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Application of Low Temperature PVD Coatings in Roller Bearings - Fatigue Prediction of Thin Hard Coatings - Tribological Tests and Experiments with Spindle Bearing Systems.

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Abstract

A dominant obstruction preventing the general application of high speed cutting is the performance of machine tool spindle systems, due to the speed and service insufficiency of conventional bearings. The development of low temperature PVD processes allows the application of hybrid bearings with ceramic balls and coated steel rings, improving their tribological behaviour and reducing the necessary lubricant amount, the operational temperature, as well as their noise level. Furthermore, the rotational speed and the whole stiffness of machine tool spindles increase.

The application of coatings for high speed hybrid rolling bearings with coated races and ceramic balls has been studied within the framework of the European BRITE-EURAM Project BE 5963. In this paper the main achievements of the project are presented as follows: First of all, the PVD-coating-process „Enhanced Sputter Ionic Plating”, developed by CemeCon to enable low process temperatures is described. Following the presentation of the coating-fatigue-prediction accomplished by LMD. Thirdly the paper focuses of the results of tribological tests for the characterisation of coatings in lubricated conditions performed by Tekniker. Finally the outcome of the spindle bearing tests with actually coated races, carried out at WZL are presented.

1 Introduction

As a result of the increasing use of high speed and high performance cutting on the grounds of economic efficiency, angular contact ball bearings, which attain a speed characteristic of $n \times d_m = 2$ to 2.5×10^6 mm/min at a bore diameter d_m of 50 to 100 mm, are required /3/. However, due to their life and wear accomplishment, conventional steel bearings achieve a maximum speed characteristic of approximately 1.7×10^6 mm/min that does not fulfil the required performance. A decisive influence on the service life and frictional behaviour of bearings is the minimisation of their lubrication, which is favoured in order to reduce power dissipation and spindle temperature as well as meet future ecological demands. The oil minimisation is dependent on the affinity existing between the rolling partner materials as well as on their wear attitude and is restricted.

To overcome such difficulties, the so called hybrid bearings, bearings with ceramic balls made from Si_3N_4 or even full ceramic bearings, were proposed. This led to a significant improvement of the rotating capacity, as a result of the density reduction of the rolling elements and consequent] y of the centrifugal forces. However, the performance of such bearings is restricted by the tribological behaviour of the steel races. Taking into account the extended applicability of PVD processes, the superficial enhancement of steel races, by means of thin hard coatings was proposed and accomplished in the EuroBearing project /6/.

2 Technical description

2.1 *Development of Coatings*

The most significant requirement of *100Cr6* steel that is usually used for the metallic component of hybrid bearings is not to exceed the annealing temperature during the whole coating process, otherwise changes in microstructure would occur and cause a loss in hardness. For this requirements investigations had to be done to fulfil these demands and to ensure a successful process under these conditions.

The development work started with the development of a *PVD MSIP process* (physical vapour deposition-magnetron sputter ion plating) that ensured high quality coatings deposited at a maximum process temperature of *160* ‘C. Due to the complex shape of the inner and outer rings, the hardware (fixtures) and all basic parameters were set up in view of all restrictions and high quality. Within a next step different kinds of coatings were deposited to find out the best material-coating combination for the high speed application of hybrid spindle bearings.

AH the development work was carried out with a *PVD*-coating unit (type *CC800*). This unit is the most modern one due to its high flexibility and the ideal environment for development and production. *PVD* coating processes comprise about *50* different coating steps. Manual control of the system would therefore lead to a high error probability. The reproducibility of the process conditions and of the coating results would not be guaranteed under these circumstances.

An automatic process control system configured around a powerful and rugged process computer ensures that the coating process is operated under fully reproducible conditions. Potential sources of error such as the critical reference temperature, which indicates the exceeding of the maximal permissible temperature of *160* “C for *100Cr6* steel during the so-called low temperature process, could be detected and remedial action could be taken at once.

The automatic process control system will thus ensure an optimum coating result and reproducible deposition parameters, a quality which is of key importance particularly in laboratory as well as in series production.

The *PVD* coating system CC800 is a new type of unit specifically designed for depositing coatings on tools and components of complex shape such as bearing components. The system combines the benefits of a mature vacuum technology and latest plasma electronics with powerful process control facilities to ensure a smooth and reliable deposition process with difficult parts.

2.1,1 Substrate material and their preparation

The substrate material was 100Cr6 steel. The desired coating material was mounted on the sputtering source in the form of a 200x88x5 mm plate with was transferred to the work-piece through a deposition process performed either in normal or in reactive mode. The sputtering sources could accommodate plates made of a wide range of materials. This allowed components and work-pieces to coated with pure metals as well as complex alloys. For quality control such as thickness, hardness measurement Rockwell indentation and scratch tests, discs with a polished surface were coated. For tribological testing balls, rods and discs with a polished or fine finished surface were plated. The high precision ball bearings with a lapped surface finish on the races were not treated subsequently. All parts were degreased in an ultrasonic bath with a water based alkaline solution. No further treatment was carried out before etching.

2.1.2 R.f.-ion etching of bearing components

Sufficient ion bombardment of internal geometry, e.g., the track of outer rings, with dimensions of the magnitude of the mean free pass during etching could represent a problem. By means of suitable fixture design /12/, a concentration of the plasma could be attained within the outer ring of the bearing. In so-called hollow cathodes (e.g., thin-walled cylinders), secondary electrons were emitted more intensively, which led to an increasing electron density with its maximum on the cylinder axis. This caused an increasing ionisation in the opening area of the hollow cathode where the outer ring was fixed. The formation of the temperature could indicate the consistency of the ionisation. The higher the ionisation inside the ring, the more effective was the cleaning of the race produced by the ion bombardment that had been produced. Furthermore the influence of the hollow cathode effect on the formation of the internal temperature, as an indicator of the order of ionisation, diminished with increasing diameter. The temperatures were recorded with thermocouples and with surface thermometer.

Fig. 1 illustrates the increase in temperature on the inside of outer rings dependent o-n the argon pressure and the r. f.-power during etching when hollow cathode fixturings were used. The r. f.-power was increased from 300 to 800 W in discrete steps of 100 W. Only the respective graphs for 300 and 800 W are illustrated. The graphs represent the limits of temperature and the d.c.-potential field. The total surface of the electrode “substrate” was varied (A_2 = 9x1O cm’ = $2A_1$) to detect the influence on the substrate temperature. With increasing substrate surface the self biasing potential that arose on the substrates decreased at constant r. f-power and pressure, The same tendency showed the substrate temperature.

The increase in temperature in outer rings when using a hollow-cathode fixturing was higher than on the outside. Therefore this effect had to be taken into consideration mainly for the parameter adjustment. The studies led to a batch that allowed the etching parameters to be varied within a wide range without exceeding the critical temperature of 160 ‘C.

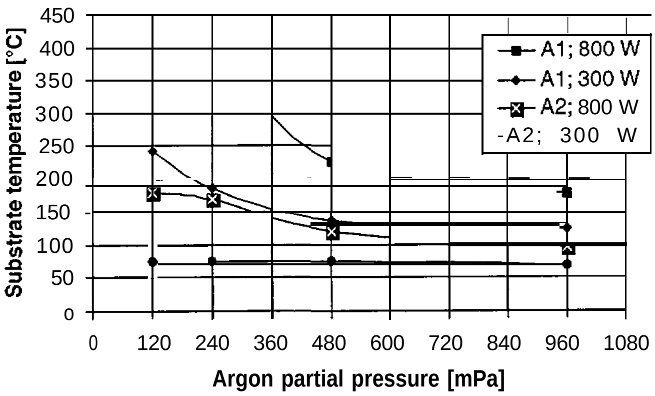

Fig. 1: Maximum internal temperature of outer rings in dependence on the argon partial pressure and the r. f.-power with varying total substrate surface.

The following optimisation regarding sufficient cleaning of the races resulted in an optimal etching time of 1h at 600 W r. f.-power and at an argon pressure of 300 mPa.

2.1.3 Coating process

To guarantee an even thickness distribution of the coating, bearing parts were turned around their own axis and between the two sputter sources, placed at right and left of the chamber, The angle of inclination of the cathodes in relation to the substrates cold be changed, During the coating process the cathodes proceeded vertically in discrete steps, as regards time and path. As a result of this, the thickness of the layer was distributed evenly. Owing to the high emission of secondary electrons from the cathodes, the substrates were heated when passing the area near the cathodes. The higher the cathode power was the higher the substrate temperature became, although the variation of temperature was only slight.

There were only minor differences measured between the temperatures which rose in the area near the cathodes and the mean temperature which appeared at the substrate with the longest distance from the cathodes. The low temperature process was carried out with a total cathode power level of 4 kW. The rise in temperature was independent on the rotating speed of the substrate table (planetary substrate movement). Also the bias voltage level caused no measurable variation in temperature within the suitable range. The d.c.-voltage level was varied between 80 and 130 V at a total cathode power of 4 kW. In all cases the substrate temperature was below 160 “C.

2.1.4 Coating properties

The layers studied are the following: CrN, Mo, hard coatings TiAlN, TiAICN, TiCN and graded TiN coated with pure carbon. Due to the fact that UBAM´s sputtering sources could also evaporate mechanical mounted targets, almost any target composition was available. In Table 1 the main coating parameters and coating properties of the deposited coatings are listed. The micrographs in Fig. 2 illustrate the fracture of a TiAlN coating deposited at a temperature of 160°C with an immaculate dense crystalline structure.

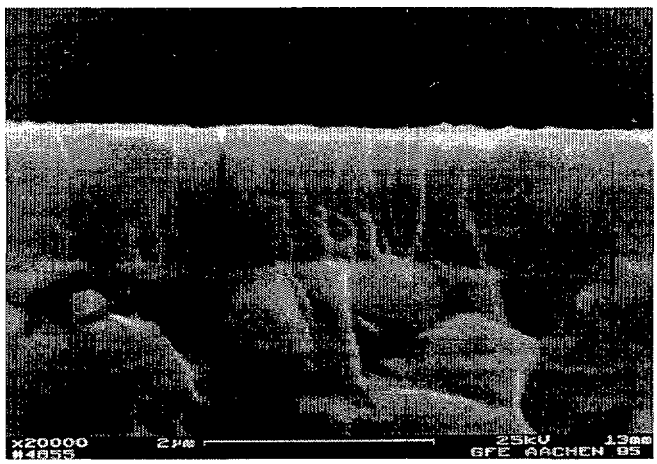

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Table 1: Deposited coatings and the main properties

Type of coating	D.c.-bias voltage (V)	Thickness (pm)	Hardness HV0.05/15	Critical Load (N)
CrN	130	2.5	1300	90
Mo	130	2,5	650	100
TiAlN	100	2	2900	100
TiCN	90	2	1800	70
TiAlCN	90	2	2200	90
TiN+C*	60-90 (graded)	1	900	

Standard parameters: 4kW total cathode power. 500 mPa total pressure.
*C is a sputtered carbon layer

2.2 Fatigue prediction of thin hard coatings

In order to define critical coating fatigue stress values, a procedure using the impact test and its Finite Element Method (FEM) simulation was developed. The analytically, experimentally obtained and validated coating fatigue critical stresses were used to calculate the fatigue behaviour of bearing coatings /7/. The most endangered contact positions between rolling elements and bearing rings were investigated through a FEM simulation, considering every design, loading and geometric specification.

2.2.1 Determination of coating fatigue stress values

To serve the demand for precise knowledge of several coating substrate compounds fatigue behaviour, the impact test that offers mainly qualitative information is used /8,9/. The test arrangement and corresponding typical experimental results of this test are shown in Fig. 3. During the impact test a plane coating-substrate compound is exposed to a contact pressure, by impacting its surface through a cemented carbide ball. Hence diagrams of the contact load that leads to coating fatigue fracture versus the corresponding number of impacts can be obtained. The coating fracture is designated by gradual or abrupt coating removal and exposure of the substrate material /10/. By means of a developed FEM simulation of the impact test, the transformation of critical impact loads to critical stress values, associated to specific and distinct failure modes (adhesive, cohesive) is enabled. The evaluation of the coating fatigue behaviour, as it derives experimentally by the impact test, is carried out through Scan Electron Microscopy, Scan Electron Spectroscopy and profilometry.

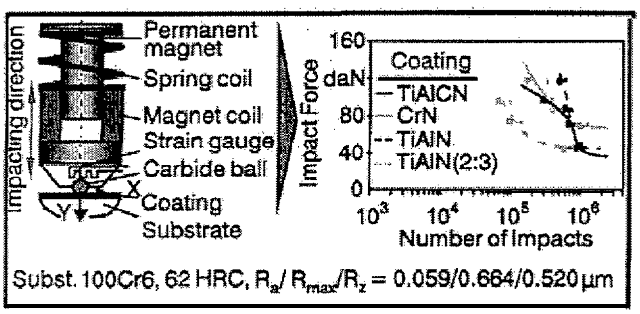
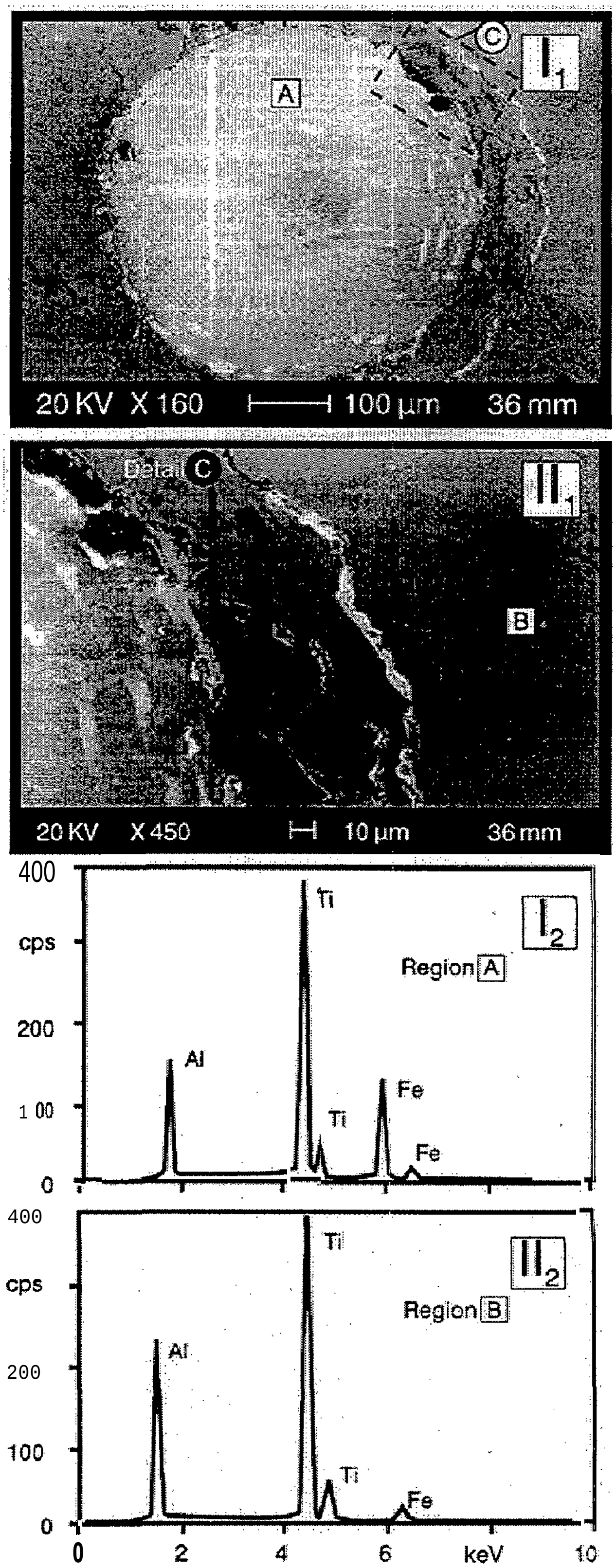


Fig. 3: Principles of the impact test and typical results.

A cohesive failure mode is observable in the case of TiAlCN coated specimens as photograph I_1 that Fig, 4 illustrates. The brittle TiAlCN coating demonstrates a purely cohesive fracture type. This failure mode is designated by circumferential cracks at the vicinity of the contact circle, as it shown in the inserted magnified photograph II_1, and chipping that accompanies the radial microcracks within the imprint. A spectral analysis within the crater (see diagram I_2 in the same figure), confirms these observations.

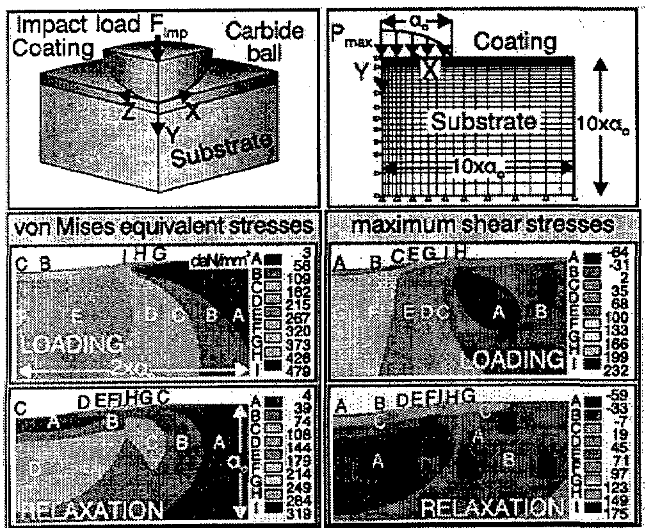


Coating TiAlCN, Substrate 100 Cr 6, F_b = 100 daN, N = $4x10^5$, Bias Voltage = 80 Volt, t = 2 µm

Fig. 4: SEM photographs and spectral analyses of a cohesively failed coating.

The successive cemented carbide ball impacts lead to a continuous removal of small coating fragments and herewith to the gradual exposure of the base material. The initial superficial composition is depicted by the micro spectrum diagram II2, which is unvarying outside the imprint. For such cases, the hazardous stress component that initiates the destruction of the intrinsic cohesion of a thin superficial coating is the normal stress, especially the tensile one developed within the film. Therefore, in such matters the von Mises equivalent stresses, which disclose the dissimilarity of the stress field regarding its principal components, are the appropriate ones to denote the potential stress distribution to cause cohesive failure.

The Hertzian stress field during the impact test indicates an overstressed substrate, in comparison to the coating. On that account, in order to reach high coating stress values, heavy loads are applied onto the coated specimens, causing plastic deformation within the steel substrate. The FEM modelling procedure, considering these circumstances, for the simulation of the impact test is illustrated in Fig. 5. The test geometric configuration, as it is shown in the right part of the figure, is used to create an adequate FEM simulation of the experimental procedure. The loading and the geometrical symmetry have been contemplated to produce a two dimensional axisymetric solid model of the semi-infinite layered half space, as it is illustrated in the right part of the same figure.



Coating TiAlN, Substrate 100 Cr 6, F_{imp} = 100 daN, a_o = 0.279 mm, Bias Voltage=95 Volt, t=1 .3 µm

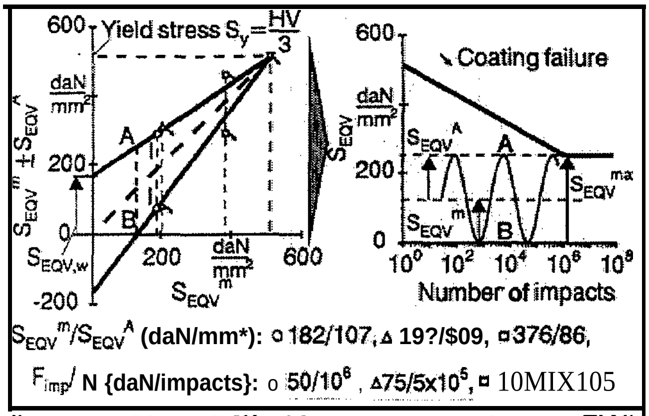
Fig. 5: Modelling procedure of the impact test and typical test results.

The quasi static simulation of the test has been performed considering two load steps. The first load step, the so called loading stage, represents the time period when the load is being applied onto the coated surface. During the second load step, the so called relaxation stage, the pressure distribution is removed and the exclusive potential of the stress field leads to an elastic recovery. The developed von Mises equivalent $S_{EQ}V$ and maximum shear stress T_{max} distributions during the loading and the relaxation stages respectively, for TiAIN coating on steel substrate, are illustrated in Fig. 5. During the relaxation stage, while the indentor is moving upwards, a residual strain can be observed within the substrate that keeps coating also deformed. The essential for the previously described simulation coating material properties are obtained through nanohardness tests /11,12/. The determination of the plastic behaviour of the hardened substrate materials is conducted according to a developed procedure, presented in/1 3/.

Table 2: Determined mechanical properties of the investigated coatings (daN/mm2).

Coating	E	í	HV	$S_y=R_m$	$S_{EQV,w}/R_m$
TiAIN	48000	0.23	1527	509	0.33
TiAIN(2:3)	46000	0.23	1530	510	0.29
TiAICN	35800	0.23	1305	435	0.28
CrN	24500	0.23	810	270	0.39

The coatings fatigue behaviour can be expressed through a Smith diagram of the critical stress components for cohesive failure mode i.e. the von Mises stresses, that ensure their continuous endurance (see Fig. 6). The Smith diagram of a TiAIN coating is penned in this figure. The stress limit for coatings is assumed to be their yield stress, since they are considered to be brittle materials /14/, Due to the lack of permanent deformation within the bearing races, the coating deforms purely elastically during the pass of each ball and fully recovers by the end of each contact. For this case, the fatigue limit for coatings that ensures continuous endurance, is derived from the region A-B of the Smith diagram that has a zero minimum stress. This value and the static stress limit are used to compose the Woehler diagram as it is also presented in the right part of the figure. By means of this procedure, critical stress values for different coatings have been derived and are inserted in Table 2. The further presented computational results of this paper refer to the hardest and softest inspected coatings, i.e. the TiAlN and CrN respectively. Taking into account that the following presented calculations regard mechanical stresses, the attitude of the other coatings is almost analogous, according to their bulk stiffness /6/.



'ig. 6: Smith and Woehler representation of TiAlI coating fatigue behaviour.

2.2,2 Coating fatigue prediction of coated hybrid bearing races

During the evolution stage of the hybrid bearing types with ceramic balls and coated races, several design parameters were investigated and optimised. The most significant of them were the geometry, the PVD process parameters, the substrate heat treatment and the coating materials. During the long term and full scale bearing operation in special test rigs and high speed electrospindles /3,6,12,15/ many problems encountered, having as final result the coating fracture. Such problems for example were the uncontrolled substrate annealing within the coating chamber that led to improper bearing rings eccentricity etc. To clarify whether the each time occurred coating fracture was an immature fatigue appearance or not, the precise knowledge of the dynamic stress level under the applied operating conditions was required. To solve this problem, the presented coating fatigue life time model was applied simultaneously with a FEM simulation of the most endangered contact positions that are formed between balls and races, during the bearing operation /6,16/. The contact loads were calculated with the aid of a digital program that performs the quasi static simulation of the bearing operation, considering every cinematic and dynamic parameter /17/. The performance evaluation of such bearings was conducted, with the axial preload and the effect of inertia being the only loads.

The developed FEM modelling procedure is illustrated in Fig. 7. The calculation refers to the contact between the ceramic rolling elements and the coated outer race, which is the most dangerous one, due to the centrifugal forces. Owing to the load symmetry of the angular contact bearings, every contact position is identical to the others.

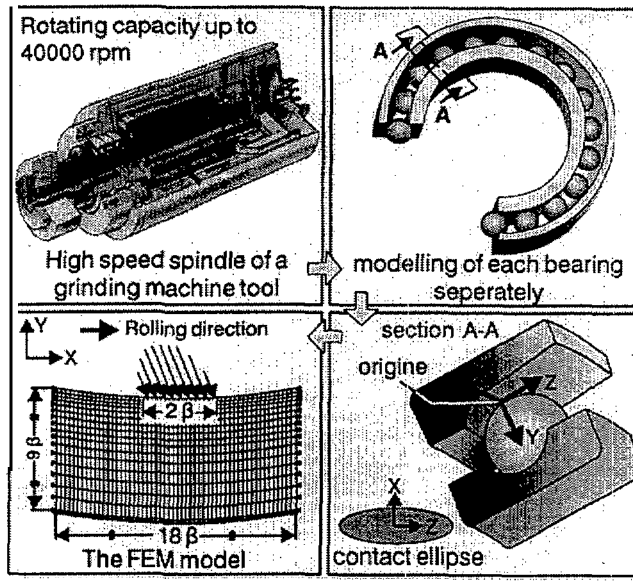


Fig. 7: Modelling procedure and FEM simulation of the contact positions.

The FEM solution considers also the friction effects that influence significantly the stiffer coatings. The model was built in terms of multiples of the small semi- axis of the contact ellipse. $\hat{a}$, in a way to be finer near the coated surface and coarser apart from it. Rolling was simulated by applying onto the coated surface a normal Hertzian elliptical pressure distribution with maximum value P_{max}, whereas sliding by a corresponding tangential one, The tangential press vectors were proportional to the normal ones, having ratio the friction coefficient ì. The coating thickness was assumed stable and perfectly bonded together with the base material. To judge the model sufficiency to simulate satisfactorily the required stress fields, the homogeneous case, i.e. races without coating was solved and the results were compared with the analytical solution that exists only for uncoated rings /18/.The analytical and FEM solutions were identical /6/,

Fig. 8 illustrates the superficial distributions of various stress components of a 7010 hybrid bearing under the same preload and for the cases of the stiffest examined coating TiAlN and the softest one CrN. As expected, friction increases the stress level and herewith the fatigue danger. The stress components presented here are the potential ones for cohesive failure mode i.e. the normal stresses that are developed within the coating during the bearing operation. A comparison of the stress values between the TiAIN and CrN coatings, shows that under the same preload and thus contact load, the soft coating develops lower stress values, having on the other hand the same distribution with the stiffer one. The maximum stress values of these distributions dictate the bounds of the stress alteration, since coatings are stressed between

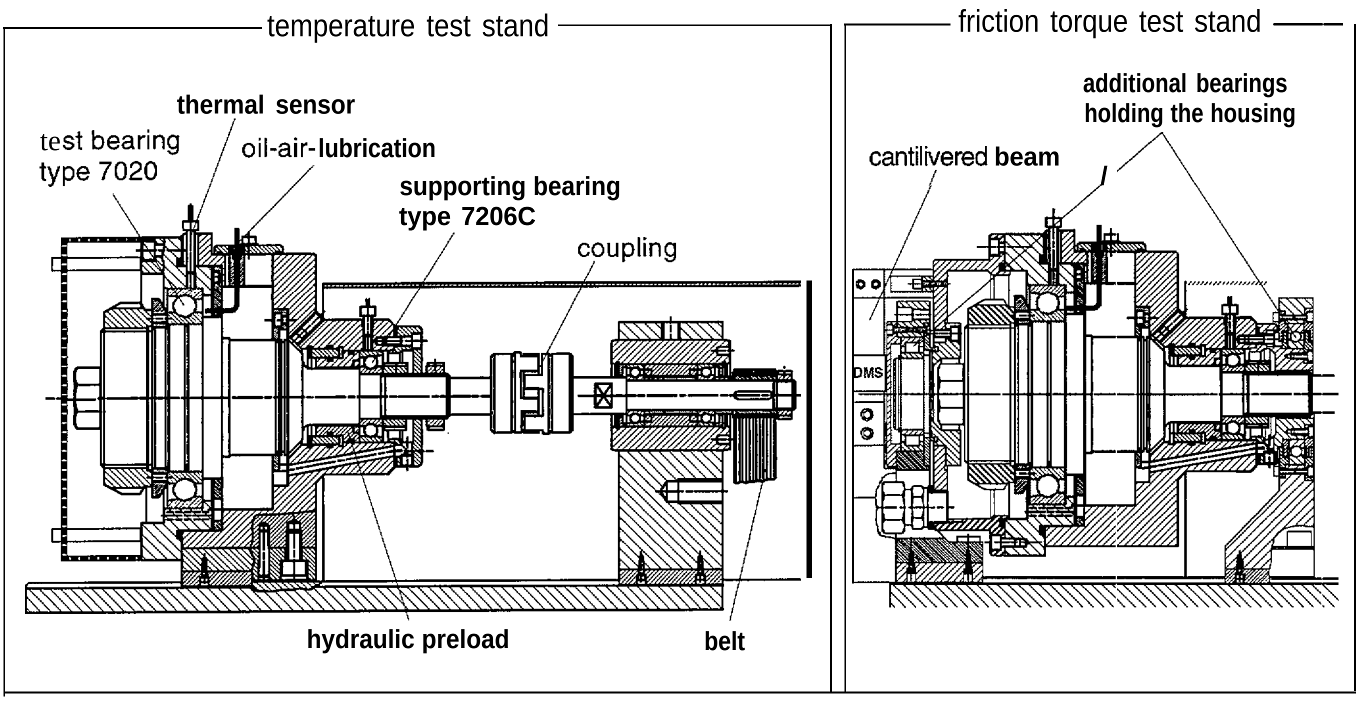


Fig. 11: Test stand for investigation of temperature and friction torque behaviour.

2.4 *Test results*

It was previously believed that thin surface coatings would have little effect on fatigue behaviour because maximum shear stresses often occur as deep as 10-150 μm below the surface and the coatings typically have only about 1-2 μm thickness. However, the experimental results corroborate previous results, showing that hard coatings and specially graded coatings may considerably increase the fatigue lifetime of rolling elements /4/. The results obtained in the present tests are now described.

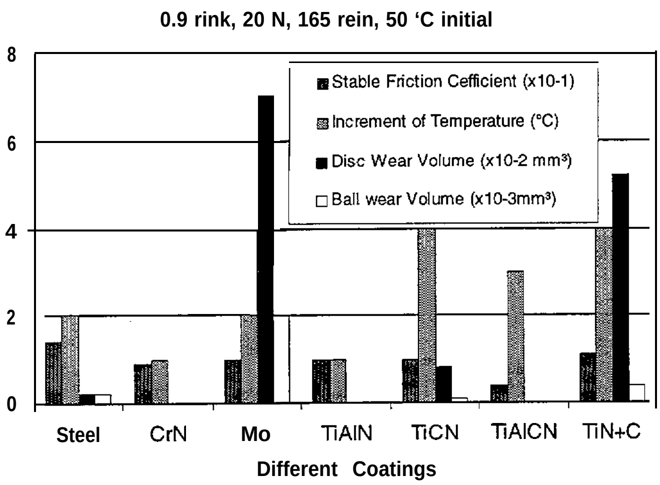


Fig. 12. Selection of coatings in grease lubricated conditions by means of ball-on-disc machine.

2.4.1 Model tests

2.4.1.1 Ball-on-disc

The friction and wear characteristics of different coatings with grease lubrication have been studied. The lowest wear, increase of temperature and friction coefficients were observed for CrN and TiAlN coated discs, where no wear at all was detected (see Fig. 1.2). Lithium and calcium based greases were tested. The behaviour of the lithium grease with higher speed factor improves the wear behaviour of the coatings

2.4.1.2 Ball-on-rod testing machine

four batches of experiments have been carried out with stop times of 100, 270, 350 and 1000 million cycles, respectively. In the first batch of experiments (stop time 100 million cycles) the lifetime of CrN and Mo coatings were determined. These coatings failed by pitting beneath the coating, thus having much lower duration than Ti-derivative coatings that only presented micropitting. The harder coatings may inhibit ploughing /4/. In order to study differences between various Ti-derivatives, 270 million cycles tests were performed. In the nine tests performed only three failed and, in two of them, it was not the coating but the steel ball that failed. This is an interesting result since the probability of failure in the ball should be lower than in the rod. In the 350 million cycles batch, tested specimens failed by pitting, except the specimen coated with graded TiN having pure carbon on the top. This coating resisted more than 1000 million cycles without pitting. Possibly the soft carbon layer on the top of the hard coating results in a smoothening of the surface, which can have a beneficial effect because of the lower stress levels of asperities in contact.

The most resistant coatings against fatigue, presented a central blue coloured region in the wear track. The SEM analysis of the ce ntral coloured region of a TiAlN rod revealed 0.7 and 2% ofTi and Al, respectively. In order to detect possible oxides formed by triboxidation process in the wear track, an X-ray diffraction analysis (XRD) of this rod was performed. Unfortunately, this layer was too thin to perform the phase analysis on the wear track, even when using a fibre optic as primary beam. By means of this technique, however, presence of TiN osbomite was detected in the original coating area.

2.4.1.3 Four-ball testing machine

By means of the “four ball machine”, the wear behaviour of the coating was analysed using a base oil (without additives). A higher load carrying capacity and a lower wear was observed for the CrN, TiAlN and the graded TiN+C coatings. Similarly to the scratch test, delamination was observed for the TiCN coating. When using an oil with additives, the effect of the additives was higher than the effect of the coating and no large differences could be observed between the coatings.

2.4.1.4 Selection of the coatings

A summary of the characteristics of different coatings is presented in Table 3. Load carrying capacity and protection against chipping were evaluated by means of the four-ball-machine ad the scratch tester, wear resistance was evaluated by means of the four-ball and ball-on-disc machines, and fatigue resistance by means of the ball-on-rod test. Combining these properties, the optimum coatings to be applied in high speed rolling bearings are CrN, TiAlN and graded TiN topped with pure carbon.

2.4,2 Experiences with spindle bearing systems

Tests with spindle bearing systems have been carried out with the best coatings as selected in the model tests. The effect of the coatings (CrN, TiAlN and TiN+C) on the increase of speed in spindle systems has been analysed. A comparison of-the steady state temperatures (in the bearing stand as previously described) measured at the outer ring of the bearings with various coatings can be seen in Fig. 13. While the steel bearing reaches only 17000 rpm at the upper temperature level of 60°C, the hybrid bearing goes up to 18000 rpm (due to the excellent characteristics of Si_3N_4 compared to steel with 60% less density and 50% higher modulus of elasticity). An additional coating of the races further improves this behaviour so that a rotational speed of 20000 rpm has been achieved with CrN-coated races.

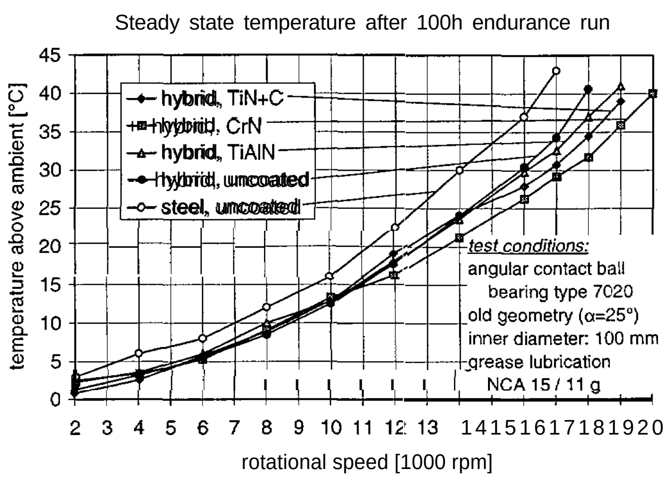


Fig. 13: **Comparison of steady state temperatures of uncoated and various coated hybrid bearings (type 7020).**

The almost linear increase of steady state temperatures with the rotational speed underlines that the bearing would be able to run at even higher speeds if higher temperatures were acceptable or the system

Table 3: **Selection of coatings by means of model tests**

Type of coating	Load carrying capacity	Against chipping	Wear protection	Hardness	Fatigue resistance
CrN	Good	Good	Good	Medium	Bad
Mo	Good	Good	Bad	Low	Bad
TiAlN	Good	Medium-good	Good	High	Good
TiCN	Bad-medium	Bad	Good	High	Good
TiAlCN	Medium	Medium	Good	High	Good
TiN+C	Medium-good	Good	Medium-good	Medium-high	Very good

these highest loads and a zero value, when each rolling element moves away from the examined position.

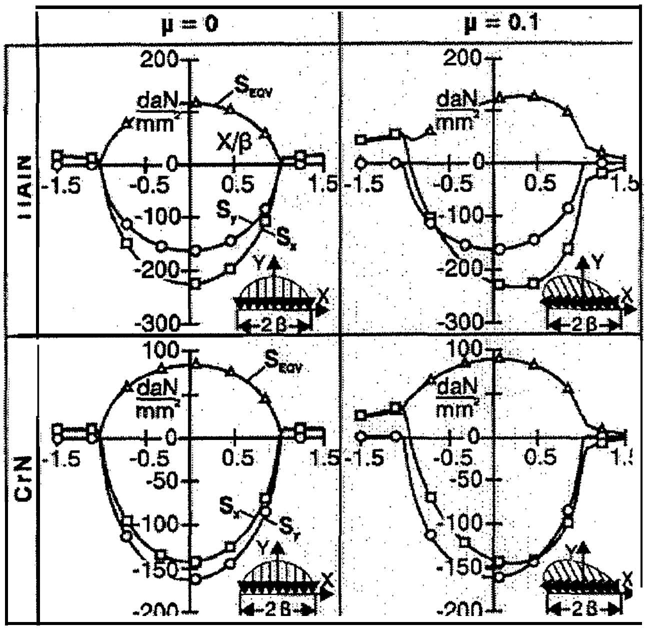
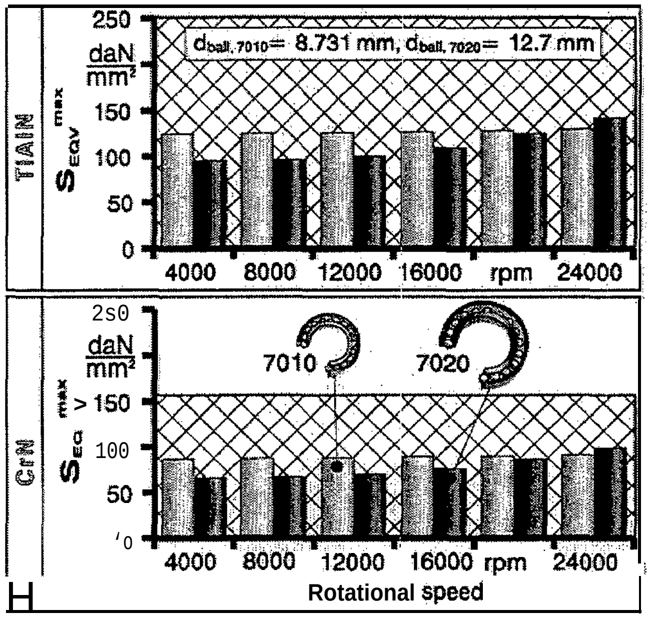


Fig. 8: Superficial **distribution of coating stresses occurring during the bearing operation.**

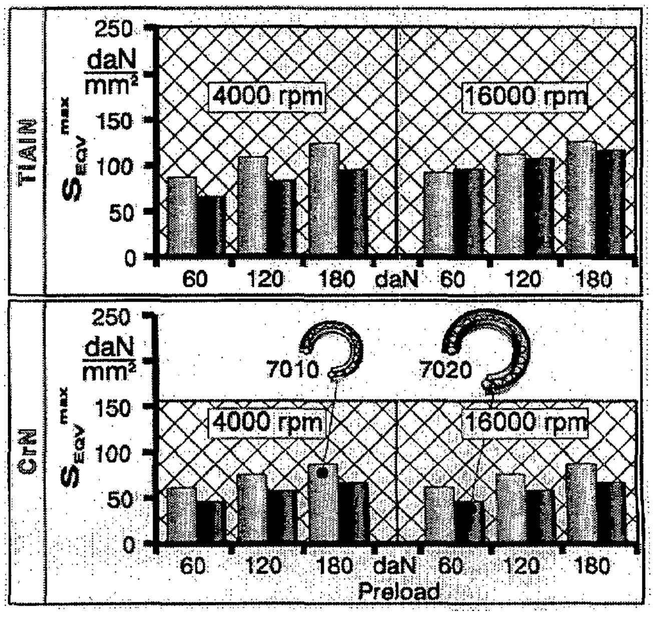
The maximum von Mises stress values, which are obtained by means of the previously described procedure, changing each influencing factor separately, are compared with the safe fatigue bounds derived by the corresponding Smith diagram. In the examined bearing cases, due to the pure elastic deformation of the contact material, the area of the Smith diagram that is offered for fatigue prediction, is that with a zero minimum stress value. Fig. 9 illustrates fatigue prospects for both examined coatings, as a function of spindle rotational speeds, in two different cases i.e. that of the 7010 bearing with mounting diameter 50 mm and of the 7020 one with 100 mm. The hatched area in each diagram corresponds to loads that are associated with coatings continuous endurance. The enlargement of rotational speed increases the fatigue danger due to the effect of the centrifugal forces. This effect is more evident in the case of the 7020 bearing, due to the larger diameter and herewith increased mass of the rolling elements. On that account, for the same level of axial preload, even if at lower speeds the big 7020 bearing develops lower stresses, due to its dimensions and number of rolling elements, this situation inverts in higher speeds.

Fig. 10 displays the effect of axial preload on the occurred coating contact stresses for two different levels of the rotational speed. The preload increase leads to the enlargement of the stresses developed. This remark becomes more obvious in the case of the small bearing. The reasons are the same as above, since both the smaller radii of curvature of the contact bodies and the lower number of rolling elements that characterise the smaller bearing, are associated with higher contact stresses /15/.



μ=0. 1, t=2.5 μm, preload 180 daN

Fig. 9: The influence of rotational speed on coating contact stresses.



μ=0.1, t=2.5 μm

Fig. 10: The influence of preload on coating contact stresses.

Both coatings in the previous presented figures express an analogous behaviour, considering their strength reserves and the developed stresses under operating conditions. A comparison between the Smith diagrams of TiAlN and CrN coating materials gives the impression that TiAIN is more fatigue resistant in relation to CrN. However, both coatings regarding their fatigue behaviour, exhibit a similar attitude, since the stiffer TiAlN coating develops higher stresses for the same level of contact loads. In the investigated cases, even for the hardest conditions, coatings operate within safe bounds having a satisfactory fatigue safety factor. The secure indication of the fatigue sufficiency of the examined coatings, permitted a moderate depiction and judgement of the design and technological parameters that had a significant influence on the occurred coating failure. The optimised bearings indicated experimentally the expected behaviour /6/.

2.3 *Tests description*

The objective of the model tests is to select the most promising coating combinations whereas spindle bearing test are intended to demonstrate the improvements for the selected coatings. The model tests carried out by TEKNIKER with "ball-on-disk", "ball-on-rod" and "four-ball" machines are described. Final tests in complete bearings performed by WZL are then detailed.

2.3.1 Model tests

Some tribological tests have been carried out at TEKNIKER to compare the performance and select the most convenient thin film layers. Results of high speed angular contact ball bearings, maximum stress in the ball and race, linear speeds and the percentage of rolling/sliding, calculated for steel and ceramic balls were previously reported by TEKNIKER /4/. The results of these calculations have been used to define working conditions for simulation of wear and friction machines and tests.

2.3.1.1 Ball-on-disk testing machine.

Tests to study the friction and wear behaviour of different combinations of ceramic/coating with lubricant in pure sliding contact have been performed. These tests, performed in a Falex Multispecimen Machine, consist of a unidirectional continuos movement of a ceramic ball running against a fixed steel/coated disc. Testing conditions are as follows: load, 20 N; speed, 0.9 ins-l; grease lubrication; initial temperature, 50 "C; duration, 165 min.

2.3.1.2 Ball-on-rod testing machine

In the "new high speed ball on rod machine" developed by TEKNIKER the fatigue behaviour of different coatings have been studied in an accelerated pure rolling contact. In the tests performed with this machine, the spans of classic subsurface origin were obtained mainly on the wear track of the test specimen, increasing the vibration level. The shutdown sensitivity was sufficient to terminate the test when a small fatigue span developed in the test track. The testing conditions selected for coated rod and steel balls were: speed, 5.7 ins-l; load, 755 N, air/oil lubrication (air pressure 3 bar with 220 mm^3/h, 68 cSt, rolling bearing base oil).

2.3.1.3 Four-ball test machine.

In order to test different combinations of coating/lubricants, a "four ball testing machine" was used. In this machine one ceramic ball rotated against three steel/coated balls, held stationary in the form of a cradle. The lubricant, oil or grease, covered the lower three balls. A series of tests of 5min duration and at a speed of 0.4 ins-] was made at increasing loads until a defined scar could be observed Two kinds of parameters have been studied: the load carrying capacit y, defined as the minimum load to produce significant wear in the stationary balls, and the relation between the scar wear diameter in the ball at increasing loads.

2.3.2 Tests with complete bearings

Fig. 11 shows a belt driven test stand which is used to investigate the temperature and wear behaviour of 7020 angular contact ball bearings. The inner diameter of the test bearing is 100 mm. The preload of the bearings can be easily adjusted by changing the hydraulic pressure, which also enables constant pressure to be maintained independently of thermal deformations caused by temperature differences between spindle and housing, A constant preload of 1200 N has been selected. Two types of lubrication systems, typical for machine tool spindles have been used: air/oil lubrication (air pressure 3 bar with 90 mm^3/h, 68 cSt rolling bearing base oil) and grease (15 g calcium grease). For the friction torque measurements the housing is held in two additional bearings so that the friction torque tries to rotate the housing which is prevented by a cantilevered beam. The bending of this beam is measured with wire strain gauges and is proportional to the friction torque.

could be cooled down. The excellent temperature behaviour can be explained by the decreased wear and reduced friction torque of CrN coated bearings. As expected, the friction torque increases with the rotational speed and the preload. However, it becomes clear that the friction torque can be reduced by coating the races.

3 Conclusions

Steel bearings can be coated with sufficient adhesion power by means of a low temperature PVD process below 160 “C. Titanium derivative coatings bring advantages in avoiding tribological trouble in high stress conditions.

The fatigue properties of coatings were determined through the impact test and its FEM simulation. The derived fatigue critical stress values were successfully applied in the evaluation stage of the experimental results of the ball on rod RCF test, permitting herewith their further application in full scale bearings. The results of the bearing simulation predicted the adequacy of coatings to operate in prescribed conditions without fatigue failure. The experimental results during the long term bearings evaluation confirmed the predicted behaviour.

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