex-Hone® is self-centering, self-aligning, and self-compensating for wear so it does not require an elaborate fixture or special training to use it [6]. The Flex-Hone is widely used in the USA for rebuilding engines and is also used by at least one