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Near-surface and depth-dependent residual stress evolution in a piston ring hard chrome coating induced by sliding wear and friction

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ABSTRACT

The microstructure, texture and residual stresses of a hard chrome piston ring coating, which was subject to sliding wear in tribological contact with a thermally sprayed, iron-based liner coating, were studied using laboratory X-rays and synchrotron X-rays. The near-surface evolution of residual stresses induced both tribologically and thermally was analyzed in the sliding direction and perpendicular to the sliding direction. The tribologically induced residual stresses correlate with the piston ring tribology as a function of the tribological parameters 'test duration', 'sliding speed', 'piston ring load' and 'piston ring temperature' and with the evolution of the piston ring wear, particularly as a function of the accumulated dissipated frictional energy. A tribologically impacted residual stress zone of approximately 15 μm was identified and a considerable tribological impact on the residual stresses was detected. A smaller impact depth of only 10 μm could be assigned to the thermally impacted residual stress zone. Exposed to high temperatures, the residual stresses tribologically induced in sliding direction within the whole depth range are shifted towards compressive residual stresses. There was a very good agreement between the energetic approach to wear and the evolution of tribologically induced residual stresses as a function of the dissipated frictional energy. Furthermore, the evolution of the wear volume as a function of the tribological parameters, such as 'sliding speed', 'piston ring temperature' and 'piston ring load', could be correlated to the depth-dependent evolution of thermally and tribologically induced residual stresses.

1. Introduction

On the endeavor to reduce CO_2 emissions, great attention is paid to the fuel economy of modern cars. As a consequence of continual downsizing coupled with the simultaneous increase in the combustion pressure, direct injection as well as both turbocharging and supercharging, the steady improvement of power density and thermal efficiency in modern internal combustion engines is leading to increasingly higher mechanical and thermal stresses on engine components and resulting in a higher degree of wear in these components. Thus, increased wear resistance within the friction contacts of the engine components is required. In an internal combustion engine, the top ring is the part of the piston ring package that is subjected to the most stress, as it is stressed by the highest temperatures and loads, especially at peak pressure as well as at and around fired top dead center (FTDC). Various investigations and studies also prove that both the friction and wear of tribologically stressed components strongly influence the near-surface residual stress evolution [1,2]. In many respects, the wear resistance strongly depends both on the type and distribution of the internal residual stresses. Additionally, it is suggested that compressive residual stress may slow down wear by reducing the activity of the metal atoms [3].

In previous work, the residual stresses of automotive components due to manufacturing and coating deposition were analyzed. The process-related residual stress profiles in aluminum cast engine blocks [4–7] as well as in nitride steel crankshafts [8] and in cast-in iron liners [9,10] were analyzed in detail. Moreover, the residual stress states in various automotive components such as springs [11,12] and gears [13,11] were studied and its properties recorded using X-ray diffraction (XRD). The effects of surface treatments such as shot peening [14] and heat treatment [15] on the fatigue durability of automotive components were also investigated. Astashkevich et al. [16] analyzed the influence of surface layer residual stresses on the wear resistance of tempered gray iron liners subjected to induction hardening with double-sided cooling. Sokolov et al. [17] studied the influence of residual stresses in different coatings of chrome, chrome steel and aluminum oxide on compression rings and revealed the influence of the residual stresses on the properties of the piston rings.

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Furthermore, the influence of residual stresses on the fatigue of pistons in contact with cylinder liners [18] and piston rings [19,20] was investigated.

The basic interactions of residual stresses and sliding wear of metals have been analyzed in various studies [2,21–23]. Also, the residual stresses in electrochemically hard chrome-plated coatings [24–28] as well as in physical vapor deposited chrome coatings [29,30] were analyzed in different studies. However, the depth-dependent evolution of residual stresses in piston ring coatings that are induced by both thermal and tribological stresses has not yet been investigated in detail. Furthermore, the influence of these thermally and tribologically induced residual stresses on the piston ring wear has also not yet been studied in detail. This paper investigates both the depth-dependent and the near-surface residual stresses in a worn hard chrome piston ring coating induced by sliding wear and friction using energy-dispersive synchrotron X-ray diffraction and angle-dispersive laboratory X-ray diffraction. The depth-dependent distribution of residual stresses was analyzed as a function of the tribological parameters 'test duration', 'sliding speed', 'piston ring load', 'piston ring temperature' and, in particular, as a function of the accumulated dissipated frictional energy. The evolution of the wear volume of the hard chrome piston ring coating with increasing dissipated frictional energy correlated with the depth-resolved evolution of tribologically induced residual stresses as a function of the dissipated frictional energy. Residual stress depth profiling was performed using the energy-dispersive diffraction EDDI beamline at the electron storage ring BESSY II [31], Berlin, Germany. Furthermore, near-surface induced residual stresses were analyzed in angle-dispersive mode using an X-ray diffractometer with monocapillary optics [32].

2. Experimental

2.1. Samples

For the tribometer test runs and the residual stress analyses, diamond-reinforced hard chrome-plated piston ring segments were used. The coating and the piston ring segments were already described in detail in [33,34]. Fig. 1 shows the cross section of the multilayered hard chrome coating with microcracks and substructure (a) and the polished running surface with the diamond particles embedded in the microcracks (b). In the illustrated cross section, the microcracks show a preferential orientation perpendicular to the substrate. Moreover, the propagation of the microcracks during deposition is prevented by the deposition in single layers.

The analyzed multilayered hard chrome coating consists of seven single layers. The bottom layer has an average thickness of approximately 18 μm and the top layer has an average thickness of approximately 3 μm to 4 μm due to the final surface finishing process. The intermediate layers have an average thickness of 10.5 μm to 11 μm. The total coating thickness is between approximately 75 μm and 78 μm.

As shown in Figs. 1 and 2, which presents the microcrack density analyzed as a function of the depth with depth intervals of 2.5 μm, the coating has a multitude of microcracks both in the near-surface areas and at depths greater than 35 μm. Within the first 5 μm, the hard chrome coating has a microcrack density between 150 cracks/mm and 170 cracks/mm. At greater depths, the microcrack density is significantly decreased to values of between 110 cracks/mm and 130 cracks/mm. At depths greater than 35 μm, the microcrack density increases again to values between 130 cracks/mm and 150 cracks/mm.

2.2. Tribological testing

Tribological testing was performed according to the method described in a previous paper [34]. The XRD-analyzed hard chrome-plated piston ring samples were run against a thermally sprayed, iron-based and nanocrystalline cylinder liner coating in rotational tribometer test runs. Fig. 3 (a) illustrates the methodology of the tribometer testing, while Fig. 3 (b) shows the geometrical design of the piston ring segments. The tribometer test runs were conducted under laboratory conditions and air atmosphere with piston ring loads of 50 N and 200 N, sliding speeds of 1 m/s and 4 m/s, piston ring temperatures of 150 °C and 200 °C and with an oil flow rate of 0.0724 μL per revolution using a fully formulated engine oil of SAE class 0W-20 (HTHS: 2.6 mPa · s) and a density of 835 kg/m^3 as lubricant.

Before and after the test runs, the specimens were cleaned with cleaning petroleum benzine in an ultrasonic bath for ten minutes and dried with a nitrogen gas flow. Additionally, the specimens were cleaned after the test runs in a cold cleaning bath [34] for three hours and then neutralized in isopropyl alcohol in order to remove oil and wear particle deposits from the running surface. The coefficient of friction of the tribometer test runs was determined using a force transducer [34]. The wear volume was measured using a confocal light microscope with green emitted light (μ-surf custom, Nanofocus AG) and an objective with a numerical aperture of 0.6 and a working distance of 0.9 mm. Before and after each test run, the entire coated surface of each piston ring segment was measured in full using a very high lateral resolution of 1.6 μm and a very high vertical resolution of 4 nm.

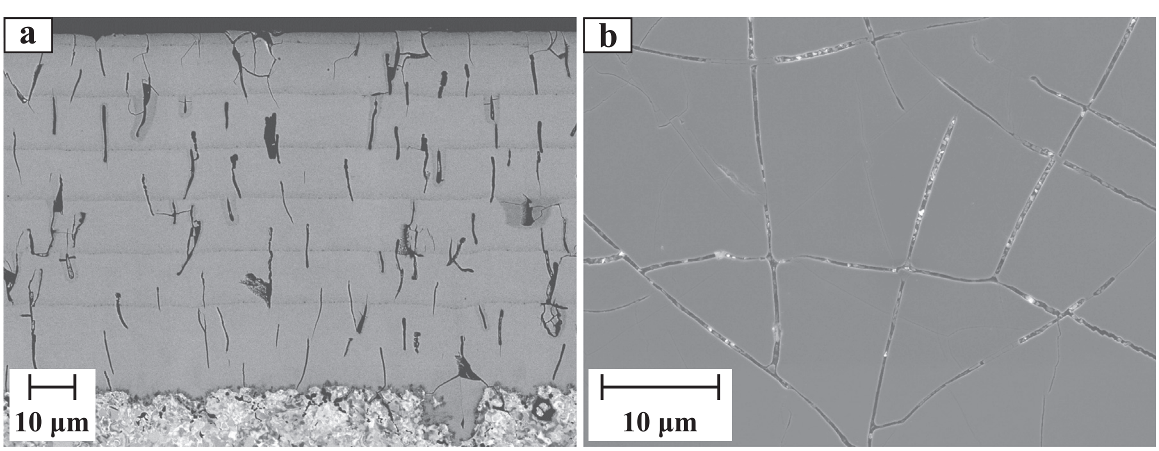

Fig. 1. (a) SEM image (BSE) of the polished cross section of the hard chrome coating. (b) SEM image (SE) of the polished running surface of the hard chrome coating.