

## Comparing the life-wear of steel on PTFE and steel on steel bearings in tie rod ends

Alaaddin Toktaş<sup>a\*</sup>, Tolgahan Burak Parik<sup>b</sup> & Gülcan Toktaş<sup>a</sup>

<sup>a</sup> Balıkesir University, Department of Mechanical Engineering, Balıkesir, Türkiye

<sup>b</sup> NSK Automotive, Rota Steering, Suspension and Hydraulic Parts Factory, Bursa, Türkiye

*Received: 27 April 2024; accepted: 13 July 2024*

This study has aimed to design and manufacture a new type of steel/polytetrafluoroethylene (PTFE) bearing to replace the traditional steel/steel bearing used in tie rod ends. The study has focused on investigating the life-wear test and mechanical resistance of the new steel/PTFE bearing type at tie rod ends. For this purpose, rotational torque tests, backlash (collapse) tests, pull-out tests, and life-wear tests have been carried out. The obtained values were compared with the life-wear and durability values of tie rod ends using steel/steel bearings. After life-wear tests on both types of bearings, backlash values increased and torque values decreased. The backlash values for the steel/PTFE bearing type (0.05–0.07 mm) are significantly lower than that for the steel/steel bearing (0.35 mm). The new type of steel/PTFE bearing is more durable and has a longer lifetime in terms of test results compared to steel/steel bearings.

**Keywords:** Steel/PTFE bearing, Tie rod end, Life-wear test

### 1 Introduction

A vehicle suspension is defined as a group of elastic elements and bars that connect the axles and individual wheels of a car to a frame or directly to a vehicle body. The suspension's goals are to minimize the impact of road imperfections like bumps, cracks, and potholes, to maximize comfort, and to safeguard the materials and living things inside the car from collisions and damaging vibrations. The protection of the vehicle against strong impacts also has a significant effect on the durability of various mechanisms<sup>1</sup>.

The suspension system serves to transmit and regulate both static and dynamic forces and reactions between the vehicle and the ground. The primary components of a suspension system include tires, springs, shock absorbers, and connections that link the vehicle's wheels<sup>2</sup>. The tie rod end is a crucial component of the steering mechanism that plays a vital role in ensuring driving safety. The tie rod end is used to ensure the alignment of the wheels. It aligns the wheel and prevents tire wear on the inside and outer edges<sup>3</sup>.

Tie rod ends have the main components of a body, ball (sphere), spring, bearing, sealing elements, and lid. The body allows it to be attached to the rod arm

with the help of a screw. The ball is a movable connection enabling a rotationally oscillating movement of one of the connected components relative to the other<sup>1</sup>. The bearing element is the joining part between the body and the sphere that produces the rotation torque. Loads in different directions and sizes come to these spherical connections at the tie rod end. These could include acceleration loads, torque moments during cornering, and dynamic loads brought about by bumps or potholes in the road. Additionally, tie rod ends are exposed to the effects of variable climate and environmental conditions.

The ball can generally be laid with three bearing materials: steel, polymer, and bronze. The existing steel/steel bearing type is widely used in the industry due to its superior technical and durability characteristics. However, wear is a great problem with this type of bearing. Therefore, steel/steel bearings require regular lubrication with special greases at specific intervals to prevent wear. On the other hand, lubrication brings dirt and oil, which can be degraded due to humidity, oxygen, temperature in service, and atmospheric conditions causing the ball to be worn.

Özsoy and Pehlivan<sup>4</sup> have carried out a structural analysis of the body, ball, and bearing of a van-type vehicle using the finite elements model. An analysis of connections has been carried out for various

\*Correspondence author (E-mail: atoktas@balikesir.edu.tr)

connection edge directions. They have studied the stress distribution and deformation properties of each component for a variety of operational loading conditions. Patil et al.<sup>5</sup> have numerically determined the natural frequency and static voltage of the rod and tie rod end for a particular vehicle. They have modeled the entire mechanism as a single piece and found it could work safely. A. H. Falah et al.<sup>6</sup> have looked into the damage of a broken tie rod end and found that it had broken because of fatigue, with the crack starting at the throat (minimum) area of the threaded part because the material wasn't strong enough and it wasn't heated properly. If fatigue, wear, buckling, vibrations, and tensions are excessive, they lead to the unwanted and structural degradation of tie rod ends<sup>7</sup>. Wozniak et al.<sup>1</sup> measured the wear of the tie rod components and found that the wear of the steel ball was much lower than that of its polyoxymethylene (POM) bearing.

PTFE (polytetrafluoroethylene, Teflon) is resistant to heat, chemicals, moisture, and electrical jump (dielectric), does not adhere to any material, and has a friction coefficient smaller than any solid. Due to the above unique properties, PTFE coating is a possible and suitable candidate for a steel bearing in the tie rod ends. Polycarpou<sup>8</sup> has investigated wear on PTFE-based coatings in air-conditioning compressors and reported that coatings had a low friction coefficient, high load capacity, and inertness to the test environment. He stated that the PTFE coating had worn significantly under high contact pressures, but at the point of the overall wear performance, the

generated debris showed a positive role by acting as a third lubricant. Yuana and Yang<sup>9</sup> have searched the friction and wear properties of PTFE coating under vacuum conditions with a ball-on-disk wear tester. They concluded that the debris of PTFE coatings sliding against a GCr15-bearing steel ball under vacuum conditions is a flake. Lan et al.<sup>10</sup> reported both adhesive and abrasive wear mechanisms on PTFE and PEEK (polyetheretherketone) coatings in their experimental study. As in the above ones, most studies on the wear of PTFE coating were conducted under laboratory conditions with standard samples. Limited studies on the life and wear of PTFE-coated bearings in the actual assembly have been found in the literature.

This study aims to create a new design of a tie rod end with a steel/PTFE bearing as an alternative to the traditional steel/steel bearing for an automotive spare parts manufacturer (NSK Automotive, Bursa, Türkiye). In addition to the design and manufacture, a series of experiments in more realistic conditions have been carried out to determine the service life and durability values of this new tie rod end, which will be used in the steering wheel system. The same experiments were also carried out for the traditional steel/steel bearing tie rod end to compare the performance of the new tie rod end with the PTFE bearing.

## 2 Materials and Methods

The technical and cross-sectional view of the designed tie rod end with steel/PTFE bearing is given in Fig. 1. The chemical compositions of the main

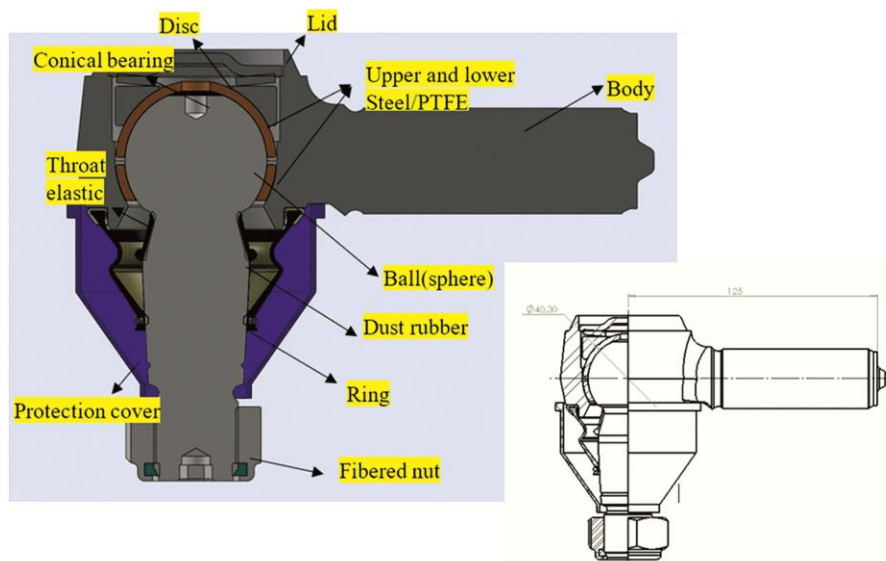


Fig. 1 — Cross-section of the designed tie rod end assembly.

elements in the assembly are given in Table 1. The body is made of hot-rolled SAE 1040, which has 420 MPa yield strength, 623 MPa ultimate tensile strength, 24 percent elongation, and 197 HB hardness. The body is formed via hot deformation by a single stroke press at a temperature range of 1000–1400 °C using 600-ton capacity press. Then the inner front and inner back surfaces and the connection part to the rod are machined, respectively. The scrubbing process created threads on the rod connection part. The traditional steel/steel bearing used an induction process to make sure the body's surface was hard. The steel/PTFE bearing type, on the other hand, did not need this because the surface did not come into contact with the hardened sphere or the body's inner surface.

SAE 5140 hot-rolled steel was used to manufacture the ball (Table 1). At a temperature between 750 and 950 °C, the forging process involved hot forming with a drop hammer in a closed mold (with a burr). After the forging, GNC-CNC applied the machining process at 2000–2400 rev/min with 0.01 mm sensitivity by fixing the ball between the double tailstock. Machining has been applied to all surfaces of the ball, except for the forged surfaces pressed by the double tailstock. The ball is given in Fig. 2 as before and after the machining. Then, to enhance the strength and hardness, the ball was austenitized at 850°C for 1 hour and quenched with oil. Tempering at 550°C for 2 hours followed the quenching process. To increase the wear resistance of the sphered surface of the ball, induction surface hardening was carried out at 860 °C

for 10 seconds. The sphered surface hardnesses after quenching/tempering, and induction surface hardening are given in Table 2. After heat treatments, surface vibration, and tooth scrubbing processes are also applied to the ball part to ensure surface roughness and mechanical joining, respectively.

The conical bearing part is machined from SAE 1040 hot-rolled steel that has a 50-mm diameter rod and a 200 HB hardness value. Table 1 shows the chemical composition of this steel. The machining was performed via Feeler CNC at 1800–2000 rev/min with 0.02-0.05 mm sensitivity.

The steel/PTFE bearing was purchased through outsourcing. The bearings consist of upper and lower parts. The technical drawings and solid models of these parts are given in Fig. 3. The chemical composition under the PTFE layer is given in Table 3. The layers and thicknesses on the cross-section of the bearing are given in Fig. 4. The macro hardness value of the bearing is 220 HB. The ball and bearing diameters and their surface roughnesses are of great importance in tie rod end performance. These values are given in Table 4.

The tie rod end lid is produced using the machining method from SAE 1040 hot rolled steel rod with a diameter of 50 mm and a 200–210 HB hardness value. Machining of this part was performed on the

Table 2 — Hardness values of the sphered surface after heat treatments.

Quenched/tempered (HRC)	Induction hardened (HRC)	Hardened layer (mm)
28.3-30.7	55.5-56.5	1.80-1.85

Table 1 — The chemical compositions of the main parts in the tie rod end (wt%).

Part	Material	C	Si	Mn	P	S	Cr	Ni	Cu	Fe
Body	SAE 1040	0.43	0.24	0.60	0.014	0.018	0.13	0.090	0.26	98.192
Ball	SAE 5140	0.39	0.17	0.67	0.014	0.005	0.93	0.14	0.24	97.381
Conical bearing	SAE 1040	0.40	0.19	0.65	0.02	0.02	0.04	0.03	0.08	98.57
Disc spring	SAE 1050	0.48	0.21	0.90	0.01	<0.003	0.07	0.02	---	98.302

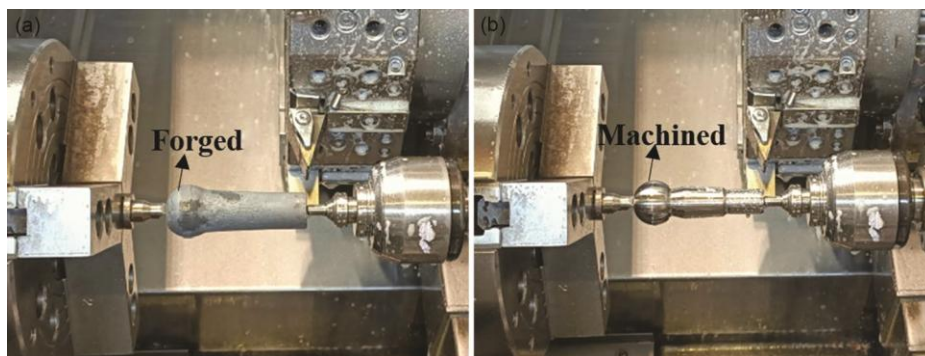


Fig. 2 — The ball (a) before and (b) after the machining.

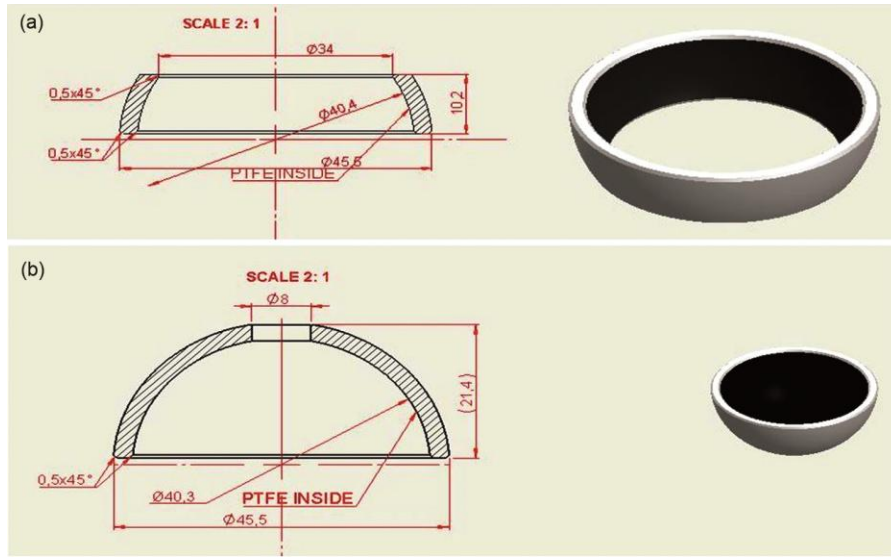


Fig. 3 — The technical drawing of steel/PTFE (a) lower and (b) upper bearings.

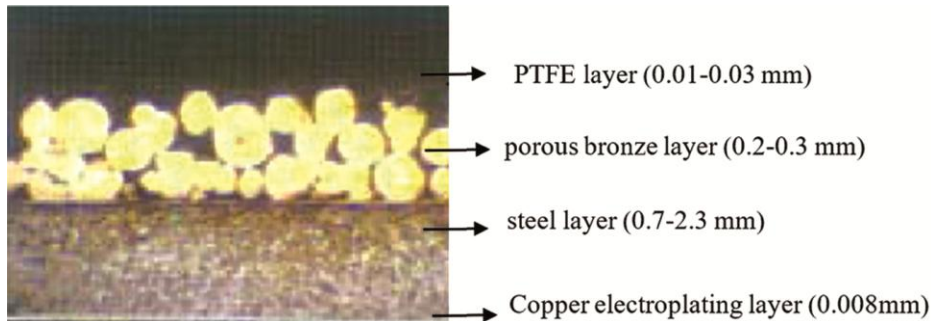


Fig. 4 — Material layers of PTFE bearings.

Table 3 — The chemical composition of the below layers of PTFE bearing (wt%).

Bronze →			Steel →				
Sn	Zn	Cu	C	Mn	P	S	Fe
7.3-8.7	2.3-3.7	87.6-90.4	0.05-0.15	0.15-0.60	≤0.035	≤0.025	99.19-99.8

Table 4 — Diameters and roughnesses of the balls and bearings.

Measurements	Steel/PTFE bearing		Steel/Steel bearing
	Sample 1	Sample 2	
Ball diameter (mm)	40.234	40.231	39.984
Bearing inner diameter (mm)	40.35	40.39	40.02
Ball roughness (Ra)	0.474	0.579	0.369
Bearing roughness (Ra)	4.25	3.36	1.167

Feeler CNC machine at 1800–2000 rev/min with 0.02-0.05 mm sensitivity.

The disc spring made of SAE 1050 steel and used in the assembly as a bearing support component was outsourced. Its hardness is in the range of 43.0–45.3 HRC, and its chemical composition is given in Table 1. The displacement limits of the spring in response to the applied force are given in Table 5.

The assembly of the above main parts and others that were manufactured or supplied was done with the help of an edge-forming machine. The lubricant used during assembly is Mobil grease, an industrial grease, whose operating temperature is between –20 and +130 °C and the dropping point is 190 °C. Fig. 5 represents the assembled tie rod end.

In all experiments, two tie rod ends were used to determine the performance of the new type of steel-PTFE bearing. A conventional assembly of a steel/steel bearing was also used to compare the performance. The rotational torque test was carried out per TS 9444 and TS 5476 standards at a dedicated production test station manufactured by the company. In rotational torque measurement, the ball is fixed at a position 90° upright to the body axis with special

Displacement (mm)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Force (kN)	0.43-0.50	1.09-1.47	2.02-2.50	3.02-3.67	4.08-5.03	5.13-5.98	6.28-7.79	7.59-9.47	9.24-11.36	11.02-13.19



Fig. 5 — The assembled tie rod end.

devices suitable for the tooth area. It was then fixed to the end of the body, allowing the ball to rotate at its axis at a 360° angle. The ball was rotated five times before measuring to spread the lubrication between the ball surface and the bearing. Then, in the last five rounds, the machine measured the maximum and minimum torque values and averaged them.

Assemblies with steel/PTFE and steel/steel bearings have been tested at a special production backlash test station per TS 9444 and TS 5476. In this experiment, the tie rod end was attached to the device, and the arm strength controlled the space between the ball and the bearing. Then the pre-load (12 kg) was applied to the ball inside the tie rod end, and then the main total load (108 kg). The amount of collapse from a comparator attached to the experimental device under load is recorded.

The push-out and pull-out tests were conducted on two types of bearings per TS 9444 and TS 5476. In these test methods, the tie rod end was connected to the test device with the help of appliances. The compression (push) and tensile (pull) forces on the ball axis are applied at a speed of 0.1 mm/s, respectively, for push-out and pull-out tests. The push force is applied until the ball comes out of the lid, and this value is determined as the push-out force for the ball coming out of the lid. The pulling force in the axis direction was applied until the ball exited the bearing, and the pulling force was determined from which the ball came out of the housing.

Life-wear tests were done according to TS 9444 and TS 5476 standards using the custom-made tool shown in Fig. 6 to find out how well steel and PTFE

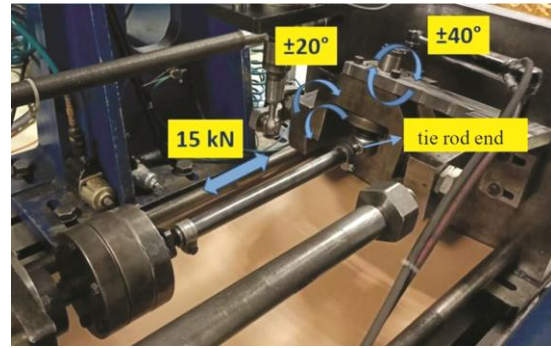


Fig. 6 — Life-wear testing device.

bearings worked in tie rod ends. This test is of great importance in tie rod end manufacturing as it provides the most realistic working conditions throughout the vehicle's lifetime. The tie rod end is connected to the test device with a dust rubber attached. The tie rod end body was made to oscillate at predetermined angular values according to its neutral state in a plane parallel to the connection end axis, with a frequency of 0.5 Hz. The ball was released at  $\pm 40$  degrees at its axis at 0.4 Hz and  $\pm 20$  degrees toward the playing angle at 0.5 Hz. Predefined tensile and compressive loads were applied along with frequency values with the above angular playback. The experiments described so far are considered a cycle if applied for one minute. The cooling process to avoid overheating the tie rod end during the experiments was achieved with the climate and local air cooling systems. The experiment was carried out at a frequency of 1 Hz at a load of 15 kN at 250.000 cycles. After the life-wear tests, backlash, and rotational torque tests were applied to the tie rod ends again to compare the resulting backlash and rotational torque values with those of the pre-life-wear test values. After these tests, the tie rod end assembly was separated (by blasting) to measure the changes in the ball and bearing diameters, and the surface roughness of these parts.

### 3 Results and Discussion

The results of the rotational torque, backlash, push-out, and pull-out tests performed before the life-wear tests of the assembled tie rod end with steel/steel and steel/PTFE bearings are given in Table 6. The torque values obtained for both bearing types were similar, with a value of approximately 11 Nm. In addition, the ball joint shaft with steel/PTFE- bearings is more

stable than steel/steel bearings and has been shown to provide an advantage in terms of its function on the vehicle.

The backlash test values of steel/PTFE bearings have been very low, with 0.005 mm and 0.006 mm compared to steel/steel bearings, which is 0.13 mm. Therefore, it can be said that the steel/PTFE bearing will be more durable due to its function on the vehicle. According to the push-out test results, the compressive forces obtained are much higher (about three times) than those of the tie rod ends with steel/steel bearings. In terms of axial forces, steel/PTFE type bearings can withstand much higher compressive forces than their counterparts, standard products with steel/steel bearings. This will ensure high safety in terms of lifetime and performance. Contrary to the push-out test results, the tensile force required for pulling out the ball of the housing at the steel/PTFE bearing was less, and about half of that was obtained at the steel/steel bearing. This result does not imply that the new bearing type lacks durability; rather, the bottom output diameter of the tie rod end's design dimensions has a significant impact on the low tensile force. The designed diameter was 38.40 mm in the PTFE bearing. By reducing the diameter, the pull-out test result (tensile force) can be increased.

Table 7 represents the rotational torque and backlash test results and also the measurements of ball and bearing diameters and their roughnesses after

250,000 cycled life-wear tests. The 250,000 cycles in this experiment correspond to approximately 173 days of non-stop operation of the tie rod end in the vehicle. The torque values (3.9–5.2 Nm) obtained after the life-wear test for both bearing types showed significant decreases compared to pre-test values (10.9–11.3 Nm). The torque value is the smallest at 3.9 Nm in the tie rod end with a steel/steel bearing. Even this smallest torque value is within acceptable limits, which are accepted as the whole service performance of the tie rod end after the life-wear test.

Backlash test values after the life-wear test in steel/PTFE bearing type (0.05–0.07 mm) increased approximately a hundred times compared to pre-test values (0.005–0.006 mm). But they are still very low from the same value of the steel/steel bearing type, which is 0.13 mm and 0.35 mm for pre- and post-life-wear tests, respectively. The backlash value is the gap between the ball and the bearing after certain service conditions and is so important for the movement of the ball in the housing. Too much tightening of the spherical bearing and joint system reduces driving comfort while under-tightening reduces driving safety by providing low torque values as seen in Table 6. Excessive tightness or looseness of the ball joint, both of which reduce the life and wear of the ball joint, may become risky in terms of vehicle safety<sup>11</sup>. In this manner, the steel/PTFE bearing presents more advantages by providing this gap at a lower value. At the same time, this lower value indicates less deformation in the steel/PTFE bearing and longer service life.

After the life-wear tests, the ball diameters of both types of bearings reduced, indicating the occurrence of the wear phenomenon (Tables 4 and 7). With a reduction of 0.024 mm in the ball diameter of the steel/steel bearing type, it has been found to have more wear than the steel/PTFE bearing type. On the other hand, the bearing diameters increased for both types of bearings after the tests. These enhancements are 0.115–0.07 mm and 0.01 mm for PTFE and steel

Table 6 — Test results before life-wear tests.

Tests	Steel/PTFE bearing		Steel/Steel bearing
	Sample 1	Sample 2	
Rotational Torque (Nm)	11.3	11.1	10.9
Backlash (mm)	0.006	0.005	0.13
Push Out (kN)	118.57	114.27	40
Pull Out (kN)	66.87	67.84	150

Table 7 — Measurements and test results post-life-wear tests.

Measurements/Tests	Steel/PTFE bearing		Steel/Steel bearing
	Sample 1	Sample 2	
Rotational Torque (Nm)	4.7	5.2	3.9
Backlash (mm)	0.07	0.05	0.35
Ball diameter (mm)	40.215	40.225	39.960
Bearing inner diameter (mm)	40.465	40.46	40.03
Ball roughness (Ra)	0.815	0.778	0.733
Bearing roughness (Ra)	2.14	2.11	2.203

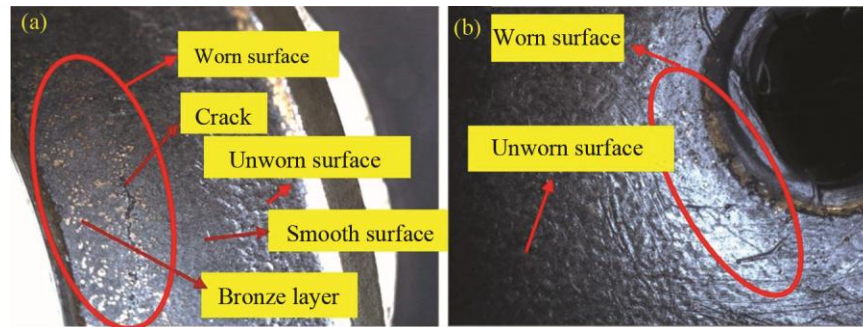


Fig. 7 — PTFE-bearing after life-wear tests a) lower and b) upper bearings.

bearings, respectively. According to these results, wear occurred both in the ball and in the bearing at each type of tie rod end. In the steel bearing type, more wear occurred on the ball and less wear on the bearing compared to the PTFE bearing type. As PTFE surfaces have a low coefficient of friction and provide self-lubricating properties, less wear is expected in the opposite ball material. The surface roughness of the balls increased for both types of bearings. These increments are 0.341-0.199 Ra and 0.364 Ra for PTFE and steel bearings, respectively.

When the bearing roughness values are examined, after the life-wear tests, the roughness of the steel/PTFE bearing showed a decrease and an increase in the steel/steel bearing. In PTFE bearings, the roughness of both the ball and bearing is lower than that of steel bearings. This can be attributed to the self-lubricating and non-abrasiveness effects of the third-body PTFE particles separated during tests.

Fig. 7 shows the worn lower and upper parts of the PTFE-bearing after the life-wear tests. It is recognized that the bearing has inhomogeneous wearing; some regions are worn while others are unworn. The lower part of the bearing had more worn regions and apparent cracks on the PTFE layer. It is understood from Fig. 7 that the worn PTFE surfaces were first smoothed by severe plastic deformation, then micro-cracked and flaked (spalled). In this flaked region, it has been observed that the PTFE layer has been replaced by the bronze layer below. This also reduced the surface roughness of the PTFE bearing. Yuana and Yang<sup>9</sup> studied the wear behavior of PTFE-coated surfaces versus GCr15 steel. On the coated surfaces, they observed microcracks from SEM images and smooth surfaces from the self-lubricating effect of PTFE. Furthermore, under high contact pressures, they reported that wear of the coating increased, yet wear debris formed acted as a third-body lubricant, with a good influence on total wear performance.

#### 4 Conclusion

A tie rod end with a new type of PTFE bearing was designed and manufactured (assembled). Rotational torque, backlash, push-out, pull-out, and life-wear tests looked at its performance. The test results were compared with the tie rod end with a traditional steel bearing. The main conclusions can be drawn as follows:

- Before life-wear tests, the rotational torque values of the steel/PTFE bearing tie rod end and the traditional steel/steel bearing are close to each other, with relatively low collapse (backlash) values (0.005-0.006 mm) and approximately three times higher compressive (pushing) forces (118.57–114.27 kN).
- The low tensile (pulling) forces (66.87–67.84 kN) in the steel/PTFE bearing can be increased by reducing the bottom output diameter of the body.
- After life-wear tests on both types of bearings, collapse values increased and torque values decreased. The collapse values for the steel/PTFE bearing type (0.05–0.07 mm) are much lower than the same value (0.35 mm) for the steel-steel bearing.
- The life-wear test increased the surface roughness of the balls in both types of bearings, reduced the bearing roughness in the steel/PTFE bearing, and increased the steel/steel bearing.
- Steel/PTFE bearings do not require induction heat treatment of the body component. The absence of it will provide savings in labor, energy, time, and cost.
- For future studies, consider applying black nitriding surface hardening to the ball part as an alternative to induction surface hardening.

#### Acknowledgement

As a part of the P21-01 Teflon Bearing Tie Rod End Project under the design center, NSK Automotive Industry (Bursa, Türkiye) supported this work.

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