Lubrication of Plastic Worm Gears

A. Bormuth, J. Zuleeg, C. Schmitz, R. Schmitz, M. Pfadt and H. Meven

Introduction

In the selection of lubricating greases for plastic worm gears, the user needs to know the influence of each grease constituent on the tribological performance in order to choose the appropriate lubricant. In this work, the effect of NLGI class, viscosity, baseoil and thickener type are investigated separately regarding the efficiency and temperature close to the tribo contact. With the help of this contribution the user understands the effect of each parameter and learns about the potentially reachable efficiency and temperature ranges.

Polymers are becoming ever more important in today's industrial applications. Especially in actuators, plastics are increasingly applied and substituting metal/metal contacts with plastic/metal or plastic/plastic contacts. Concerning lubrication of plastic worm gears, one has to take the specific material properties of polymers into account. Concepts and data for lubrication of pure metal worm gears cannot simply be transferred, due to two main causes. On the one hand, polymer and lubricant might interact, which could lead to aging of the polymer and result, for example, in softening, embrittlement, environmental stress cracks, and other material changes. These processes are considered within the field of polymer compatibility, which is discussed in a preceding publication (Ref. 1) and therefore is not part of this contribution. On the other hand, plastics are visco-elastic materials, exhibiting pronounced non-linear temperature dependence of mechanical and tribological properties (Ref. 2). In addition, plastic properties also change with frequency, sliding speed, pressure, humidity, wetting behavior and other parameters. These dependencies have to be considered during the design of a gear. Although some of these parameters are discussed in the literature (Refs. 3–5), comprehensive studies on lubricated plastic worm gears remain scarce. In particular, systematic investigations on the influence of the lubricant on the gear performance are limited or incomplete. In this presentation we focus on grease-lubricated small gears comprised of a steel worm driving a polyamide gear wheel under various loads. Test rig, measurement procedure and the model greases used are described in the next section.

Greases are comprised of three components: baseoil, thickener and additives. The baseoil (if needed, may be a blend of various oils) is fulfilling the basic requirement of each lubricant, resulting in the separation of sliding surfaces by generating a hydrodynamic film. The thickener — usually a soap or a polymer powder — is added to adjust the consistency, thus reducing the flowability of the lubricant and equipping it with the possibility to stay at the place where initially applied. Therefore the thickener often is also called "consistence enhancer" and the consistency of a grease is described by its NLGI number (Ref. 6), which classifies nine different grades, ranging from 000 to 6; i.e. — the higher the number, the firmer the grease. Additives finally are added to ensure specific features; e.g. — corrosion inhibition, reduced aging of the oil or simply color. The greases used in the present study are model greases without additives and are listed in Table 1 at the end of this paper.

The effect of the different grease constituents on the performance of the plastic worm gear is evaluated consecutively. Starting with an inspection of thickener concentration, we switch to baseoil viscosity, then evaluate the effect of baseoil type, and finally examine the influence of thickener type. In the final section we draw conclusions and provide an outlook.

Test Procedure

As described in the previous section, we focus on a small worm gear comprised of a cylindrical steel worm driving a helically toothed gear wheel comprised of polyamide PA66. The worm is driven by an electric engine and the input torque is measured via a torque sensor. The gear wheel is connected to a brake, whereby a sensor on the output shaft is measuring the transmitted torque. The temperature of the worm is measured close to the tribological contact. A constant grease amount corresponding to tooth filling is applied on the gear wheel. The gear is located within a temperature chamber, so

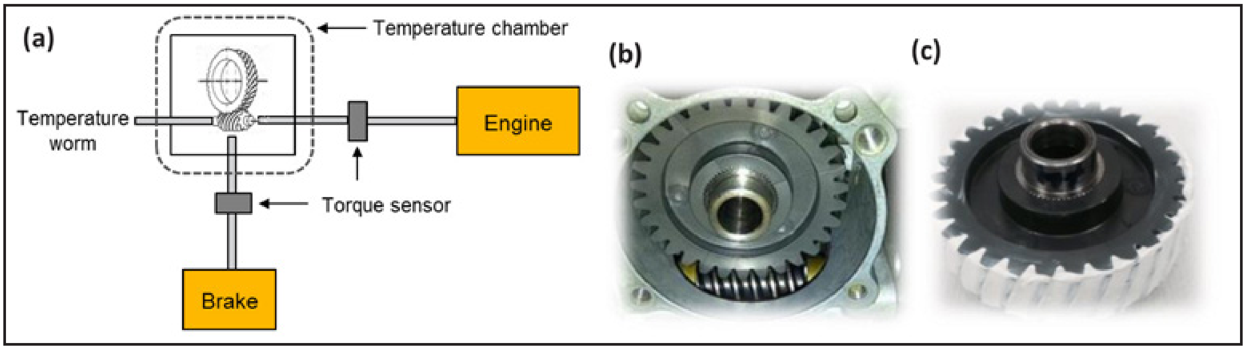

Figure 1 (a) Working principle of the small worm gear test rig used in this contribution. (b) Insight into the tribological contact. (c) Lubricated gear wheel.

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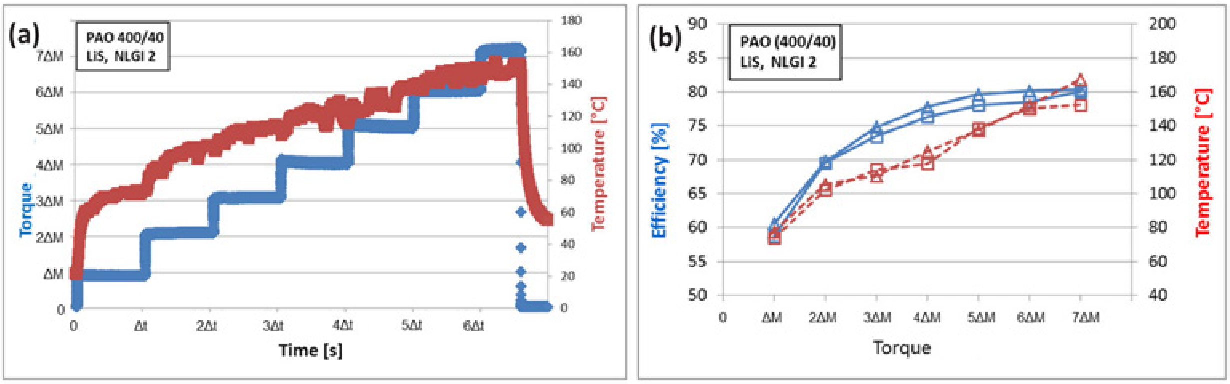

Figure 2 (a) Example of the time-resolved raw data received from the load step test. Torque shown refers to output i.e. on the brake. (b) Result data obtained after time averaging process for two tests with the same grease.

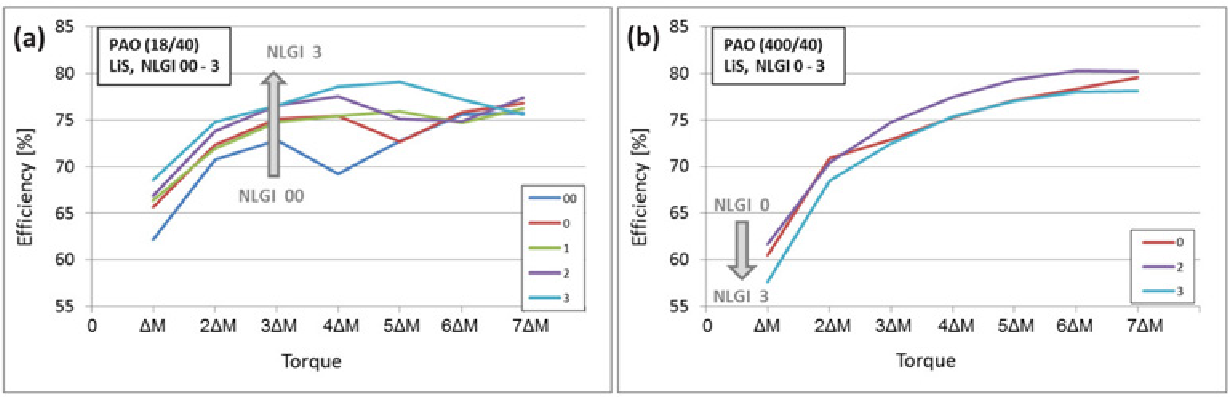

Figure 3 Efficiency as function of the torque for various thickener contents, i.e. NLGI class. Thickener is Li-soap. Baseoil is PAO with (a) low viscosity and (b) high viscosity respectively.

the ambient temperature can be controlled and is fixed to room temperature. Pictures of the test rig, as well as a sketch of the working principle, are presented (Fig. 1).

To investigate the gear performance under constant velocity and various loads, we successively increase the torque in discrete steps ΔM every time periode Δt, as shown (Figure 2(a)). Exploiting Equation 1, we calculate the efficiency η, using the input torque M_{in}, the output torque M_{out} and the gear ratio i.

$$\eta = \frac{M_{in}}{M_{out} \cdot i} \tag{1}$$

The time-resolved raw data is used to calculate the average efficiency for each load step. Regarding the temperature, only the last 10% data points are used to calculate an average final temperature for every load step. The average efficiency and final temperature as a function of the load, i.e. — output torque — are depicted (Fig. 2(b)). One can easily see the efficiency increase for higher loads, which is a result of multiple facts. First, the friction coefficient of visco-elastic materials is decreasing with increasing load, due to a non-linear dependence of the real contact area; for instance, as described by Bartenev et al (Ref. 7). Second, the contribution of losses occurring, for example, within the bearings becomes progressively negligible. Third, the rheological properties of the grease and, in consequence, the lubricating film formation depend on shear stress and temperature c.f. (Refs. 8–9). The temperature measured close to the tribological contact increases monotonically with the torque transmitted, reaching values around 160°C and above at the final load step. Under such severe conditions, the polyamide should be used only temporarily. Investigations of the reproducibility of the method show a statistical error of approximately 1–2% in efficiency, as can be seen when comparing the two identical tests presented (Fig. 2(b)). In the following, we always conduct at least two tests, and consider the average values.

Effect of Thickener Concentration

Consistency is one of the most prominent properties of a grease an user inevitably experiences; for example, while applying the lubricant. Hence, this section aims to elucidate the effect of consistency — meaning concentration of the thickener — on efficiency and temperature. Therefore, we start with a low viscosity PAO (18/40) thickened by a Li-soap (i.e. greases No. 1–5). The NLGI class of the greases used ranges from 00 to 3. Efficiency data is shown (Fig. 3(a)) as a function of the output torque. With increasing consistency (i.e. NLGI class) the efficiency turns out to increase also. This finding we attribute to a synergistic effect of the thickener to the lubricant film formation. Whereas the low viscous baseoil by itself is not capable to fully separate the sliding surfaces, the thickener molecules also contribute to the load carrying capacity of the lubricant.

Now we chose a high viscosity PAO (400/40) as baseoil, whereas the thickener system is kept constant using the Li-soap (i.e. — greases No. 7–9). Corresponding efficiency data is presented (Fig. 3(b)). Here the influence of consistency is less pronounced, and furthermore seems to be contrary to the observation for low viscous PAO greases. The decrease of efficiency with increasing consistency found for the high viscous PAO is easy to understand when assuming that the baseoil by itself is capable of building up a stable lubricating film separating both surfaces. Then the contribution of the thickener to the load carrying capacity is significantly reduced, in addition the internal friction caused by shearing the grease increases the firmer the grease gets.

Comparing efficiency for the low torque regime for the two different PAO-based greases, one finds PAO (18/40) to exhibit higher efficiency values than PAO (400/40). Regarding the high torque regime, the PAO (400/40) greases show better efficiency. This effect is investigated more deeply in the next section. At the end of this section, we regard the temperature close to the tribo-contact shown in Fig. 4. As anticipated from the efficiency curves, the high viscous baseoil greases show a higher temperature than the ones with the low viscous baseoil. In case of high torques the situation is reversed, there the high viscous baseoil greases exhibit lower temperatures. It therefore can be concluded that, depending on the operating conditions 5% (high torque) to 10% (low torque) in efficiency can be gained by choosing the right consistency and baseoil viscosity of the grease. Furthermore temperature can be reduced at least by 20°C, permitting an extended operation under high loads.

Effect of Baseoil Viscosity

In this section we investigate the influence of baseoil viscosity more deeply than in the previous section. Therefore we focus on Li-soap thickened PAO based greases with NLGI 2 (i.e. — greases No. 4, 6, 8). In Figure 5(a), efficiency values of the corresponding greases are depicted. It clearly can be seen that for low torques, efficiency decreases with increasing baseoil viscosity. Starting from η ~ 67% for PAO (18/40) efficiency declines to η 59% for PAO (400/40). We ascribe this observation to rising internal friction within the lubricating film. Inspecting the load dependence of efficiency, we now regard the high torque regime. Here we find a reversed order compared to the low torque regime. In detail PAO (18/40) exhibits η ~ 75%, whereby PAO (400/40) shows η ~ 80%. In case of high loads the lubricating film is assumed to break down for the low viscous oil, for example efficiency starts to break down around 4 ΔM. The high viscous oil is able to maintain a stable lubricating film, capable of separating the sliding surfaces for all loads inspected; thus no drop or kink in efficiency is observed.

Since dissipation leads to heat generation, the discussed behavior of efficiency reflects fairly well in the temperature curves shown in Fig. 5(b). Attention here has to be focused on the high torque regime, since there temperature is reaching up to 180°C for the low viscous oil; hence the system should run only temporarily under such severe conditions.

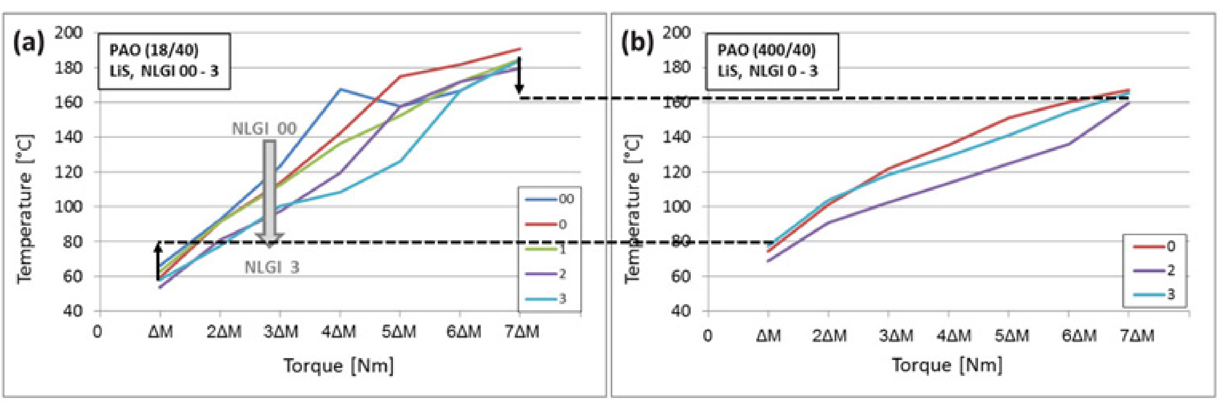

Figure 4 Temperature as function of the torque for various thickener contents, i.e. NLGI class. Thickener is Li-soap. Baseoil is PAO with (a) low viscosity and (b) high viscosity, respectively.

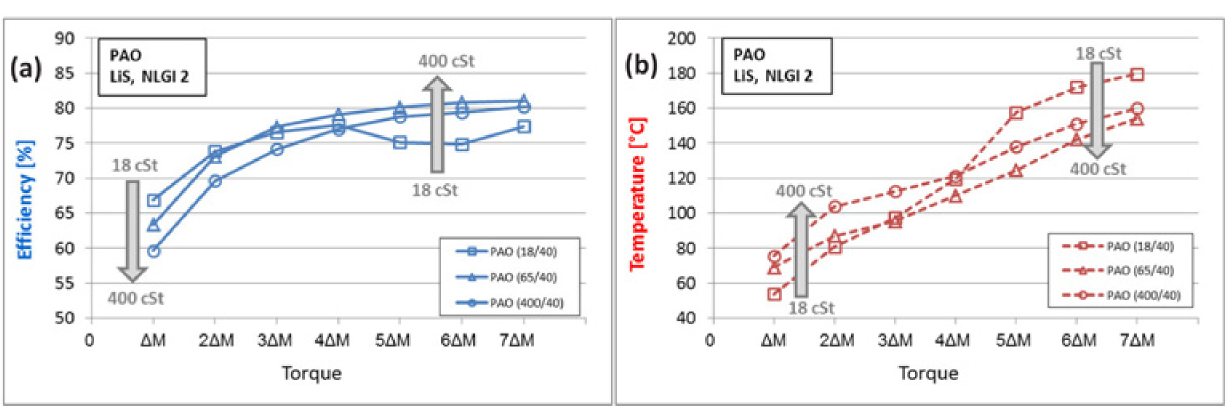

Figure 5 Data for (a) Efficiency and (b) Temperature as a function of the torque for PAO greases with various baseoil viscosity. All three greases are Li-soaps with NLGI 2.

Effect of Baseoil Type

There is a broad variety of different molecules available to be used as baseoils. Chemically, most of these can be grouped into polyalphaolefins PAO, polyalkylene glycols PAG, mineral oils and esters. Within this section, we investigate the influence of the mentioned baseoil chemistry on the gear performance. Therefore, we select Li-soaps with NLGI 2 (i.e. — greases No.4, 6, 8, 10, 11–13). The corresponding efficiency data are given (Fig. 6). The behavior of the three PAO based greases were already discussed in the previous section; so we will not discuss the viscosity dependence of the polyalphaolefins again, as data are plotted for completeness.

At vast overview, efficiency turns out to be more sensitive to baseoil chemistry in the low-torque region than in the high-torque limit. Comparing the low viscous PAO (18/40) to the low viscous PAG (30/40), for small loads both perform almost similarly. For high loads, the PAG turns out to maintain its lubrication capability, whereby the PAO drops down. Furthermore, if one regards the two different polyalkylene glycols PAG (30/40) and PAG (360/40), the former shows superior performance for low torques, while exhibiting identical efficiency values for high loads. Finally, the ester (73/40) stands out, showing high efficiency over the whole torque spectrum.

At the end of this section we clearly want to point out that the selection of a baseoil cannot be made on the basis of tribological data alone. Moreover, polymer/lubricant compatibility (Ref. 1) and thermal stability of the oils (and mostly many other requirements) must be considered. Mineral oils, for example, in many cases are ruled out due to their low thermal stability.

Effect of Thickener Type

The goal of thickeners is to give the lubricating oil the feature to stay at the applied place by reducing its flowability. In most cases, soaps are used, but there are also other possibilities available; e.g. — using a polymer powder. In this section the influence of the thickener system is examined by investigating PAO baseoils thickened with a Li-soap or PTFE power to NLGI 2 (i.e. — greases No. 4,6,8,14–16). Respective data for efficiency and temperature is depicted (Fig. 7). In general we find PTFE greases to exhibit higher efficiency and thus show

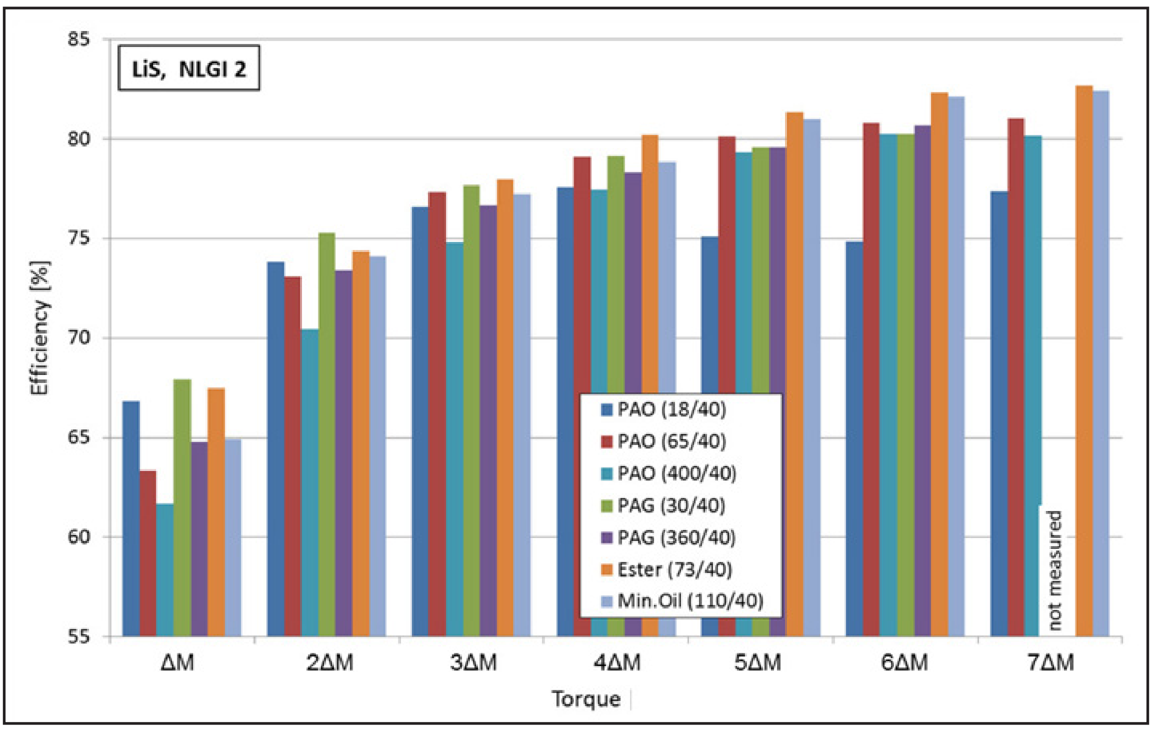

Figure 6 Efficiency as a function of Torque for greases with chemically different baseoils. All greases are Li-soaps with NLGI 2.

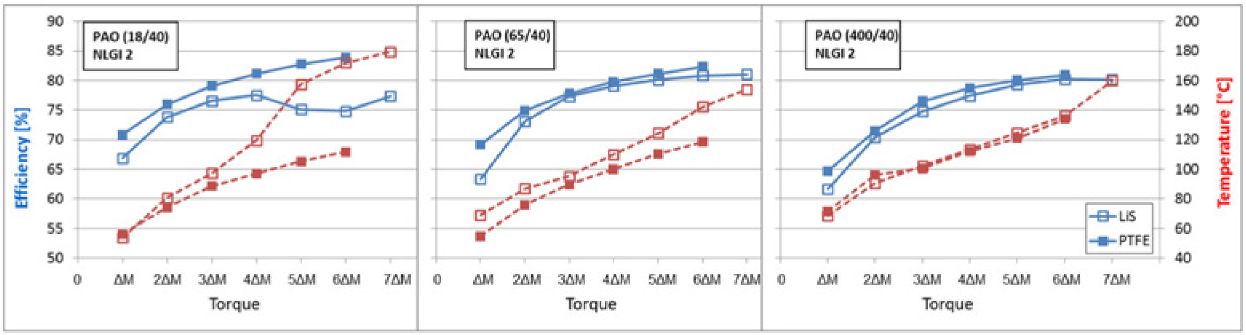

Figure 7 Efficiency and Temperature as a function of Torque for greases with PAO baseoil and NLGI2. As thickener Li-soap (open symbols) and PTFE (closed symbols) are used.

lower temperatures than Li-soaps. This effect becomes more pronounced, the lower the viscosity. For PAO (18/40) no drop in efficiency above 4 Δ*M* is observed anymore; we thus conclude the PTFE to fill in for the collapsed baseoil film at high loads. As a result, temperature is significantly reduced, making the PTFE-enhanced PAO (18/40) useful also for higher loads, and therefore being a multi-purpose grease. This finding is underlined when directly comparing the different viscosity grades within one thickener class as it is done in Figure 8. Within Fig. 8(b) the advantages of the low viscous PAO with PTFE thickener are obvious.

In Figure 9 we finally compare the efficiency data for both thickeners for various baseoil types. The biggest influence of the thickener occurs for PAO, which we already discussed. For the other oil types effects are diminished or negligible, respectively. The PTFE-thickened low viscous PAO shows very high efficiency for all load steps, outrunning the up to now superior ester-based grease. This fact is an example for the interdependence of different grease constituents and demonstrates well the complexity of grease development.

Conclusion and Outlook

In this contribution the effect of various grease constituents on efficiency and temperature in small plastic gears comprised of a steel worm and PA66 gear wheel is elucidated. Conducting load step tests, the efficiency and temperature close to the tribo-contact are evaluated for a broad variety of model greases. Investigating different NLGI classes, it turns out that for greases with low viscous baseoils, efficiency increases with NLGI class. For high viscous baseoils the opposite behavior is found; moreover, the dependence on consistency seems to be less pronounced. The effect of baseoil

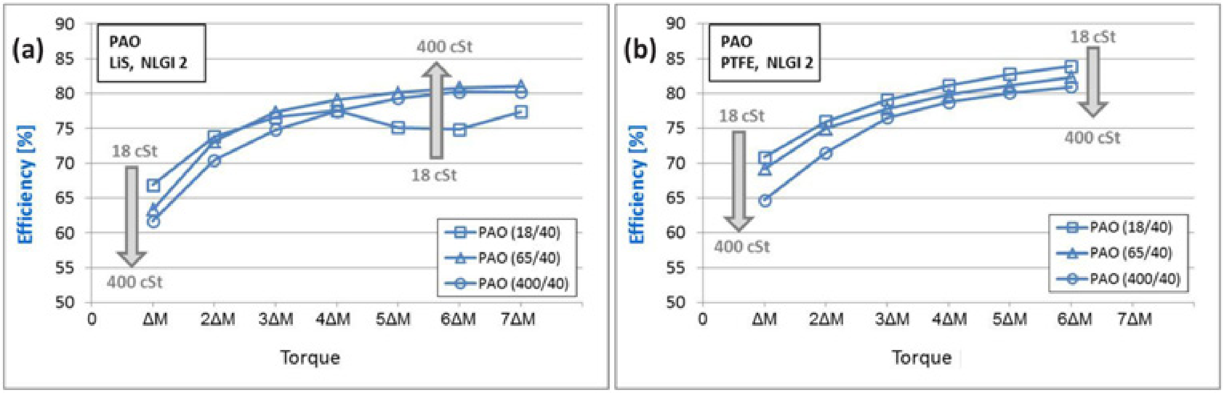

Figure 8 **Efficiency as a function of Torque for (a) Li-soaps and (b) PTFE pastes. All greases exhibit NLGI 2 and are comprised of PAO baseoils with viscosity 18- 400cSt.**

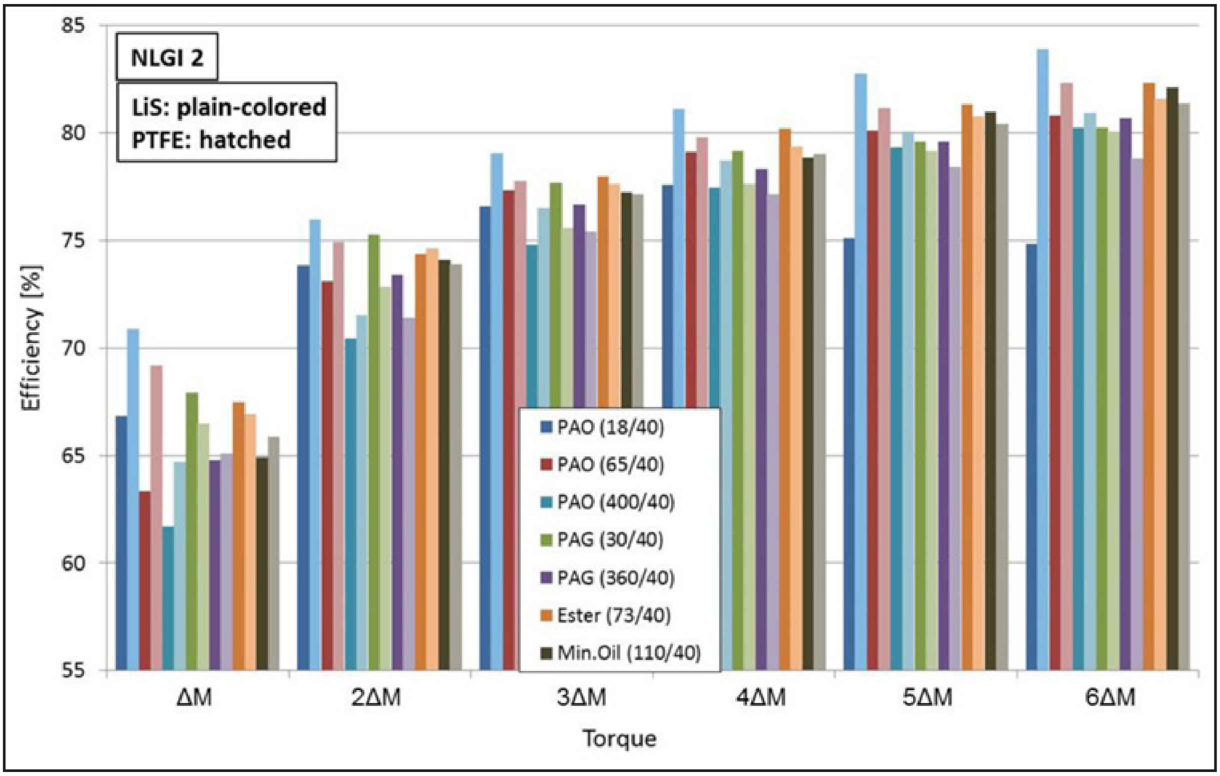

Figure 9 **Efficiency as a function of Torque for greases with chemically different baseoils. All greases exhibit NLGI 2. Thickener is Li-soap (plain-colored) and PTFE (hatched).**

Table 1 List of greases used in this contribution; oil viscosity refers to T = 40°C.

Serial Number	Baseoil		Thickener	
	Type	Viscosity [cSt]	Type	NLGI
1	PAO	18	Li-soap	00
2	PAO	18	Li-soap	0
3	PAO	18	Li-soap	1
4	PAO	18	Li-soap	2
5	PAO	18	Li-soap	3
6	PAO	65	Li-soap	2
7	PAO	400	Li-soap	0
8	PAO	400	Li-soap	2
9	PAO	400	Li-soap	3
10	Mineral Oil	110	Li-soap	2
11	PAG	30	Li-soap	2
12	PAG	360	Li-soap	2
13	Ester	73	Li-soap	2
14	PAO	18	PTFE	2
15	PAO	65	PTFE	2
16	PAO	400	PTFE	2
17	Mineral Oil	110	PTFE	2
18	PAG	30	PTFE	2
19	PAG	360	PTFE	2
20	Ester	73	PTFE	2

viscosity depends on the load. For low loads one finds low viscous baseoil greases to exhibit higher efficiency than greases with high viscous oils, which is attributed to internal friction caused by shearing the lubricating film. In case of high loads, ranking is reversed, meaning the low viscous baseoil leads to low efficiency. This is explained through a collapse of the lubricating film. Variation of baseoil chemistry reveals that for low loads polyalkylene glycols lead to higher efficiency values than polyalpha olefins, while they are almost similar for high loads. The ester oil stands out by showing high efficiency over the whole load range. Finally, the type of thickener is inspected. For PAO-based greases PTFE shows a significant increase in efficiency compared to Li-soap. This effect is more pronounced the lower the baseoil viscosity, hence we assume the PTFE to fill in for the collapsed oil film — especially at high loads. This makes the PTFE-thickened, low- viscous PAO to the superior lubricant under the greases investigated. For the other oil types effects of PTFE are diminished.

Future work will focus on the effect of additives. In addition the scope of operating conditions will be extended to different rotation speeds and temperatures. Finally the distribution of grease within the gear — especially the adhesion to the worm and gear wheel — will be inspected. **PTE**

For more information. Questions or comments regarding this paper? Contact A. Bormuth at: *Andre.Bormuth@klueber.com.*

References

1. Robert, J. Lubrication of thermoplastic materials," Journal of Synthetic Lubrication 23 (4), 2006, pp. 153–166.
2. Sinha, S. K. Polymer Tribology, Imperial College Press 2009.
3. Ehrenstein, G. W. Maschinenelemente aus Kunststoffen, 'Konstruktion' series. Dusseldorf: Springer VDI Verlag 2005.
4. Barton, P. Tragfahigkeit von Schraubrad-und Schneckengetrieben der Werkstoffpaarung Stahi/Kunststoff. Ruhr-Universitat Bochum Diss. 2000.
5. Wassermann, J. "Einflussgrollen auf die Tragfahigkeit von Schraubradgetrieben der Werkstoffpaarung Stahi/Kunststoff," Ruhr-Universitat Bochum Diss. 2005.
6. ASTM 217. Standard Test Methods for Cone Penetration of Lubricating Grease.
7. Bartenev, G. M. *Friction and Wear of Polymers*, Khimiya Press, Moskau 1972.
8. Mezger, T. G. Das Rheologie Handbuch, Vincentz Network 2012.
9. Stribeck, R. "Die wesentlichen Eigenschaften der Gleit-und Rollenlager," Z. VDI Vol. 46, 1902, pp. 1341–1348

André Bormuth studied physics and chemistry at the TU Darmstadt, Fraunhofer LBF and Center for Smart Interfaces (CSI), focussing on polymers and molecular dynamics simulations. After finishing in 2012 his Dr.rer.nat. degree in physics, he went the following year (2013) to the CSI and finished his B.Sc. in chemistry. That same year he started as Project Leader Polymertribology at Freudenberg Corporate Innovation and switched to Klüber Lubrication München in 2015. Bormuth is currently focused on Group Tribology Fundamentals and Component Analysis for Kluber.

Jan Zuleeg graduated in mechanical engineering focused on production engineering at the University of Erlangen-Nürnberg in 1998. After that he started at Klüber Lubrication München as a tribologist and is now responsible for the development of tribological test methods especially for automotive applications.

Reiner Schmitz studied physics with a focus on surface analytics. After graduation he joined Kodak before moving on to Molykote, where he worked in tribology and subsequently joined Klüber Lubrication. During his more than 20 years at Klüber he worked as product developer for greases. Schmitz focused increasingly on automotive applications — plastic actuators, for example — before his retirement earlier this year.

Christof Schmitz studied chemistry at the RWTH Aachen before completing his doctorate in polymer chemistry at the Leibniz Institute for Interactive Materials. He joined Freudenberg Corporate Innovation in 2008 as project manager and moved to Klüber Lubrication München in 2013. Since 2014 he has worked as a group leader in product development for the automotive industry.

Helmut Meven trained as a skilled chemical worker and completed further training as a technician. Since 1998 he has been working in lubricant development at Klüber Lubrication in various fields (automotive, oils and gears). Since 2013 Meven has been active in training with supporting activities in the laboratory.

Matthias Pfadt, M. Sc., has since 1915 been a manager for Application Engineering at Klüber Lubrication München. He received his master's degree in mechanical engineering from TU München in 2015. He has given presentations at the VDI conference for plastic gears, ATV-SEMAPP for plastic tribology and a keynote speech at the 21st International Colloquium Tribology. Since 2017 Pfadt has been investigating the potential of water containing hydro lubricants for gear applications.

For more information.
Have questions or comments regarding this technical paper? Contact Andre Bormuth at *andre.bormuth@kluber.com.*