Researches on Tie Rod Ends Lubricated by Grease with TiO$_2$ and ZrO$_2$ Nanoparticles

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Abstract. The nanoparticles of some materials can be used successfully to improve tribological properties through decreasing both wear and friction borne out of contact between the contact surfaces of elements in different devices, particularly vehicles. Nanoparticles of TiO$_2$ and ZrO$_2$ were chosen as additives to the lithium grease lubricating the contact surfaces in tie rod ends. The object of study was the steel ball – the component of the tie rod end – mating with the polymer insert and lubricated with the pure lithium grease or containing the addition of pure TiO$_2$, pure ZrO$_2$ nanoparticles, with a 1%wt. Studies on friction were carried out using the tester allowing cyclical rotational motion and different loading of contact. Wear was investigated by driving a car, whose tie rod ends were analysed, on a fixed ‘eight’-shape track and with a fixed velocity pattern. The aim of the study was to obtain the values and waveforms of friction moment and wear versus cycles, loading and composition of lubricating grease. The waveforms of friction coefficient were obtained using the FEM model of the analysed contact zone. Based on the obtained waveforms, recommendations for the composition of additives for lithium grease were made.

1. Introduction

Recently, interest has increased regarding the use of nanoparticles as a lubricant additive for various devices, as in [1]. Nanoparticle additives can reduce friction and wear through various mechanisms. According to ref. [2] such mechanisms are classified as direct and indirect effects of nanoparticle additives on the friction and wear process. Studies described in ref. [3–5] show that nanoparticle additives play the role of ball bearings between friction surfaces, resulting in decreased friction and wear. Further studies, described in [6–8], show that nanoparticle additives can also form a protective film over friction surfaces. Study [9] describes the formation of nanoparticle additive depositions on contact surfaces which compensate the loss of material. Nanoparticle additives can also reduce the roughness of contact surfaces due to their abrasive action as described in [10]. Study [11] presents research on the effect of nanoparticle additives on journal bearings using the finite element method. Study [12] presents investigations on the effects of nanoparticle lubricant additives on the performance of externally adjustable fluid film bearings. The studies described in [11, 12] point to an increase in the load-carrying capacity and stability of journal bearings using a nanoparticle-dispersed lubricant, and use the viscosity data reported in [5] for TiO$_2$, CuO and nano-diamond dispersions in base oil to compute the bearing characteristics. The variation in lubricant viscosity with changes in nanoparticle
concentrations and the effect of nanoparticle size and its aggregation properties were omitted during these studies. Paper [13] describes a novel method for evaluating the load-carrying capacity of journal bearings operating on lubricants containing nanoparticle additives. It was found that variations in lubricant viscosity due to the nanoparticle additives can be simulated accurately using a modified Krieger-Dougherty viscosity model. Study [13] presents research on the effect of the viscosity variation of engine oil, following the addition of TiO$_2$ nanoparticles at volume fractions ranging from 0.005 to 0.025, on the load-carrying capacity of a journal bearing. The TiO$_2$ nanoparticles, even at low concentrations of 0.01 volume fraction, could increase the load-carrying capacity of journal bearings by 40% in comparison to plain engine oil without nanoparticle additives. The TiO$_2$ nanoparticles of primary size <~100 nm dispersed in engine oil formed aggregates of an average size of 777 nm, forming a particle packing fraction of 7.77. The load-carrying capacity of the journal bearing operating on a TiO$_2$-based nanolubricant at a constant volume fraction increased with higher nanoparticle aggregate packing ratios. Increasing the particle packing fraction from 7.77 to 10 resulted in a 35% increase in the load-carrying capacity for a TiO$_2$ nanoparticle concentration of 0.015 volume fraction.

The studies on effect of TiO$_2$ as an additive to oil are presented in [14, 15].

In studies reported in [17], TiO$_2$/CuO nanoparticles were dispersed into lithium grease to improve its lubricating properties. Then, the process of sliding friction was tested. The friction force of the contact interface between a ball and a flat surface with TiO$_2$/CuO nano-grease was measured for a ball on a flat sliding wear tester. The tested lithium grease was synthesised with 0.5wt.%, 1.0wt.%, 1.5wt.% and 2.0wt.% TiO$_2$/CuO nanoparticles. It was found that the TiO$_2$/CuO nanoparticle additives can improve the wear resistance of lithium grease and decrease the friction coefficient. A 1.0 wt.% content of TiO$_2$ nanoparticles was the best in reducing friction and wear, and reduced the friction coefficient of the rubbing interface by about 40%, according to the friction tests. The wear of the lithium grease with a 2.0wt.% content of added CuO nanoparticles, reduced wear by about 60% in comparison with pure lithium grease. Furthermore, the addition of components creating tribo-film and TiO$_2$/CuO nanoparticles on the worn surface also decreased friction and wear.

Study [18] presents investigations on the friction and wear of lithium grease using the ZrO$_2$ nanoparticles as the additive, aimed at studying the change of the tribological properties of lithium grease. The friction coefficient decreased by over 30% when ZrO$_2$ nanoparticles with mass fractions of 0.25% and 0.5% were added. The ZrO$_2$ nanoparticles with mass fraction of 0.25% and 0.5% achieved the best results, and the wear scar diameter decreased by 48.8% and 46.5% respectively.

In almost all vehicles, one can find the ball joint of the tie rod end (Figure 1a, as in [19]), which is a moveable connection (kinematic pair) enabling a rotationally oscillating movement of the connected components relative to one another. The axis of rotation of a wheel coincides with the axis of the pin. Ball joints perform a rotationally oscillating movement, and for this they are lubricated with solid lubricant through a grease nipple, or with graphite grease when a grease nipple is absent.

The kinematic scheme of the steering mechanism is presented in Figure 1b. The steering angle $\delta_f$ is the independent variable. Force $F$ loading the steering rod is the function of geometrical parameters: $H_C$ - length of the tie rod, $\alpha_C$ - auxiliary angle, $h_C$ - length of the steering knuckle arm, $R_C$ - radius approximately equal to the distance of the middle point of contact between the wheel and the road surface from the axis of the steering knuckle, lateral offset at the ground $s$, lateral inclination angle $\lambda$, caster angle $\nu_C$, tire radius $r$, vehicle mass $m$, rolling resistance coefficient $f_t$, air density $\rho$, drag coefficient $C_x$, reference frontal area $A$, vertical load of wheel $F_z$, vehicle speed $v$. 

- $\delta_f$: steering angle
- $F$: force
- $H_C$: length of the tie rod
- $\alpha_C$: auxiliary angle
- $h_C$: length of the steering knuckle arm
- $R_C$: radius
- $s$: lateral offset at the ground
- $\lambda$: lateral inclination angle
- $\nu_C$: caster angle
- $r$: tire radius
- $m$: vehicle mass
- $f_t$: rolling resistance coefficient
- $C_x$: drag coefficient
- $A$: reference frontal area
- $F_z$: vertical load of wheel
- $v$: vehicle speed
The aim of the study was to obtain the values and waveforms of friction moment and wear versus cycles, and the loading and composition of lubricating grease for the contact between the steel ball and polyethylene bearing of the tie rod end.

2. Materials and methods

2.1. Samples preparation

Samples for researching the friction coefficient include the rotating ball mating with the fixed counterpart. A ball with a diameter of 18 mm was made out of steel and polished. It rotated with constant speed and was loaded by the tribotester head with a constant force. The mating counterpart contained the polyethylene sample immersed in an epoxy resin cast and chemically cured in the steel ring. The counterpart inner diameter was 30 mm. The contact zone was lubricated with lithium grease with or without the addition of 1% wt. of ZrO$_2$ or TiO$_2$ nanoparticles. The ZrO$_2$ nanoparticles were manufactured by the Institute of High Pressure Physics of the Polish Academy of Sciences. Their size was 10–20 nm, as reported in [20]. The TiO$_2$ nanoparticles were introduced via the commercial product NanoTitanium delivered by Lodz Ameox, reported in [21]. Such a product was formulated with nanosize TiO$_2$ particles of 10 nm in size, with a concentration of 1%wt. dispersed in isopropanol, which was evaporated directly before the application of TiO$_2$ into the grease. The grease was mixed with the commercial product using the High-Speed Planetary Mixer THINKY SR-5000, reported in [22], and the amount resulted in a concentration of 1% wt. of nanoparticles in the lithium grease. This was then treated with ultrasonic waves in the GT Sonic VGT-800 Ultrasonic Cleaner, for only about 2 min., to avoid agglomeration or the structural break of the nanoparticles.

2.2. Researching the friction coefficient

The friction coefficient in the contact zone between the steel ball – the component of the tie rod end mating with the polymer insert and lubricated with the lithium grease containing different nanoparticles – could only be estimated, due to the available tribotester, described in [23] (Figure 2). This tester allowed the measurement of the spinning friction torque in the contact zone between ball 4 and its counterpart 5, based on the twisting angle of string 7 supported by the aerostatic bearing of table 9. The twisting angle was read on shield 8. Measurement was done at a constant rotating speed of shaft 1 equal to 36 rpm and constant loading from the set of weights 3 increased in a step manner for the consecutive series 7.2 to 27.2 N. The abovementioned estimation of the friction coefficient was made using the modelled contact zone between steel ball 4 and its counterpart 5 made out of the same material as the original bearing. The force loading of the ball and rotating speed were chosen so that similar averaged values of contact pressure and sliding speed as in the original case would be obtained. Using the mentioned tribotester, reported in [23], the waveforms of friction torque against time were obtained for the 1%wt. amount of TiO$_2$ and ZrO$_2$ nanoparticles in the lithium grease. The friction coefficient was
calculated using measured values of the friction torque, diameter of contact zone and averaged contact pressure in the contact zone. The averaged contact pressure and diameter of the contact zone were estimated using the FEM model of such a zone (Figures 3a, 3b). The contact model had the assumed material properties of the steel ball and polymer counterpart, and the initial geometrical parameters and loading force of the real tribotester.

**Figure 2.** The ball-on-inner-sphere tribotester for measurement of the spinning friction torque; a) photograph of the tester. 1 – shaft, 2 – electric motor, 3 – weights, 4 – ball, 5 – inner sphere or plane counterpart, 6 – compressed air supply, 7 – string, 8 – shield for measurement of twisting angle, 9 – table with aerostatic bearing, as in [23]; b) Scheme of the tester. F – filter, G – weight, M – electric motor, N – tachometer, K – shield for measurement of twisting angle, S – compressor, ST – string, R – reducer, Z – motor power supply.

**Figure 3.** a) Model of steel ball – polymer insert contact, b) Network of finite elements, c) Contact pressure, d) Displacements.
2.3. Researches of wear coefficient

It was assumed, for simplicity, that the linear wear intensity \( I_h \) for both the steel ball stud and the polymer bearing is of the form (1):

\[
I_h = \frac{k_1 p_a^2}{a^2} \quad \text{for steel ball stud}
\]

\[
I_h = \frac{k_2 p_a^2}{a^2} \quad \text{for polymer bearing}
\]

where:

\( k_1 \) and \( k_2 \) - the proportional factor for the steel ball stud and polymer bearing, respectively,

\( p_a = F/S \) – average contact pressure,

\( F \) – force loading contact zone,

\( S \) – contact area between contact surfaces.

The wear intensity factor \( k \) characterizing the linear wear intensity was estimated from the equation (2):

\[
W = w_z \cdot t_u = \frac{I_h \cdot S \cdot \sum_{j=1}^{N} [v_{\text{aver}}(j) \cdot t_u(j)]}{w} = k \cdot F \cdot p_a \cdot \sum_{j=1}^{N} [v_{\text{aver}}(j) \cdot t_u(j)] \rightarrow k = \frac{W}{F \cdot p_a \cdot \sum_{j=1}^{N} [v_{\text{aver}}(j) \cdot t_u(j)]}
\]

where:

\( w_z \) – volumetric wear rate,

\( j \) – consecutive number of drive cycle in series,

\( N \) – number of cycles in series.

The wear intensity was calculated using values of the measured volumetric wear, and calculated: the averaged sliding speed and the averaged contact pressure. The volumetric wear was investigated while driving a car with tie rod ends analyzed, on the track of the fixed ‘eight’-shape and with the fixed velocity pattern (Figure 4). Each series contains \( N = 1000 \) cycles. The bearing was lubricated with analysed grease, applied into contact zone via a grease nipple specially mounted to the tie rod (Figure 5). The total wear value could be obtained from the measured diameters: the ball outer diameter \( D_1 \) and the bearing inner diameter \( D_2 \) before and after test series. As the changes of steel ball diameter \( D_1 \) were negligible, the volumetric wear resulted only from the changes of the bearing inner diameter.

The wear \( W_{\text{seat}} \) of polymer bearing was calculated as a difference between volumes contained within the worn and new bearing and bordered by its inner surface. It was assumed, that the shape of new bearing volume is a sphere of diameter \( D_2 = 22 \) mm. The worn seat volume is a rotated ellipse with two main diameters equal \( D_2 \) and the third main diameter equal the sum \( D_2 + \Delta D_2 \). The \( \Delta D_2 \) is the change of the measured inner diameter due wear process occurring between the ball end of the steel stud and polymer seat. So, the wear of ball end of the steel stud is estimated from the equation (3):

\[
W_{\text{seat}} \approx \frac{4}{3} \cdot \pi \cdot D_2^2 \cdot \Delta D_2
\]

Figure 4. a) The track of the fixed ‘eight’-shape, b) waveforms of vehicle velocity \( v \).
The contact pressure was obtained from the steady state analysis using the FEM model of contact between rotating steel ball stud and its polymer bearing fixed in the steel insert (Figure 4). The network of finite elements was generated automatically by the program. The boundary conditions were following:

- \( C_1 \) - the cylindrical surface of the part the steel insert was fixed.
- \( C_2 \) - the top surface of the ball stud could move only perpendicularly to the axis the stud.
- \( C_3 \) - the conical surface of the ball stood was loaded by the constant horizontal force \( F \).

The network of FE and boundary conditions were presented in the Figure 6.

**Figure 5.** Modified tie rod end with grease nipple.

**Figure 6.** FEM model of contact between rotating steel ball stud 1 and its polyethylene bearing 2 fixed in the steel insert 3.

Averaged pressure was calculated from the equation (4):

\[
p_a = \frac{1}{M} \sum_{e=1}^{M} p_e
\]

where:

- \( p_e \) – contact pressure on the \( e \)-th contact element,
- \( M \) – number of contact elements loaded by contact pressure (based on status number: 1 – in contact, 0 – not in contact, assigned to each contact element after solution convergence).

The horizontal force \( F \) loading the ball stud was estimated using measurement by dynamometer positioned as in the Figure 7.
2.4. The scheme of cornering
To estimate the average sliding speed of ball stud against the polyethylene bearing, the scheme of cornering was assumed. During first one fifth of the turn length \( l_{\text{max}} \) the driver turned the steered wheels to the needed value of angle, namely \( \alpha_{\text{max}} \). The next three-fifths of the turn length he kept the steered wheels with such needed value. During last one fifth of the turn length the driver turned the steered wheels back to the initial positions. Such algorithm was illustrated in the Figure 8.

The time \( t_{\text{corn}} \) of cornering can be estimated from the equation (5):

\[
t_{\text{corn}} \approx \frac{l_{\text{max}}}{v_{\text{aver}}} = \frac{\alpha_{\text{max}} \cdot R}{v_{\text{aver}}} \quad (5)
\]

The time of turning the steered wheel forward and back is equal \( 0.4 \cdot t_{\text{corn}} \).

The average sliding speed \( v_b \) of ball stud relative to the polyethylene bearing is estimated from the equation (6):

\[
v_b = \frac{2 \alpha_{\text{max}} \cdot D_1}{0.4 \cdot t_{\text{corn}}} \quad (6)
\]

Figure 7. The measurement of horizontal force \( F \) loading the ball stud. a) spring sensor, b) measuring unit.

Figure 8. The scheme of cornering.
3. Results and discussion

The contact pressure distribution in the polymer bearing obtained from the FEM model of contact between the ball stood and its bearing was presented in the Figure 9. Average value was of 1.6 MPa and maximal about 4.6 MPa.

The values of the volume wear \( W \) for the polymer bearing and calculated corresponding values of parameter \( k \) is equal 48 mm\(^3\) for \( \text{ZrO}_2 \) and 32 mm\(^3\) for \( \text{TiO}_2 \) were shown in the Table 1. It was observed, that the addition of 1%wt both the \( \text{ZrO}_2 \) and \( \text{TiO}_2 \) into the pure lithium grease can decrease twice the volume wear in contact between the steel ball of stud and its polyethylene bearing in the test conditions. It was in agreement with the report given in [17] for the \( \text{TiO}_2 \) nanoparticles and also with the report given in [18] for the \( \text{ZrO}_2 \) nanoparticles, although the amount of \( \text{ZrO}_2 \) in the lithium grease was twice lower, than for the present study.

![Figure 9. Contact pressure distribution in the polyethylene bearing.](image)

| Grease         | Volume wear \( W \) [mm\(^3\)] | Parameter \( k \) [1/MPa\(^2\)] |
|---------------|---------------------------------|---------------------------------|
| Lithium       | 1.143                           | 0.285                           |
| Lithium + 1%wt \( \text{TiO}_2 \) | 1.143                           | 0.285                           |
| Lithium + 1%wt \( \text{ZrO}_2 \) | 2.571                           | 0.109                           |

The friction coefficient against force \( F \) loading contact zone between the steel ball mating with the polyethylene inner sphere is presented in the Figure 10. The values of the friction coefficient in contact between steel ball and polyethylene inner sphere nonlinearly decreased with the increase of the force \( F \) loading contact zone for investigated lubrication cases: with pure lithium grease, lithium grease with the addition of 1%wt \( \text{ZrO}_2 \) nanoparticles and lithium grease with the addition of 1%wt \( \text{TiO}_2 \) nanoparticles. The decrease is the highest for addition of 1%wt of \( \text{ZrO}_2 \). It was also in agreement with results reported in [17] for the \( \text{TiO}_2 \) nanoparticles and also with those reported in [18] for the \( \text{ZrO}_2 \) nanoparticles, although the amount of \( \text{ZrO}_2 \) in the lithium grease was twice lower, than for the present study.
Figure 10. The friction coefficient against force loading contact zone between the steel ball mating with the polyethylene inner sphere for the case of lubrication by: the pure lithium grease, the lithium grease with additive of 1%wt of ZrO$_2$ nanoparticles and the lithium grease with additive of 1%wt TiO$_2$ nanoparticles.

4. Conclusions

1. For all investigated cases of lubrication for components the tie rod end, the coefficient of friction in contact between ball surface of steel stud and inner spherical surface of polyethylene bearing nonlinearly decreased with the increase of the force $F$ loading contact zone.
2. The addition of 1%wt ZrO$_2$ nanoparticles into pure lithium grease decreased the mentioned coefficient of friction by up to 50%, especially for lower values the loading force $F$.
3. The addition of 1%wt TiO$_2$ nanoparticles into the pure lithium grease decreased the mentioned coefficient of friction by up to 20 % in the almost whole range of the loading force $F$ tested.
4. The addition of 1%wt both the ZrO$_2$ and TiO$_2$ into the pure lithium grease decreased twice the volumetric wear occurring in contact between the steel ball of stud and its polyethylene bearing in the test conditions.

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