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Failure analysis of worn valve train components of a four-cylinder diesel engine

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ABSTRACT

This work investigates the causes of excessive wear occurring at the rocker arm/pushrod and rocker arm/valve interfaces of a diesel engine for industrial cleaning machines, after only 1000 h of engine operation. In this engine, the recent replacement of tappets by hydraulic valve lifters not only reduced the running time but also required supplementary maintenance. The chemical composition of the worn components was verified by optical emission spectroscopy. The microstructures, mechanical properties and surface textures were determined by optical microscopy, Vickers hardness and non-contact 3D profilometry. To evaluate the wear mechanisms, the worn surfaces were analyzed by scanning electron microscopy with energy dispersive spectroscopy. The results indicated non-uniform wear damage at the rocker arm/valve interface, probably due to a misalignment of valves with respect to valve seat inserts. For rocker arms and pushrods, improper austenitization parameters and/or unsuitable design of the inductor left some free ferrite, responsible for non-compliance with required specifications for the induction hardening treatment. All worn surfaces were characterized by material removal by scuffing; initiation of fatigue cracks was also observed at the rocker arm/valve interface, and probably erosive cutting occurred at the rocker arm/pushrod interface.

1. Introduction

Diesel engines for industrial machines generally undergo heavy using conditions, thus wear may quickly jeopardize their functions unless carefully monitored and controlled. From a tribological point of view, since 1950 the use of more efficient fuels and compact engines with low environmental impact caused an increase of specific loads, operative velocity and temperature of all components subject to wear and friction. Moreover, the use of low-viscosity lubricating oils necessarily has led to a reduction of lubricating film thickness between the contact surfaces in reciprocating sliding motion [1]. The cost of diesel engines has been greatly affected by the increasing demand for long duration and prolonged maintenance intervals [2, 3]. The increasing request by laws and customers for abatement of pollutant emissions has also favored the development of several technologies to eliminate soot, mostly produced by obstruction of injectors and accumulation of carbon particles in manifolds [4]. Soot particulate emissions are known to reduce wear and fatigue resistance of diesel engine components due to the interactions between soot, metal and lubricant additives or among soot particles [5–8].

Recently, modeling and simulation in engine designing have emerged as important tools for optimizing and predicting wear of mechanical systems under variable load and/or sliding speed. For example, a model of rigid body mechanics was used to simulate the

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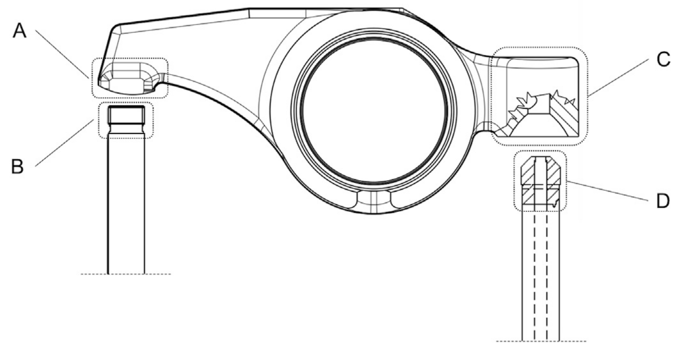

Fig. 1. Schematic representation of outlet/inlet rocker arm and parts of pushrod and exhaust/intake valve. The dashed lines enclose the regions with worn surfaces. A: outlet/inlet rocker arm pad. B: exhaust/intake valve stem tip. C: outlet/inlet rocker arm pivot socket. D: pushrod ball end.

contact between the rocker arm pad and the valve bridge in the cam mechanism of a diesel engine: the results showed that the radius and the center position of the wear pad influenced the maximum wear depth and distribution [9]. When a re-design of the tribological system is required, it is advisable to perform a control of the wear mechanism in real components, where the main cause of failure is faulty manufacturing involving cracks, stress concentration or improper heat treatments. The failure analysis of two rocker arms from heavy duty diesel engines [10] showed a banded microstructure and the spheroidization of cementite in pearlite, deriving from an unsuitable normalizing heat treatment. These metallurgical defects lowered fatigue strength and favored initiation and growth of fatigue cracks with multiple origins. Another study attributed to stress concentration the failure by fatigue of a diesel engine rocker arm [11].

The present study investigates the causes of excessive wear occurring at rocker arm/pushrod and rocker arm/valve interfaces of a diesel engine for industrial cleaning machines. In this engine, the recent replacement of tappets by hydraulic valve lifters not only reduced the running time but also required supplementary maintenance. The chemical composition of the worn components was determined by optical emission spectroscopy (OES) and the microstructures were identified by optical microscopy (OM). Vickers hardness and surface texture measurements were also performed. Finally, to determine the wear mechanisms the worn surfaces were studied at high magnification by scanning electron microscopy with energy dispersive spectroscopy (SEM/EDS).

2. Material and methods

Four pairs of rocker arms, pushrods and valves were collected from a four-cylinder diesel engine for industrial cleaning machines. In this engine, all clearances at the induction hardened regions were set back to zero due to excessive wear after only 1000 h of engine operation. A schematic representation of the outlet/inlet rocker arm and parts of the pushrod and exhaust/intake valve is shown in Fig. 1, together with an indication of the regions with worn surfaces. The outlet/inlet rocker arm, pushrods and the exhaust and intake valves were prepared for analysis of the chemical composition of the steel types by optical emission spectroscopy (OES) through a SPECTROLAB analyzer (SPECTRO Analytical Instruments GmbH, Kleve, Germany). The details of chemical composition of the different steel types are shown in Table 1. In order to increase surface hardness and contact fatigue resistance, in this engine some regions of the outlet/inlet rocker arm pad, the outlet/inlet rocker arm pivot socket, the pushrod ball ends and the exhaust/intake valve stem tip were induction hardened. The required specifications concerning Rockwell hardness values (HRC) and effective depth of the regions undergoing induction hardening treatment are shown in Table 2.

The worn surfaces were first observed by a Leica MZ6 (Leica, Wetzlar, Germany) stereomicroscope. To determine the microstructures of alloys, longitudinal sections (parallel to the metal surface) and cross-sections (perpendicular to the metal surface) of the samples were prepared, mounted in resin, polished and analyzed by a Leica MEF4M optical microscope (Leica). Microstructural investigations were carried out after chemical etching by Nital 4 (4% nitric acid in ethanol) under the same optical microscope. The micrographs of the cross-sections were processed by Leica Application Suite (LAS, Leica) image analysis software to evaluate the area fraction of metallographic phases occurring in the induction hardened regions. A mean of 15 micrographs were analyzed for each component. On the cross-sections, Vickers hardness measurements (HV1) under 1000 g_f load and 15 s loading time were performed in triplicate at increasing distances from the worn surfaces (0.2–4.0 mm) by a Future-Tech FM-110 Vickers microindenter (Future-Tech

Table 1
Chemical composition (wt%) of steel types of the worn components of a four-cylinder diesel engine for industrial cleaning machines.

Component	C	S	Mn	Si	Cr	Ni	Mo	Cu	Fe
Outlet/inlet rocker arm	0.42	0.020	0.71	0.16	0.13	0.08	< 0.03	0.17	balance
Pushrods	0.37	< 0.002	0.67	0.20	0.19	0.07	0.06	0.14	balance
Exhaust valve	0.50	0.006	0.47	3.34	7.68	0.13	0.03	0.03	balance
Intake valve	0.88	< 0.002	0.60	0.61	16.15	0.13	1.75	0.05	balance