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COMPARISON OF PVD COATINGS NACRO[4] AND TIALN + DLC DEPOSITED ON HIGH CONTACT RATIO GEARING INTERACTING WITH CONVENTIONAL AND ECOLOGICAL LUBRICANTS

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Proposed paper deals with experimental tests performed on the Nieman M01 FZG test rig. Experiments were carried out in accordance with STN 65 6280 standard for FZG scuffing tests, from which load values for each load level were obtained. HCR gears made of 16MnCr5 material were utilized during experimental tests. Gear surface was deposited by PVD coatings of nACRo[4] and TiAlN + DLC. Conventional lubricant MADIT PP 90H and biological lubricant OMW Biogear S150 were selected for lubrication environments. Aim of the experimental tests lied in application and comparison of PVD coatings deposited on HCR gears. Values of the maximum height of the assessed profile *Rz* for tip and reference diameters were measured after each load level. Results of experimental tests were statistically processed and relations between the maximum height of assessed profile *Rz* and load levels for both utilized coatings in both environments were established on the basis of these results.

Keywords: HCR gearing; PVD coating nACRo[4]; PVD coating TiAlN + DLC; FZG scuffing test; ecological oil introduction

Gears and power transmissions are 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 current state-of-the-art form of technology (Hoehn et al., 2008; Rackov et al., 2014; Kadnár et al., 2017).

High Contact Ratio (HCR) gears are non-standard gears with a modified form of a basic involute profile (Bošanský et al., 2013a). Changes are related to addendum height; it does not equal 1 like standard involute gears. Addendum height h_a* increases and exceeds 1 (h_a* >1). Such gears have contact ratio $\varepsilon_\alpha \geq 2$. Teeth with this profile can reach contact ratio up to 4 (Tulík et al., 2017; Tulík et al., 2013; Máchal et al., 2013).

Principle of physical vapour deposition (PVD) lies in conversion of deposited material to the gas phase (evaporation, sputtering) in a vacuum, followed by application to a substrate at low temperatures (150–500 °C) (Lümkemann et al., 2014). Coating material or its components must be present directly in the deposition chamber, in which they are transferred to gaseous state. Typical layer thickness ranges from 1–5 µm (Hatamleh et al., 2009; Bošanský et al., 2013b; Dostál et al., 2019).

The PVD coating method was utilized for experimental study in order to ensure more appropriate temperature course during coating and lower procurement costs. Other method of coating with higher deposition temperatures was not utilized, since gears were surface-hardened and deposition temperature would exceed quench temperature (Bobzin et al., 2009). After considering these factors and options in cooperation with the LISS CZ company, it was decided to use PVD coatings. Coating production was carried out in laboratories of LISS and selected coatings were deposited by means of the ARC PVD using device π411PLUS. Parameters of coatings used are described in the chapter Materials and Methods.

Material and methods

Experimental tests were performed at the Center of Innovation laboratories at the Faculty of Mechanical Engineering, Slovak University of Technology in Bratislava. Experiment was performed in accordance with STN 65 6280 standard for FZG (Forschungsstelle für Zahnräder und Getriebebau – Gear Research Centre) scuffing tests, from which the load values for different load levels were obtained (STN 656280, 1985). Experiment was performed using the FZG test rig (back-to-back) with closed performance flow, portable surface roughness tester Mitutoyo SJ-201 and ultrasonic cleaner Ecosom U7-STH (Bromark et al., 1992; Pengbo et al., 2017).

Niemann M01 device was developed at laboratories of the Slovak University of Technology in Bratislava for the comprehensive measurement of scuffing tests. Niemann M01 gear test rig is a back-to-back rig (Fig. 1).
The device itself is complemented by a number of devices for tracking of measured data during machine operation.

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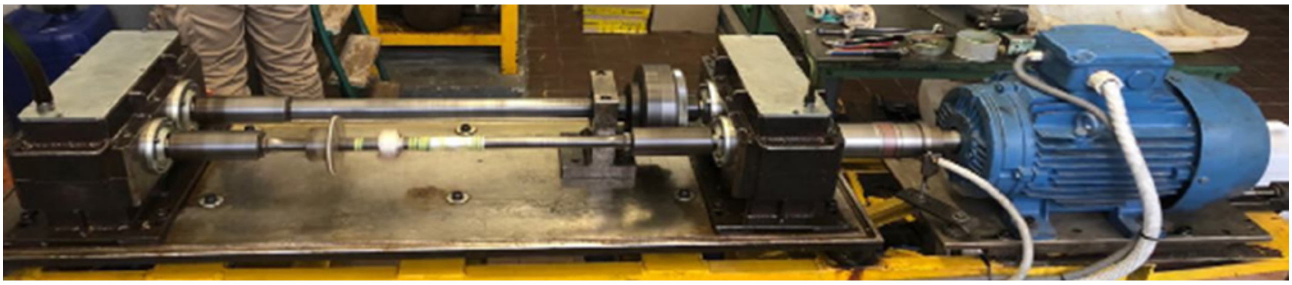

Fig. 1 Niemann M01 FZG back-to-back test rig

These devices serve as feedback to the data set before the measurement (Michalczewski et al., 2013).

Utilized lubricants for experimental tests included OMV BioGear S 150 and MADIT PP90H. The reason for using of biological and conventional lubricants was to test the durability and resistance of coating in selected lubricants under extreme conditions. Furthermore, specific types of lubricant – OMV Biogear S150 and MADIT PP 90H – were used since these were previously observed in experiments at the Center of Innovation, making it possible to compare them with previous research (Bošanský et al., 2012; Bošanský and Rusnák, 2017).

OMV Biogear S 150 is fully synthetic, biodegradable, industrial gear oil based on synthetic environment-friendly esters; basic specifications of this device are shown in Table 1. It is designed for mechanically and thermally heavy load transmissions of various constructions, for bearing lubrication in agriculture, forestry, construction industry, shipping and protcted natural areas.

Table 1 Technical properties of OMV Biohyd S 150 oil

Property	Value
Viscosity at 40 °C	150.00 $mm^2 \cdot s^{-1}$
Viscosity at 100 °C	24.45 $mm^2 \cdot s^{-1}$
Ignition point	224 °C
Pour point	-27 °C
Density at 15 °C	945 $kg \cdot m^{-3}$
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 specification is shown in Table 2.

Table 2 Technical data of MADIT PP 90H

Property	Value
Viscosity at 40 °C	140.00 $mm^2 \cdot s^{-1}$
Viscosity at 100 °C	15.00 $mm^2 \cdot s^{-1}$
Ignition point	200 °C
Pour point	-27 °C
Density at 15 °C	905 $kg \cdot m^{-3}$
Viscosity index	95

It is suitable for gearboxes working under extremely demanding operating conditions. It is designed for hypoid transmissions and is preferred in case of elevated temperatures, ensuring reliable function.

Portable surface roughness tester Mitutoyo SJ-201 with a retrofitted measuring apparatus was used for measuring of roughness before loading and after each load stage. The device was installed on the apparatus and used for measurement of the maximum height of assessed profile *Rz* on tip and reference diameter on both pinion and gear. Pinion and gear were degreased, washed in technical gasoline, cleaned from oil residues in an ultrasonic cleaner and dried with a flow of air before each measurement.

Test gears were made of 16MnCr5 steel and carburized, case hardened and tempered before coating. Basic parameters, such as the number of teeth of pinion and gear, are shown in Table 3.

Table 3 Main parameters of test HCR gears

Property	Value
Transmission ratio	$i = 2.43$
Centre distance	$a = 144$ mm
Module	$m = 4$ mm
Number of teeth – pinion – gear	$z_1 = 21$ $z_2 = 51$
Face width	$b = 15$ mm
Reference cylinder helix angle	$\beta = 0\,^{\circ}$
Reference pressure angle	$\alpha = 20\,^{\circ}$
Addendum	$h_a^* = 1.3$
Dedendum	$h_f^* = 1.7$
Profile shift correction – pinion – gear	$x_1 = 0.4$ $x_2 = -0.4$
Tip diameter – pinion – gear	$d_{a_1} = 97.6$ mm $d_{a_2} = 2$ mm
Traverse contact ratio	$\varepsilon_\alpha = 2.003$

For the experimental tests, PVD coatings nACRo[4] and TiAlN + DLC were selected, the properties of which are shown in Table 4. Selected coatings are manufactured with a thickness ranging from 1 to 7 µm. The coating thickness of 7 µm was utilized in experiment according to the standard.

Experimental tests for each coating were performed in 2 phases. In the first phase, experiments were carried out with OMV Biogear S150 ecological lubricant and with

Table 4 Properties of nACRo[4] and TiAlN + DLC coatings

Property	nACRo[4]	TiAlN + DLC
Colour	Grey	Violet-black
Nanohardness up to	40 GPa	36 GPa
Thickness	1–7 µm	1–7 µm
Friction coefficient	0.45	0.60
Maximum usage temperature	1,100 °C	700 °C
Deposition temperature	480 °C	480 °C

conventional lubricant MADIT PP 90H in the second phase. After completion of both phases, testing of another coating was carried out.

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 gear in a solvent;
- weighing the pinion and gear on scale with an accuracy of at least 1 mg.

Conditions of experiment were determined by standard STN 65 6280:

- required circumferential velocity on the pinion – v = 6.4 $m \cdot s^{-1}$, corresponding to the pinion revolutions of 1,450 rpm in this case;
- test duration for each load stage – 20.6 min, showing that the test pinion has performed 30,000 cycles (STN 656280, 1985).

Expected procedure for the experiment:

- insertion of testing gears into the test chamber, pouring of oil into chamber and assembling the measuring device;
- loading the test gears with the torque according to standard;
- launching the device for 20.6 min.;
- draining used oil;
- demounting the test chamber and removal of the test gear;
- degreasing the gears, washing the gears in technical gasoline and cleaning from oil residues in the ultrasonic cleaner, drying gears with the flow of dry air,
- weighing gears and measuring roughness.

Results and discussion

Experimental tests were performed on HCR gears, coated with nACRo[4] and TiAlN + DLC coatings in accordance with STN 65 6280 standard for FZG scuffing tests utilizing the Nieman M01 testing rig. Conventional lubricant MADIT PP 90H and ecological lubricant OMW Biogear S150 were selected for lubrication purposes. Results obtained from experimental tests were statistically processed and assessed. Test results were graphically evaluated as the course of the maximum height of the assessed profile *Rz* depending on the load level. Increasing load level was followed by a gradual increase of the *Rz* values caused by abrasion of the coating layers. When the value of the *Rz* would reach a limit 7 µm, this load level is marked as a border level of load.

Table 5 Values of the maximum height of the assessed profile *Rz* (pinion, nACRo[4], Biogear S150)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)	*n*	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)
3	10	5.600	0.189	0.059	10	3.65	0.092	0.029
4	10	6.080	0.077	0.024	10	4.68	0.204	0.064
5	10	5.670	0.061	0.019	10	3.11	0.086	0.027
6	10	5.030	0.089	0.028	10	1.36	0.077	0.024
7	10	3.760	0.165	0.052	10	1.20	0.074	0.023
7.5	10	5.070	0.075	0.023	10	1.44	0.094	0.029
8	10	5.460	0.085	0.027	10	1.85	0.079	0.025
9	10	5.380	0.076	0.024	10	1.89	0.072	0.023
10	10	2.770	0.092	0.029	10	1.24	0.044	0.014
11	10	3.310	0.089	0.028	10	1.09	0.067	0.021
12	10	2.700	0.154	0.049	10	1.40	0.076	0.024

Table 6 Values of maximum height of the assessed profile *Rz* (gear, nACRo[4], Biogear S150)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)	*n*	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)
3	10	5.890	0.094	0.030	10	3.61	0.110	0.035
4	10	6.530	0.041	0.013	10	6.59	0.112	0.039
5	10	5.880	0.056	0.018	10	4.48	0.107	0.034
6	10	5.940	0.108	0.034	10	4.94	0.133	0.042
7	10	5.410	0.069	0.022	10	4.14	0.117	0.037
7.5	10	6.480	0.105	0.033	10	3.78	0.164	0.052
8	10	6.360	0.098	0.031	10	4.68	0.154	0.049
9	10	5.820	0.092	0.029	10	3.46	0.175	0.055
10	10	5.640	0.104	0.033	10	4.07	0.133	0.042
11	10	5.470	0.133	0.042	10	2.70	0.193	0.061
12	10	5.150	0.112	0.035	10	2.70	0.198	0.063

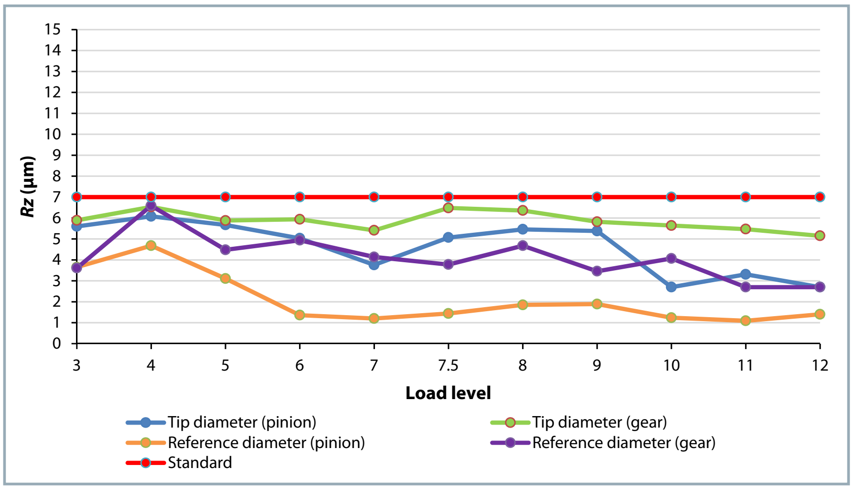

Fig. 2 Dependence of change maximum height of the assessed profile *Rz* on load level for nACRo[4] in OMV Biogear S 150

Fig. 2 shows a change in the maximum height of the assessed profile *Rz* depending on the load level for both pinion and gear. Gear pair was coated by PVD coating nACRo[4] and lubricated with biological oil OMW Biogear S150. There are 5 lines in graph showing reference and tip diameters for the pinion and gear and limit value of the maximum height of the assessed profile *Rz* defined by the standard. These lines are colour-coded for better clarity. Tables 5 and 6 show that the maximum value of assessed profile *Rz* did not reach a limit value of 7 µm.

Fig. 3 shows a change in the maximum height of the assessed profile *Rz* depending on load level

Table 7 Values of the maximum height of the assessed profile *Rz* (pinion, nACRo[4], MADIT PP90H)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)	*n*	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)
3	10	4.140	0.105	0.033	10	3.910	0.096	0.030
4	10	5.310	0.156	0.049	10	4.010	0.163	0.052
5	10	4.610	0.191	0.060	10	1.890	0.124	0.039
6	10	4.010	0.144	0.045	10	2.520	0.132	0.042
7	10	4.570	0.136	0.043	10	2.240	0.099	0.031
7.5	10	3.550	0.137	0.043	10	4.180	0.130	0.983
8	10	4.260	0.126	0.040	10	1.950	0.119	0.038
9	10	4.640	0.155	0.049	10	1.340	0.150	0.048
10	10	4.770	0.131	0.041	10	1.530	0.112	0.035
11	10	5.180	0.128	0.040	10	1.660	0.123	0.038
12	10	4.920	0.082	0.026	10	1.720	0.119	0.038

Table 8 Values of the maximum height of the assessed profile *Rz* (gear, nACRo[4], MADIT PP90H)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)	*n*	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)
3	10	6.040	0.131	0.041	10	5.030	0.114	0.036
4	10	5.510	0.159	0.050	10	5.010	0.144	0.046
5	10	5.510	0.147	0.047	10	4.260	0.103	0.033
6	10	6.670	0.131	0.042	10	4.240	0.138	0.044
7	10	4.890	0.121	0.038	10	5.560	0.120	0.038
7.5	10	5.530	0.104	0.033	10	4.520	0.114	0.036
8	10	5.810	0.129	0.041	10	2.210	0.115	0.036
9	10	4.990	0.126	0.040	10	3.880	0.121	0.038
10	10	5.840	0.174	0.055	10	1.510	0.141	0.044
11	10	4.810	0.102	0.032	10	2.850	0.122	0.039
12	10	5.370	0.148	0.047	10	3.090	0.110	0.035

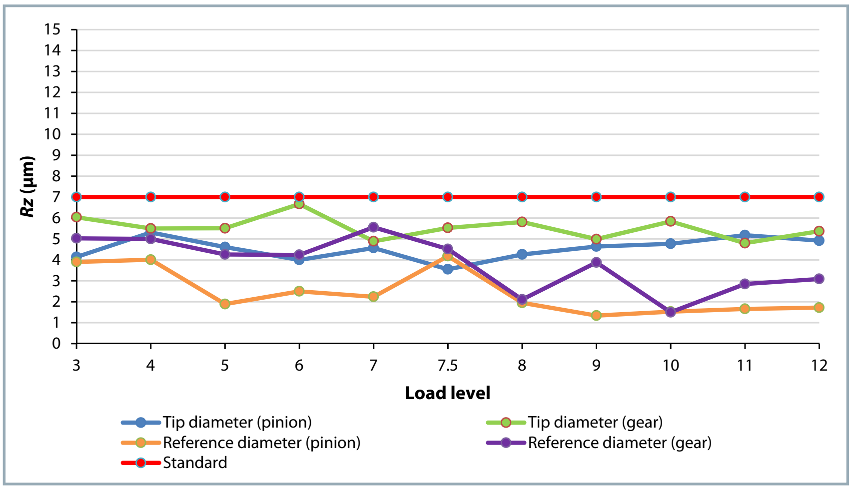

Fig. 3 Dependence of change in the maximum height of the assessed profile *Rz* on load level for nACRo[4] in MADIT PP 90H

for both pinion and gear. Gear pair was coated by PVD coating nACRo[4] and lubricated with conventional oil MADIT PP 90H. There are 5 lines in the graph showing the reference and tip diameters for the pinion and gear and limit value of the maximum height of the assessed profile *Rz* defined by the standard. These lines are colour-coded for better clarity. Tables 7 and 8 show that the maximum value of the assessed profile *Rz* did not reach a limit value of 7 µm.

Fig. 4 shows a change in the maximum height of the assessed profile *Rz* depending on load level for both pinion and gear. Gear pair was coated by PVD coating TiAlN + DLC and

Table 9 Values of the maximum height of the assessed profile *Rz* (pinion, TiAlN + DLC, Biogear S150)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)	*n*	*R´z* (µm)	*S* (µm)	$S_{R'z}$ (µm)
3	10	6.920	0.137	0.043	10	6.410	0.113	0.036
4	10	5.760	0.127	0.040	10	4.710	0.098	0.031
5	10	6.210	0.134	0.042	10	5.070	0.144	0.036
6	10	4.910	0.176	0.056	10	5.350	0.130	0.033
7	10	5.030	0.160	0.034	10	4.360	0.121	0.038
7.5	10	4.830	0.139	0.044	10	5.890	0.114	0.036
8	10	6.340	0.128	0.041	10	3.970	0.134	0.042
9	10	4.840	0.117	0.037	10	2.710	0.123	0.039
10	10	5.790	0.145	0.046	10	2.870	0.136	0.043
11	10	5.780	0.145	0.046	10	3.940	0.104	0.033
12	10	5.080	0.128	0.040	10	2.240	0.096	0.030

Table 10 Values of the maximum height of the assessed profile *Rz* (gear, TiAlN+DLC, Biogear S150)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (μm)	*S* (μm)	$S_{R'z}$ (μm)	*n*	*R´z* (μm)	*S* (μm)	$S_{R'z}$ (μm)
3	10	5.510	0.089	0.028	10	6.730	0.094	0.030
4	10	6.250	0.139	0.044	10	5.750	0.086	0.027
5	10	5.740	0.116	0.037	10	4.890	0.084	0.026
6	10	5.410	0.106	0.033	10	4.870	0.085	0.027
7	10	5.210	0.088	0.028	10	4.870	0.067	0.021
7.5	10	5.440	0.102	0.032	10	4.230	0.076	0.024
8	10	6.060	0.122	0.039	10	4.340	0.095	0.030
9	10	5.970	0.096	0.030	10	5.320	0.0118	0.037
10	10	4.460	0.106	0.034	10	5.240	0.070	0.022
11	10	5.510	0.099	0.031	10	4.790	0.090	0.028
12	10	5.450	0.098	0.032	10	4.140	0.079	0.025

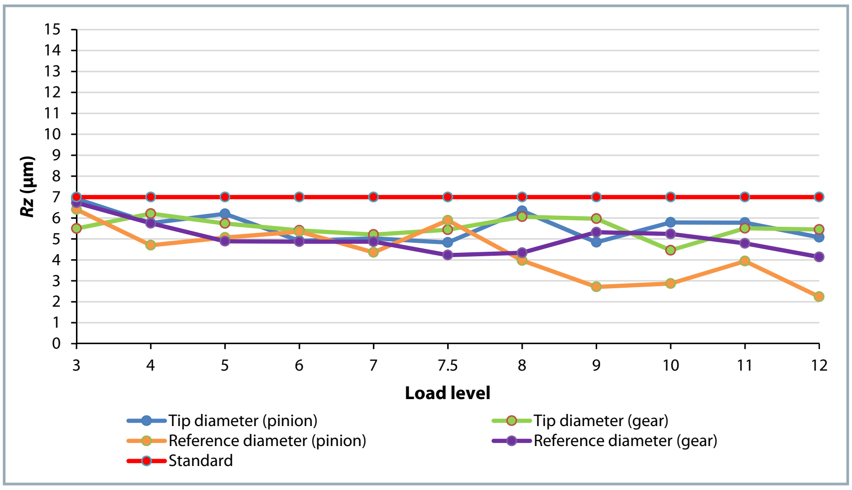

Fig. 4 Dependence of change in the maximum height of the assessed profile *Rz* on load level for TiAlN+DLC in OMW Biogear S150

lubricated with conventional oil OMW Biogear S150. There are 5 lines in the graph showing the reference and tip diameters for the pinion and the gear and limit value of the maximum height of the assessed profile *Rz* defined by the standard. These lines are colour-coded for better clarity. Tables 9 and 10 show that the maximum value of the assessed profile *Rz* did not reach a limit value of 7 μm.

Fig. 5 shows a change in the maximum height of the assessed profile *Rz* depending on load level for both the pinion and the gear. Gear pair was coated by PVD coating TiAlN + DLC and lubricated with conventional oil MADIT PP 90H. There are 5 lines in the

Table 11 Values of the maximum height of the assessed profile *Rz* (pinion, TiAlN + DLC, MADIT PP 90H)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (μm)	*S* (μm)	$S_{R'z}$ (μm)	*n*	*R´z* (μm)	*S* (μm)	$S_{R'z}$ (μm)
3	10	4.770	0.072	0.023	10	3.680	0.081	0.026
4	10	5.260	0.061	0.019	10	3.270	0.058	0.018
5	10	4.830	0.071	0.023	10	3.410	0.082	0.026
6	10	5.770	0.073	0.023	10	3.420	0.063	0.020
7	10	5.570	0.069	0.022	10	3.590	0.062	0.019
7.5	10	5.480	0.077	0.024	10	2.960	0.085	0.027
8	10	3.540	0.059	0.019	10	2.550	0.098	0.031
9	10	5.010	0.063	0.020	10	3.110	0.083	0.026
10	10	5.260	0.090	0.029	10	3.630	0.087	0.028
11	10	4.990	0.069	0.022	10	3.890	0.110	0.035
12	10	4.310	0.064	0.020	10	4.470	0.085	0.027

Table 12 Values of the maximum height of the assessed profile *Rz* (gear, TiAlN+DLC, MADIT PP 90H)

Load level	Tip diameter				Reference diameter			
	n	*R´z* (μm)	*S* (μm)	$S_{R'z}$ (μm)	*n*	*R´z* (μm)	*S* (μm)	$S_{R'z}$ (μm)
3	10	5.530	0.086	0.027	10	5.680	0.078	0.025
4	10	6.560	0.089	0.028	10	5.210	0.074	0.023
5	10	4.750	0.105	0.033	10	5.910	0.091	0.029
6	10	3.810	0.090	0.028	10	4.360	0.086	0.027
7	10	5.870	0.074	0.024	10	6.050	0.096	0.030
7.5	10	6.440	0.104	0.033	10	3.410	0.077	0.024
8	10	4.780	0.107	0.034	10	5.470	0.091	0.029
9	10	5.720	0.0106	0.033	10	4.580	0.088	0.028
10	10	6.610	0.117	0.037	10	2.930	0.087	0.027
11	10	4.480	0.085	0.027	10	3.290	0.112	0.036
12	10	5.640	0.117	0.037	10	2.990	0.104	0.033

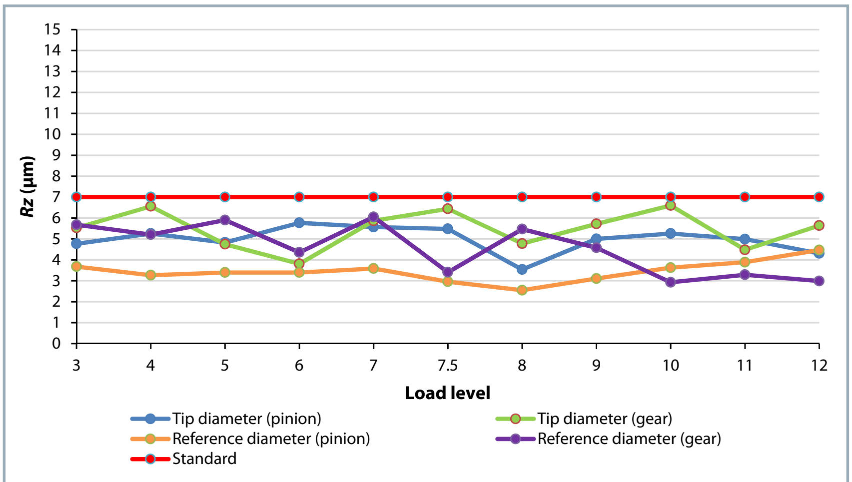

Fig. 5 Dependence of change in the maximum height of the assessed profile *Rz* on load level for TiAlN+DLC in MADIT PP 90H

graph showing the reference and tip diameters for the pinion and the gear and limit value of the maximum height of the assessed profile *Rz* defined by the standard. These lines are colour-coded for better clarity. Tables 11 and 12 show that the maximum value of the assessed profile *Rz* did not reach a limit value of 7 μm.

In comparison to research previously carried out at the Centre of Innovations of the Slovak University of Technology in Bratislava, it is possible to conclude that the adhesive properties and wear resistance of the coatings nACRo[4] and TiALN + DLC have shown better results than previously observed TiCN-MP coating + MOVIC (Mišány, 2015), since in observing those, scuffing occurred at the 11th load level, as well as and DLC coating (Zápotočný, 2014) where scuffing occurred at the 7th load level.

Conclusion

Experimental test was carried out on HCR gears coated by PVD coatings nACRo[4] and TiAlN+DLC. Conventional oil MADIT PP90H and biological oil OMW Biogear S150 were selected for lubrication environments. Both coatings were deposited in ACR PVD mode with the *π*411PLUS device. Coatings were produced at a thickness of 7 μm and tested according to STN 65 6280 standard. Measured values were evaluated statistically in the form of tables and graphically as the dependency of the maximum height of the assessed profile *Rz* in relation to the load level. In terms of obtained values, it is evident that the maximum height of the assessed profile *Rz* did not exceed interval 7 μm established by the standard. Therefore, it can be concluded that scuffing did not occur, and adhesive properties and wear resistance of selected coatings are satisfactory for both lubricating mediums.

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