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Wear Resistance Assessment of Fluoropolymer Coated Gears

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Power transmissions that incorporate gears dissipate a significant amount of energy and noise. Thus, any improvement in their performance contributes to reducing energy consumption and noise pollution. In recent years, the opportunities offered by conventional technologies to increase gear performance have been fully exploited. Therefore, surface depositions on gear teeth have become increasingly important technologies in achieving objectives such as: improving energy performance, providing greater protection against superficial defects, increasing load capacity and reducing acoustic emissions generated during operation. However, gear coating technologies have begun to be developed, but the investigations are still insufficient. In this study, we carried out wear resistance investigations performed on fluoropolymer coatings for different working speeds, loads and lubrication conditions. The results point out that the deterioration rate of the coating increases with the increase of the working speed and the applied load. In addition, a slight lubrication, applied at the start of testing, leads to a noticeable improvement in wear behaviour. This study represents one step further in understanding the wear process of fluoropolymer coated gears.

Keywords: *Coating, fluoropolymer, gear, wear resistance*

1. Introduction

Different gear coating technologies are being used currently in industrial applications; depending on the purpose, the gear deposition material can be: a fluoropolymer (very often the product Xylan 1052), molybdenum disulphide (MoS_2), tungsten carbon carbide (WC/C), titanium nitride (TiN) and/ or titanium carbide (TiC), or boron carbide (B_4C) respectively.

Molybdenum disulphide (MoS_2) is a lamellar compound, originally developed for space applications [1-3], but successfully used for precision bearings [4] and gear systems [5], [6] as well. It has been shown that by applying a MoS_2 coating [5], the gear efficiency can be increased by 2,7 to 3,1%, compared to uncoated gears [5]. This improvement of the gear efficiency has been explained by the decrease of the average friction coefficient during the engagement process.

The tungsten carbide/carbon (WC/C) coating is usually applied on case hardened gears by either Physical or Chemical Vapour Deposition (PVD/ CVD). By involving this coating technology, benefits such as improved friction, superior wear resistance and a better lubrication, can be obtained [7], [8].

TiN and TiC depositions are also known as ceramic coatings. They are the most widely used coatings in engineering applications, due to the fact that they improve the protection of the base material against wear, erosion, corrosion and other surface damages [9], [10]. They are applied in thin layers (<10 μm), by PVD or CVD method. The combination of low friction coefficient, chemical inertness, wear resistance and high hardness, these two coating technologies offer, make them attractive for tribological coatings and thus, widely used for several applications, such as: cutting tools, moulds, gears or bearings.

Boron carbide (B_4C) is a very hard (>3000 HV), amorphous ceramic material, applied in very thin layers (2 to 3 μm) by a PVD process. Although, being initially used for manufacturing tank shields or bulletproof vests, in the last decades, the industrial applications of this product have been extended as coating technologies for transmission gears in the automotive industry [11].

Even though surface deposition technologies are available in various deposition materials and techniques, the coating technologies applied to gears are only beginning to be developed. That is, such processes have insufficiently been investigated. Furthermore, the friction behavior and the wear resistance assessment of these superficial coatings are only possible through experimental research, which is carried out by means of special devices called tribometers.

The present study is concerned with the investigation of the wear resistance of a fluoropolymer coating, performed under different working speeds, loads and lubrication conditions.

2. Motivation of research

Due to the lack of data regarding the wear behaviour of gears with Xylan 1052 coating, in the laboratory of Doctoral School from "Eftimie Murgu" University of Resita, researches were started with respect to this topic.

Following experimental investigations on fluoropolymer coated gears, whose results were presented in previous publications [12-14], after a visual inspection of the gears, it was a finding of wear at the beginning and the end of the tooth engagement (see Figure 1- where the areas where marked for an easier identification). In these sections, a slip friction is acting in addition to the rolling friction.

The area between these two affected sections, where the rolling of the teeth flank is predominant, showed fine scratches and slight superficial peeling points. The reported phenomena may be associated with pitting and scuffing encountered on steel produced gears.

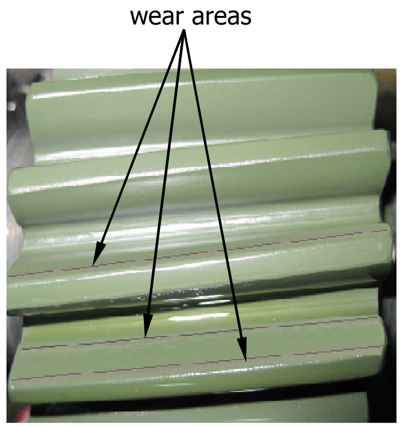

Figure 1. Xylan 1052 coated gear with incipient wear [15]

From the tribological point of view, the wear phenomenon could be explained by the fact that, with the increase of the frictional speed (at the beginning and the end of the tooth engagement), the temperature in the superficial deposition material also increases. Due to the high frequency of the phenomenon's occurence, this leads to the incapacity of the coating to dissipate the lost energy, in the form of heat.

3. Experimental setup

The experimental research was carried out on a Ball-on-Disk tribometer which was developed in the laboratory of the Doctoral School from "Eftimie Murgu" University of Resita and is shown in Figure 2.

The test disk, which was coated with Xylan 1052, is driven by an adapting flange mounted on a shaft which is connected to an electrical motor through a torque flange of type T 10 FS, manufactured by HBM, Germany. The speed of the electrical motor varies in the range from 0 to 1500 rpm. Reading of the exact speed was possible by using a module MP 60, which is connected to the torque flange.

Pressing the ball on the test disk was performed by means of the arm joint, which was pushed by a helical spring. By fixing a hexagonal nut in a certain position, the spring provided a pushing force of the ball holder on the test disk. The adjustment of the pushing force was carried out in a previous calibration, by means of weights of 3, 6 and 12 kg. The spring was compressed by the weights, while the corresponding deformations were measured.

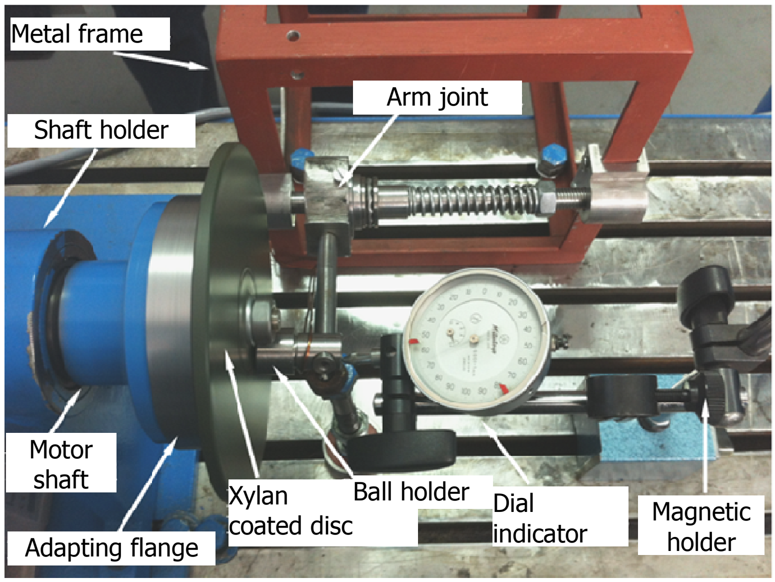

Figure 2. Ball-on-Disk tribometer

The wear measurement of the fluoropolymer deposition was assessed with a dial indicator, whose road was in contact with the end of the ball holder.

For evaluating the wear resistance of the fluoropolymer coating under various working conditions, two layers of Xylan 1052 were deposited on the test disk, together creating a thickness of 35 µm. The test conditions concerned three sliding (ball- disk) speeds: v_s = 970, 1,540 and 2,910 mm / s, and three loading steps corresponding to 30, 60 and 120 N, respectively.

Furthermore, because in practice, accidentally or willingly, dry operation or a poor lubrication may occur, following two conditions, regarding the lubrication, have been simulated:

- dry running;
- running with a slight initial lubrication.

The investigation with a slight initial lubrication was performed by wetting the disk surface with oil, prior starting the wear test. By this procedure, it was also assessed the ability of the fluoropolymer coating to maintain the lubrication during the test run.

4. Results and discussion

The collected experimental data are presented in Table 1. The results of the measurements according to the lubrication conditions, the sliding speed and the applied load are shown. Figures 3 and 4 display the wear time variation, depending on the applied load and the sliding speed, respectively.

Table 1. Results of the wear test

Lubrication conditions	Sliding speed [mm/s]	Time of wear T [h] for the applied load F [N]		
		30	60	120
dry running	970	5,33	1,92	0,83
	1.540	0,95	0,97	0,58
	2.910	0,72	0,3	0,25
slight initial lubrication	970	42,00	17,83	2,50
	1.540	40,83	12,00	1,25
	2.910	32,67	10,00	0,75

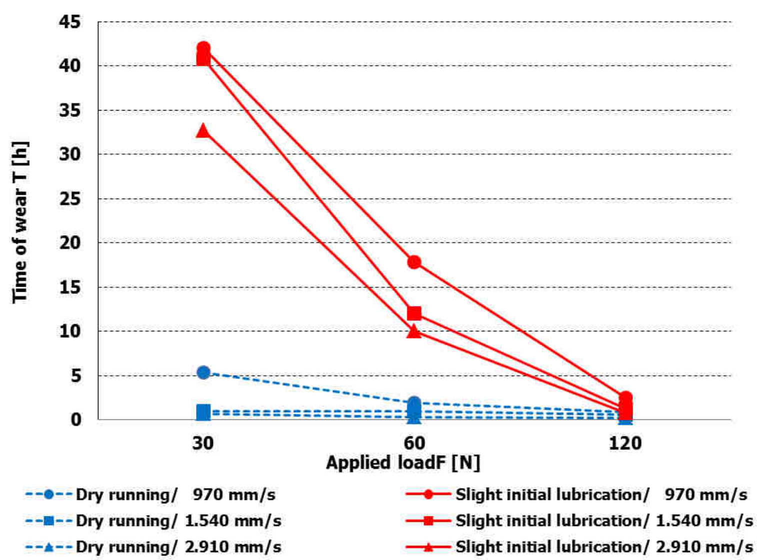

Figure 3. Evolution of wear time depending on applied load

The most evident deterioration has been observed after the tests performed under dry running conditions, where the coating layer was burned and transformed into a black powder. The deterioration rate was proportional to the sliding speed and the applied load. Furthermore, it has been found that for high loads but low speeds, the fluoropolymer layer shows exfoliations on small areas adjacent to the wear path.

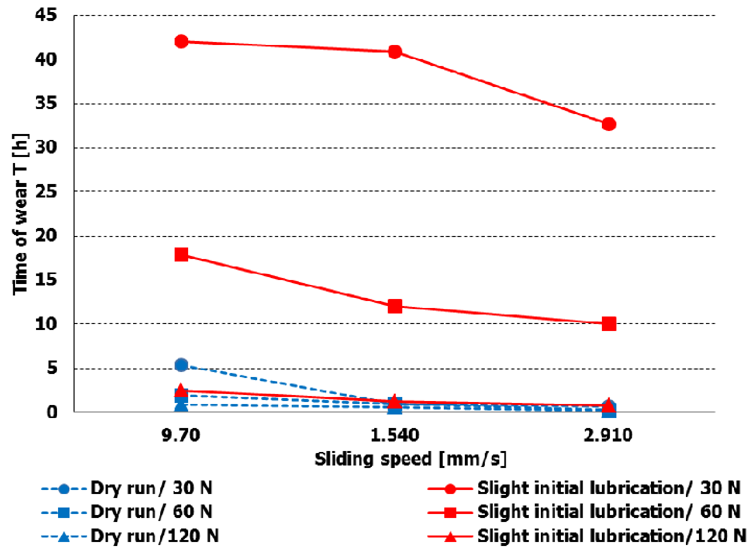

Figure 4. Evolution of wear time depending on sliding speed

Analysing the results presented in Table 1 and in Figures 3 and 4 respectively, one can observe that in the dry running condition, for all speeds and applied loads, a rapid wear of the coating layer occurs. An improvement in the wear resistance was recorded after applying an initial slight lubrication. In addition to the decreasing the sliding friction, the oil also acts as a cooling agent for the outside surface of the coating in the area of mechanical contact with the testing ball. Likewise, the variation of the sliding speed does not provide a major difference of wear in the domain of maximum applied load (120 N). However, some small differences in the time of wear are observed for the lower range of the loads (30 and 60 N).

Table 2. Wear evolution in time

Lubric. cond.	Applied load F [N]	Sliding speed v_s [mm/s]	Wear h [µm] after time T [h]														
			0,00	0,02	0,08	0,17	0,33	0,50	0,67	0,83	1,00	1,33	1,67	2,00	2,33	2,67	3,00
dry running	120	9.70	0	1	10	13	18	22	27	35							
		1.540	0	10	17	22	27	35									
		2.910	0	3	15	23	35										
slight initial lubrication	120	970	0	2	5	8	9	10	11	12	14	17	20	23	28	35	
		1.540	0	5	9	11	15	19	23	27	31	35					
		2.910	0	3	11	14	18	23	28	35							

The evolution of the wear speed was also of interest in this project, which was evaluated for the maximum applied load (120 N.). Thus, for the three sliding speeds, wear measurements were performed at the following time intervals: 1′, 5′, 10′, 20′, 30′, 40′ 50′, 1h, 1h20′, 1h40, 2h, 2h20′, 2h40′, 3h, 3h20′, 3h40′, 4h, 4h20′, 4h40′, 5h, 5h20′ and 5h40′ (h-hours; ′-minutes). Table 2 shows the results of these evaluations, while, for a better understanding, Figures 5, 6 and 7 provide a more detailed view of the wear evolution. A net detachment in terms of wear resistance in time can be observed in the slight initial lubrication condition. The decrease of the time of wear is exclusively due to the increase of the sliding speed.

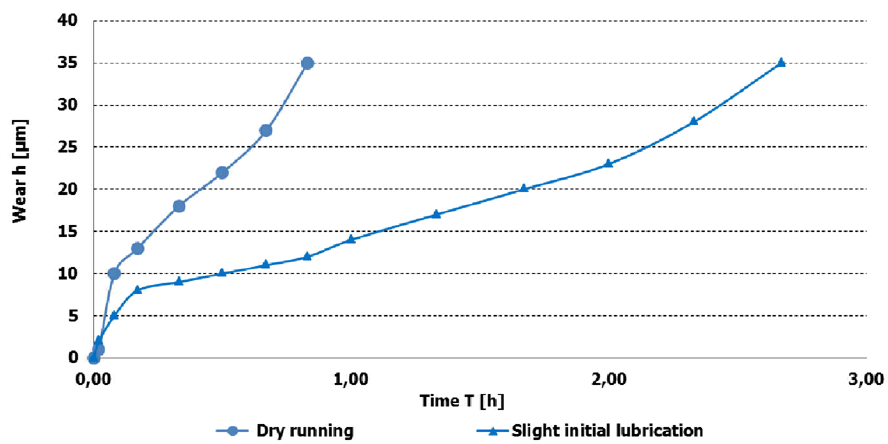

Figure 5. Wear evolution at a load of 120 N and a sliding speed of 970 mm/s

For the investigated conditions, the wear process shows a typical evolution, similar to the theoretical wear curves. After the initial stage, when the wear rate becomes significant, the process continues linearly, so that, at the end, the wear rate increases again (catastrophic wear). The slopes of the wear curves are steeper when the lubrication is missing, while the wear is rate decreasing with the improvement of the lubrication conditions. Furthermore, one can observe that at the maximum sliding speed (2.910 mm/s), the wear is progressing rapidly, but is also maintaining its typological evolution character.

Based on the Figures 5 to 7, it can be noticed, that in the first 5 minutes of testing, depending on the speed, the fluopolymeric layer has a metal-like behaviour. Thus, during the run-in period, the wear increases to about 15% of the total coating thickness, followed by a linear evolution, where the wear rate is much lower than in the run-in period. Finally, when the coating layer remains at about 15% of the initial thickness, the wear rate increases again, but not as strongly as in the initial phase (run-in period).

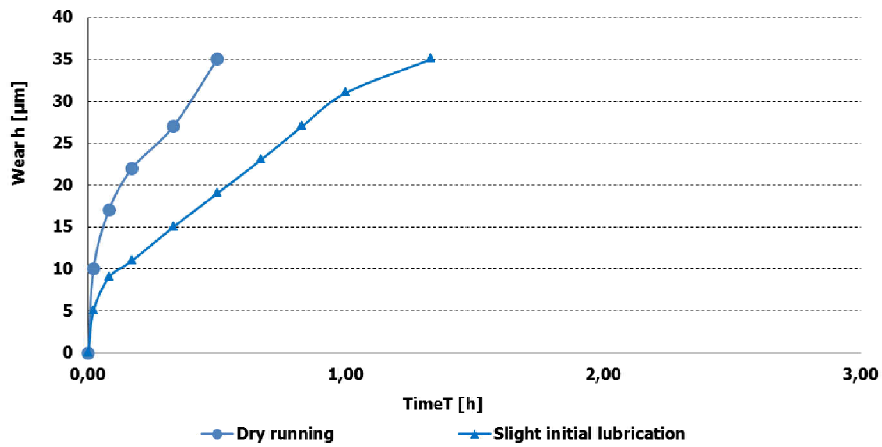

Figure 6. Wear evolution at a load of 120 N and a sliding speed of 1.540 mm/s

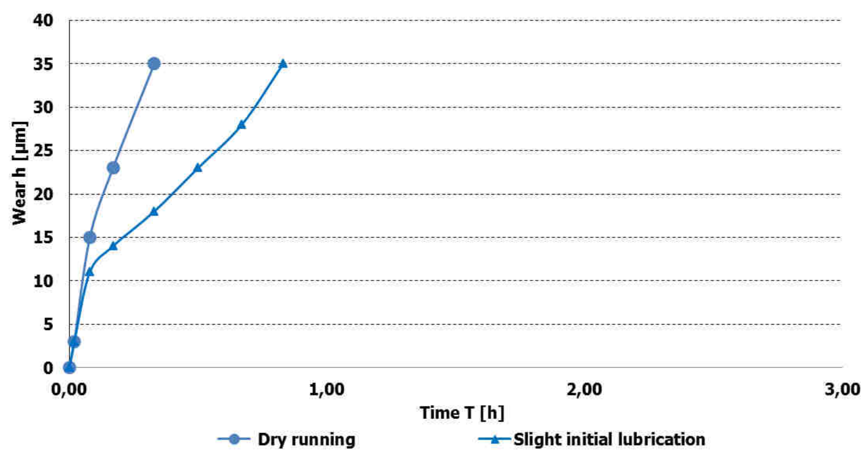

Figure 7. Wear evolution at a load of 120 N and a sliding speed of 2.910 mm/s

Extending these results to the more general setting of fluoropolymer coated gears, we learned that the period where the wear rate has the lowest values is optimal for the coating layer, because the deposition is still having a sufficient thickness to enable a good shock absorption during the teeth engagement. In the area of catastrophic wear however, the coating material remains too thick to be efficient in the damping process. In this domain, the wear progression is very fast and with an unpredictable decline.

5. Conclusions

The friction behaviour as well as the wear resistance of superficial coatings applied to the gears can be investigated and further developed by means of tribometers. The present paper presents considerable experimental results following an assessment of the wear behaviour of gears coated with Xylan 1052. The project was carried out on a Ball-on-Disk tribometer.

The test conditions included different working speeds (970, 1.540 and 2.910 mm/s), loads (30, 60 and 120 N) and lubrication conditions (dry and slight initial lubrication). Our results show that, in time, the deterioration process increases with the increase of the applied loads, as well as the sliding speeds, especially in the dry running condition, where the coating layer was burned and transformed into a black powder.

Also, for high loads but low speeds, the coating layer shows exfoliations on small areas. Regarding the wear evolution, a typical evolution and good shock absorption in the initial stage is shown. However, at the end, the wear was a catastrophic one, where the coating layer was too thick to be efficient in the damping process of fluoropolymer coated gears.

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