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Wear of hardfaced valve spindles in highly loaded stationary lean-burn large bore gas engines

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ABSTRACT

The technological evolution of more efficient natural gas-fuelled large bore engines aggravates the load situation within the engine and thus as well the tribological system valve spindle/seat ring. As a result of these changes, valve recession increases and component lifetime decreases, i.e. higher failure rates and more frequent service intervals. The tribological issues can be traced back to the cleaner combustion which demonstrably suppresses the formation of a protective layer on the sealing faces.

In this work, Stellite® and Tribaloy®-hardfaced valve spindles with different operating hours and from the same gas engine were analyzed in terms of quantitative wear, oxidation and microstructural alterations in the wear scar. The observed wear mechanisms are based on microstructure fatigue and delamination, depending on the microstructure of the hardfacing. The severely worn sealing interfaces show no tribofilm at all, whereas a protective oxide layer is observed on the surface of the Tribaloy® hardfacing that features low wear.

The second part of this work describes wear phenomena observed on specimens from laboratory experiments using a newly developed component test rig – the valve spindle tribometer. The authors describe their approach to investigate wear mechanisms by separated simulation of valve closure and peak combustion pressure depending on different key parameters such as valve closing velocity, temperature or atmosphere. From these preliminary results, probable wear mechanisms are derived and correlated with microstructural properties of the hardfacing alloys.

1. Introduction

Disregarding all efforts towards lowering the private and industrial energy consumption by increasing the efficiency of buildings, transportation and manufacturing, the global demand of electric energy will further increase [1]. Parallel to the increasing demands, the ongoing transition from nuclear and fossil-fuelled energy to renewable and sustainable energy sources calls for intermediate solutions. One important application in this field is stationary gas-fired power plants that are developed for decentralized electrical power generation. The development of large bore gas engines towards 50% electrical efficiency, the operating conditions become more demanding for the conventional construction materials. Since highest valve wear is a consequence of this development numerous studies focus on this subject.

The most critical parameters that may strongly reduce the lifetime and reliability of gas engines are temperature and peak combustion pressure [2–6], atmosphere [4,5], and closing velocity [4,7]. Further studies took into account axial misalignment [3,6,8], operation time [2,4–7], valve rotation [3,4,6], and operation frequency [4–7]. The most important finding was that increasing the temperature and combustion pressure result in higher valve wear. Yet, increasing these two parameters is usually desired since this measure improves the engine efficiency and emissions. Most of the mentioned studies have been focusing on diesel engines. Nevertheless, they provide some fundamental insight in the complex tribological situation of the component pair valve spindle/seat ring which might show similarities to natural gas-fuelled engines.

On principle, the constructional changes of gas engines in comparison to diesel and gasoline driven engines are small, but the operational conditions give rise to different thermal and mechanical loads on the wear pair valve and seat ring. In state-of-the-art large bore diesel engines, common valve recession of Stellite® 12-hardfaced valves is about 0.5 mm after 24,000 h of operation, i.e. a linear wear rate of 21 nm/h. However, wear rates of about 600 nm/h were measured by the authors on valves from highly loaded large bore gas engines which achieve nearly the efficiency

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of diesel engines. This multiple increase in valve wear demands a sustainable approach in component design or material selection. These changes and choices shall be based on a fundamental understanding of the occurring wear mechanisms in the conventional components. An important aspect is the formation of so-called protective tribofilms which are mentioned by several researchers.

According to de Wilde, severe valve wear results from micro-sliding between the contact surfaces of the valve and seat ring as a result of high peak combustion pressure. The detrimental effect of high impact loading by valve closure can be suppressed by adjustment of the valve train dynamic [9]. De Wilde also states that a mixed FeO-Cr_2O_3 oxide layer on the surface of austenitic steel valves provides a low coefficient of friction and ensures low wear.

Liang et al. associated wear patterns on different valve seat inserts with seizure and thus adhesive wear, especially for iron base alloys [10]. Furthermore, Liang et al. observed the formation and propagation of cracks in the microstructure underneath the worn surface as a result of shear stress. Thus, the tribological load conditions may be described as a superposition of adhesive contact and relative shear movement.

Zhao et al. studied the wear behavior of different material combinations in a valve seat wear simulator at 538 °C and 649 °C [11]. Abrasive wear was considered to result from increased amounts of wear particles due to misalignment of valve and seat ring, whereas adhesive wear is attributed to incompatibility of the applied materials. Furthermore, plastic deformation was related to hardness and oxidation of the surface, which are all temperature-dependent factors. Wang et al. tested similar material combinations in order to rank the wear resistance in component tests [12]. Based on their microstructural investigations, Wang et al. came to the rather general statement that valve wear is a complex combination of adhesion, shear strain, and abrasion in which the formation of a protective oxide films on the surface is crucial for valve lifetime. Since the formation of oxides on metals and alloys depends strongly on the surrounding gas atmosphere and its water vapor content [13], this aspect must not be neglected when analyzing wear of valve sealing surfaces.

Two studies of Forsberg et al. focused on the role of tribofilms on exhaust valves and seat inserts [5,14]. It was concluded that oxidation is the dominant mechanism acting on valve seat insert materials: oxides can form a thin yet highly protective tribofilm that suppresses abrasive wear [14]. Furthermore, a triboflim is preferentially found on the seating faces of valves and not on seat rings. This tribofilm is based on combustion residues of oil vapor in hot air (600 °C) that are compacted by the repeated valve closure impact and micro-sliding due to high combustion pressures [5]. The investigations by Forsberg et al. showed a significantly lower hardness of the tribofilm at room temperature as well as a qualitatively lower surface roughness in comparison to the unworn valve seat material. Chun et al. observed the formation of tribofilms that are based on tribochemical reaction products from valve, valve seat insert and surrounding liquefied petroleum gas (LPG) containing atmosphere at 350 °C [4]. Thus, the reduction of particulates in lean-burn gas engines is considered to reduce the formation probability of such a protective layer.

Most studies on valve wear point out the presence of a protective tribofilm on the seating faces. Three sources of educts for the formation of a protective tribofilm are known from literature and can be confirmed by the authors for lean-burn large bore gas engines, as depicted in Fig. 1:

- Partially burned and combustion products of fuel and oil form deposits on all accessible surfaces inside the combustion chamber, especially on the seating faces of valve and seat ring [5];

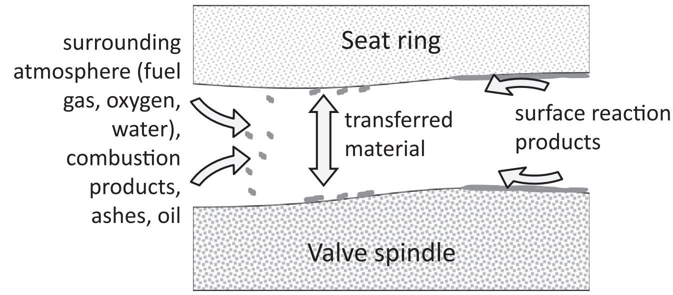

Fig. 1. Possible sources of educts for tribofilm formation in the contact of seat ring and valve.

- Transferred material from seating faces of the seat ring to the valve and vice versa, which undergoes grain refinement and can form a built-up layer based on adhesion [10,12];
- Chemical reaction products of the surfaces with the surrounding atmosphere, enhanced by the high operating temperatures, preferably forming oxide layers [4,14].

Nowadays lean-burning gas engines show highly reduced particulates from combustion processes and operate at higher temperatures and higher pressures than former generations. Due to this, the tribofilm is less probable to be formed and at the same time, the tribological load on the sealing surfaces becomes more severe, giving rise to higher valve wear.

The intention of this paper is to describe the wear mechanisms found on valves taken from real lean-burn gas engines and to compare the phenomena with those found on valves that were tested in a newly designed valve wear tribometer. The features of this tribometer will be described in short in Section 2.

2. Experimental

2.1. Wear analysis of valves from engine tests

The component pairs investigated consist each of one inlet and one exhaust valve which were taken from the same cylinder in a large bore natural gas-fuelled engine (prototype engine with ca. 10 MW output). Two pairs were investigated that are different concerning hardfacing alloy composition (Table 1) and operation hours. Pair A has a state-of-the-art hardfacing made of Stellite® 12 and had been in operation for 250 h. Pair B has a hardfacing of Tribaloy® T400 and has been in use for 5000 h. Despite the significant differences in run-time, analysis will show that comparison is justified. The analysis comprises quantitative wear measurements and microstructural analysis of the subsurface material for further comparison with the specimens from tribometer tests. Quantitative wear measurements are based on profile measurements which were acquired by 3D-laser-scanning microscopy (Keyence VK-9700). Specimens were prepared by wirecutting and cross sections were polished and chemically etched to provide good images of the microstructure. Worn surfaces and cross sections were investigated by means of scanning electron microscopy

Table 1
Composition of the new hardfacing alloys of inlet and exhaust valve pairs from the same large bore gas engine as measured using energy dispersive spectroscopy.

	Composition in wt%					
	C	Co	Cr	Mo	Si	W
Pair A – Stellite® 12	4.0	57.1	29.8	–	0.8	8.3
Pair B – Tribaloy® T400	1.6	61.9	9.5	25.5	2.0	–