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Research Article

The wear of polytetrafluoroethylene helical gears under dry and lubricated conditions

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Abstract

The wear and thermal characteristics of Polytetrafluoroethylene (PTFE) helical gears were experimentally investigated using a rig test under dry and lubricated conditions. The study employed two gear ratios (1:1 and 0.75:1) at constant speed and torque to determine the effect of ratio on wear. Both wear and temperature increased for the driving and driven gears in all test environments. The experimental results highlighted the critical role of lubrication: significant surface wear began much earlier in dry conditions (after $100x10^4$ cycles) than in lubricated conditions (after $120x10^4$ cycles). This confirms that lubrication significantly improves the wear resistance of PTFE gears.

1. Introduction

Industrial development fundamentally depends on machines that have high capability and reliability in their components. Traditionally, metal gears have been the go-to choose for many applications. Over time, polymer gears have become increasingly popular due to their unique benefits, such as being lightweight, producing less vibration, reducing noise, offering high corrosion resistance, and being self-lubricating. While metal gears are prone to issues like distortion, cracking, and rupture under stress, polymer gears offer a promising alternative. These types of failures are a concern in any industry, but especially in the fast-paced world of manufacturing, where downtime or performance issues can lead to costly delays. Back in the 1700s, testing machines were first introduced, using simple methods like pulling, bending, and twisting materials to understand how they behave under stress [1]. Despite these advances in testing, the goal remains the same: to prevent failures and ensure the longevity and efficiency of machine elements. Today, avoiding gear failure is especially important in industries like automotive, printing, and food, pharmaceuticals, and beverages, where production depends on the smooth operation of every part. Metals can corrode or contaminate products, posing health risks to humans and animals. This is particularly problematic in food and pharmaceutical production, where safety and hygiene are paramount. Polymer gears offer a much-needed solution. They are not only lighter and quieter, but they also resist corrosion and require less maintenance due to their self-lubricating properties. Materials like MC blue, polytetrafluoroethylene (PTFE), and polyoxymethylene (POM) are often used to make these gears, either on their own or in combination. These materials are perfect for use in industries that demand high standards of hygiene and safety, like food and pharmaceuticals.

Nearly every mechanical device has some form of transmission elements. For example, motor vehicles use gears to transfer power, washing machines rely on pulleys to rotate the drum, computer printers have gears, cams, and pulleys to move paper and adjust the printing heads, and

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even photocopiers and ATMs are full of various power transfer components [2-3]. In industries like food and pharmaceuticals, where equipment is exposed to harsh environments, it's vital to choose the right type of steel to avoid corrosion. Even with careful selection, corrosion can still happen, and it can have serious consequences. Not only can it affect the quality of food and medicine, but it can also change their taste, texture, or safety. Plus, corrosion can damage the equipment used in production, potentially causing costly breakdowns and slowing down manufacturing. The risk of corrosion is present during different stages of production, like processing raw materials, making food or medicine, and packaging the final products. For example, in food production, equipment can come into contact with acidic substances, chloride solutions, and protein-rich media, especially at high temperatures, all of which increase the chances of corrosion. On the other hand, drug production involves oxidizing environments and the use of high-purity water and steam [4-5]. Wear process of gears specially made by polymers have been studied, such as, polyformaldehyde gears [6-13]. Studies on polymer gears regarding durability [14-15], composite gear design [16-18], the effects of temperature and lubrication [19-22], and acoustic noise [23] have been the focus of many researchers. While there have been some experimental studies on the topic, the wear process of polymer gears still presents an interesting area for further research, especially when using polymers produced in Indonesia. In this study, we looked at how polytetrafluoroethylene (PTFE) helical gear pairs wear under both dry and oil-lubricated conditions. The findings from this experiment give us a better understanding of the wear mechanisms and show how polymer gears' load capacity can be improved.

2. Wear Test Rig for Polytetrafluoroethylene Helical Gears

2.1. Testing Methodology

The experiment was conducted using a gear test that comply with ASTM D5182–19 as shown in Fig. 1. The drive gear is directly connected to the electromotor using a shaft. The driven gear is connected to a shaft equipped with a controlled loading instrument. The test rig allows the adjustment of the center distance to accommodate gears of different sizes or modules. The specimens were set in the box, which was filled empty or oil in order to realize the continuous dry and lubricated conditions. The experiments were performed with a rotational speed of 2400 rpm, while the output torque is maintained 5.8 N.m by adjusting the load on a disk brake system.

In this study, the testing procedure was carried out as shown in Fig. 3. The testing was carried out in 2 stages. The first stage is durability testing, in which in this stage, the gear is not removed to measure the weight and scan tooth profile, but continues to run, only temperature measurements are taken per $20x10^4$ cycles. The next stage is wear testing, at this stage the gear is removed per $20x10^4$ cycles to measure the initial and final gear weights then the lost weight can be calculated and the profile of each tooth scanned.

2.2. Gear samples

To observe the effect of gear ratio on wear under overdrive conditions which are commonly found in pharmaceutical and food industry machines, three bevel gear geometries with different nominal values are used. The gear ratios are 1:1 and 0.75:1. For simplicity, the geometry of the driving gear is maintained the same for both driven gears while the driven gear is adjusted. The gear geometries and mechanical properties are shown in Table 1 while sample gear photos are shown in Fig. 2.

Table 1. Helical gear geometry and properties

Gear	Material	Dimensions				Module (mm)	Number of teeth	Yield strength (MPa)	Density (kg/m^3)
		DO (mm)	DP (mm)	Width (mm)	Angle (°)				
Drive	PTFE	100	96	25	12	2	48	10,47	2200
Driven-1	PTFE	100	96	25	12	2	48	10,47	2200
Driven-2	PTFE	75	71	25	12	2	36	10,47	2200

1. Motor
2. Gear specimens
3. Data acquisition
4. Velocity sensor
5. Shaft
6. Frame
7. Inverter
8. Load sensor
9. Hand winch
10. Load disk brake
11. Bearing

Fig. 1. Gear test rig

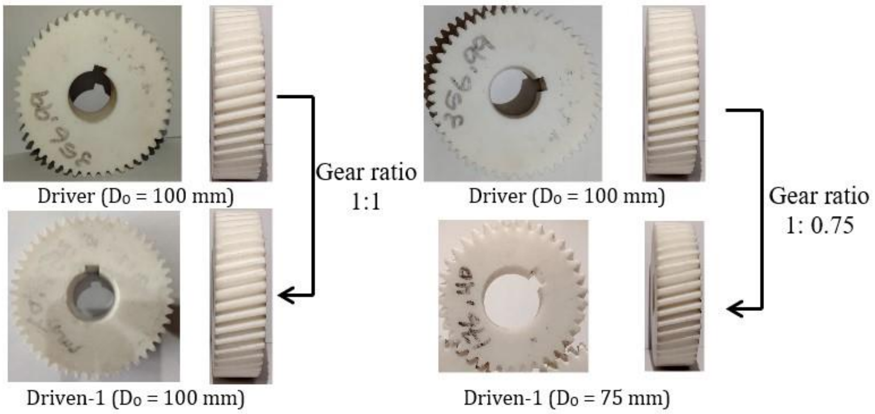


Fig. 2. Gear samples

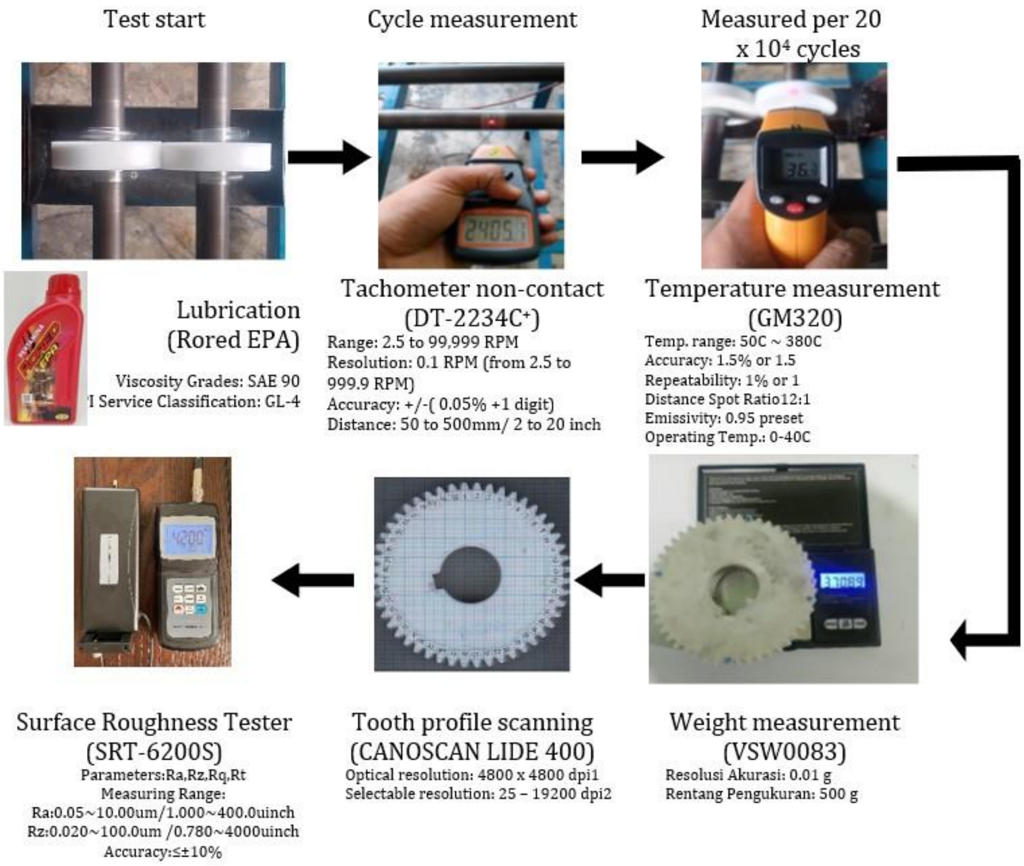
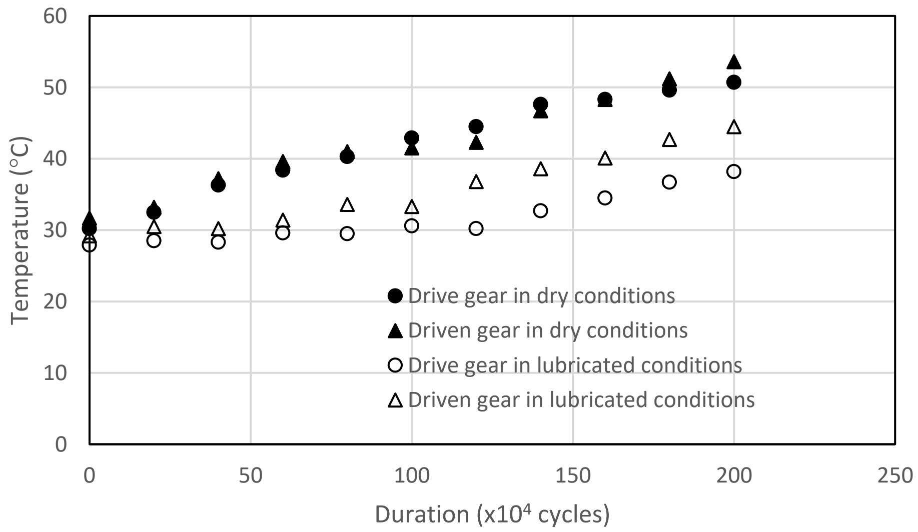


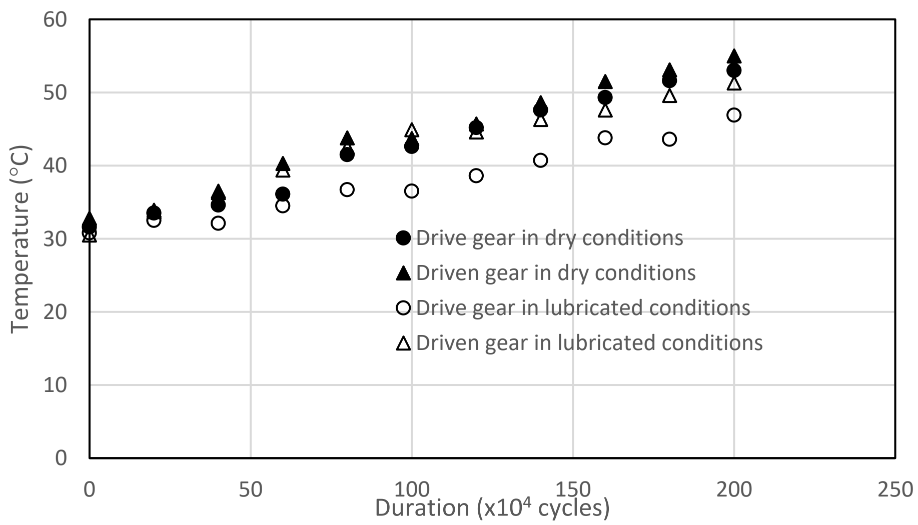
Fig. 3. Testing methodology

4. Results and Discussion

Figure 4 shows the results of temperature measurements on the gear operated in dry and lubricated conditions. A total of 11 hours of gear running continuously without any breaks. Starting from 30°C -31°C of room temperature, the maximum temperature is reached at 55,6°C on driven gear operated in dry condition. By comparing Fig. 4(a) and Fig. 4(b), the lower gear ratio does not show significant temperature different. The complete results of the temperature and gear weight measurements for gear ratios 1:1 and 0.75:1 is shown in Table 1 and Table 2 respectively. Figure 5 presents the wear accumulation for PTFE helical gears across different gear ratios. A significant difference was observed between the dry and lubricated conditions, with the drive gear exhibiting greater wear than the driven gear in both cases. For the 1:1 ratio (Fig. 5a), the final wear accumulation reached 0.38 g in dry conditions and 0.18 g in lubricated conditions. Conversely, for the 0.75:1 ratio, the maximum accumulation was 0.42 g (dry) and 0.24 g (lubricated). This demonstrates that a lower gear ratio increases the overall accumulation of tooth wear, though the notable difference between dry and lubricated results persists.

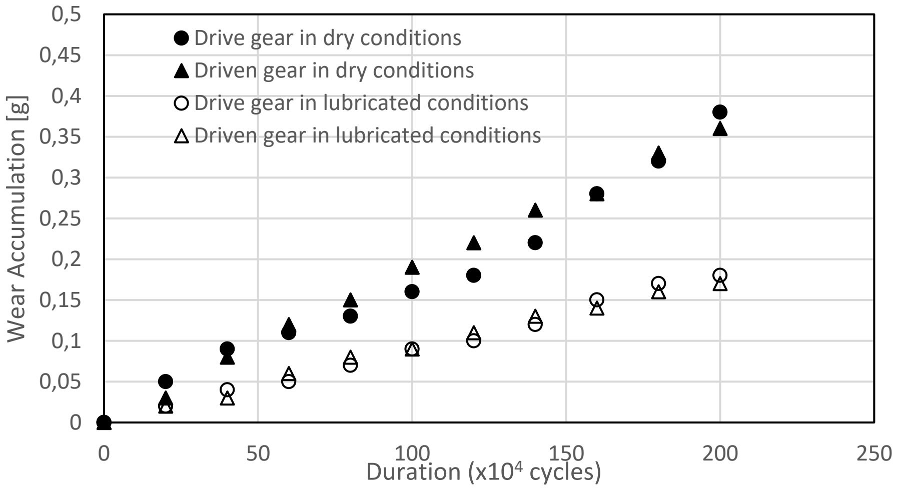


(a) Temperature of helical gear with a ratio 1:1

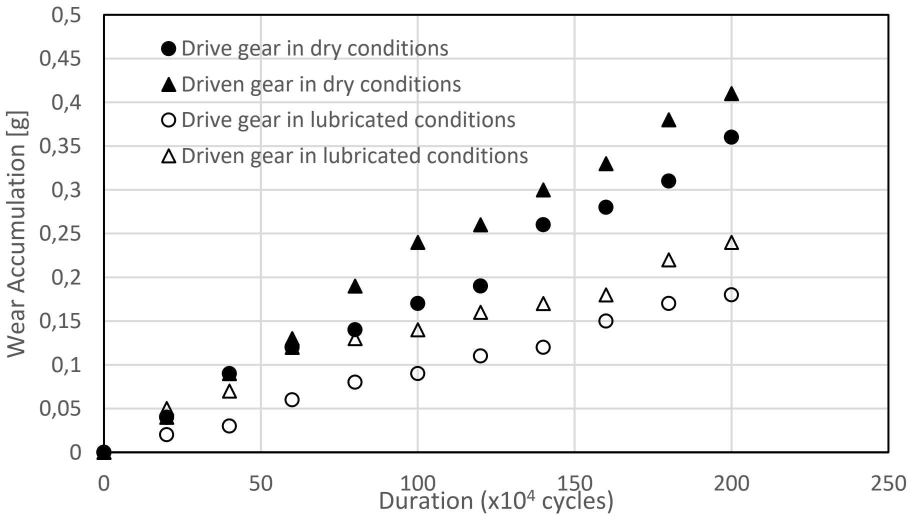


(b) Temperature of helical gear with a ratio 0.75:1

Fig. 4. Surface temperature of PTFE helical gear with different gear ratio.



(a) Wear accumulation of helical gear with a ratio 1:1



(b) Wear accumulation of helical gear with a ratio 0.75:1

Fig. 5. Wear accumulation of PTFE helical gear with different gear ratio

The PTFE gears were monitored for permanent damage every 20x104 cycles by scanning the changes in their geometric profiles. This damage initiates through material tearing caused by mating tooth engagement, resulting in a characteristic rough, torn surface (Fig. 6). Figure 6 summarizes the wear accumulation, demonstrating a significant disparity between dry and lubricated environments, and showing that the driven gear accumulated slightly more wear than the drive gear overall. Significant surface wear became clearly visible after 100x104 cycles. At this point, the severity of the dry condition was evident: the driven gear teeth (Fig. 6b) were torn to almost half their original shape. While damage was also clear under lubricated conditions (Fig. 6c and 6d), the resulting surface profile was noticeably smoother.

To gain detailed insight into the surface damage of the PTFE gear, damaged and undamaged teeth were sectioned and observed using Scanning Electron Microscopy (SEM). The SEM results in Fig. 7 clearly distinguish between the undamaged and worn tooth profiles. Figure 7(a) displays the initial roughness from the machining process (fine parallel lines, marked by the red circle) on a clean section. Conversely, the damaged section (Fig. 7b) shows the obliteration of these initial marks in the red-circled area, replaced by an entirely modified, smooth, worn, or polished surface, which confirms the extent of material degradation. This observation is consistently supported by images captured at both 30 μm and 20 μm resolutions.

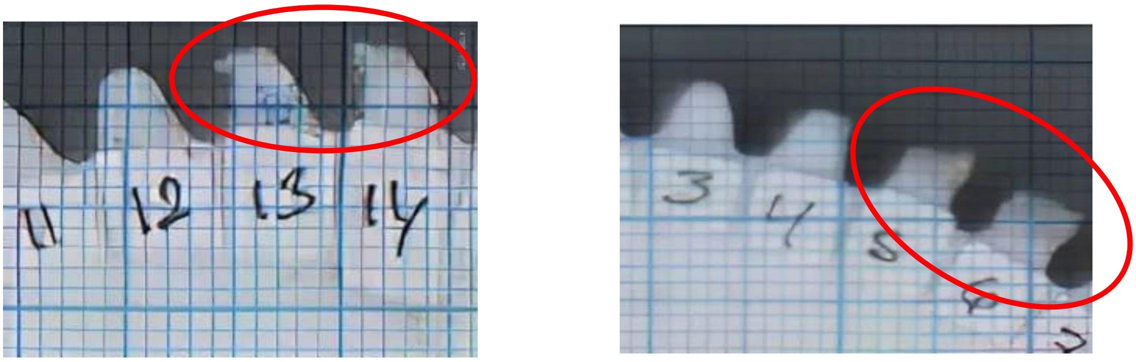
The surface roughness test was conducted for each condition after 200x10^4 cycles of wear test. The top land of tooth gear of PTFE gear was tested. The average data of roughness test results is presented in Table 4. Initial surface roughness measurements under dry, 1:1 ratio conditions were 4.30µm (driving) and 4.43µm (driven). After approximately 11 hours of wear loading, the roughness decreased significantly to 2.66µm (driving) and 2.56µm (driven), representing a 40-45% reduction. A similar pattern of surface roughness reduction (38-45%) was observed when the gears were tested under lubricated conditions across both gear ratios. Overall, lubrication was found to have a positive impact, further reducing the final surface roughness value by an additional 14-16% compared to the dry condition.

Table 2. Experimental results of helical gears with a ratio of 1:1

Test duration (x104)	Dry conditions				Lubricated conditions			
	Temperature (°C)		Weight (g)		Temperature (°C)		Weight (g)	
	Drive	Driven	Drive	Driven	Drive	Driven	Drive	Driven
0	30.2	31.7	369.14	373.70	27.9	29.2	368.34	373.30
20	32.5	33.2	369.09	373.67	28.5	30.5	368.32	373.28
40	36.3	37.2	369.05	373.62	28.3	30.2	368.30	373.27
60	38.4	39.6	369.03	373.58	29.6	31.4	368.29	373.24
80	40.3	41.0	369.01	373.55	29.5	33.6	368.27	373.22
100	42.9	41.5	368.98	373.51	30.6	33.3	368.25	373.21
120	44.5	42.3	368.96	373.48	30.2	36.8	368.24	373.19
140	47.6	46.7	368.92	373.44	32.7	38.6	368.22	373.17
160	48.3	48.3	368.86	373.42	34.5	40.1	368.19	373.16
180	49.6	51.2	368.82	373.37	36.7	42.7	368.17	373.14
200	50.7	53.6	368.76	373.34	38.2	44.5	368.16	373.13

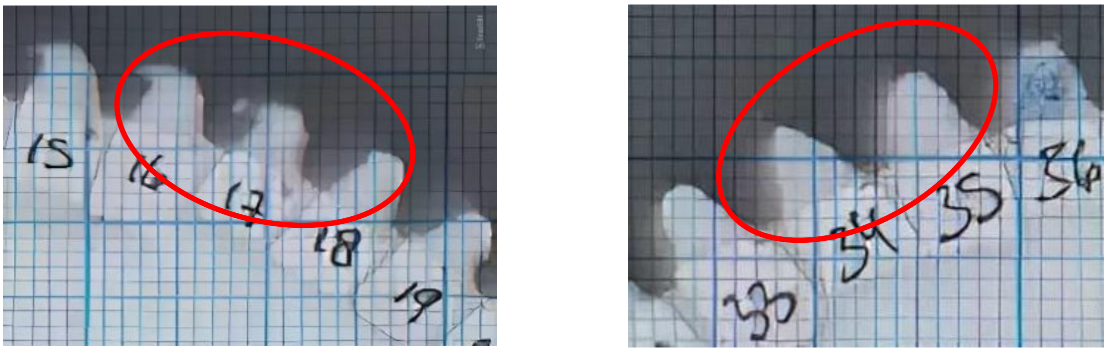
Table 3. Experimental results of helical gears with a ratio of 0.75:1.

Test duration (x104)	Dry conditions				Lubricated conditions			
	Temperature (°C)		Weight (g)		Temperature (°C)		Weight (g)	
	Drive	Driven	Drive	Driven	Drive	Driven	Drive	Driven
0	31.6	32.8	368.73	182.42	30.8	30.5	368.14	179.53
20	33.5	33.9	368.69	182.38	32.5	33.7	368.12	179.48
40	34.6	36.5	368.64	182.33	32.1	36.3	368.11	179.46
60	36.1	40.3	368.61	182.29	34.5	39.4	368.08	179.41
80	41.5	43.8	368.59	182.23	36.7	42.5	368.06	179.4
100	42.6	43.7	368.56	182.18	36.5	44.9	368.05	179.39
120	45.2	45.7	368.54	182.16	38.6	44.6	368.03	179.37
140	47.6	48.6	368.47	182.12	40.7	46.3	368.02	179.36
160	49.3	51.5	368.45	182.09	43.8	47.6	367.99	179.35
180	51.6	53.1	368.42	182.04	43.6	49.6	367.97	179.31
200	53.0	55.0	368.37	182.01	46.9	51.3	367.96	179.29



Gear damage under dry conditions

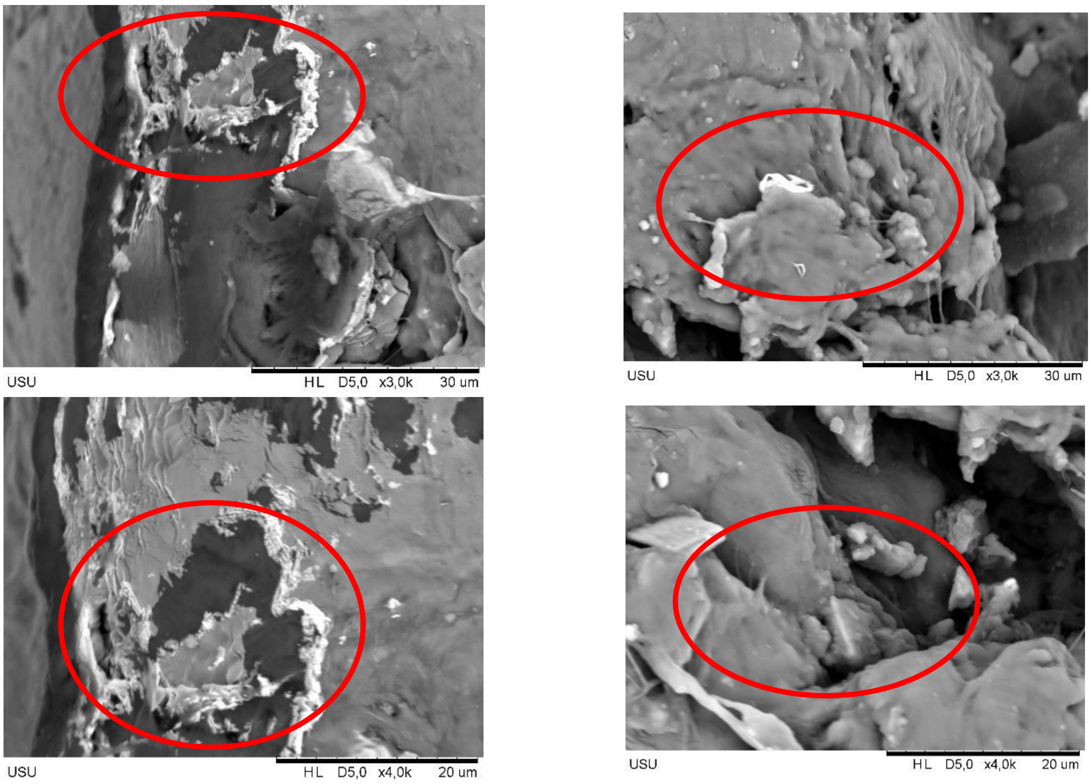
(a) After 100×10^4 cycles for drive gear (b) After 100×10^4 cycles for driven gear



Gear damage under lubricated conditions

(c) After 120×10^4 cycles for drive gear (d) After 120×10^4 cycles for driven gear

Fig. 6. Result of tooth profile scanning for dry and lubricated conditions.



(a) Undamage teeth (b) Damage teeth

Fig. 7. SEM test results for damaged and undamaged teeth on gears.

Table 4. Surface Roughness Test of helical gears.

No	Wear test conditions	Gear Ratio	Initial wear test [Ra (μm)]		After wear test [Ra (μm)]	
			Drive	Driven	Drive	Driven
1	Dry	1 : 1	4.30	4.43	2.66	2.56
2		0.75 : 1	4.41	4.47	2.72	2.45
3	Lubricated	1 : 1	4.38	4.45	3.96	3.81
4		0.75 : 1	4.32	4.50	3.91	3.74

5. Conclusions

The experimental investigation into the wear behavior of PTFE helical gear pairs under dry and lubricated conditions yielded several key findings. First, temperature significantly affects PTFE gear wear, though the overdrive (0.75:1) and fixed (1:1) ratios exhibited no observable temperature difference. Second, wear accumulation increased as the gear ratio was reduced. The lower 0.75:1 ratio resulted in higher maximum wear (0.42 g dry; 0.24 g lubricated) compared to the 1:1 ratio (0.38 g dry; 0.18 g lubricated), confirming that lubrication's protective benefit persists despite the increased mechanical wear at the lower ratio. Finally, SEM analysis clearly confirmed the extent of material degradation: the initial machining marks on undamaged teeth were entirely obliterated and replaced by a modified, smooth, worn surface on the damaged sections.

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