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PVD Cr_xN coatings for tribological application on piston rings

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Abstract

Besides the established PVD coatings for the wear protection of machining tools, this paper deals with coating development and model wear test results from PVD coatings on piston rings for combustion engines. Piston rings are examples for the application of thin films on commonly used mechanical components. The PVD Cr_xN coatings are deposited by RF magnetron sputtering and characterized by their fundamental mechanical properties like thickness, hardness, residual stress and adhesion, which are important for the tribological behaviour of the coating substrate compound. The contact mechanics of the tribological system piston-ring–cylinder are determined by high mechanical loading and changing geometry caused by the sliding kinematics. Therefore, the range of thickness is about 7 μm. The selected rings are made of steel DIN 1.4112 (DIN X 90 Cr Mo V 18) with a bore diameter of 97.5 mm. The results of the coating substrate characterization — high hardness, moderate compressive residual stresses and sufficient adhesion on metallic substrates — provide good behaviour of coatings in this tribological application. This is confirmed by the results of the tribological test procedures which have been performed with ring-on-disc model-wear tests and a short-stroke test rig. © 1997 Elsevier Science S.A.

Keywords: Chromium nitride; Piston rings; PVD coatings; Wear tests

1. Introduction

Tribological coatings must fit the application they are used for. In this paper, piston rings in combustion engines are noteworthy as mechanical components in tribology with high demands for reliability over a long lifetime. The field of the development of functional coatings which influence the wear behaviour of piston rings is presented. The mechanical and tribological loading by oscillating sliding velocity and gas pressure as well as elevated temperature and corrosive exhaust gases is very high. The tribological system is still a subject of industrial investigation [1,2]. Fig. 1 shows the fundamentals of the tribological system piston-ring–cylinder and gives examples of some typical values. In addition, the geometry of the investigated piston rings is shown. Therefore, the wear behaviour must be optimized: a certain wear rate is required for good sealing with high pressure in the compression stroke and a maximum admissible wear rate is required for sufficient mean pressure and efficiency of the engine over a long time [3,4].

Today, the most commonly used piston rings are coated with electroplated chromium layers. In recent years, much development work has be performed to replace chromium plating by chromium nitride alternatives [5,6]. In the present investigation, physical vapour deposition (PVD) sputtering technology is used to influence the wear behaviour by thin films within a wide range of mechanical properties. This depends on vacuum deposition in Cr_xN, which is very promising in relation to other coatings [7]. Studies on different coating materials have taken place [2,8] and emphasize the demand for suitable surfaces.

The coating of piston rings is taken as an example to represent mechanical components in contrast to coated machining tools, the coating of which is already established. A similar developmental procedure and analysis of effecting functional mechanisms could be performed for the cylinder liner in engines or even other tribological systems, e.g. hydraulics or fluid technology.

2. Experimental details and results

2.1. Coating process

The PVD coatings were produced in a magnetron sputtering unit with a double cathode arrangement of

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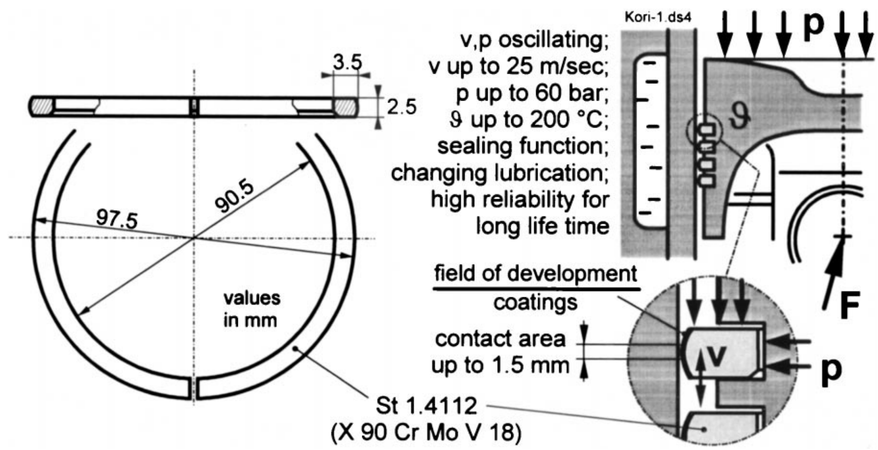

Fig. 1. Structure of the tribological system piston-ring–cylinder and geometry of piston rings.

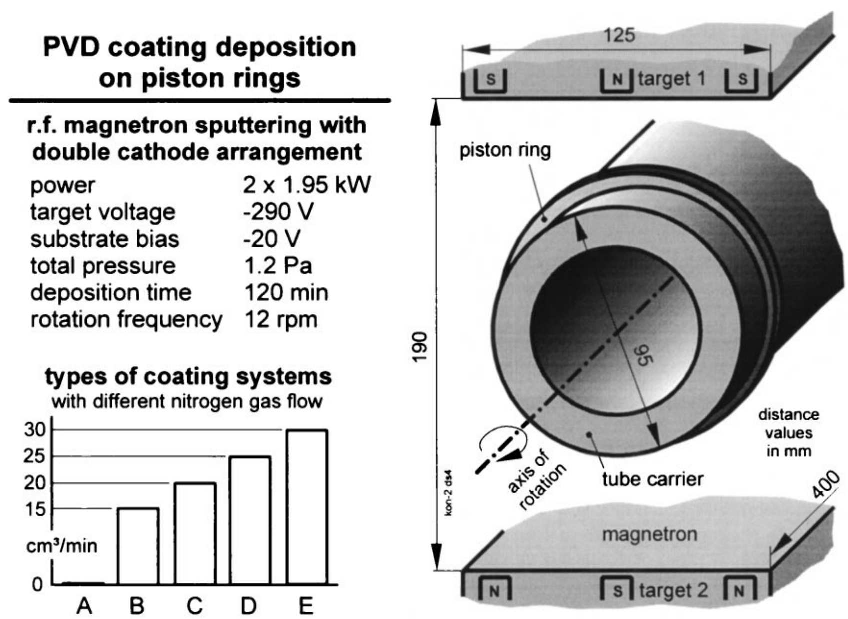

Fig. 2. Equipment and parameters for PVD coating deposition.

two targets, as is shown in Fig. 2. The piston rings were carried on a rotating tube made of austenitic steel with circular grooves, so the piston rings were positioned during deposition without radial deformation. To obtain qualified coating properties, different substrate carriers, different target to substrate distances, and different process cycles have been pre-selected.

The fundamental deposition parameters and the geometry of deposition are also given in Fig. 2. In this work, a variation of the reactive nitrogen gas flow is evaluated. These types of coating systems are named A–E. As reference materials, uncoated and chromium electroplated surfaces of piston rings are taken.

2.2. Coating properties

The relevant fundamental properties [9] of the coating substrate compounds with a coating thickness of between 6 and 8 μm for the PVD coating systems were characterized. The coating thickness of the electroplated ring was approximately 100 μm. Fig. 3 shows the XRD spectra showing the crystallographic phases. The XRD examination was performed with a Siemens D 5000 goniometer and CuKα radiation using focussed and defocussed Bragg–Brentano geometry. The X-ray diffraction results show clearly changes from Cr (A) over Cr_2N (B and C) to CrN (D and E) with wide peak half-width for the unstoichiometric types B and D, which is mainly caused by low crystallinity (high number of lattice defects and small crystallite size). In addition, XRD stress measurements were performed, resulting in a high compressive stress of about −3.5 GPa for the unstoichiometric CrN coating (D), a low compressive stress state of about −0.4 GPa for Cr (A) and a moderate compressive stress up to −2.0 GPa for the other PVD coating systems, B, D and E.

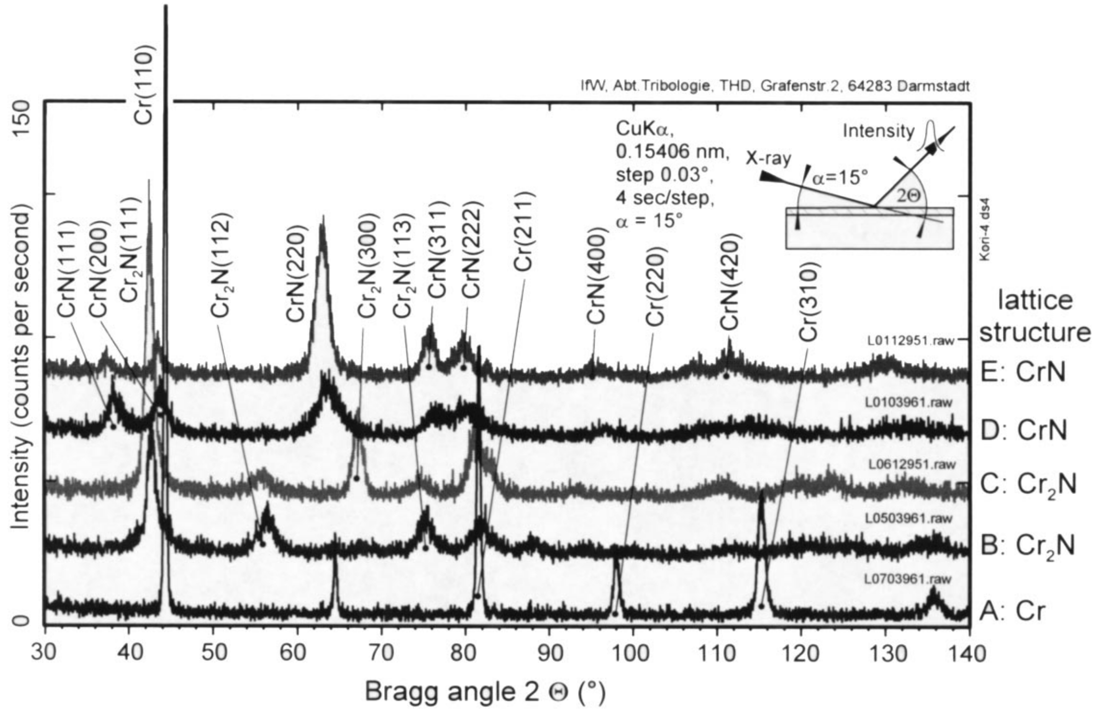

Fig. 3. XRD analysis of PVD coating systems.

Fig. 4 shows the important macroscopic properties for contact mechanics under mechanical loading, which can be represented by the surface hardness. Using a computer-controlled testing device, the universal hardness under test force (HU) and the plastic part of the universal hardness after reloading (HU_{pl} which corresponds to the conventional Vickers hardness measurement) are evaluated [10]. HU and HU_{pl} have same behaviour; the difference between these hardness values is determined by the elasticity of the coating system under normal test force (corresponding to Young's modulus). The maximum indentation depth always was restricted to values lower than 1/10 of the coating thickness.

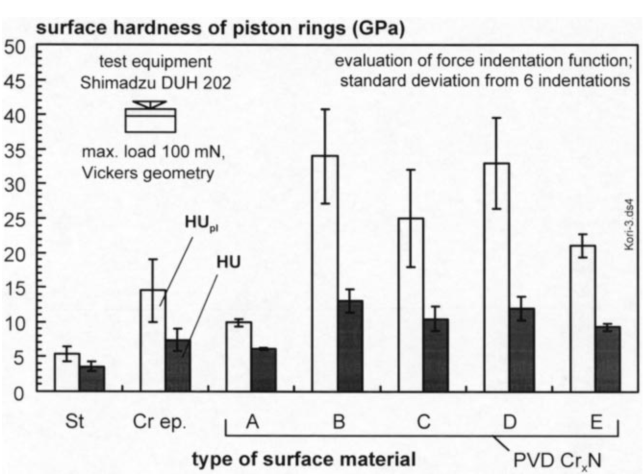

Fig. 4. Surface hardness of piston rings.

The PVD coating systems have higher hardness values than the reference materials except the PVD–Cr coating (A), which is sputtered without a reactive gas flow. The highest hardness values of these investigations show the nonstoichiometric coating systems B and D.

The scratch test adhesion performed according to DIN V ENV 1071 T3 and evaluated according to Ref. [11] showed critical loads for adhesive failure with delaminations at a critical normal force of 30 N or higher depending on the coating system. This adhesion is sufficient in this application as the tribological tests showed (see Section 2.3). Stoichiometric phases with moderate residual stress have the highest critical loads of up to 60 N for first delaminations.

Fig. 5 gives an impression of the coating morphology with an SEM analysis of fracture behaviour and a photograph of cross-section. The reactively sputtered coating systems have a dense structure in general; for Cr (coating A, not shown in Fig. 5) and CrN (coating E), the most columnar growth is obtained. The cross-section shows the ground surface roughness of the investigated piston rings ($R_a = 0.18$–0.35 μm, $R_t = 2.4$–4.6 μm from contact stylus measurement ISO 4287/DIN 4768) and the coating interface to the steel substate. In addition, the cross-section shows the columnar structure from CrN in contrast to the more dense Cr_2N.

2.3. Tribological behaviour

The analysis of the tribological behaviour was carried out with segments of piston rings under normal force

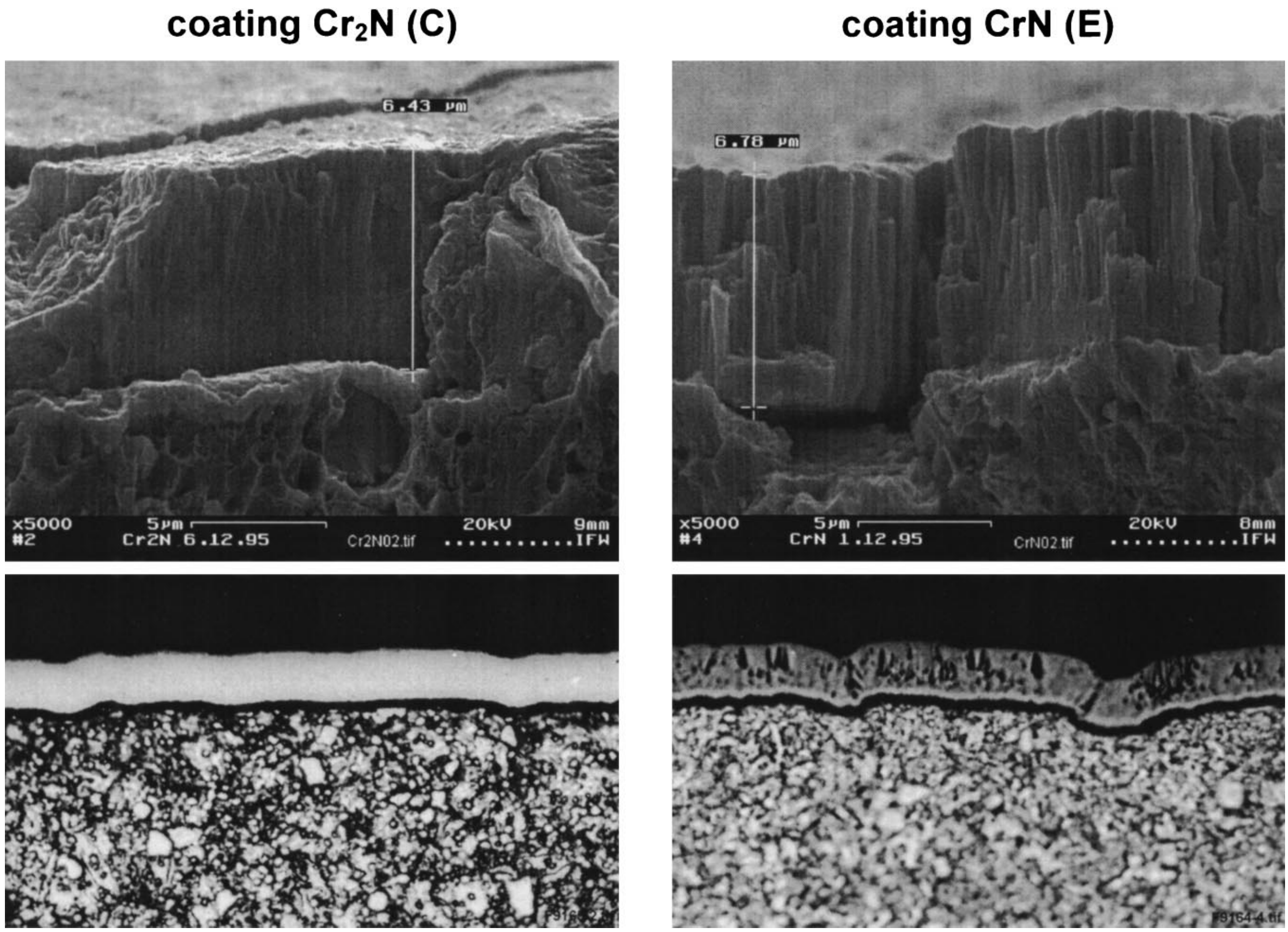

Fig. 5. Morphology of PVD coating systems in SEM image and cross-section.

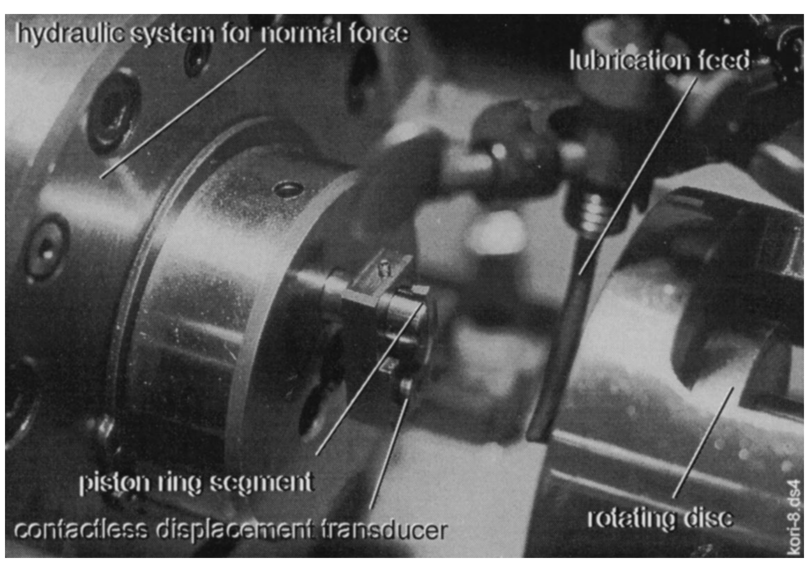

Fig. 6. Ring-on-disc equipment for tribological testing.

on a rotating disc, like the well-known pin-on-disc model test (similar tests were performed in Ref. [12]) and also with a short-stroke test rig. Fig. 6 shows the ring-on-disc test equipment.

Fig. 7 contains the summarized linear wear and friction coefficient over the applied test distance of 700 m for selected coating systems (electroplated Cr, C and E) in the ring-on-disc test procedure. ‘‘Summarized’’ means

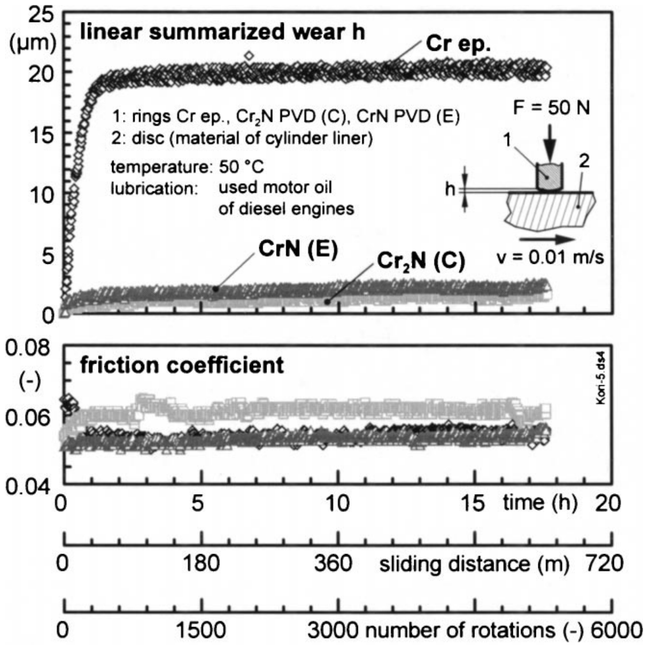

Fig. 7. Linear wear and friction coefficient over time of the model test cycle of the coating systems: electroplated Cr, PVD Cr_2N and PVD CrN.

wear of ring and disc together, whereas the linear wear of the disc itself is always smaller than 0.7 μm (from contact stylus measurement). The test conditions simulated the low sliding velocity with mixed friction and solid body friction at the dead centres of the engine. Further test parameters are given in the figure.

The diagram shows the very effective wear reduction of about 94% by hard coatings compared with the electroplated piston rings in this test. The friction coefficient for the nitride coatings is similar to the electroplated rings, but it should be reduced in future optimization with respect to the necessary high efficiency of engines [13,14]. As a possibility, a special roughness texture of the rings could help. Another point is the almost missing running-in wear for the hard coated rings (C and E), which is caused by the low wear rate and the high surface roughness of the rings. For obtaining a short running-in wear at low wear rates, it could also be interesting to have a well-defined surface roughness with respect to surface texture or to produce a thin ductile chromium layer on the chromium nitride coating at the outer surface for defined running-in behaviour. This is no problem in PVD deposition technology.

In Fig. 8, the significant difference of wear rates with ellipsoid abrasive craters at the sliding face of two exemplary piston rings (electroplated Cr and Cr_2N from coating type C) is demonstrated. The wear crater dimension of all PVD hard-coated rings is similar to the illustrated Cr_2N coating. The depth of both craters is completely within the coating thickness. It is also obvious that adhesion between coating and steel substrate is no problem; there are no cracks or delaminations. An interesting aspect of the PVD coatings which can reduce wear by an order of magnitude is the fact that defined surface roughness can survive over the period of use. This may be of great interest as far as lubrication and, as a consequence, the friction coefficient and the economy of the whole tribological system are concerned.

Fig. 9 summarizes the tribological behaviour of the tested piston rings in the ring-on-disc model test. Summarized wear and friction are scaled logarithmically because of the high differences in wear behaviour between PVD coatings and reference materials. Wear rates in the diagram correspond very well to the hardness measurements (see Fig. 4). In addition, the friction coefficient is slightly decreasing with increasing hardness, caused by the reduced plasticity in the local contact area. The ring with the highest hardness showed the lowest wear in this test. All test cycles were repeated at least three times to guarantee a minimum statistical reproducibility.

Fig. 10 gives an overview of the results from the short-stroke test rig for examplary coating systems. This test is modelling both piston ring and cylinder liner in an engine. The kinematics are realistic, but the piston travel is restricted to 0.8 mm to simulate the tribologically relevant dead centres. The material of the cylinder face was always centrifugal casting steel as used in series production. Linear wear is determined after the desired test cycle by contact stylus measurement of piston ring and cylinder liner at eight circumferential positions. The number of strokes (45×10^6) equals about 20 000 km driving distance in a motor vehicle. The results obtained with the short-stroke test correspond with the results from the ring-on-disc model test. The wear of the coated rings is clearly reduced related to the conventional St, electroplated Cr and also the PVD chromium. In contrast to the ring-on-disc model test, the wear of the counterbody in the tribological system — here the cylinder liner — plays an important role. Whereas the wear rate of the rings coated with types B to E decreases enormously, the wear of the cylinder liner increases in the same range. For this reason, the summarized linear wear measured in the short-stroke test rig keeps almost constant as shown in Fig. 10.

To reduce the summarized wear, the cylinder liner also needs to be hardened, as confirmed in other investigations [2]. The basic result from this is that the whole tribological system must be optimized and the components must fit together under tribological aspects.

3. Discussion and conclusions

The wear of piston rings is investigated with respect to PVD hard coatings as a surface finish with an

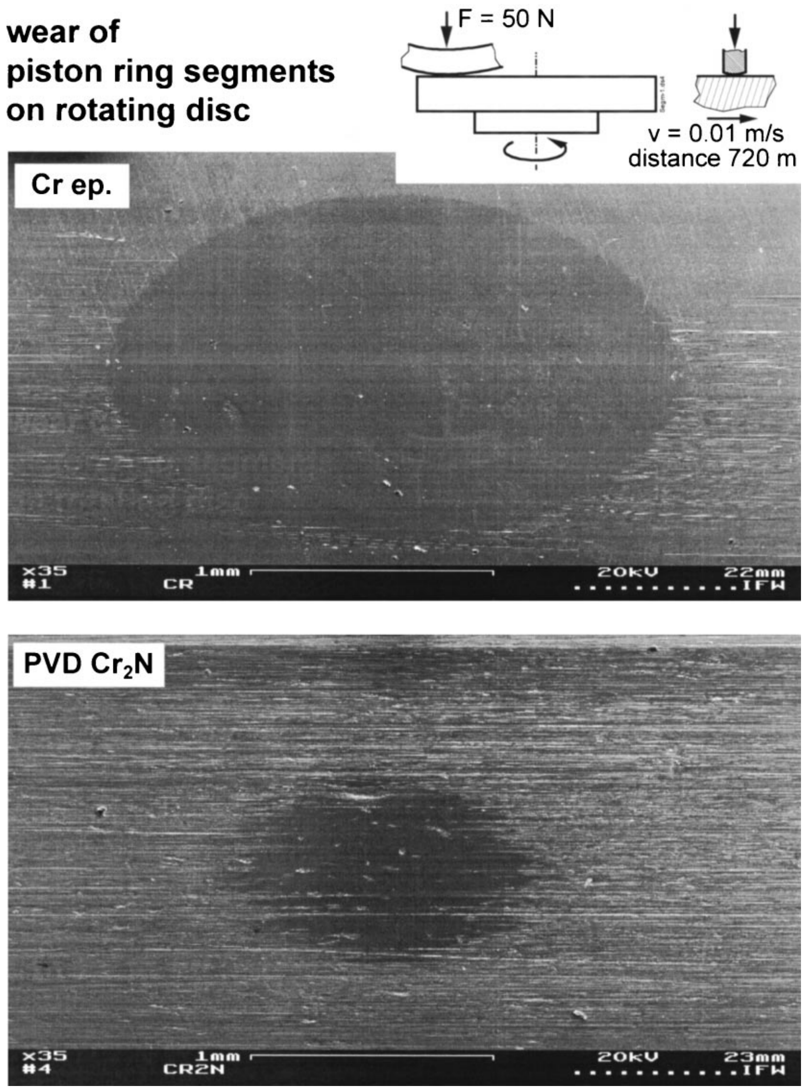

Fig. 8. SEM images of wear craters after model tests for piston-ring electroplated chromium (as reference) and the coating system PVD Cr_2N (C).

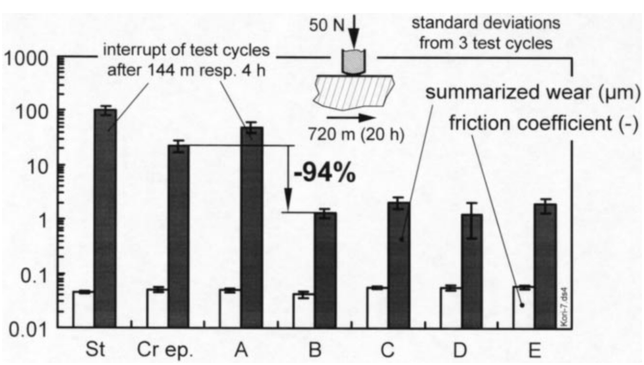

Fig. 9. Wear and friction of ring-on-disc model test for all PVD coating systems and reference materials.

adjustable profile of mechanical properties. Therefore, PVD Cr_xN coatings have been deposited, characterized and used in model wear tests for simulating the complex tribological system piston-ring–cylinder. This tribological system can be seen as an example for mechanical components working under intensive wear conditions over a long period of time. As the investigation shows, PVD hard coatings can reduce wear rates very effectively, and not only on machining tools (see Figs. 7–10).

The following aspects can be concluded from present results:

(1) the wear protection of piston rings by PVD coating systems is possible as an alternative to the surface materials used up to now; and
(2) as a consequence of the reduced wear rates, the coating thickness can be lower.

The results up to now are only the beginning of coating development with the desired profile of coating substrate properties, but they could show that PVD coatings can be applicated successfully in this

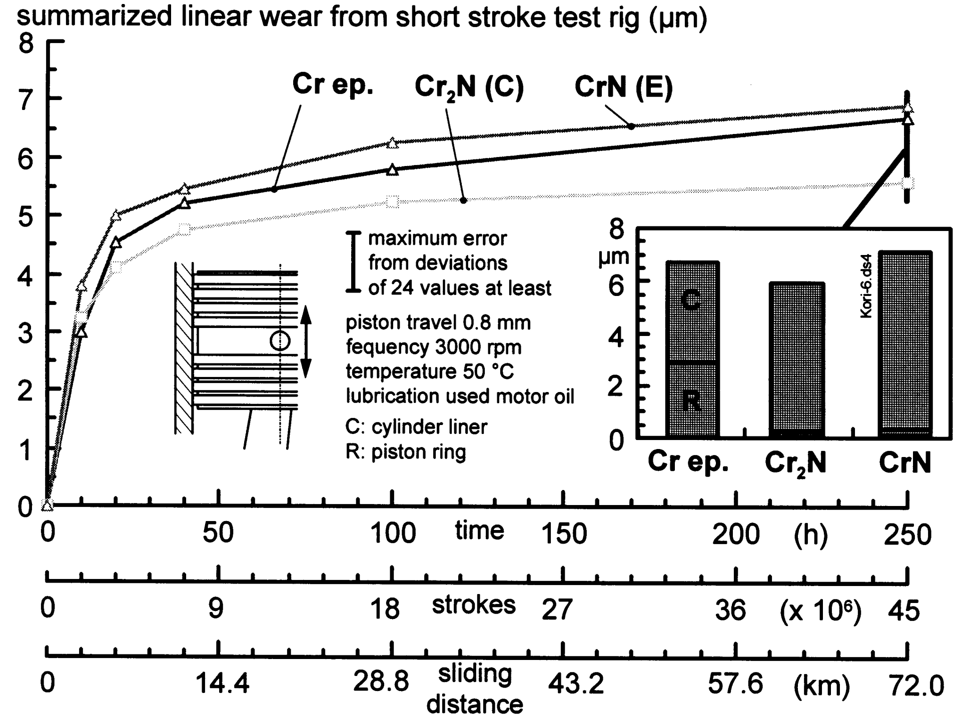

Fig. 10. Wear of coated piston rings from the short-stroke test rig for selected coating systems and reference electroplated chromium.

environment. Further aspects must be considered in future activities:

(1) the entire tribological system must be optimized and therefore the surface of the cylinder liner must be adapted;
(2) the friction coefficient must be as low as possible (hard surfaces need optimized roughness);
(3) the running-in wear must be designed by the coating system;
(4) gas pressure and a corrosive environment are added in real engine and therefore model wear tests cannot substitute a motor test in general;
(5) the coating deposition must be economic; and
(6) the reliability of tribological behaviour must be guaranteed.

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