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Analysis of the running-in of thermal spray coatings by time-dependent stribeck maps

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ABSTRACT

As thermal spray coated cylinder surfaces eliminate the need for cast iron sleeves or hypereutectic AlSi alloys, these coatings are becoming the main cylinder liner technology. Moreover, it has been found that these coatings also lead to low friction and wear. The reason for improved tribological performance is believed to result from a nanocrystalline layer that forms in the sliding contact. In this paper, we use on-line wear measurement to study the dynamics of the running-in process. A pin-on-disk tribometer coupled to a radionuclide wear measurement (RNT) system was used to investigate the friction and wear behavior of wire arc spray (LDS) coatings sliding against chromium coatings under lubricated conditions. After the friction experiments, X-ray photo electron spectroscopy (XPS) and Focused Ion Beam analysis (FIB) was used to characterize the worn surfaces. By introducing a time-dependent Stribeck plot, we analyzed running-in under constant and transient sliding conditions and observed a strong reduction of friction in the boundary lubrication regime. Wear rates of the LDS disks as well as of the chromium plated pins are ultra-low. XPS revealed carbon diffusion at room temperature in wear tracks of disks that showed a very low coefficient of friction (CoF) of 0.01, whereas this carbon diffusion could not be detected in the wear track of a disk without running-in, i.e. a final CoF of 0.12. As this is the most significant difference found between differently run-in systems, the described carbon diffusion might be relevant for the observed friction behaviour. Running-in behaviour can only be discussed in terms of friction, as, even with RNT, no significant wear could be measured. The comparison of running-in under transient and constant conditions showed only minor differences in the final friction behavior.

1. Introduction

A higher power density in combustion engines due to downsizing and turbocharging leads to harsher environments that challenge the durability of conventional AlSi liner surfaces in terms of wear. In recent years, thermal spray iron coatings have been used to improve the wear behavior of cylinder bore surfaces [1,2].

In order to further improve the tribological behavior of these iron-based coatings, it is necessary to understand the fundamental mechanics and dynamics in these systems that lead to superior friction and wear. If a model system is operated with comparable wear rates and with materials that are also used in the real system, the understanding of friction and wear mechanisms in the model system is a first step for defined adaptions of the real system [3]. In the present case, a pin-on-disk tribometer is used as a model system. Industry standard piston rings are nitrided or coated, e.g. with chromium. This is why, in the present work, the tribological system of a chromium-coated pin against a thermal-spray-coated, ground disk is used.

Publications in the field of thermal spray coatings also deal with mechanical or tribological stability of thermal sprayed layers. Rabiei et al. [4] identify the crack propagation in amorphous oxide layers between the splats, and also Milanti et al. [5] find a lower microhardness for coatings with slightly defected particle boundaries. The work of Hahn and Fischer et al. [6,3,1] is concerned with microstructural and chemical alterations at the surface, describing the impact of alloy modification on the tribological behavior of the coatings. To the knowledge of the authors, there is no publication explicitly considering the running-in behavior of thermal spray coatings so far.

To fulfill engine life times of several thousand hours, wear rates of bearings and liners have to be in the ultra-low wear regime with a few nanometers per hour. In many cases, wear rates in the ultra-low wear regime are connected with a running-in behavior,

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that usually entails a decrease in friction as well as in the wear rate [7,8]. It has been shown for several tribological systems, that running-in behavior strongly depends on the load and speed conditions. Considering pin on disk experiments, many published results are measured at load and speed conditions, that are constant until a constant wear rate or friction is measured [9,10,8,11]. The present paper addresses the question, if there is an influence of a dynamic load and speed variation during the running-in on the final friction value and the system wear rate. Moreover, microstructure and chemical composition of worn surfaces are analyzed to understand the mechanisms leading to differences in friction behavior.

2. Materials and methods

2.1. Materials

2.1.1. Disks

Grey cast iron disks (ASTM A48: NO.30, EN-GJL-200) have been roughened with a high-pressure water jet (Hammelmann, Oelde, Germany) and coated with a thermally sprayed layer (Fe-0.9 wt-% C, Daimler AG, Germany) with a thickness of approx. 500 µm. SEM images of metallographic sections show the characteristic splats and pores of a thermal spray coating (see Fig. 1(b)). The porosity of the coating is 3 %. As a final machining step, the disks have been grinded to a roughness R_a of 0.43 µm. Focused ion beam (FIB) cross sections in the machined, unworn surface show a grain-refined layer up to a depth of approx. one μm due to the final machining.

2.1.2. pins

Steel pins (Fe 0.85 wt-% C) have been coated with a galvanic chromium layer (Federal Mogul, Burscheid, Germany; "Goetze Diamond coating" (GDC)). After coating, the pins were grinded and lapped to a final thickness of 100 µm. In FIB cross sections, the unworn pins show a submicrocrystalline microstructure. Changes of microstructure due to final machining could not be imaged. XPS measurements on the unworn pins revealed an increased oxygen content of up to 40 at-% in the first 200 nm depth and a varying carbon concentration from 2 to 25 at-%. This is due to the deposition process, where alternate layers of chromium and, according to the manufacturer, diamond is deposited. The diamond agglomerates in pores or cracks of the chromium layer according to the producer of the layers [12]. XPS measurements revealed that the diamond, that is deposited, partially consists of carbides. The carbide content varies with sputter depth and measurement position from 15 to 60 %. A light-microscope image of an unworn pin is shown in Fig. 1(a).

2.1.3. Oil

The oil used for all pin-on-disk experiments was fully formulated engine oil Castrol Edge FST 5W30 at a temperature of 80 °C. The oil circuit was filled with 2.5 liters. Using a nozzle, oil was directly supplied to the disk.

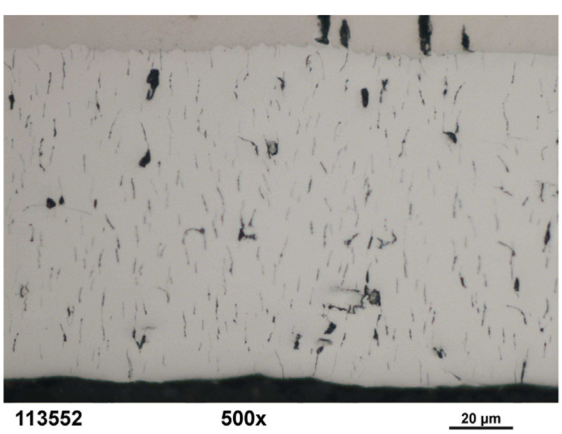
2.2. Methods

2.2.1. Tribometer

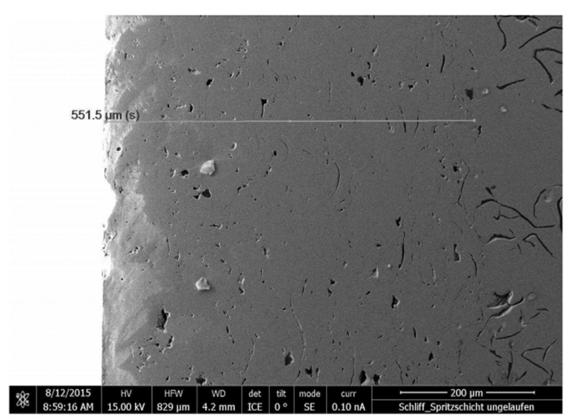
All measurements were performed on a pin-on-disk tribometer "Basalt" produced by Tetra (Tetra Ilmenau, Germany) with a customized software and force sensor equipped with strain gauges. Resolution of the force sensor was 1 N, which yields an error for the measurement of the friction coefficient of 0.02 for the lowest pressure of 2.5 MPa.

2.2.2. Radionuclide technique

When measuring wear with the radionuclide technique (RNT), one or both samples being in tribological contact are slightly radioactively marked so that also wear debris is radioactive. The activity in the oil is measured and correlated to the wear particle weight using a reference sample of known mass. Advantages of the method are the high resolution of 0.1 micrograms of wear per hour and online wear measurement [9]. To obtain radiotracers, pins were subjected to low-energy neutron radiation at FRM II in Munich. The oil circuit of the tribometer was connected to a gamma detector (Zyklotron AG, Leopoldshafen, Germany) allowing



(a) Light microscopic image of metallographic cross section of the chromium coating on the pin. Black lines in the coating are the cracks as described in the text.



(b) Electron microscopic image of a cross section of the unworn thermal spray coating.

Fig. 1. Images of metallograhpic cross sections of the unworn coatings of pin and disk.