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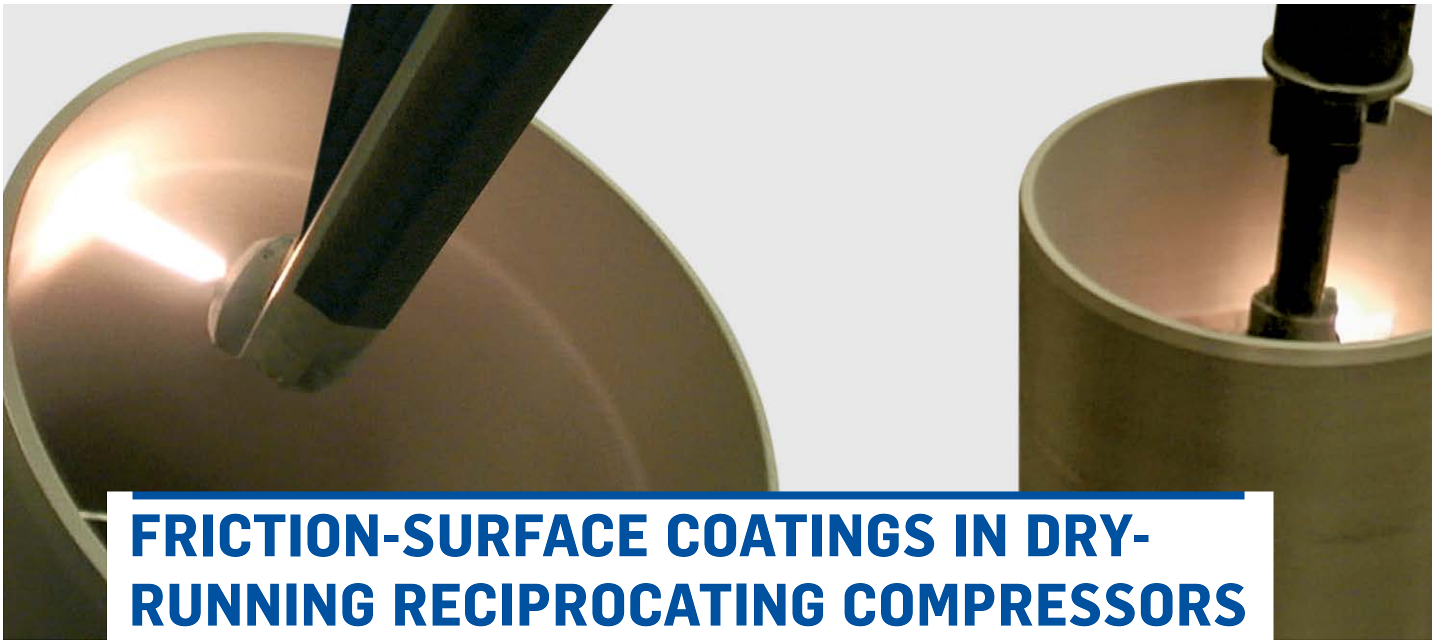

FRICTION-SURFACE COATINGS IN DRY-RUNNING RECIPROCATING COMPRESSORS

BENEFITS AND RISKS

Dr. Norbert Feistel

Compressors for a Lifetime™

Due to increasing demands on the reliability of Process Gas Compressors, measures to protect the counter-body surfaces of the sealing and rider rings are becoming increasingly important. In this regard, the influences of different coatings on the processes involving dry-running friction contact are not clear. Bench tests with dry-running sealing systems have revealed notable changes in surface texture, typically accompanied by severe wear of the sealing elements after just 500 hours of testing in the case of some coatings, despite high hardness values significantly in excess of 1'000 HV. In addition to surface topography, the chemical resistances of the various coatings appear to be an important factor influencing the formation of transfer film. Especially with high-pressure loads, all coatings recommended for use in corrosive media achieved poorer wear rates compared to nitrided-steel piston rods.

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In 1988 N. Feistel joined the R&D Group of Burckhardt Compression in Winterthur. After approximately two years, in which N. Feistel's activities concentrated mainly on the labyrinth piston compressors, his responsibilities are now for the development of oil-free sealing systems. In 2002 he gained a PhD at the University Erlangen-Nuremberg, Germany, with a thesis on the operational behavior of dry-running sealing systems in crosshead compressors.

CHAPTER 1

INTRODUCTION

The application of coatings to prevent damage during compression of corrosive gases has proven successful over many years. Due to ever-increasing demands on the reliability of Process Gas Compressors, coatings are now also being used increasingly in the absence of corrosive media to protect surfaces subjected to tribological loads. API 618 recommends wear-reducing coatings for piston rods, regardless of the base material1. A wear-resistant coating inside the cylinder might also become necessary in case of a high load exerted on the sealing system, a use of piston and rider rings with abrasive fillers, or a presence of abrasive contaminations in the gas.

Today's complex set of requirements concerning the use of coatings in Process Gas Compressors and involving, in particular, a diversity of gases, gas mixtures and impurities, are met through numerous combinations of coating materials and processes. Especially in the case of dry-running reciprocating compressors, the interactions taking place between the friction pair and ambient medium must be considered too. The coating's surface texture, of importance to stable dry-running conditions, also raises questions about optimal parameters and feasibility. To be taken into account furthermore is the large bandwidth of parameters influencing production of the desired coating quality.

CHAPTER 2

REQUIREMENTS FOR FRICTION-SURFACE COATINGS IN DRY-RUNNING RECIPROCATING COMPRESSORS

A sound knowledge of materials as well as detailed information regarding the load parameters involved are needed to determine the most appropriate combination of coating material and procedure for a given application. High corrosion resistance and/or high wear resistance are required depending on the specific application. The maximum permissible layer thickness which already precludes individual coating processes or at least necessitates use of a special intermediate layer is of importance depending on whether a new coating or repair of a worn component is involved. In addition to the piston rod's outer coating, the diameter of the cylinder to be coated on the inside can range from less than 50 mm to more than one meter. Finally, also to be considered in the case of oil-free compression is the suitability of the friction surface's coating for dry-running operation with a broad spectrum of filled plastic materials.

2.1 CORROSION RESISTANCE

Coatings of the highest possible chemical resistance are used to avoid damage to the metallic friction surfaces inside the cylinder and the piston rod during compression of corrosive gases such as chlorine, hydrogen chloride, hydrogen sulphide etc. Especially ceramic coatings such as chromium (III) oxide (Cr2O3) have proven suitable for such applications for many years.

In addition to ceramics, hard-metal coatings are being used increasingly for compression of corrosive media. In the most common variant of friction-surface coating comprising tungsten carbide in a cobalt matrix, however, the base cobalt constitutes a weakness in terms of corrosion resistance. To mitigate this drawback, about one-third of the metallic cobalt matrix is replaced with chromium. In reciprocating compressors, these WC/CoCr coatings quickly proved successful in many applications involving corrosive media. Another very corrosion-resistant variant of a hard-metal coating is chromium carbide in a matrix of nickel and chromium. Suitable especially for high-temperature applications, this wear-resistant layer has performed well in the chemical and aerospace industries, and is also used now as a friction-surface coating in compressors.

Ceramics and hard metals suitable for corrosion protection are usually applied through thermal coating. Due to the nature of this process, however, thermal spray coatings always exhibit a porosity whose degree is influenced, in particular, by the type of process employed. The porosity ranges from 0.5% in the case of very dense layers to more than 2%. Through these pores and microcracks in the spray coating, corrosive media can penetrate as far as the substrate. To prevent this kind of underlying corrosion, it is necessary to implement additional measures such as surface sealing, thermal after-treatment by means of self-fluxing alloy powders, or use of a dense, corrosion-resistant intermediate layer between the base material and coating. Intermediate layers comprising, for example, nickel-chromium-molybdenum alloys or chemically deposited nickel are employed as diffusion barriers. Available finally as an alternative coating process is high-temperature CVD, in which repeated spraying and annealing of a ceramic suspension followed by sealing also makes it possible to create a layer almost free of pores.

2.2 WEAR RESISTANCE

Dry-running materials with abrasive fillers such as ceramics, glass or carbon fiber can already cause severe wear-related damage on counter-body surfaces made of cast iron. If abrasive gas contaminations such as aluminium oxide are involved additionally, the wear resistance limits of even high-quality nitrided steel are rapidly exceeded7. Even hard chrome coatings offer no protection here. The only remedy in this case is to use a coating with a significantly higher wear resistance. The highest possible degree of hardness, in particular, is usually favored during selection of this kind of wear-protection coating. Thin layers deposited using the PVD or CVD process, and possessing a maximum thickness of only a few micrometers, theoretically offer a very good performance. The well-known titanium nitride layers are specified to have micro-hardness values of over 2'000 HV. The extremely hard diamond-like carbon (DLC) coatings have significantly higher micro-hardness values of 4'000–6'000 HV. However, high hardness values alone are no guarantee of adequate protection for the base material, for example, if requirements for bonding strength are not met so that the layer fails by flaking during operation.

In addition to ceramic coatings with a high hardness of about 2'000 HV, some hard-metal coatings have proven themselves superbly during operation with the afore-mentioned alumina particles present in the gas flow. Though a hard metal comprising 88% WC and 12% Co has a hardness of just 1'300 to 1'400 HV, the heterogeneous structure of this sintered composite of hard carbides in a soft metal matrix has proven to be wear-resistant even in the presence of very hard gas impurities.

2.3 COATING QUALITY

Requirements for the quality of a friction-surface coating are described by coating specifications, which stipulate agreed limiting values for the layer's composition, thickness, hardness, porosity, tensile adhesive strength etc. In actual fact, however, a coating's properties depend on a variety of further parameters. In the case of thermal spraying, for example, the coating's quality is also influenced to a large extent by the process, spray gun, fuel, application rate etc. In dependence on these boundary conditions, the coater selects a powder of the most appropriate particle size. Despite a constant powder composition, any change to these parameters can significantly affect coating quality, as Figure 1 already shows in terms of the differences between the structures of two WC/Co coatings applied using different processes. The coating applied using a detonation process has a much coarser structure, with carbide sizes ranging from 10 to 25 µm, whereas a WC/Co coating of a nearly identical composition applied by high-velocity oxygen fuel spraying (HVOF), exhibits a very fine structure with carbide sizes ranging from just 4 to 5 µm[9]. **Fig. 1, right**

Process-specific variations in the coating quality are not always avoidable in practice. From a critical value onward, the internal coating of a cylinder of a small diameter can no longer be applied using the process, spray gun or powder particle size optimal for a piston rod's outer coating, for example. To achieve reproducible coating qualities, it is therefore essential that all process parameters, the preparation of the substrate surface and the after-treatment of the coating are defined by means of a spraying instruction, in addition to defining a coating specification[2, 3].

2.4 SUITABILITY FOR DRY-RUNNING OPERATION

Practice has shown that cast iron or nitrided steel as the counter-body material in dry-running applications achieve a very good service life for the sealing and rider rings. At least the same expectations are placed on friction-surface coatings. The requirement to produce a functional friction pair from various available dry-running materials is therefore a key criterion which significantly restricts the choice of available coatings.

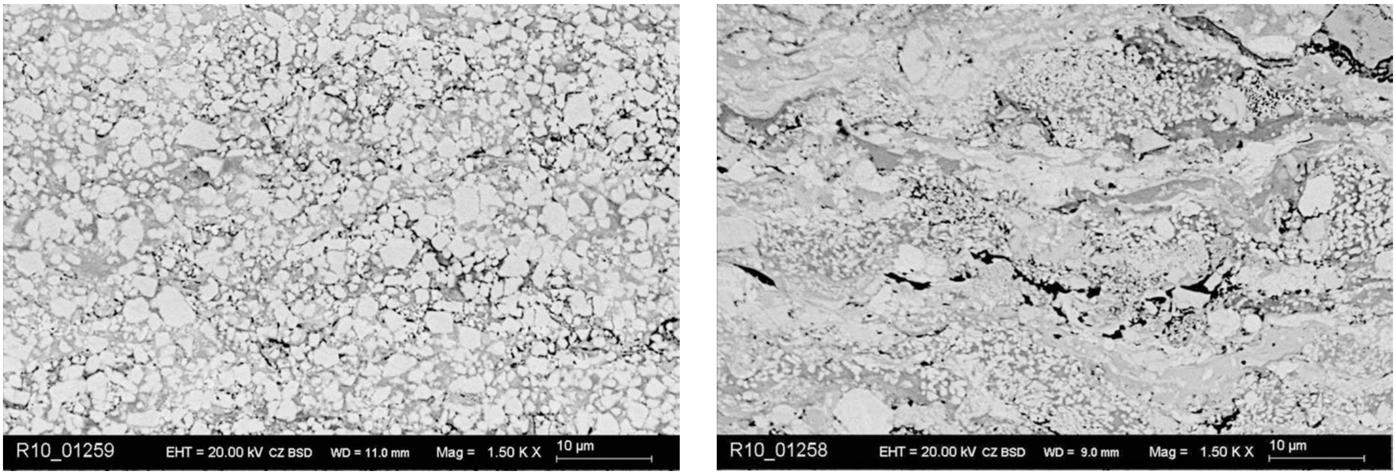
Key requirements for friction-surface coatings intended for dry-running can generally be described as follows:

- Resistance to local, high temperatures above 300 °C
- Highest possible thermal conductivity
- Favorable properties for formation of a stable transfer film
- Favorable influence on tribochemical processes

The thermal conductivity values of eligible friction-surface coatings might differ notably from those of conventional metallic counter-body materials. For instance, carbon-based coatings exhibit significantly better values. WC/Co coatings also have a very good thermal conductivity. Ceramics range from materials with excellent thermal conductivity, such as silicon carbide, to insulators (e.g. zirconia).

An optimal roughness range instead of an extremely smooth surface has proven successful during dry-running[7]. Appropriate precise surface finishing by means of grinding, lapping, honing

Fig. 1
WC/Co coatings applied using a detonation process (right), and using high-velocity oxygen fuel spraying (HVOF)[9]

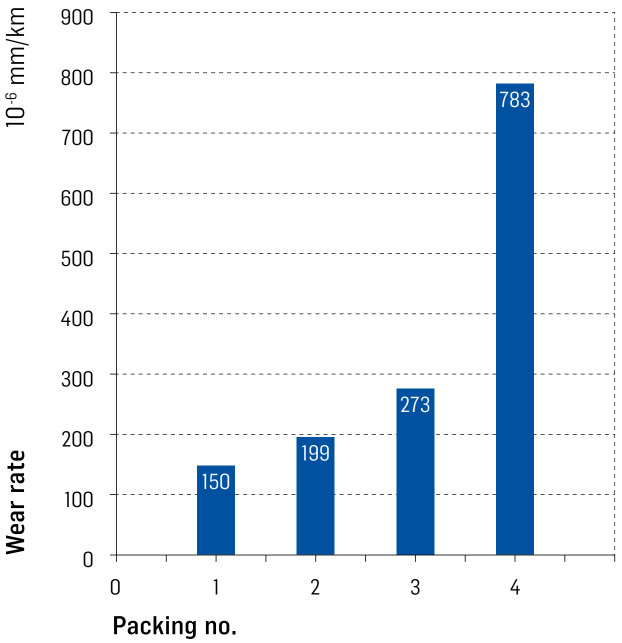


etc. is required after the application of the coating. At present, it is unclear whether proven roughness values for metallic counterbody materials can be implemented for specific coatings, and whether the resultant combinations have optimal effects.

Attention must also be drawn to the fact that tribochemical processes take place during dry frictional contact, significantly influencing friction and wear, and can thus have a positive effect, for example, through formation of a protective layer on the sealing elements' running surface[6]. However, adequate empirical data regarding tribochemical interaction with a variety of combinations of filled plastic materials and gases are not available for all coatings. Especially in the case of ceramics with a low chemical activity, as well as coatings with pronounced anti-adhesive properties, such as hard chrome and composite materials made of nickel-phosphorus with embedded PTFE particles, significant differences to conventional metallic counter-body materials can be expected. Particularly with regard to coatings containing PTFE, it is necessary to note that they are not identical to the tribochemically modified transfer film formed during operation, and therefore do not advance the process of transfer film formation, but instead can affect it negatively.

Fig. 2

Average wear rates of four sets of packing rings for sealing a piston rod coated with hard metal



CHAPTER 3

FRICTION-SURFACE COATINGS IN PRACTICE

The afore-mentioned requirements for friction-surface coatings in dry-running reciprocating compressors are now met mainly by hard-metal and ceramic layers applied by a thermal spray process. This method offers the greatest variation in terms of coating materials as well as layer properties and thicknesses, thereby holding a lot of potential especially for the repair of worn friction surfaces.

Hard metals are handled differently than ceramics, however. Thus, hard metals are now favored increasingly as piston-rod coatings. For instance, their lower impact sensitivity compared to ceramics has a positive effect highly valued during everyday handling. In addition, hard-metal powders applied using the HVOF technique can be used to produce very dense, low-porosity layers. Spraying of ceramic layers requires higher temperatures, achievable by plasma processes. However, smaller spray-gun dimensions here also make it possible to realize internal coatings of cylinders with a diameter of slightly less than 50 mm. Optimized multi-component systems are also continually broadening the scope of applications for ceramic coatings. An alternative process to thermal coating of cylinders with small diameters is the high-temperature CVD method.

Despite the additional costs, the application of friction-surface coatings in reciprocating compressors has increased significantly. For example, coated piston rods are increasingly replacing nitrided piston rods, which were still widespread until a few years ago, especially in dry-running applications involving low loads. When investing in such surface finishing, however, customers expect added value in the form of notably longer lifespans of the coated components.

Operational experience with coatings has shown that demands placed on them, especially in terms of increased wear protection compared to uncoated friction surfaces, are usually fulfilled in a most excellent manner. However, practical experiences with the performance of dry-running packings in practice have been mixed. In applications involving pressure differences in excess of about 20 bar, packings occasionally had a very short service life, the piston rod exhibiting conspicuous, very smooth surface areas. Figure 2 shows the average wear rate of all sealing elements forming part of dry-running packings of a hydrogen compressor with a pressure difference of 54 bar. Evidently, the wear rate deteriorates continuously despite constant conditions for assembly and operation of the packings, until premature failure of the fourth sealing system. Each packing was operated on the same rod with a hard metal coating, which was in excellent condition except for a low roughness along the packing rings' friction path. **Fig. 2**

CHAPTER 4

INTERACTIONS BETWEEN DRY-RUNNING MATERIAL AND COUNTER-BODY SURFACE

Insights into the phenomena observed on coated piston rods in practice were to be provided by bench tests on a dry-running compressor. For this purpose, the compressor's 550-mm-long tail rod with a diameter of 50 mm was coated with the hard metal WC/Co using both the detonation as well as the HVOF process. For comparison with the two chromium-free coatings, the hard metal WC/CoCr containing chromium was applied to another piston rod, also using the HVOF process. Finally, a quaternary ceramic consisting of aluminium oxide, chromium oxide, zirconium oxide and titanium oxide was included in the test series. A piston rod made of nitrided steel served as a reference for a metallic counter-body surface. An arithmetical mean deviation of the profile Ra in the range from 0.20 to 0.30 µm was specified for all surfaces. **Table 1**

A suction pressure of 16 barg, final pressure of 40 barg and average piston velocity of 3.18 m/s were specified as the load parameters for the tests conducted with dry nitrogen. Used in each case was only one sealing element comprising PTFE/PPS polymer blend in a cooled packing, to ensure clearly defined conditions during subjection of the piston rod to friction power. The PTFE/PPS polymer blend selected for the packing rings and filled with graphite and carbon fiber has proven to be non-abrasive in many applications, even in combination with cast iron of a low hardness[7]. Each test was to have a duration of 500 hours, though this was not possible with the WC/CoCr-coated piston rod. In this case, test had to be interrupted due to a sudden rise in the temperature of the sealing element's chamber. **Fig. 3**

The removed sealing element had been thermally damaged by the excess temperature, and therefore had to be replaced with a new one. On the piston rod, the roughness in the region of the sealing element's friction surface had declined significantly; this is clearly visible in comparison with the surface in its new state. There was another temperature rise later on, and the test eventually had to be cancelled after 424 hours due to high leakage. The piston rod's friction surface was polished smooth and glossy. **Fig. 4, bottom**

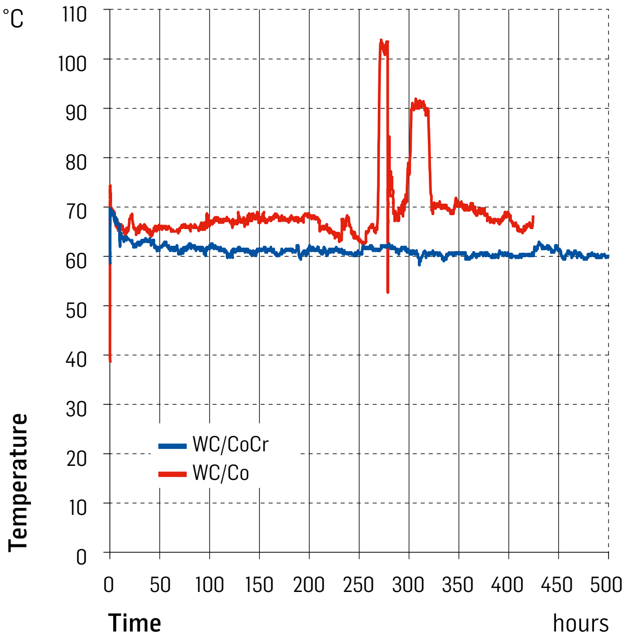
Such steep rises in temperature to values above 100 °C were not observed in the other tests. Here, the chamber temperatures remained stable in the range between 60 to 70 °C after running in. Figure 3 therefore only shows the temperature profile of the piston rod coated with WC/Co (HVOF process) for the purpose of comparison.

Table 1
Hardness and roughness values of the tested counter-body materials

Counter-body material	Nitrided steel	WC/Co	WC/Co	WC/ CoCr	Ceramic
Coating process	–	HVOF	Deto-nation	HVOF	Plasma
Hardness HV0.3	731	1'128	1'156	1'279	926
Ra [µm]	0.237	0.263	0.223	0.277	0.280
Rz (DIN) [µm]	1.797	2.093	1.793	1.957	2.487
Rk [µm]	0.773	0.840	0.667	0.933	0.303
Ratio Rk/Rz	0.430	0.401	0.372	0.477	0.122
Rmr [%]	31.29	46.86	53.47	32.15	82.12

Hardness as average from 10 measurements, roughness parameters as average from 6 measurements by profile method[4, 5]

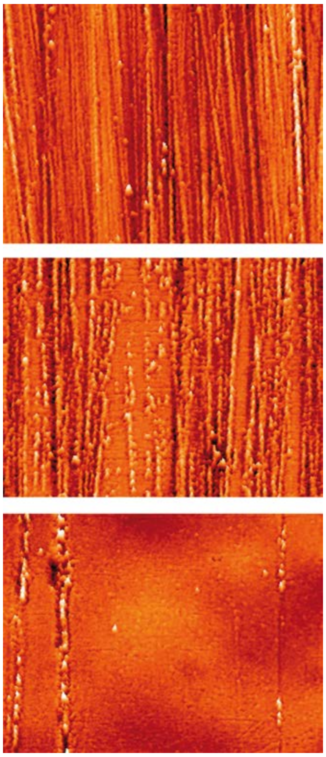
Fig. 3
Temperatures measured in the sealing element's chamber, for piston rods coated with WC/CoCr and WC/Co using the HVOF process



Especially during the running-in period of a dry-running friction pair, surface topography is altered through breakage of roughness peaks, deposition of wear particles and reorganization of surfaces, even on extremely hard counter-body materials. Because these effects can vary highly along the friction surface, roughness measurements in this region usually provide results which fluctuate greatly. Consequently, zones exhibiting minimal roughness were sought and evaluated on the surfaces of all piston rods.

Comparing the thus obtained arithmetical mean deviation of the profile Ra to the values in the original state reveals a reduction in the case of all surfaces, except the ceramic coating. On this coating, formation of the transfer film even led to a slight increase in the Ra value. Especially evident is the reduction in roughness on the WC/CoCr-coated piston rod, although it turned out to have the

Fig. 4
Friction surface of a piston rod coated with WC/CoCr in the new condition (top), after an operating period of 270 hours (center) and after 424 hours (edge length 300 * 225 µm)



highest hardness values. The two chromium-free hard-metal coatings and even the nitrided steel exhibit a much smaller drop in Ra values. **Table 1, Fig. 5**

A further result shown in Figure 6 comprises the wear rates of the sealing elements operated on the various surfaces under otherwise identical conditions. The lowest value was obtained in the test of the ceramic-coated piston rod. Very good results were also obtained with the two chromium-free hard-metal variants. The wear rates of the sealing elements are also significantly lower than that of the nitrided steel surface. The highest wear rate was established in the test of the WC/CoCr-coated piston rod involving high chamber temperatures at times, and revealing the greatest drop in the Ra value. **Fig. 6**

CHAPTER 5

ANALYSIS OF INFLUENCING PARAMETERS

Although a functional design of counter-body surfaces is of particular importance for the dry-running friction pair comprising soft and hard, the surface of the hard counter-body material is usually described only by specifying a permissible range for the Ra value. Ignored in this case is the known fact that the arithmetical mean deviation of the profile Ra is totally unsuitable for characterizing surfaces, as it does not permit any distinction between different profiles. Peaks and valleys are treated equally during determination of the Ra value. The arithmetical mean deviation of the profile is therefore only suitable as a quality

Fig. 5
Ra values measured on the friction surfaces of different counter-body materials, compared with the original finish in each case

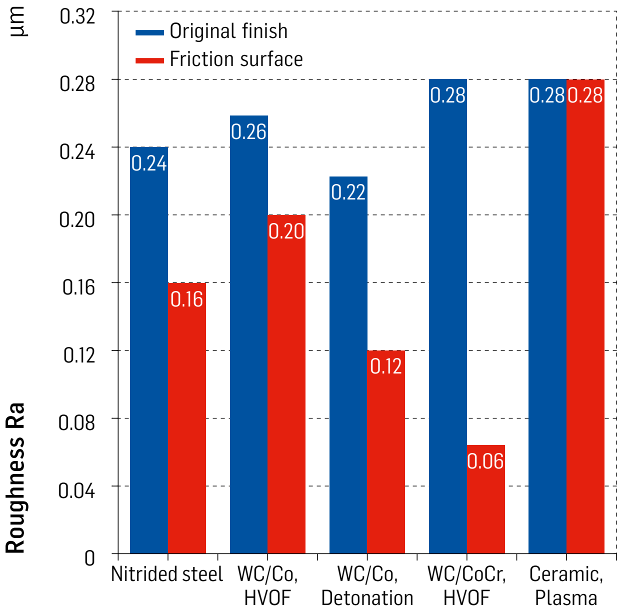
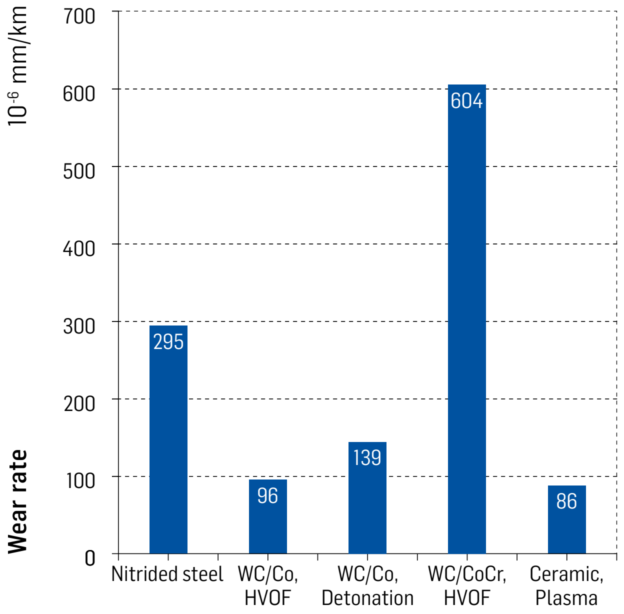


Fig. 6
Wear rates of a single packing ring in dry nitrogen on various counter-body materials

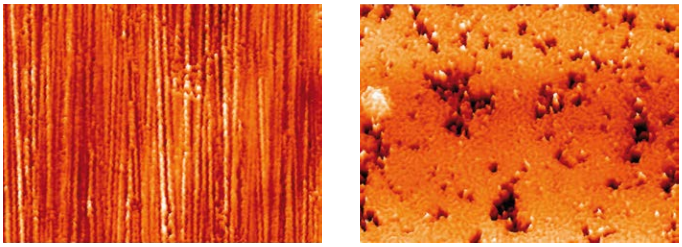


control parameter if the character of the roughness is known, i.e. whether a fissured or plateau-like surface is involved, for example[8].

Several surface texture parameters permit a characterization of surfaces and therefore serve to supplement the results of an Ra measurement. This is achievable, for example, by means of the following parameters:

- Ratio of core roughness depth Rk to average roughness depth Rz (DIN)
- Ratio of average peak-to-valley height Rp to average roughness depth Rz (DIN)
- Relative material ratio of the profile Rmr

Fig. 7
Porous surface of a ceramic applied using a plasma process (right) compared to a nitrided steel surface (edge length 300 * 225 µm)



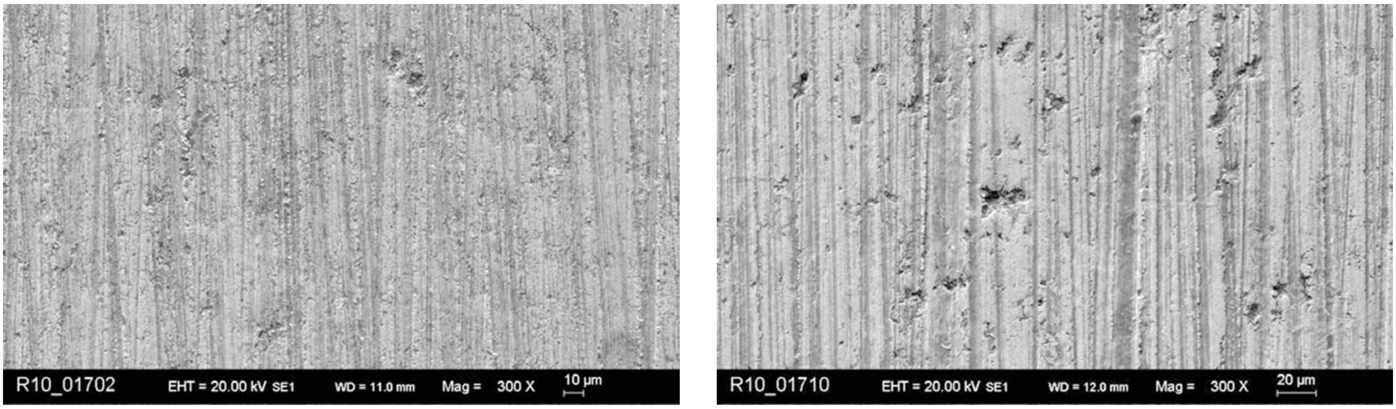
Especially in the case of the porous ceramic coatings applied using the plasma process, the surface after completion of processing might be characterized by a plateau-like roughness profile comprising a high proportion of valleys attributable to the pores. However, the upper limit of the permissible Ra value is often exceeded by this kind of surface. While an inadmissibly large Ra value of a profile with a pronounced proportion of peaks leads to high abrasive wear on the soft dry-running sealing element, it is not necessarily a drawback in the case of a plateau-like roughness profile. A quick initial conclusion about the nature of the roughness profile can be drawn from the ratio between the core roughness depth Rk and the average roughness depth Rz (DIN)[8]. In practice, surfaces achieving a value of less than or equal to 0.25 in terms of this ratio have also proven successful in dry-running if their Ra value exceeds the permissible upper limit. **Table 1, Fig. 7**

Conclusions about the characteristics of the various piston rod surfaces can also be drawn from the material ratio of the profile Rmr indicated in Table 1. In each case, the material ratio was determined with a reference line c0 shifted by about 2% with respect to the highest peak at an profile section level of c1 = Rz/4. A comparison between the Rmr values of the three hard-metal layers reveals that the material ratio of the WC/CoCr-coated piston rod is significantly lower than that of the two chromium-free variants, and only slightly higher than the minimum value of 31.3% ascertained for the nitrided-steel piston rod. The highest value of 82.1% was obtained with the ceramic coating.

A comparison of the surface topographies of both layers applied by means of the HVOF process reveals that the piston rod coated with WC/CoCr has a coarser structure. Powder with a particle size of –45 +15 µm was employed for both hardmetal variants; as a result, the carbides present in the WC/CoCr coating and sized about 3 µm were slightly smaller compared to the sizes of 4 to 5 µm in the chromiumfree coating. **Fig. 8, right**

The differences in surface topographies observed after processing can therefore hardly be explained by their structure, but rather by the different composition of the matrix material and the resultant material properties. Whereas the cobalt content of the chromium-free variant is 12% by weight, it drops to 10% by weight in the WC/CoCr powder, and is supplemented there by a chromium content of 4% by weight. The chromium content has a negative effect on the composite's toughness, apparently making it difficult to produce a surface profile with a high material ratio, and resulting in the observed coarse surface topography[9].

Fig. 8
Different surfaces after processing of a WC/Co coating and a WC/CoCr coating (right)[9]



An analysis of the test results obtained with the ceramic coating and the two chromium-free WC/Co coatings shows that plateau-like surfaces with the greatest possible material ratio offer favorable conditions for dry-running. Plateau-like structures can be realized, for example, by levelling the roughened profile's peaks using a suitable superfinishing process, thereby creating a surface with a dominant proportion of valleys.

CHAPTER 6

INFLUENCE OF COATINGS ON THE PERFORMANCE OF DRY-RUNNING SEALING SYSTEMS

The single-ring test results concerning the influence of various coatings' surface texture on the performance of dry-running sealing systems were studied in more detail in a hydrogen compressor. For this, the piston rods possessing a diameter of 50 mm were coated with both hard-metal variants with and without a chromium content using the HVOF process, and their surfaces furnished with highest possible material ratio Rmr in an additional superfinishing process. Table 2 shows that this was achieved more successfully with the chromium-free coating. To counter the conspicuously high roughness loss on the WC/CoCr-coated piston rod, slightly lower Ra values in the range from 0.15 to 0.25 µm were selected for all surfaces. A conventionally finished piston rod made of nitrided steel again served as a reference for a metallic surface. **Table 2**

A suction pressure of 14 barg, final pressure of 40 barg and average piston speed of 3.41 m/s were specified for the tests, conducted in the first stage of a horizontal compressor which was operated with dry hydrogen (dew point of about –65 °C). The piston rod sealing system in each case comprised a cooled packing of six packing rings made of a PTFE/PPS polymer blend. An operating period of 500 hours was planned for each test. In this series of tests, too, the WC/CoCr-coated piston rod's behavior was conspicuous. Though the test in this case did not pose any problems, the average wear rate of the six packing rings was more than twice that of the chromium-free variant, and higher by about one third even compared to the result obtained for the nitrided-steel piston rod, despite the higher material ratio Rmr. **Fig. 9**

Accordingly, laboratory analyses were conducted to reveal whether friction and wear are influenced not only by different surface topographies, but also the different compositions of the two hard-metal variants via tribochemical interactions between the friction pair and the ambient medium[9]. However, investigations carried out using energy dispersive X-ray analysis (EDX) and micro-probe analysis (WDX) revealed no differences, such as a depletion of oxygen or chromium, between the coatings' used and original areas. Nor was there any change in the layer structure near the surface. The test series was nonetheless supplemented

Table 2
Roughness values of the counter-body materials tested in dry hydrogen

Counter-body material	Nitrided steel	WC/Co	WC/CoCr	CrC/NiCr
Coating process	–	**HVOF**	**HVOF**	**HVOF**
Rmr, original finish [%]	33.89	64.36	40.60	43.58
Ra, original finish [µm]	0.220	0.227	0.170	0.237
Ra, friction surface [µm]	0.157	0.140	0.102	0.077

Fig. 9
Average wear rates of packings in dry hydrogen on various counter-body materials

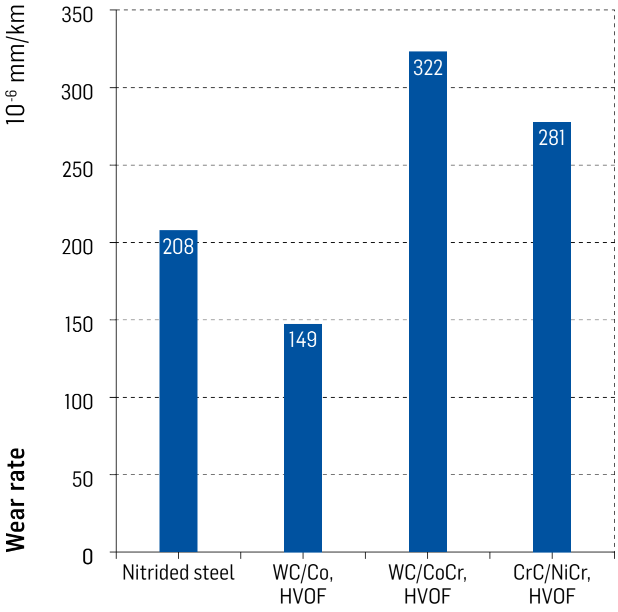


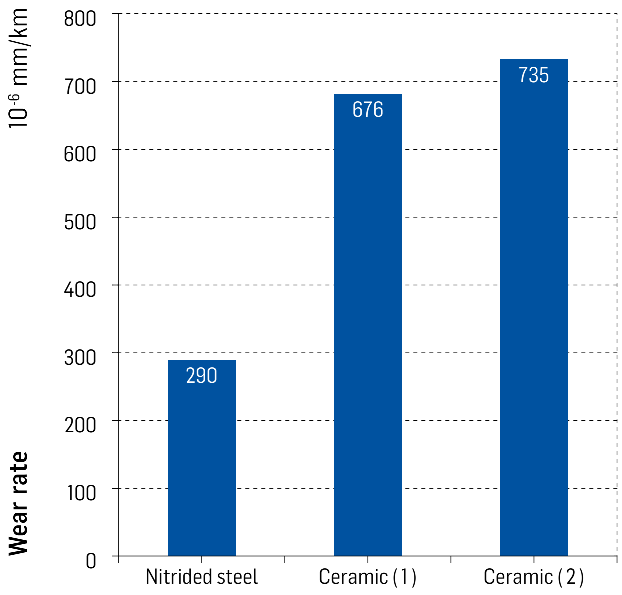
Fig. 10
Silver-colored layer on the friction surface of a dry-running packing ring after operation on a CrC/NiCr-coated piston rod

by a further hard-metal coating which, like WC/CoCr, is highly resistant to corrosion. Though the average wear rate of the sealing elements operated on this CrC/NiCr-coated piston rod is somewhat lower than the result obtained for the WC/CoCr coating, it is still significantly higher compared with the values obtained for the chromium-free hard-metal variant and the nitrided-steel piston rod. In addition, the friction surface of the CrC/NiCr-coated piston rod exhibited a significant decrease in Ra value from 0.237 to just 0.077 µm. This loss of surface roughness was accompanied by formation of a striking, silver-colored layer on the sealing elements' friction surfaces. **Table 2, Fig. 10**

The quaternary ceramic which successfully passed the single-ring tests also has an excellent corrosion resistance. Due to the very good results obtained at a final pressure of 40 barg, this coating was to subsequently prove its dry-running suitability under a significantly higher load comprising a suction pressure of 40 barg and a final pressure of 100 barg in the hydrogen compressor's second stage. The sealing system employed here comprised a cooled packing with a total of 10 packing rings made of a PTFE/PPS polymer blend and optimized for this application.

Already during the test, unfavorable operating characteristics were indicated by conspicuously high temperatures on the piston rod's surface and at the outlet for leakage gas and cooling water. The average wear rate of the sealing elements operated on the ceramic coating is more than twice the value obtained for a conventional piston rod made of nitrided steel. This poor result was confirmed in a repeated test. At variance to the compact structure of the transfer film observed in all other tests, both tests here revealed a large amount of loose, powdery particles on the ceramic coating's surface. **Fig. 11**

Fig. 11
Average wear rates of two packings operated on a ceramic coating in comparison to a nitrided steel piston rod



CHAPTER 7

SUMMARY AND CONCLUSIONS

Despite high hardness values significantly in excess of 1'000 HV, the arithmetical mean deviation of the profile Ra of some hard-metal coatings dropped by more than 0.1 µm in the region of the sealing element's friction surface after only 500 hours. This change in surface texture was typically accompanied by high wear rates on the packing rings, thereby confirming the observations made in practice.

Differences in roughness loss indicate an influencing role played by the composition and structure of the hard-metal composite. For example, hard-metal coatings with a pure cobalt matrix exhibited a considerably smaller decline in roughness than those with a matrix material containing chromium.

Another important factor influencing roughness loss is the counter-body's surface topography. The tests showed that plateau-like surfaces with the highest possible material ratio Rmr offer favorable conditions for dry-running, besides reducing roughness losses. Coating composition turns out to play an influential role here too, a generation of such surfaces with the highest possible material ratio Rmr being more successful in the case of WC/Co coatings than in the case of the two hard-metal variants WC/CoCr and CrC/NiCr.

These WC/Co coatings possessing a high material ratio Rmr also exhibited lower wear rates compared with the tests of a conventional piston rod made of nitrided steel. A quaternary ceramic tested as an alternative to hard-metal coatings, and possessing a significantly higher material ratio Rmr yet due to its porous surface topography, achieved the best test results with a final pressure of 40 barg. After the load pressure was increased to 100 barg, however, the ascertained wear rates were reproducibly worse compared to the result obtained for the nitrided-steel piston rod.

Large amounts of loose particles on the counter-body surface suggest that the corrosion-resistant ceramic coating adversely affects a formation of transfer film. In addition to surface topography, variations in chemical resistance among the coatings therefore also appear to be an important factor influencing wear characteristics. Especially with high-pressure loads, all coatings recommended for use in corrosive media achieved poorer wear rates than a nitrided-steel piston rod, despite higher values for the material ratio Rmr.

Notation

PTFE	Polytetrafluorethylene
PPS	Polyphenylensulfide
CVD	Chemical vapour deposition
PVD	Physical vapour deposition
HVOF	High velocity oxygen fuel
DLC	Diamond-like carbon
Ra	Arithmetical mean deviation of the profile (AA, CLA)
Rz (DIN)	Average roughness depth
Rk	Core roughness depth
Rp	Average peak-to-valley height (Rpm)
Rmr	Relative material ratio of the profile
c0	Reference level
c1	Profile section level

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