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INFLUENCE OF NACRO4 NANO-COATING ON THE WEAR RESISTANCE OF GEARING IN TRANSMISSION MECHANISMS

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Abstract: The proposed paper presents the results of experimental scuffing tests performed on the Niemann FZG test rig in accordance with the STN 65 6280 standard for FZG scuffing tests. Experimental investigations were conducted on gears made of 42CrMo4 steel, with two gear pair variants: an uncoated pair and a pair coated with nACRo4 PVD coating. For the lubrication environments, the conventional lubricant MADIT PP 90 and the synthetic lubricant TOTAL Carter Bio 150 were selected.
The aim of the experimental tests was to evaluate and compare the scuffing resistance of uncoated and coated gears. The surface roughness parameter Rz was measured at the tip and reference diameters after each load level. Values presented represent averages from ten repeated measurements.

KEYWORDS: PVD coating nACRo4; FZG scuffing test; ecological oil; surface roughness Rz

1 Introduction

Power transmission using gear mechanisms belongs to the oldest and most technologically advanced solutions in mechanical engineering [6, 8, 13]. In order to increase the service life, reliability, and reduce gear wear, advanced combinations of thermochemical treatments and thin-film coatings have been investigated over the past decades [1].

Nitriding of 42CrMo4 steel (analogous to the material used in this study) is a proven method for increasing surface hardness and enhancing resistance to micropitting and wear [12]. When combined with thin PVD coatings such as Cr/CrN or CrN/ZrCN, significant improvements are achieved in terms of rolling–sliding wear and tribocorrosion resistance [1, 14].

The principle of PVD coating, based on vapor-phase deposition at temperatures around 150–500 °C, enables the application of hard coatings with thicknesses of 1–5 µm without significantly affecting the combined properties of the substrate [5]. Additionally, the use of low-temperature PVD techniques (e.g. ARC PVD) prevents overheating of the hardened layer, as confirmed by Bobzin et al. (2009) in the context of surface-hardened gears.

Duplex treatments—nitriding combined with PVD coatings—have already demonstrated advantages in surface hardness, contact fatigue strength, and residual stress behavior in gear applications [10]. A balanced nitrided layer and a suitably selected PVD coating can significantly delay crack initiation and reduce shear wear [16].

In this context, the present study focuses on the complex evaluation of the effects of nitriding and subsequent PVD modification (type nACRo4) on gear wear and surface roughness, tested on a real gear test stand. The methodology includes surface roughness measurements at critical

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points (tooth tip and reference diameter), wear quantification in accordance with STN 65 6280. The results are statistically analyzed and visually correlated with load level and Rz profile.

This approach follows extended studies focused on the evaluation of PVD coatings in hydraulic and environmentally sensitive lubrication conditions [1].

2 Material and methods

Experimental testing was conducted at the Laboratory of Tribology, Faculty of Engineering, Slovak University of Agriculture in Nitra. The experiment was carried out in accordance with the STN 65 6280:1985 standard, which aligns with ISO 14635 1:2000, specifying the procedure for FZG (Forschungsstelle für Zahnräder und Getriebebau) scuffing tests. Based on this methodology, the corresponding load stages were determined (ISO 14635 1, 2000).

A back to back FZG gear test rig with a closed-loop lubrication system was used, enabling reliable evaluation of scuffing resistance under defined operating conditions. Surface roughness measurements were performed using a portable profilometer Mitutoyo SJ 201, and sample preparation included ultrasonic cleaning with the Ecosom U7 STH unit [9, 15].

The Niemann gear test rig, also featuring a back to back configuration (Fig. 1), was equipped with a set of sensors for real-time monitoring of operational parameters during testing. These monitoring systems provide feedback before and during the measurement process, ensuring high precision and repeatability of the results [11, 18].

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

Within the scope of experimental tests, two classes of lubricants were utilized: TOTAL Carter Bio 150 and MADIT PP 90. The motivation for employing both a biodegradable and a conventional lubricant was the systematic assessment of the durability and wear resistance of the applied coatings in specified lubrication environments and under extreme operating conditions. The specific selection of TOTAL Carter Bio 150 and MADIT PP 90 was also conditioned by their previous utilization in related experiments, which allowed for direct comparative analyses with prior research [3, 4].

TOTAL Carter Bio 150 is a fully synthetic, biodegradable industrial gear oil, formulated based on synthetic environmentally friendly esters; its basic specifications are available in Table 1. This oil is primarily intended for mechanically and thermally heavily loaded transmissions of various configurations, as well as for bearing lubrication in specialized sectors, including agriculture, forestry, the construction industry, shipping, and ecologically sensitive protected natural areas.

MADIT PP 90 is a year-round transmission oil developed for lubricating extremely heavy-duty transmission systems and final-drive assemblies in modern cars and various mobile technology. This oil is primarily intended for gearboxes operating under extremely demanding operating conditions. Its formulation also makes it suitable for hypoid transmissions, ensuring reliable performance, especially in environments with elevated temperatures. Detailed basic specifications of this oil can be found in Table 1.

Table 1 Technical properties of the lubricants used

Property	TOTAL Carter Bio 150 Value	MADIT PP 90 Value
Viscosity at 40 °C	150.00 $mm^2 \cdot s^{-1}$	150.00 $mm^2 \cdot s^{-1}$
Viscosity at 100 °C	22.00 $mm^2 \cdot s^{-1}$	15.00 $mm^2 \cdot s^{-1}$
Ignition point	288 °C	230 °C
Pour point	-42 °C	-30 °C
Density at 15 °C	984 $kg \cdot m^{-3}$	883 $kg \cdot m^{-3}$
Viscosity index	147	97

For the determination of surface roughness before loading and after each load stage, a portable surface roughness tester Mitutoyo SJ-201, equipped with a special measuring auxiliary unit, was utilized. This device was installed on the apparatus and employed for measuring the maximum height of assessed profile Rz on the tip and reference diameter of both the pinion and gear. Prior to each measurement cycle, the pinion and gear underwent thorough preparation, which included degreasing, washing in technical gasoline, cleaning from oil residues in an ultrasonic cleaner, and subsequent drying with a flow of air.

The test gears were manufactured from 42CrMo4 steel and, before coating application, were carburized, case hardened, and tempered. The basic parameters of these gears, including the number of teeth of both the pinion and gear, are detailed in Table 3.

Table 2 Chemical composition of the utilized base material (%)

42 CrMo4 1,7225	C	Si	Mn	P	S	Cr	Mo	Ni	V
Min.	0.38	-	0.6	-	-	0.9	0.15	-	-
Max.	0.45	0.4	0.9	0.025	0.035	1.2	0.3	-	-

Table 3 Main parameters of test gears

Property	Value
Transmission ratio	$i = 1.5$
Centre distance	$a = 91.5$ mm
Module	$m = 4.5$ mm
Number of teeth – pinion – gear	$z_1 = 16$ $z_2 = 24$
Face width	$b = 20$ mm
Reference cylinder helix angle	$\beta = 0$ °
Reference pressure angle	$\alpha = 20$ °
Tip diameter – pinion – gear	d_{a1}= 88.7 mm d_{a2}=112.5 mm

For the experimental tests, a PVD coating of the nACRo4 type was applied. The characteristic properties of this coating are clearly summarized in Table 4. It should be noted that, although the manufacturer offers coatings with a thickness ranging from 1 to 7 µm, a specific coating thickness of 7 μm was utilized for the experimental samples in accordance with the valid standard.

"The execution of experimental tests for each investigated coating was divided into two sequential phases. The initial phase involved testing with the biodegradable lubricant Carter Bio 150, while the subsequent second phase was carried out with the conventional lubricant MADIT PP 80. Upon the complete conclusion of both phases for a given coating, testing of a new coating was then commenced."

Table 4 Properties of nACRo4

Property	nACRo^4
Colour	Grey
Nanohardness up to	40 GPa
Thickness	1 – 7 μm
Friction coefficient	0.45
Maximum usage temperature	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 gear in a solvent.

Conditions of experiment were determined by standard STN 65 6280:

- required circumferential velocity on the pinion – v = 8.3 m·s-1, corresponding to the pinion revolutions of 2,170 rpm in this case;

- test duration for each load stage – 15 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 15 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,

- measuring roughness.

3 Results and discussion

Experimental tests were carried out on gears in accordance with the STN 65 6280 standard for FZG scuffing tests, using the Niemann testing rig. One gear pair was coated with nACRo4, while the other gear pair remained uncoated. Two lubricants were employed: conventional oil (MADIT PP 90) and environmentally friendly oil (TOTAL Carter Bio 150). The experimental data were subjected to statistical processing and subsequent evaluation. The results were analyzed in terms of the evolution of the maximum profile height parameter Rz as a function of the applied load. A progressive increase in Rz values was observed with increasing load, attributed to the abrasion of the coating layers. The load level at which the Rz value reached the threshold of 7 μm was defined as the critical load limit.

Table 5 Basic statistical evaluation of the maximum profile height Rz for an uncoated gear under lubrication with TOTAL Carter Bio 150 oil

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (μm)	S (μm)	$S_{\overline{Rz}}$ (μm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (μm)	S (μm)	$S_{\overline{Rz}}$ (μm)	$V_{\overline{Rz}}$ (%)
3	6.48	0.146	0.048	2.642	4.12	0.115	0.034	3.152
4	6.11	0.159	0.051	2.645	4.23	0.124	0.041	3.032
5	5.89	0.121	0.034	2.036	6.08	0.205	0.058	3.514
6	6.72	0.139	0.049	2.266	5.18	0.135	0.045	2.636
7	6.38	0.131	0.044	2.138	4.75	0.124	0.039	3.124
8	6.81	0.174	0.056	2.629	4.26	0.175	0.048	4.379
9	6.89	0.157	0.051	2.471	5.68	0.151	0.041	2.668
10	6.94	0.109	0.034	1.637	6.48	0.139	0.044	2.424
11	8.46	0.134	0.048	1.791	7.89	0.128	0.051	1.808
12	19.86	0.145	0.039	0.715	13.11	0.134	0.038	1.081

Table 6 Basic statistical evaluation of the maximum profile height Rz for an uncoated pinion under lubrication with TOTAL Carter Bio 150 oil

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (μm)	S (μm)	$S_{\overline{Rz}}$ (μm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (μm)	S (μm)	$S_{\overline{Rz}}$ (μm)	$V_{\overline{Rz}}$ (%)
3	6.26	0.158	0.033	1.858	5.37	0.115	0.031	2.091
4	5.65	0.110	0.032	2.098	6.71	0.109	0.034	1.839
5	5.49	0.164	0.048	2.858	5.8	0.141	0.044	2.524
6	5.27	0.104	0.038	2.029	5.69	0.121	0.041	2.187
7	6.07	0.156	0.049	3.013	6.04	0.169	0.051	3.119
8	5.99	0.151	0.045	2.415	6.1	0.149	0.051	2.838
9	6.31	0.141	0.039	2.348	4.66	0.138	0.044	3.219
10	6.61	0.120	0.040	1.712	6.79	0.169	0.056	2.719
11	13.09	0.141	0.044	1.168	11.12	0.171	0.055	1.676
12	19.32	0.139	0.045	0.779	15.68	0.199	0.062	1.346

Figure 2 shows the dependence of the maximum profile height, Rz, on load levels for both the pinion and the wheel without coating operating in TOTAL Carter Bio 150 lubricated conditions, measured at the tip diameter and reference diameter. Rz values represent averages of ten repeated measurements, with the limit value indicating the onset of scuffing.

For the pinion, Rz ranged from 5.27–6.61 μm (tip diameter) and 4.66–6.79 μm (reference diameter). The limit was exceeded after the 11th load level, reaching 13.09 μm (tip) and 11.12 μm (reference), and further increased at the 12th level to 19.32 μm and 15.68 μm, respectively.

For the wheel, Rz ranged from 5.89–6.94 μm (tip diameter) and 4.12–6.48 μm (reference diameter). The limit was exceeded after the 11th load level (8.46 μm and 7.89 μm) and reached 19.86 μm and 13.11 μm at the 12th level.

In both components, the 10th load level was identified as the threshold and the 11th load level as the damaging level. The unified graphical representation allows direct comparison of Rz evolution for both gear components and clearly highlights the critical load level for scuffing initiation.

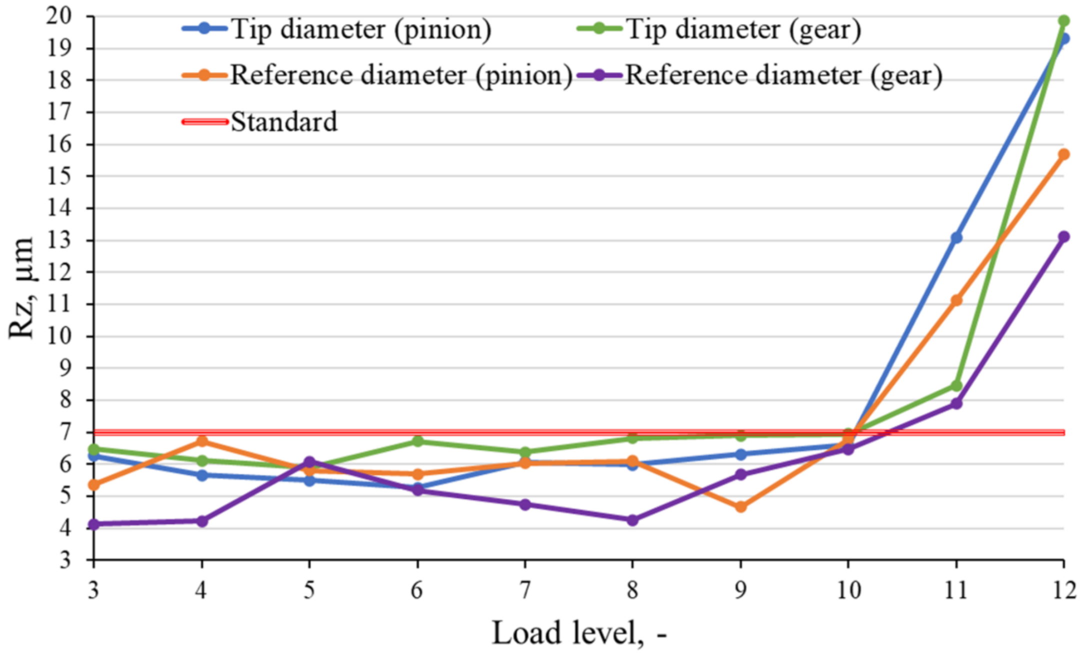

Fig. 2 Evolution of the surface roughness parameter Rz for uncoated samples as a function of load level under lubrication with TOTAL Carter Bio 150 oil

Text Figure 3 shows the dependence of the maximum profile height, Rz, on load levels for both the pinion and the wheel without coating in MADIT PP 90 lubricated conditions, measured at the addendum and pitch circle diameters. Rz values represent averages of ten repeated measurements, with the limit value indicating the onset of scuffing.

For the pinion, Rz ranged from 4.99–6.85 µm (tip diameter) and 5.26–6.74 µm (reference diameter). The limit was exceeded after the 11th load level (12.56 µm tip diameter, 12.25 µm reference diameter) and increased at the 12th level to 18.61 µm and 17.54 µm. For the wheel, Rz ranged from 5.12–6.89 µm (tip diameter) and 4.39–6.81 µm (reference diameter), exceeding the limit after the 11th level (10.56 µm and 9.25 µm) and reaching 17.84 µm and 15.26 µm at the 12th level.

In both components, the 10th load level was identified as the threshold and the 11th load level as the damaging level. The combined representation allows direct comparison of Rz evolution and clearly highlights the critical load level for scuffing initiation.

Table 7 Basic statistical evaluation of the maximum profile height Rz for an uncoated gear under lubrication with MADIT PP 90 oil.

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)
3	5.42	0.161	0.049	2.641	4.42	0.131	0.036	3.154
4	5.12	0.158	0.046	2.629	4.91	0.123	0.041	3.042
5	5.86	0.121	0.040	2.038	5.05	0.181	0.058	3.516
6	5.45	0.139	0.051	2.254	4.39	0.134	0.049	2.641
7	5.74	0.121	0.045	2.159	5.84	0.126	0.045	3.134

8	6.89	0.165	0.055	2.627	4.92	0.164	0.048	4.379
9	6.57	0.174	0.050	2.464	5.53	0.149	0.041	2.678
10	6.81	0.123	0.038	1.652	6.81	0.145	0.048	2.428
11	10.56	0.139	0.049	1.776	9.25	0.143	0.039	1.824
12	17.84	0.146	0.041	0.734	15.26	0.131	0.047	1.081

Table 8 Basic statistical evaluation of the maximum profile height Rz for an uncoated pinion under lubrication with MADIT PP 90 oil

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (μm)	S (μm)	$S_{\overline{Rz}}$ (μm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (μm)	S (μm)	$S_{\overline{Rz}}$ (μm)	$V_{\overline{Rz}}$ (%)
3	5.42	0.171	0.032	1.868	5.26	0.108	0.035	2.086
4	4.99	0.114	0.038	2.114	5.64	0.129	0.038	1.827
5	6.32	0.149	0.055	2.871	5.84	0.139	0.044	2.505
6	6.01	0.116	0.042	2.042	5.79	0.124	0.035	2.187
7	6.23	0.162	0.049	3.012	6.08	0.165	0.052	3.131
8	5.84	0.151	0.051	2.414	6.74	0.151	0.045	2.839
9	6.38	0.149	0.049	2.368	5.89	0.139	0.048	3.217
10	6.85	0.121	0.041	1.710	6.67	0.165	0.056	2.722
11	12.56	0.155	0.048	1.181	12.25	0.170	0.051	1.676
12	18.61	0.149	0.045	0.789	17.54	0.212	0.059	1.342

Figure 4 shows the dependence of the maximum profile height, Rz, on load levels for the pinion and the wheel with nACRo4 coating operating in TOTAL Carter Bio 150 lubricated conditions, measured at the tip diameter and reference diameter. The Rz values represent averages of ten repeated measurements, and the graph also indicates the limit value defining the onset of scuffing.

For the pinion, Rz ranged from 3.02 to 6.12 μm (tip diameter) and from 1.25 to 4.92 μm (reference diameter). For the wheel, Rz values ranged from 5.31 to 6.84 μm (tip diameter) and from 2.92 to 6.48 μm (reference diameter). All recorded values were without significant extremes and did not reach the limit value during testing.

Based on these results, it can be concluded that no damaging load level was reached for either the pinion or the wheel with the nACRo4 coating.

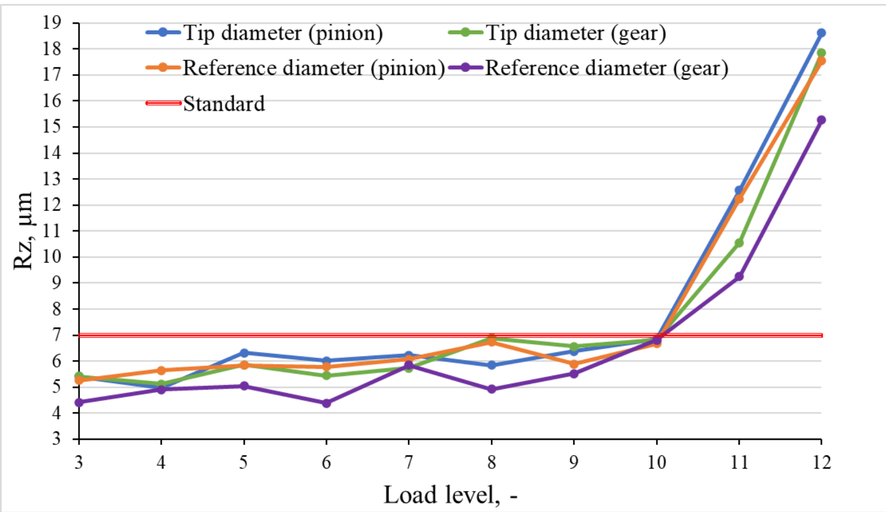

Fig. 3 Evolution of the surface roughness parameter Rz for uncoated samples as a function of load level under lubrication with Madit PP 90 oil

Table 9 Basic statistical evaluation of the maximum profile height Rz for a gear with nACRo4 coating under lubrication with TOTAL Carter Bio 150 oil

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)
3	6.14	0.084	0.027	1.584	3.92	0.109	0.033	3.001
4	6.84	0.052	0.017	0.618	6.48	0.123	0.038	1.912
5	5.61	0.058	0.019	0.939	4.71	0.115	0.031	2.351
6	6.12	0.114	0.031	1.808	5.26	0.129	0.039	2.689
7	5.61	0.068	0.023	1.254	4.39	0.124	0.035	2.795
8	6.12	0.089	0.029	1.536	4.82	0.159	0.042	3.216
9	6.02	0.086	0.028	1.584	3.61	0.164	0.051	5.043
10	5.82	0.109	0.032	1.851	4.29	0.142	0.043	3.146
11	5.69	0.126	0.041	2.448	3.05	0.191	0.058	7.089
12	5.31	0.107	0.033	2.157	2.92	0.187	0.060	7.221

Table 10 Basic statistical evaluation of the maximum profile height Rz for a pinion with nACRo4 coating under lubrication with TOTAL Carter Bio 150 oil.

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)
3	5.84	0.156	0.055	3.348	3.81	0.088	0.030	2.534
4	6.12	0.095	0.027	1.239	4.92	0.186	0.059	4.348
5	5.54	0.085	0.021	1.058	3.62	0.091	0.028	2.767
6	5.54	0.101	0.029	1.761	1.61	0.068	0.023	5.632
7	4.12	0.145	0.050	4.415	1.45	0.078	0.024	6.142
8	5.61	0.078	0.026	1.553	2.21	0.084	0.026	4.258
9	5.48	0.089	0.028	1.431	2.15	0.078	0.024	3.791
10	3.12	0.106	0.030	3.384	1.54	0.056	0.019	3.528
11	3.64	0.075	0.031	2.718	1.25	0.074	0.022	6.119
12	3.02	0.136	0.044	5.674	1.56	0.081	0.023	5.401

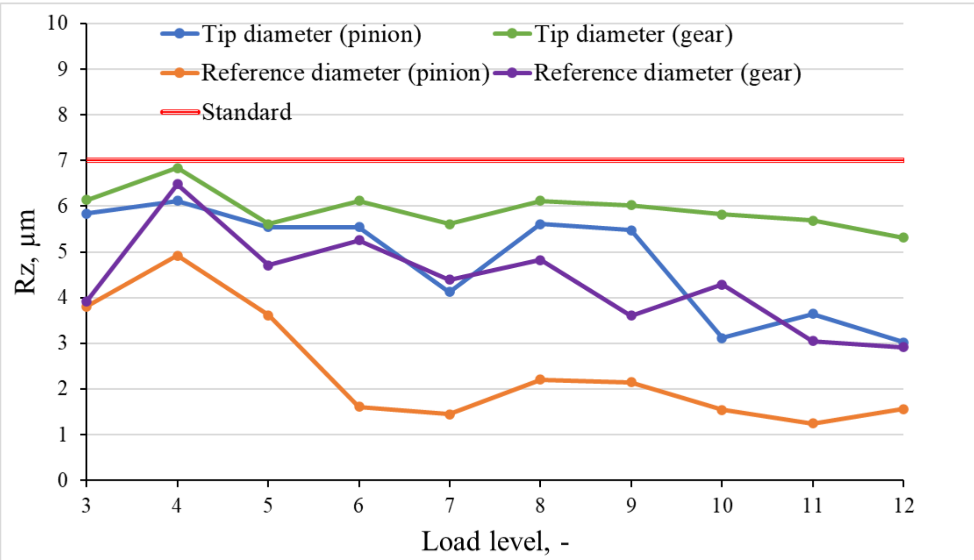

Fig. 4 Evolution of the surface roughness parameter Rz for coated nACRo4 samples as a function of load level under lubrication with TOTAL Carter Bio 150 oil

Table 11 Basic statistical evaluation of the maximum profile height Rz for a gear with nACRo4 coating under lubrication with MADIT PP 90 oil

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)
3	6.25	0.142	0.043	2.151	5.32	0.117	0.035	2.252
4	5.76	0.163	0.051	2.884	5.09	0.128	0.044	2.874
5	5.65	0.155	0.048	2.642	4.51	0.101	0.036	2.415
6	6.28	0.148	0.044	1.964	4.36	0.142	0.041	3.237
7	5.11	0.132	0.039	1.859	5.68	0.131	0.039	2.141
8	6.12	0.136	0.043	2.511	2.34	0.124	0.034	5.434
9	5.29	0.134	0.042	2.509	4.08	0.119	0.039	3.105
10	6.05	0.169	0.050	2.965	1.74	0.154	0.045	9.375
11	5.14	0.109	0.035	2.142	3.12	0.135	0.040	4.284
12	5.59	0.156	0.044	2.757	3.51	0.119	0.036	3.541

Figure 5 illustrates the dependence of the maximum profile height Rz on load levels for both the pinion and the wheel with nACRo4 coating operating in MADIT PP 90 lubricated conditions. The parameter Rz was evaluated at two positions – the tip diameter and the reference diameter – and the graph also includes the limit value of Rz at both diameters, which defines the onset of scuffing during experimental testing. The values shown represent averages of ten repeated measurements at each load level, with the same procedure applied to all experimental tests.

At the tip diameter, the Rz values for the pinion ranged from 3.69 to 5.41 µm, while for the wheel the values ranged from 5.11 to 6.28 µm. At the reference diameter, the pinion showed Rz values between 1.65 and 4.35 µm, whereas the wheel exhibited values in the range of 1.74 to 5.32 µm.

All recorded values were free of significant extremes and did not exceed the defined limit threshold. Based on these findings, it can be concluded that no damaging load level was reached during the tests for either the pinion or the wheel with the nACRo4 coating.

Table 12 Basic statistical evaluation of the maximum profile height Rz for a pinion with nACRo4 coating under lubrication with MADIT PP 90 oil.

Load level	Tip diameter				Reference diameter			
	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)	$\overline{Rz}$ (µm)	S (µm)	$S_{\overline{Rz}}$ (µm)	$V_{\overline{Rz}}$ (%)
3	4.36	0.121	0.038	2.518	4.19	0.089	0.029	2.468
4	5.41	0.162	0.053	2.924	4.25	0.174	0.050	4.064
5	4.86	0.185	0.059	4.135	2.14	0.132	0.041	6.574
6	4.39	0.156	0.046	3.567	2.68	0.121	0.046	5.288
7	4.82	0.141	0.044	2.992	2.54	0.101	0.035	4.427
8	4.65	0.115	0.046	2.938	2.23	0.145	0.042	6.154
9	4.95	0.164	0.052	3.312	1.65	0.164	0.051	11.231
10	5.19	0.145	0.043	2.731	1.74	0.132	0.038	7.275
11	5.32	0.137	0.042	2.449	1.89	0.111	0.032	7.422
12	5.21	0.099	0.028	1.654	1.95	0.108	0.041	6.941

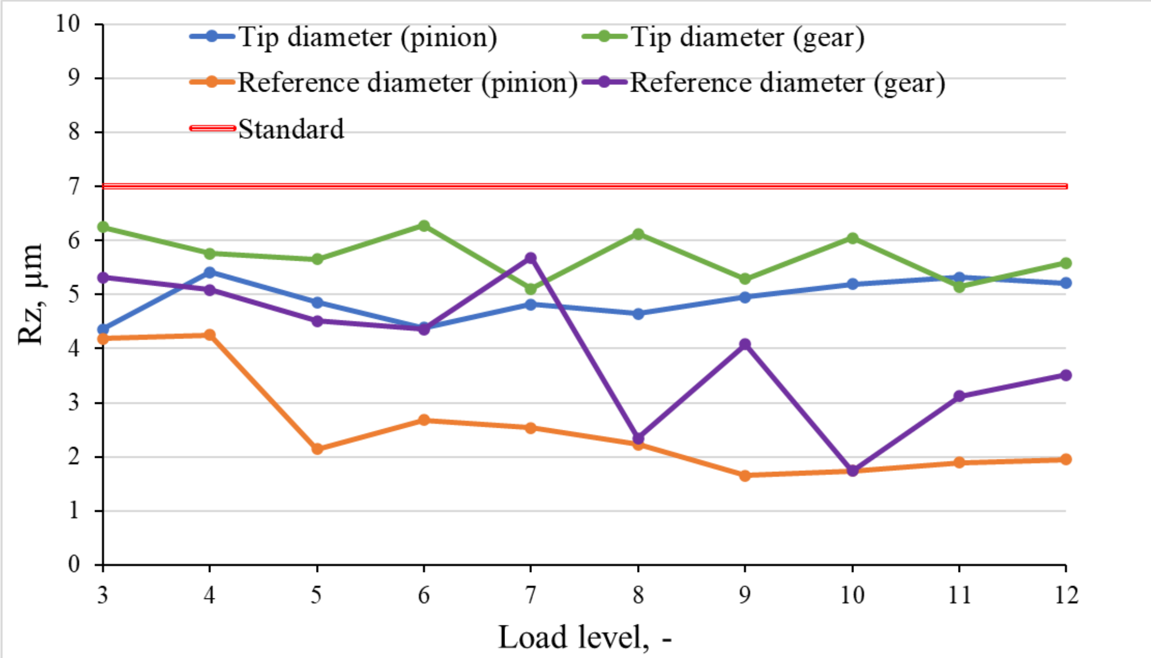

Fig. 5 Evolution of the surface roughness parameter Rz for coated nACRo4 samples as a function of load level under lubrication with MADIT PP 90 oil

CONCLUSION

In this experimental study, two gear pairs were tested – one uncoated and one coated with nACRo4. Each pair was evaluated under two different lubricants, MADIT PP 90H and TOTAL, using the FZG Niemann test rig.

The results showed that the uncoated gear pair reached the limit values of the surface roughness parameter Rz after the 11th load level in both lubricated environments. Beyond this point, Rz values increased sharply, indicating the onset of damaging mechanisms and defining the 10th load level as the critical threshold.

In contrast, the nACRo4-coated gear pair did not exceed the limit values of Rz in either lubricant. The values remained within stable ranges without significant extremes, and no scuffing or damaging load level was reached during the tests.

Based on these findings, it can be concluded that the nACRo4 coating significantly enhances the resistance of gears against surface damage and, when combined with appropriate lubrication, represents an effective approach to improving the durability of gear transmission systems. Nevertheless, to fully validate the long-term functionality and stability of nanocoatings, it is essential to perform extended operational tests, which would provide more detailed insights into their performance under real service conditions.

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