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POSSIBILITIES OF APPLICATION PVD COATING nACRo^4 DEPOSITED ON HIGH CONTACT RATIO GEARING IN INTERACTION WITH THE CONVENTIONAL AND ECO-FRIENDLY LUBRICANT

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Abstract: The submitted article deals with the issue of the application of the PVD coating nACRo^4 deposited on the High Contact Ratio gearing made of 16MnCr5 material in interaction with the conventional PP 90H lubricant and biological Biogear S150 lubricant. Experimental tests were carried out on an FZG test rig with closed performance flow, followed by measuring of the surface roughness change. In experiment, we followed the STN 65 6280 norm for FZG scuffing tests, from which we gained load values for different load levels. The results of experimental tests were statistically processed and, on basis on them, relations were established between surface roughness and load level for both used lubricants.

Keywords: FZG test, HCR gearing, eco-friendly oil, PVD coating

1. INTRODUCTION

Gears and power transmissions are among the oldest mechanisms used in engineering. They were used whenever a man wanted to transfer mechanical energy to a working machine. Gears have undergone a long way of development to today's modern form of technology [1].

Standard involute gears use a normal contact ratio (NCR), i.e. the contact ratio ε_α is in the range of 1 to 2 (Fig. 1. a)). One pair of teeth in contact alternate with two pairs of teeth in contact. To ensure smooth operation, the minimum contact ratio $\varepsilon_\alpha = 1.2$ is preferred [7]. Gears should generally not be designed to have less than 1.2 contact ratio, because mounting inaccuracies may further decrease ε_α, thus increasing the possibility of impact between the teeth as well as an increase in the noise level. Contact ratios of standard involute gears are generally in the range of 1.4 to 1.6. For example, contact ratio $\varepsilon\alpha$ = 1.6 means that two pairs of teeth are in contact 60% of the time and one pair of teeth is in contact 40 % of the time [3,9].

High contact ratio (HCR) gears are a special form of the basic involute profile of non-standard gearing (Fig. 1. b)). Changes relate to the basic profile, addendum height is not equal 1 like for standard involute gears. Addendum height h_a* is increased and bigger than one, h_a*> 1. The results are gears with contact ratio $\varepsilon_\alpha \geq 2$. The teeth with this profile can reach contact ratio up to 4 [10, 11].

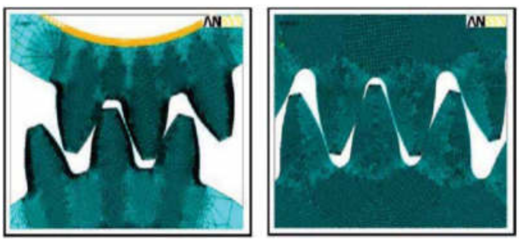

Fig. 1. a) NCR, b) HCR

The principle of PVD Physical Vapor Deposition is to convert deposited material to the gas phase (evaporation, sputtering) in vacuum, followed by application to a substrate at low temperatures (150-500°C). The coating material or its components must be present directly in the deposition chamber, where they are transferred to the gaseous state. Typical layer thicknesses are 1 - 5 μm [13, 14].

2. MATERIALS AND METHODS

Experimental tests were performed in the Center of Innovation laboratories at Faculty of Mechanical Engineering, Slovak University of Technology in Bratislava. In experiment, we followed the STN 65 6280 norm for FZG scuffing tests, from which we gained the load values for different load levels. To perform an experiment, we used a FZG test rig (back-to-back) with closed performance flow, a contact surface roughness meter Mitutoyo SJ-201 and an ultrasonic cleaner Ecosom U7-STH [12].

The Niemann M01 device was developed in the laboratories of the Slovak University of Technology in Bratislava for the comprehensive measurement of scuffing tests. The Niemann M01 gear test rig is a back-to-back rig (Fig. 4).

The Niemann M01 is mounted on a concrete base equipped with a vibration-damping feet. The device as a whole consists of two main parts, namely a test chamber and a slave chamber, where test gears and slave gears are located. These two chambers are connected to each other by two shafts. One shaft serves only as a connection between the chambers. The second shaft is composed of two parts which are connected by a load clutch. By a load clutch, both parts of the shaft can be rotated against each other and in that position they can be fixed. The left part of the load clutch is fixed to the base with the lock-pin via the clutch and its support. The right part of the load clutch is rotated by loading lever and weights to create a static loading torque in the system. When the load has been applied, the two halves of the clutch are fixed against movement with the bolts. Then, the lock-pin is safely removed. The twist size varies according to the load required, but only by step change and not during the run of the device [2, 13].

The device Niemann M01 itself is complemented by a number of devices for tracking measured data during machine operation. These devices serve as a feedback to the data set before the measurement.

The device is driven by a three-phase electric motor with a frequency converter, which makes it possible to set the output speed of the electric motor as required (Fig. 2.).

Fig. 2. Three-phase electric motor of Niemann M01

The rotation of the load clutch itself and load adjustment in system are performed by using a lever. The weight is suspended on the lever to obtain the desired torque on the pinion shaft (Fig. 3.)

Fig. 3. Creating a static torque in the system using the lever

Fig. 4. Niemann M01 FZG back-to-back test rig

The lubricants used for experimental tests were OMV BioGear S 150 and MADIT PP90H. OMV Biogear S 150 is a fully synthetic, biodegradable, industrial gear oil based on synthetic environment-friendly esters. Its basic specifications is shown in Tab. 1. It is designed for mechanically and thermally heavy load transmissions of various constructions, for bearing lubrication in agriculture, forestry, construction industry, shipping and protected natural areas.

Tab. 1. Technical data of OMV Biohyd S 150 oil

Property	Value
Viscosity at 40°C	150.00 mm^2/ s
Viscosity at 100°C	24.45 mm^2 / s
Ignition point	224°C
Pour point	-27°C
Density at 15°C	945 kg/m^3
Viscosity index	167

MADIT PP 90H is a year-round transmission oil designed to lubricate extremely heavy-duty transmissions and final-drive assemblies of modern cars and other mobile technology. Its basic specifications shows Tab. 2. It is suitable for gearboxes working in extremely difficult operating conditions. It is designed for hypoid transmissions. It is preferred to use it at elevated temperatures when reliable function is guaranteed.

Tab. 2. Technical data of MADIT PP 90H

Property	Value
Viscosity at 40°C	140.00 mm^2/ s
Viscosity at 100°C	15.00 mm^2/ s
Ignition point	200°C
Pour point	-27°C
Density at 15°C	905 kg/m^3
Viscosity index	95

A contact surface roughness meter Mitutoyo SJ-201 with a retrofitted measuring apparatus was used for measuring of roughness before loading and after each load stages. Tab. 3. shows technical parameters of Mitutoyo SJ-201 and Fig. 5. shows the process of roughness measurements.

Tab. 3. Technical parameters of Mitutoyo SJ-201

Property	Value
Measuring range	0.015 – 350 µm
Measuring speed	0.25 – 0.5 mm/s
Stylus tip material	Diamond
Stylus tip radius	1 – 5 µm
Operating temperature	5 – 40°C

Fig. 5. Process of measuring of roughness by Mitutoyo SJ-201

The test gears were made of 16MnCr5 steel. They were carburized, case hardened and tempered before coating. The basic parameters like the number of teeth of pinion and gear are shown in Tab. 4.

Tab. 4. Main parameters of test HCR gears

Property	Value
Gears ratio	i = 2.43
Center distance	a = 144 mm
Module	m = 4 mm
Number of teeth - pinion - gear	z_1 = 21 z_2 = 51
Width of teeth	b = 15 mm
Helix angle	β = 0°
Pressure angle	α = 20°
Addendum	h_a* = 1.3
Dedendum	h_f* = 1.7
Correction - pinion - gear	x_1 = 0.4 x_2 = -0.4
Tip diameter - pinion - gear	d_{a1}= 97.6 mm d_{a2}= 2 mm
Contact ratio	ε_α = 2.003

For the experimental tests, we selected PVD coating of 4. generation - nACRo[4] (Fig. 6.). It is a nanocomposite coating that is tough and resistant to wear and high temperatures. The nanocomposite coating consists of several layers: the first layer (adhesion layer) is formed by chlorine nitride, followed by the second layer (gradient core layer) AlCrN. On thus prepared gradient core layer, very thin nanolayers of AlCrN are spread. The final top layer of the nanocomposite coating nACRo[4] is formed by a nanocomposite layer nc-AlCrN/ a-Si3N4. The properties of the nanocomposite nACRo[4] coating are shown in Tab. 5.

Composition of the coating:

CrN - AlCrN (gradient core layer) - AlCrN (nanolayer) - nACRo[4] (nanocomposite top layer).

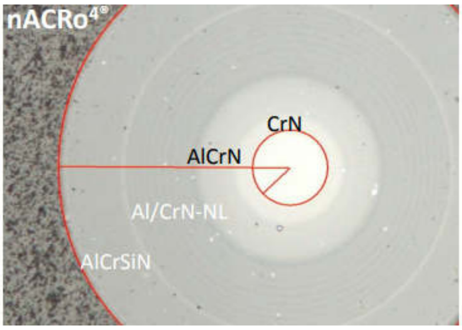

Fig. 6. Structure of the nanocomposite coating of the 4. generation nACRo4

Tab. 5. Properties of nACRo[4]

Property	Value
Color	Grey
Nanohardnes up to	40 GPa
Thickness	1 – 7 µm
Friction coeff.	0.45
Max. usage temp.	1 100°C
Deposition temperature	480°C

Preparation of the test:

To avoid errors and inaccuracies, several steps had to be taken before each test in order to prepare the device and test gears:

- cleaning the chambers twice with a suitable solvent before starting a new series of experiments with a different lubricant,
- cleaning the pinion and the gear in a solvent,
- weighing the pinion and the gear on the scale with an accuracy of at least 1 mg.

The conditions of the experiment were determined by the norm STN 65 6280:

- the required circumferential velocity on the pinion – v = 6.4 m/s, which in our case corresponded to the pinion revolutions of 1450 rpm,
- test duration for each load stage - 20.6 min. This shows that the test pinion has performed 30,000 cycles [8].

Expected procedure for the experiment:

- insertion of the testing gears into test chamber, pour oil into the chamber and assembling the measuring device,
- load the test gears with the torque according norm,
- launch the device for 20.6 min.,
- draining used oil,
- demounting of the test chamber and removal of the test gear,
- degreasing gears, washing the gears in technical gasoline and cleaning from oil residues in an ultrasonic cleaner, drying gears with the flow of dry air,
- weighing gears and measuring of roughness.

3. RESULTS AND DISCUSSION

The results obtained from the experimental tests of HCR gears coated with nanocomposive coating nACRo[4] on the device: Niemann M01 in both lubricating environments (OMV Biogear S 150 and MADIT PP 90H) were statistically processed and assessed. Test results were graphically evaluated as the course of the surface roughness *Rz* depending on the load level. The increasing load level was followed by a gradual increase of surface roughness *Rz* values which were caused by abrasion of the coating layers. When the value of surface roughness *Rz* reaches a limit 7 µm, this load level is marked as a border level of load.

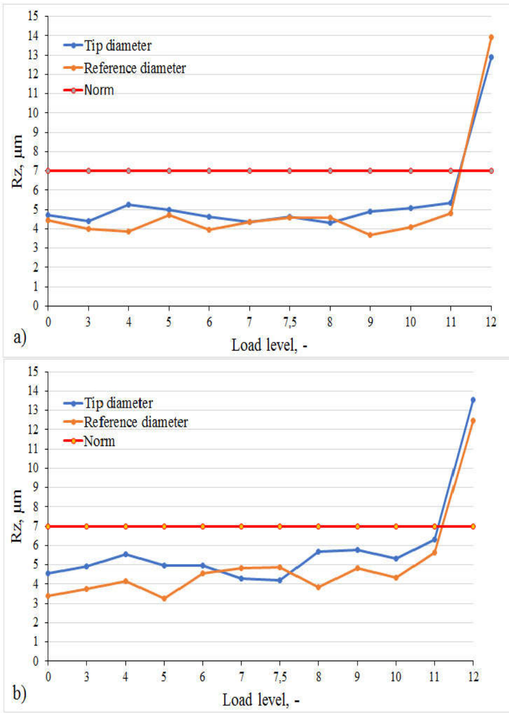

Fig. 7. Dependence of change surface roughness *Rz* on load level during scuffing test, lubricated by eco-friendly oil OMV Biogear S 150: a) pinion, b) gear

Graphs in Fig. 7. shows the dependence of the surface roughness *Rz* variation on the load level for the pinion and the gear. In this case, both the pinion and the gear were lubricated with the eco-friendlyeco-friendly oil OMV Biogear S150. The graphs in the figure shows the surface roughness of the tooth on the reference and tip diameter and the limit value set by the norm. In Fig. 7. a), it is possible to see that the pinion has exceeded the limit value of 7 µm after 12th load level on both the reference and the tip diameters. The values of the surface roughness *Rz* for the pinion on the reference and tip diameters ranged from 3.5 to 5.5 µm without any significant extremes at both diameters. After the 12th level of the load, the surface roughness *Rz* reached 12.88 µm for the reference diameter and 13.91 µm for the tip diameter. In Fig. 7. b), it is possible to see the values of the surface roughness *Rz* of the gear. The values ranged from 3 to 6 µm, the extreme occurred after the 12th load level for both diameters. After the 12th level of the load, surface roughness *Rz* reached 13.55 µm for the reference diameter and 12.47 µm for the tip diameter.

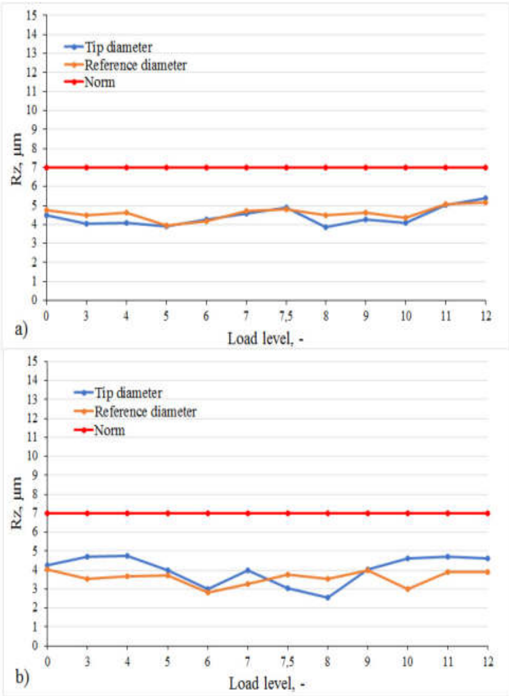

Fig. 8. Dependence of change surface roughness *Rz* on load level during scuffing test, lubricated by conventional oil MADIT PP 90H: a) pinion, b) gear

The graphs in Fig. 8. show the dependence of the surface roughness *Rz* variation on the load level for the pinion and the gear. The test chamber was lubricated with conventional MADIT PP90H oil. The graphs in the figure shows the surface roughness of the tooth on the reference and tip diameters and also the limit value set by the norm. In Fig. 8. a), it is possible to see that the values of reference and tip diameters on pinion have not exceeded the limit value. Values were in range from 3.5 to 5.5 µm. In Fig. 8. b), it is possible to see values of the surface roughness *Rz* of the gear. The values were in the range from 2.5 to 5 µm, without any significant extremes.

4. CONCLUSIONS

The main objective of the experiment was to compare the properties of the tested nanocomposite coating nACRo[4] deposited on HCR gears in two different lubricating environments. We used eco-friendly oil OMV BioGear S 150 and conventional oil MADIT PP 90H. Experimental tests were performed on Niemann M01 (back-to-back test rig). Graphically, we evaluated the scuffing tests by changing surface roughness *Rz* in connection with an increasing load level. In the case of eco-friendly lubricant OMV Biogear S 150, scuffing occurred at the 12th load level for both pinion and gear on both diameters (reference and tip). In interactions with conventional lubricant MADIT PP 90H, the limit value was not exceeded, thus no scuffing occurred. We can conclude that the coating itself has better adhesion properties in an environment lubricated by conventional lubricant.

The results show that the adhesion of the nACRo[4] coating is better than TiCN-MP+MOVIE [5], where in interaction with Biogear S150, scuffing occurs at 11th load level as well as in the DLC coating [6], where scuffing occurs at 7th load level.

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