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A concept for comparison of new and aged lubricants in transmissions of electric vehicles and a method of oil aging on a test rig

Timo König[1] · Luca Cadau[1] · Lukas Steidle[1] · Didem Cansu Güney[2] · Joachim Albrecht[2] · Katharina Weber[2] · Markus Kley[1]

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Abstract
Currently, the demand for electric vehicles is growing. In order to make them even more environmentally friendly, there is the possibility to replace conventional transmission oils with sustainable alternatives that must have at least the same positive properties. Therefore, the properties of a conventional oil must be determined. In this publication, which is part of a larger project, the properties of conventional oil are measured and evaluated at different stages of aging using suitable measurement methods. A test program is designed and carried out including various laboratory equipment such as a rheometer or a tribometer. The results of the investigation of the conventional oil show that there are differences between new and used conditions, even if these are small, as expected from a professional oil. In addition, a test rig setup with a specified load collective is presented to age oil on a test rig. Based on this, the sustainable oil can be aged, tested, and compared with the conventional lubricant in the further course of the project.

Ein Konzept zum Vergleich von neuen und gealterten Schmierstoffen in Getrieben von Elektrofahrzeugen und eine Methode zur Ölalterung auf einem Prüfstand

Zusammenfassung
Die Nachfrage nach Elektrofahrzeugen wächst stetig. Um diese noch umweltfreundlicher zu machen, besteht die Möglichkeit, herkömmliche Getriebeöle durch nachhaltige Alternativen zu ersetzen, die mindestens die gleichen positiven Eigenschaften haben müssen. Daher müssen die Eigenschaften eines herkömmlichen Öls bestimmt werden. In dieser Veröffentlichung, die Teil eines größeren Projekts ist, werden die Eigenschaften von konventionellem Öl in verschiedenen Alterungsstadien mit geeigneten Messmethoden gemessen und bewertet. Es wird ein Testprogramm entworfen und durchgeführt, das verschiedene Laborgeräte wie ein Rheometer oder ein Tribometer umfasst. Die Ergebnisse der Untersuchung des konventionellen Öls zeigen, dass es Unterschiede zwischen Neu- und Gebrauchtzustand gibt, auch wenn diese, wie von einem professionellen Öl erwartet, gering sind. Darüber hinaus wird ein Prüfstandsaufbau mit einem spezifizierten Lastkollektiv vorgestellt, um das Öl auf einem Prüfstand zu altern. Auf dieser Grundlage kann das nachhaltige Öl im weiteren Verlauf des Projekts gealtert, getestet und mit dem konventionellen Schmierstoff verglichen werden.

✉ Timo König
timo.koenig@hs-aalen.de

1 Institute of Drive Technology Aalen IAA, Aalen University, Aalen, Germany

2 Research Institute for Innovative Surfaces FINO, Aalen University, Aalen, Germany

1 Introduction

Since the industrial revolution, the concentration of CO_2 in the atmosphere has increased particularly rapidly. In the year 2020, for example, road traffic was responsible for a total of 682 Megatons or 29% of European CO_2 emissions. While overall CO_2 emissions in Europe decreased by 35% between 1990 and 2020, the percentage contribution of road traffic to CO_2 emissions increased by 12%. This is primarily due to the increasing volume of traffic and higher number of highly motorized vehicles. [1]

To reduce CO_2 emissions in road traffic, there are two main options: reducing fuel consumption through optimizing the vehicles or using a fuel with a lower carbon content [2]. In addition, electricity generated from renewable energy sources has a favorable CO_2 balance.

Therefore, it makes sense to increase the use of electric vehicles in road traffic. The rising demand for battery electric vehicles (BEVs) has transformed the automotive industry in recent years. Many vehicle components need to be revised or newly developed to fulfill the new requirements of BEVs. For instance, the typical map of an electric machine requires different transmission designs compared to a combustion engine drive. In normal BEVs, mainly single-speed transmissions are used to reduce high speeds [3, 4].

Only more powerful vehicles, such as sports cars or trucks, usually have multi-speed transmissions [4–6]. In addition, the powertrain of BEVs requires special lubricants, such as to reduce friction and wear in the transmission [7].

The finiteness of fossil energy resources and the often unavoidable release of lubricants into the environment are increasing the demand for sustainable lubricants [8]. Especially in developing countries, large amounts of oil are released into the environment due to the lack of recycling infrastructure, leading to immense environmental damage [9]. But also in Germany, around $500 * 10^6$kg of lubricants are released into the environment every year [10]. The use of sustainable transmission oils could reduce the resulting damages in the future. These lubricants exhibit a significantly lower environmental impact upon their release, as they are largely biodegradable and non-toxic [11].

Transmission oils generally must have a suitable viscosity, be oxidation-resistant and thermally stable, regardless of their sustainability. High load capacity, demulsibility and corrosion protection are also requirements for such lubricants as well as the coefficient of friction [12].

In addition, they can also perform cooling tasks, which can contribute to further simplifying the electromechanical powertrain. The suitable combination of ingredients in sustainable lubricants can increase the service life of the oil and components, leading to longer maintenance intervals and to an improvement in efficiency [7].

Lubricants used in electromechanical drive systems must meet new requirements, as they can come into contact with electrical components [7]. When an unsuitable lubricant is used, components can be damaged and attacked [13]. Lubricants for electric vehicles (EVs) additionally need to be compatible with copper. They also should be able to withstand high loads from the torque of the electric motor and minimize foaming. These lubricants must also be non-conductive, must be able to dissipate heat from the e-machine, and should have the lowest possible viscosity and friction, which benefits the vehicle's range [14, 15].

In practice, oils are often analyzed in different states to draw conclusions about their aging condition and quality. In advance of this work, a rheometer, a tribometer, and an infrared spectrometer are already used to analyze the viscosity, coefficient of friction and aging of the lubricants [16].

In this publication, selected test samples of the conventional oil in different aging states are examined. Rheological investigations are carried out to analyze the flow, regeneration and time-dependent behavior in the non-destructive range as well as temperature dependency. The composition of the base oil is analyzed by infrared spectroscopy before and after aging. Furthermore, tribological investigations of the friction coefficients are carried out. Laboratory experiments serve as a basis for comparison with which sustainable oil can be evaluated and compared. Due to the desired durability of a lubricating oil, aging in practice is a lengthy process that can take a long time. In particular, commercial lubricating oils exhibit high resistance to aging. To accelerate and control the aging of sustainable oil, an electric vehicle transmission is installed and operated on a test rig. Therefore, this publication presents a test rig concept for the aging of oil in a transmission. As a differentiation from other publications, the aim here is to create a concept for comparing sustainable lubricants with conventional lubricants to ensure that they also have at least the same properties. However, sustainable lubricants are not currently available specifically for electromechanical powertrains, underscoring the significance of this work and research project. In order to use these sustainable oils in transmissions, they must exhibit at least the same or even better properties than conventional lubricants.

2 State of the art

In this publication, a procedure for comparing lubricating oils and a test rig concept for oil aging are described. High torques and speeds as well as shaft currents are among the stress factors that can impact the performance of lubricants in electric vehicles [17]. For this reason, it is imperative to employ special lubricants capable of enduring such conditions in EVs. The lubricants used are predominantly low-viscosity, which increases the efficiency of the transmission by reducing flow losses and improves the heat transfer coefficient for cooling the electric motor. To provide adequate wear protection for the components, despite the low viscosity, specific additives are incorporated [18].

Lubricants generally consist of a base fluid, such as mineral oil or water, and several additives added to the base fluid [10]. Although more than 90% of all lubricant applications can be handled with bio-based lubricants, their use is still limited by higher production costs [11]. The composition of bio-based lubricants is subject to certain regulations. For example, there is a European standard which states that a bio-based lubricant must consist of at least 25% renewable raw materials, be more than 60% biodegradable and not be classified as environmentally hazardous [19]. In practice, synthetic ester-based Trimethylolpropanes (TMPs) are already used as environmentally friendly lubricants, although some difficulties arise [10]. Therefore, Sagraloff et al. are researching water-based lubricants and show that these are suitable for transmissions and have a lower coefficient of friction [10].

This is particularly interesting because reducing friction is considered a key element in vehicles to reduce CO_2 emissions [7]. Due to the good thermal conductivity of water-based lubricants, cooling is also improved, resulting in lower operating temperatures in the transmission. However, the chemical parameters of the components of water-based lubricants must be precisely tailored to the specific application [10].

The research group initially examines a conventional synthetic oil and compares it with a sustainable synthetic ester-based lubricant and a polyalkylene glycol-containing lubricant, both of which are environmentally friendly.

It is well known that the properties of a lubricant deteriorate with increasing operating time. Zeng et al. analyzed the performance degradation of used conventional gear oil and found that the viscosity increased and the microstructure changed. Due to the change in microstructure, the tribological properties and coefficient of friction deteriorate. In addition, the oil oxidizes and becomes acidic with increasing mileage, which significantly degrades the performance of the lubricant [12].

In a paper by Weber et al., the rheological and tribological properties of environmentally friendly lubricants made from different bases are compared with conventional mineral oil-based lubricants. The viscosity and friction coefficient of the lubricants are measured before and after oxidation stress. The results show that some of the sustainable lubricants have the potential to replace mineral oil-based lubricants in the future, making them attractive for use [16].

For oil samples, characteristics such as viscosity, total acid number (TAN), water content, infrared spectrum (IR), elemental composition and air release properties can be evaluated [20]. It is also recommended to measure iron (Fe) concentration [21]. A rotational viscometer can be used to determine viscosity, while a rotational tribometer can be used to measure the friction coefficient [12]. The present functional groups can be analyzed using fourier-transform infrared spectroscopy (FTIR) [12].

Dewangan et al. determine the fluid properties using a rheometer and viscometer, while FTIR spectroscopy is used to assess the lubricant contamination [22]. Mezger describes the theory of rheology and provides instructions for determining flow behavior, temperature behavior, performing the jump test and frequency test using a rheometer [23]. This can also be applied to the analysis of EV lubricants. Zeng et al. discover that viscosity increases with aging as well as the tribological friction coefficient also increases in used oils [12]. Weber et al., on the other hand, find that the viscosity of sustainable oils increases with aging and the friction coefficient decreases with aging [8]. Dewangan et al. also discover that temperature and shear are the main causes of aging in conventional oil [22]. Oil contamination increases with use, viscosity decreases with increasing shear rate [22]. In another publication, Aguilar-Rosas et al. investigate the impact of electrical current on tribological and chemical properties of EV fluids [17]. A four-ball tester suitable for the evaluation of EV lubricants is used for the tribological investigations [17].

Bradu et al. specifically address the properties of EV fluids and highlight low oxidation reactions as another important characteristic of these lubricants [24]. The authors emphasize the need for specialized test methods, including copper compatibility testing [24].

Through normal operation of a transmission, changes in the viscosity and additive content as well as the enrichment of acidic substances and insoluble wear debris, occur over time in its lubricant [20, 21]. The aging processes are a consequence of thermal-oxidative stress and shear stress on the lubricant affecting the gears of the transmission [20]. In general, lubricants can age during field or test operation [20]. Oils can also be artificially aged, for which four possibilities are described in the literature [25, 26]. In Uy et al., motor oil is aged in a thermal-oxidative environment [27]. An operating condition corresponding to the equivalent of 5000–6000 miles of heavy use is achieved by stirring the oil for 50 h at 160 °C while blowing in blow-by gas [27].

In Krieger, oil aging is carried out once using a special aging device that can precisely simulate application-related stress on the lubricant. In field trials, a lubricating oil is subjected to stress for 7000 h in a spur transmission of an agitator, 5400 h on average in rear axles of commercial vehicles, 2000 h on a test rig in a passenger car transmission, and 4300 h in another experiment in manual transmissions of commercial vehicles [20].

In Yan et al., for example, 19 oil samples are taken in total over an interval of 35,000 km from the e-axle of a test truck to investigate the lubricant condition, which corresponds to a sample taken every 1840 km. The sampling method can influence the evaluation. The middle of the oil pan is a suitable sampling location for obtaining a representative result [21].

To compare conventional and sustainable lubricants, a concept for testing is necessary to determine the chemical and physical parameters. Furthermore, a method for aging relevant for real applications in electrical drive systems must be established. This paper distinguishes itself by describing a concept for the real-time aging of lubricants in a transmission. Additionally, a comparative concept is outlined to assess the suitability of sustainable lubricants in the electric powertrain by comparing them with conventional counterparts.

3 Oil analysis and results

In this chapter, the test plan for oil analysis, the experimental apparatuses and the experiments themselves are presented. Additionally, some initial results obtained with two Shell Omala S2 220 GX samples are discussed. This is the standard oil according to the manufacturer's specifications for the used transmission [28]. Generally, lower viscosity oils are used in EV transmissions, which is not the case with the transmission used. One sample is in new and the other in used condition. The latter was used during transmission testing and had a running time of approximately 80 h. For this, rheological and tribological investigations as well as FTIR spectroscopy were carried out. Rheology is used to describe and evaluate the deformation and flow behavior of materials [29]. Tribology is the science of wear, friction and lubrication of surfaces [30]. The rheological tests are flow behavior, jump test, frequency test and temperature behavior of the samples. To ensure a valid scientific investigation, all experiments were conducted at least three times for each sample. The experimental plan for the oil analysis is shown in Fig. 1.

For the rheological investigations, a rotational rheometer of type "Physica UDS 200" by Anton Paar Group AG was used, which is depicted in Fig. 2a.

The rotational rheometer can be equipped with various measurement systems, which are represented in the standards ISO 3219-2 [31] and DIN 53019-1 [32]. The geometry of these systems consists of the cone-plate, plate-plate and cylinder-cup measurement systems [29].

For oil investigation, a cone-plate measuring system with integrated Peltier element was used for temperature control.

Fig. 2b shows the geometry of the measurement system. The cone is defined by a radius R (= 25 mm), a cone angle α (= 1°) and the distance a (= 0.05 mm) between the center of the cone and the plate [29].

The sample which was analyzed in the context of the investigation is located between cone and plate of the cone-plate measuring system. Attention must be paid to the correct amount of the medium (see Fig. 2c, d, e). An over- or underfilling of the measuring system leads to erroneous measurement results [29].

Furthermore, rotational and oscillatory measurements are distinguished for various investigations. The tests flow behavior, jump test and temperature behavior are measured rotationally, while amplitude test and frequency test are measured oscillatory. Rotational measurements can be used to determine the viscosity behavior of the medium [29].

A distinction is made between dynamic and kinematic viscosity. The rheometer measures the dynamic viscosity η (Eq. 1) using the shear stress τ and the shear rate $\dot{\gamma}$.

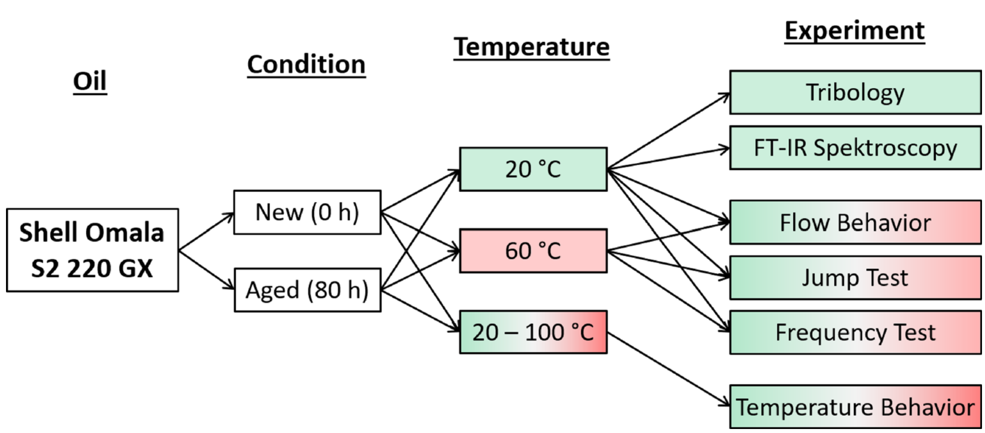
$$\eta = \frac{\tau}{\dot{\gamma}} \tag{1}$$

To determine the kinematic viscosity υ the dynamic viscosity η is divided by the density ρ of the corresponding oil, as shown in Eq. 2.

$$\upsilon = \frac{\eta}{\rho} \tag{2}$$

The flow behavior of the Shell Omala S2 220 GX oil is depicted in Fig. 3. At low temperatures, a higher viscosity η is observed. Furthermore, it is shown that the new oil has a higher viscosity η than the aged oil. At room temperature of 20 °C, the samples show a shear-thinning behavior, as the viscosity η decreases with increasing shear rate $\dot{\gamma}$. However, at operating temperature of 60 °C, the samples behave like an ideal-viscous medium, as the viscosity η remains constant over the shear rate $\dot{\gamma}$.

Fig. 1 Experimental Plan Oil Analysis



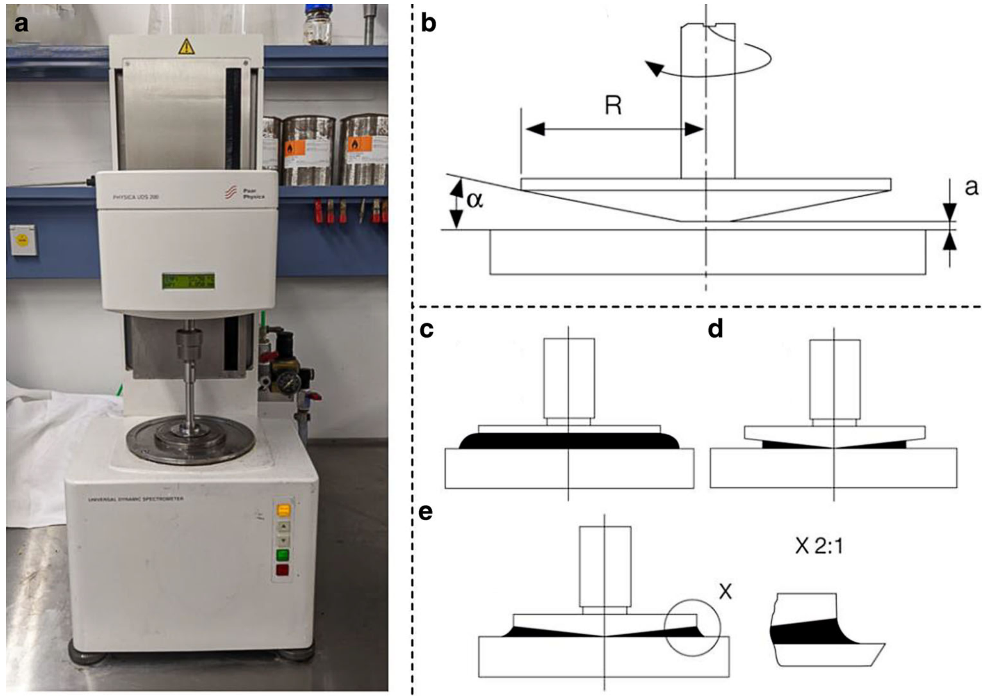


Fig. 2 **a** Rotational Rheometer of type "Physica UDS 200" by Anton Paar Group AG; **b** Geometry Cone-Plate Measurement System [29]; Filling of the Cone-Plate Measurement System: **c** Overfilled, **d** Underfilled, **e** Correct Amount [29]

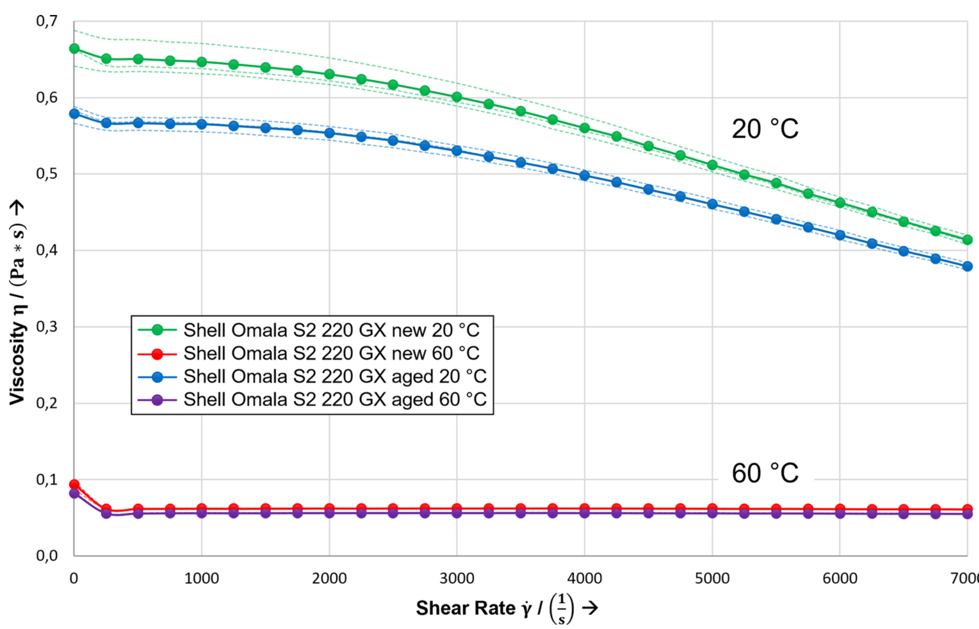


Fig. 3 Flow Behavior

The experiment on temperature behavior was conducted using a constant shear rate $\dot{\gamma}$ of 100 $\frac{1}{s}$, with a temperature gradient of 4 $\frac{°C}{min}$. Fig. 4 shows the viscosity η over temperature T. As can be seen, the viscosity η of the new sample is higher than that of the aged sample and decreases over the temperature range of 20–100 °C. The difference between the two samples is approx. 0.06 Pa s at a temperature of 20 °C and approx. 0.005 Pa s at 60 °C.

To analyze the relationship between viscosity and temperature in more detail, the Ubbelohde-Walther equation according to DIN 51563 was used, which requires the kinematic viscosity values at 40 °C and 100 °C to be calculated in order to plot the Ubbelohde-Walther diagram by Eq. 3 [33, 34].

$$\lg*\lg(v+0.8) = K_v - m*\lg*T \quad (3)$$

v = Numerical value of kinematic viscosity [$mm^2\,s^{-1}$]
K_V = Constant
m = Directional factor/gradient
T = Temperature [K]

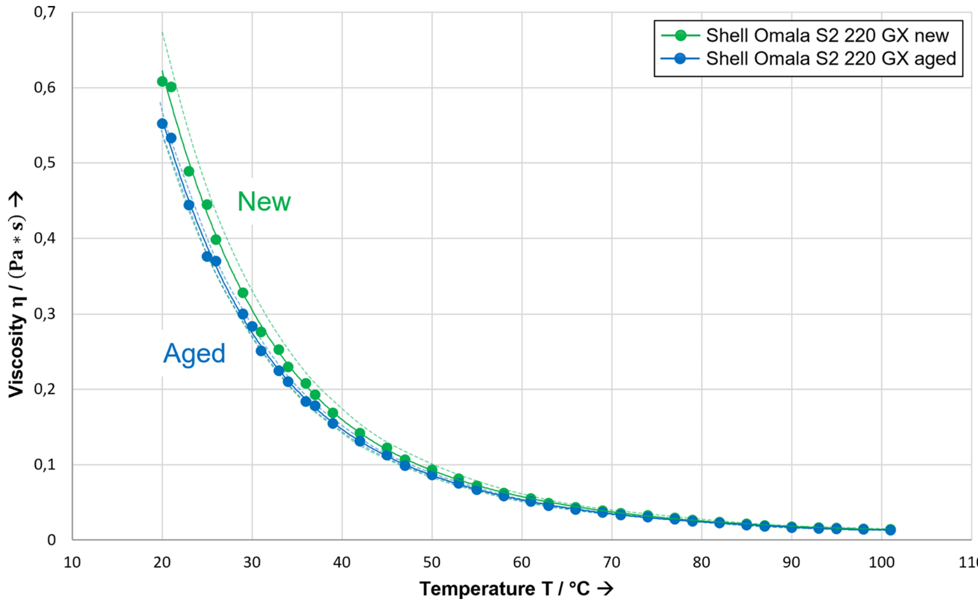


Fig. 4 Temperature Behavior

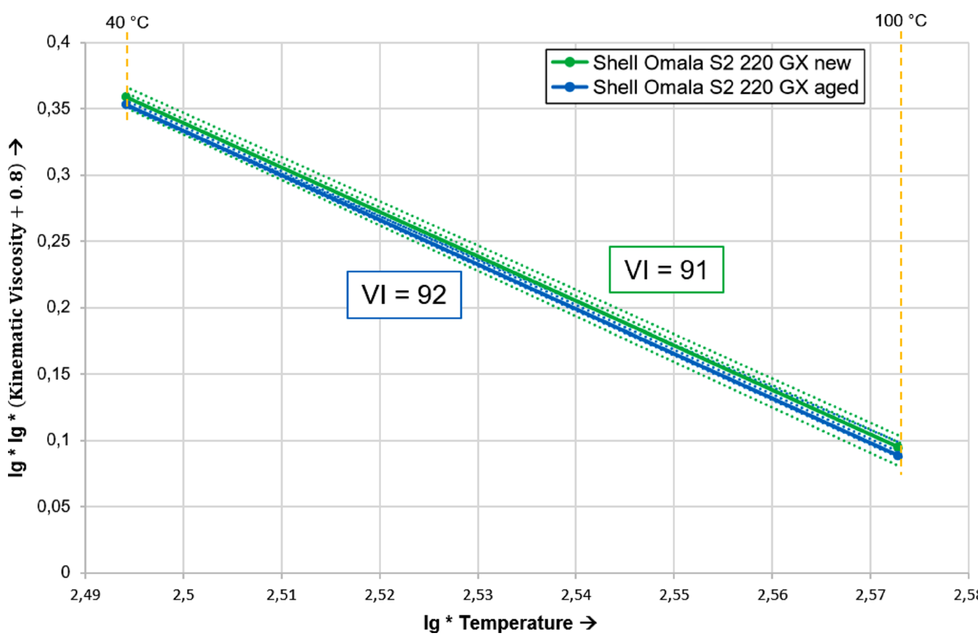


Fig. 5 Viscosity-temperature straight lines of new and aged Shell Omala S2 GX 220 according to Ubbelohde-Walther with their respective viscosity index VI. In *green*: new oil, in *blue*: aged oil

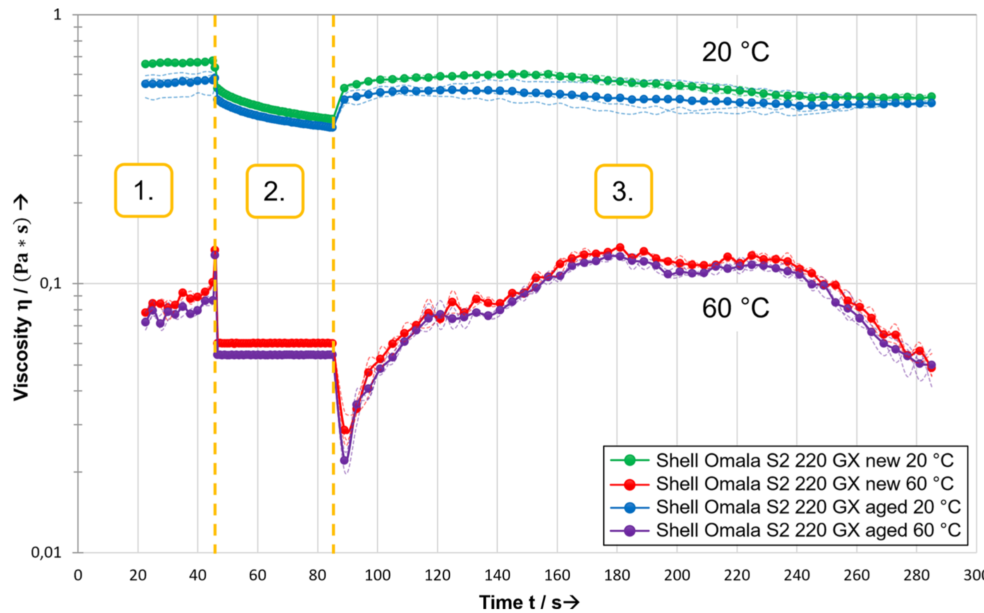
The calculated kinematic viscosities for the new and aged oil are plotted against temperature on a logarithmic axis graph, giving straight lines (see Fig. 5).

The viscosity versus temperature behavior of oils is described by the viscosity index (VI). This parameter allows one to compare the viscosity behavior of oils as a function of temperature. It is calculated according to ISO 2909 [35]. The worst mineral oils are given a VI of 0, while the mineral oils with the best viscosity versus temperature relation are given a VI of 100 or higher.

Fig. 5 shows that the viscosity of both oils decreases with increasing temperature. The higher the slope of the line, the lower the VI value of the corresponding oil. Here the two lines are parallel and have approximately the same VI. By calculation, the new oil has a VI of 91 and the aged oil has a VI of 92. The percentage change is 1.1%. Despite the aging of the oil, the viscosity index remains nearly constant. This shows that the viscosity of Shell Omala S2 GX 220 is stable to aging. For the service life of a transmission, the aging resistance of the oil in terms of viscosity is one of the most important factors.

In Fig. 6 the evaluation of the jump test that examines the regeneration behavior after a strong, sudden shear load is shown. The test is divided into three sections: (1) 0–45 s, (2) 45–85 s and (3) 85–285 s. In sections (1) and (3), the sample is at rest under a shear load of $1\frac{1}{s}$.In section (2),

Fig. 6 Jump Test



the sample is subjected to a sudden, strong shear load of $7000\frac{1}{s}$. In all three sections, the behavior of the viscosity η of the new and aged samples at their respective temperatures is almost identical. At 20 °C, the sample, after the sudden, strong shear load, quickly reaches the value of the viscosity η of section (1) in section (3). At 60 °C, the viscosity η decreases after the sudden, strong shear load and regenerates slowly. This observation can be linked to the results of the frequency test described below.

Prior to the frequency test, an amplitude test was performed for each sample (new and aged) to determine the linear-elastic range. In this range, the structure of the sample is not affected, and both the storage modulus G′ and the loss modulus G″ are constant. The following frequency test takes place in the linear-elastic range.

The frequency test represents an analysis of the behavior of the medium in the non-destructive range. This is an oscillation test in which the angular frequency is increased and the deformation amplitude $\gamma = 20\%$ is kept constant, as this is within the linear-elastic range. In Fig. 7, the storage modulus G′ (solid line) and the loss modulus G″ (dashed line) in *Pa* are shown on the y-axis, and the angular frequency ω in $\frac{1}{s}$ is shown on the x-axis. From the ratio of the two modules, a statement can be made about the consistency of the oil. If G′ > G″ , the oil has a viscoelastic solid (solid state) character with predominantly solid properties. If G″ > G′, the oil has the properties of a viscoelastic liquid (liquid state). Low frequencies describe the oil behavior under slow loading, high frequencies the behavior under rapid loading.

In diagram (a) the measurements are carried out at room temperature 20 °C and in diagram (b) at operating temperature 60 °C. An intersection of the storage modulus G′ and the loss modulus G″ can be seen in both diagrams. At room temperature 20 °C, the intersection is at a frequency of $\sim 100\frac{1}{s}$, at 60 °C at a frequency of $\sim 10\frac{1}{s}$. At 20 °C, G″ > G′ below $100\frac{1}{s}$, the oil is in the liquid state, above this frequency G′ > G″, the oil is in the solid state. With increasing oil temperature, the intersection shifts towards lower circular frequencies. The proportion of the solid state increases with increasing temperature. This explains the slower recovery of the viscosity observed in the jump test as described above.

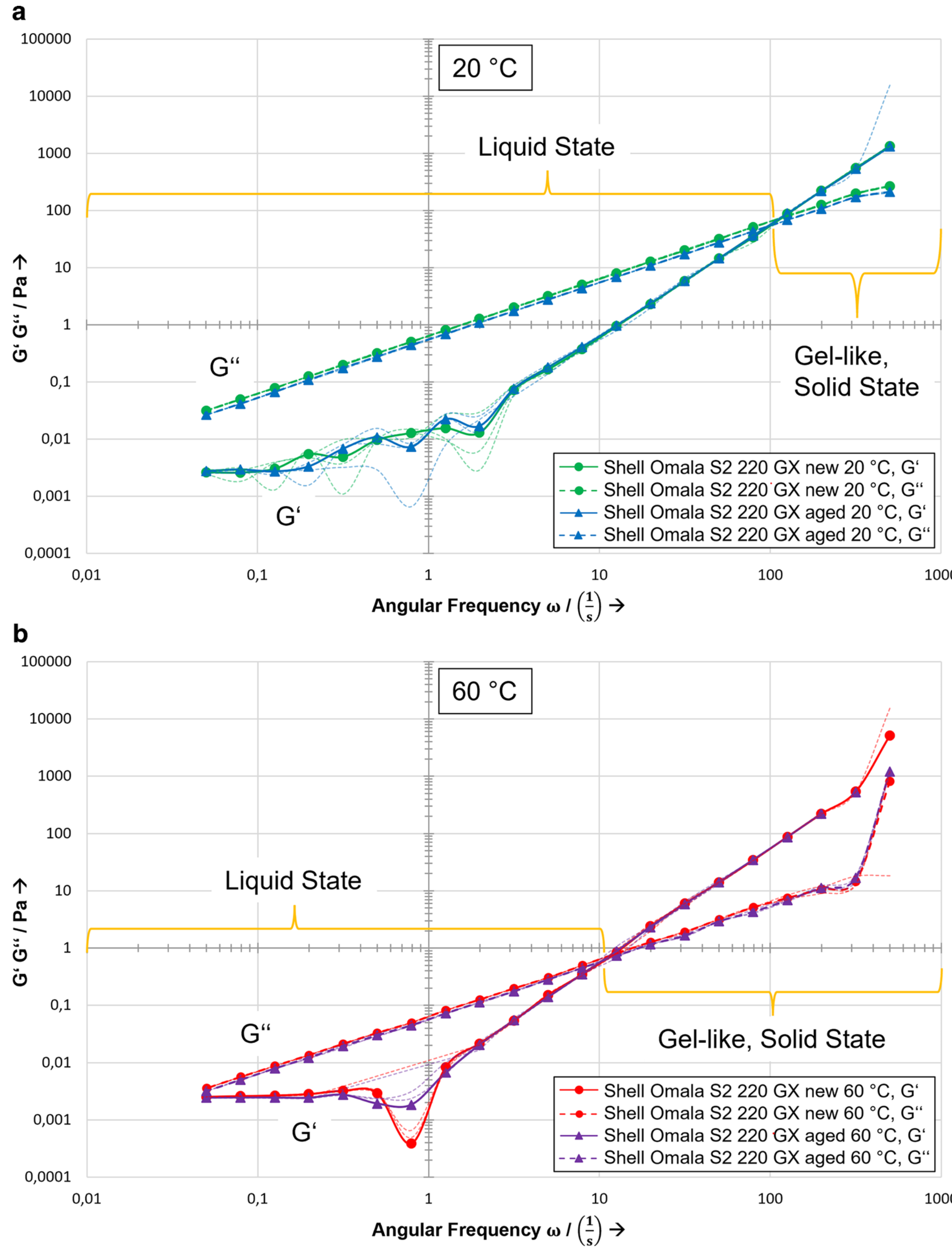
Measurements of FTIR spectroscopy are conducted as a result of the visible color difference between the two samples, making an analysis of the chemical composition meaningful.

FTIR is an advancement of IR which uses an interferometer to analyze all wavelengths and convert them into an IR spectrum via Fourier transform. This enables the identification of organic and inorganic samples through a characteristic “molecular fingerprint” based on the absorption of light in the infrared region of the electromagnetic spectrum of most molecules [36].

The FTIR spectroscopy results show an almost 1 : 1 overlap between the spectra of the new oil and the aged oil. After a running time of 80 *h*, the aged oil shows a visible material change due to the deposited decomposition products. However, these degradation products could not be detected with the IR spectrometer. Therefore, only the chemical composition of the base oil is recorded, which is indistinguishable from the new oil.

Tribology is the scientific study of friction, coefficient of friction, wear, and lubrication requirements [37]. To determine the coefficient of friction μ of the oils, an “SRV 3” series oscillating tribometer from “Optimol Instruments

Fig. 7 Frequency Test: **a** 20 °C, **b** 60 °C



Prüftechnik GmbH” was used. In an oscillation tribometry experiment, a 100Cr6 steel ball is moved under a normal load of F = 50 N on a stainless-steel surface lubricated with 30 µl of oil. The oscillatory motion has a fixed path length of 1 mm and a frequency of f = 20 Hz for a duration of t = 30 min. Fig. 8, depicts the coefficient of friction during the test run. The large values of µ up to t = 200 s refer to the running-in phase that is omitted for the following analysis. After t = 200 s, coefficients of friction of the order of µ = 0.15 are found that are typical for a state of mixed lubrication. Here, the film thickness of the lubricant is smaller than the surface roughness. Both solids are in contact during testing. Under this condition, it is found that the aged oil exhibits an increase in the friction coefficient of about 10% after the running-in period. The higher coefficient of friction leads to a lower efficiency and a higher wear of the machine elements.

4 Concept for test rig trials

The experiments discussed in more detail in Chap. 3 aimed to conduct an extensive analysis of the lubricant. This chapter deals with the powertrain test rig to bring the oil used in the transmission up to operating temperature and to age the oil in the shortest possible time. A two-stage planetary

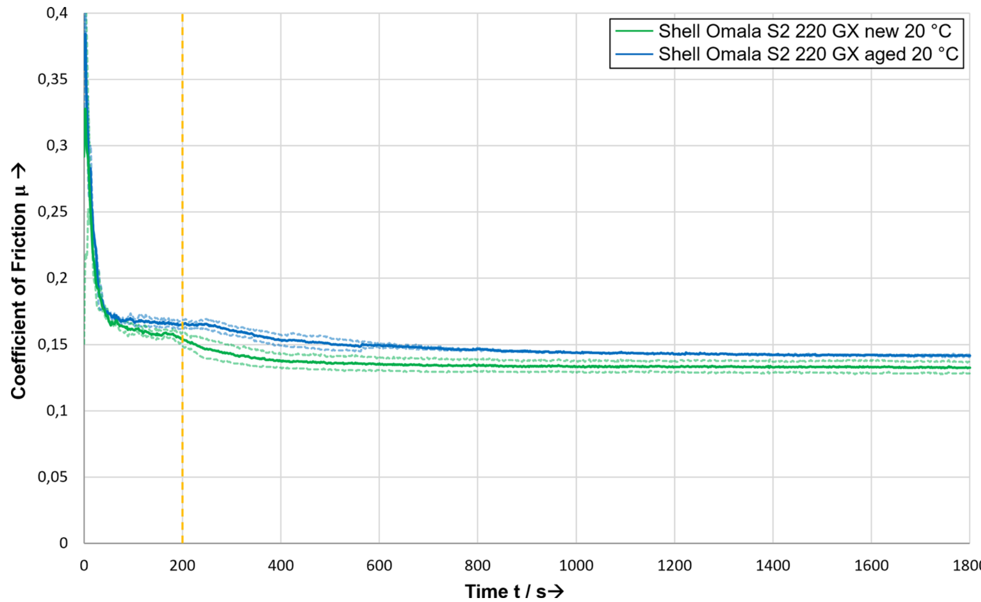


Fig. 8 Measured friction coefficient for new oil (*green*) and aged oil (*blue*) in an oscillation tribometry experiment in the mixed lubricated state. There is a significant increase of the friction coefficient in case of the aged oil after the running-in period

transmission, which is used as a wheel drive in a multifunctional implement carrier and delivers a maximum power of 8 kw, is used as a test specimen. Fig. 9 shows the construction of the transmission on the test rig. The input and output machines are located on the right and left, respectively, with torque measuring shafts to measure the input and output torques. Speed sensors are used to measure the speeds between the machines and the transmission.

To carry out the experiment to achieve the aging of the oil, a load collective is required that reflects actual driving operation. A total of seven load points is defined, which are shown in Fig. 10. Load points with high torques (1–3), high powers (3–5) and high speeds (5–7) are defined. The maximum torques and speeds of the transmission were not reached, as this could affect long-term running capability and safety on the test rig. The load points are randomized, but with a repeating sequence. Each load point is held for 180 s and additional 20 s are defined to take up and drive to the next one [28, 38].

The load points are selected according to real driving behavior, but still with the aim of aging of the oil. As an example, for the vehicle in which the transmission is installed, load points 1 to 4 can be used for work on moderate inclines. This includes mowing, pushing snow or salting. Load points 5 and 6 are for constant driving in areas with for example pedestrians. Load point 7 describes descending with trailing drive line [28].

For the oil application-related evaluation, temperature sensors are attached to the test specimen: one in the oil sump and one on the housing. Furthermore, a vibration sensor is mounted on the housing to detect changes with different oils and different running times [37].

5 Conclusion

This paper develops a method for analyzing conventional and sustainable lubricants. In addition, through application-

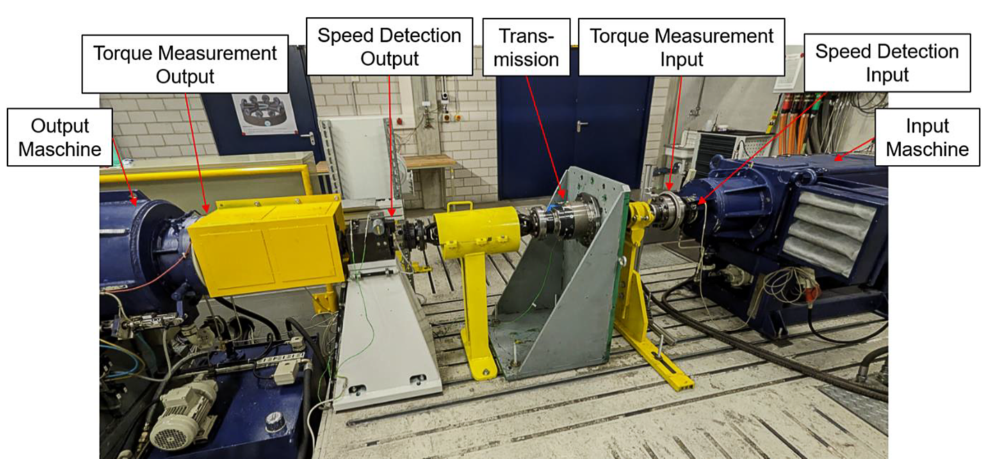


Fig. 9 Construction of the Test Specimen on the Test Rig

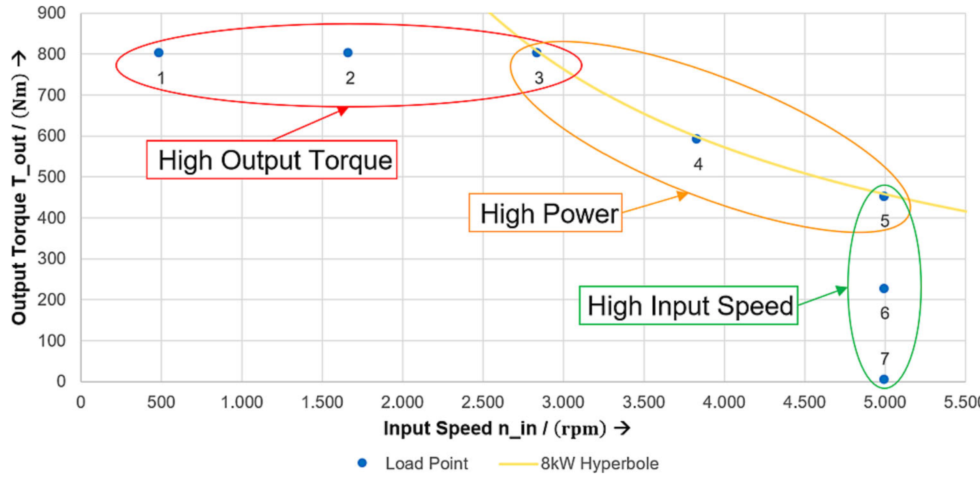


Fig. 10 Load Points in a Diagram with the 8 kW Hyperbole of the Transmission

oriented testing on a powertrain test rig, a concept for oil aging in a transmission is developed. The development of these methods allows the comparison of the performance and aging of conventional and sustainable lubricants, as sustainable lubricants are not currently used in electromechanical drive systems. The demand for sustainable lubricants is increasing due to finite fossil oil resources and the unavoidable release of lubricants into the environment. The oils were analyzed using rheological, tribological and FTIR spectroscopic tests. The rotational rheological tests examined the flow behavior, jump test and temperature behavior of the oils, with an emphasis on viscosity. Oscillatory tests on the rotational rheometer, the frequency test, provided a non-destructive analysis of the behavior of the medium. This allows a statement to be made about the consistency of the oil. In addition, the friction of the medium is analyzed by a tribological test and the chemical composition of the samples by FTIR spectroscopy. Shell Omala S2 220 GX conventional gear oil is used to validate the tests, with samples available in both new and aged (80 h) conditions. The tests were performed at room temperature of 20 °C and operating temperature of 60 °C.

The experimental results show that Shell Omala S2 220 GX oil has higher viscosity η at low temperature and shows a shear thinning behavior at room temperature. The new oil has a higher viscosity than the aged oil. At operating temperature, viscosity remains constant regardless of shear rate $\dot{\gamma}$. The viscosity decreases as the temperature increases from 20–100 °C. Both new and aged samples show similar viscosity behavior after sudden shear, with faster recovery at 20 °C and slower regeneration at 60 °C. FTIR spectroscopy confirms that the chemical composition of the base oil is identical for both samples. The aged oil experiences an increase in the coefficient of friction after the running-in phase, resulting in lower efficiency and increased wear of machine elements. These results provide valuable insights into the flow behavior, temperature sensitivity, regeneration behavior, chemical composition and tribological properties of Shell Omala S2 220 GX oil.

In addition to the oil analysis, a method to age oil in a driveline test rig is presented. The test is designed to simulate real-world driving conditions using a load spectrum with seven defined load points, with a focus on the aging of the oil. To evaluate the performance of the oil in relation to the application, two temperature sensors are installed—one in the oil pan and one on the housing. Also, a vibration sensor is attached to the housing to monitor the change in vibration caused by various oil properties over time.

By applying the proposed technique of oil analysis in combination with the concept of oil aging on a test rig, it becomes possible to evaluate conventional and sustainable lubricants under identical conditions. The knowledge gained has the potential to further advance the field of sustainable lubricants and ultimately initiate a paradigm shift in which conventional lubricants are gradually replaced by their environmentally friendly counterparts. Thus, this method represents a decisive step towards more environmentally friendly lubricant solutions.

In the subsequent stages of the experiment, a meticulously planned and closely monitored process of oil aging is carried out within the transmission. Both a conventional oil and a sustainable oil are used. The oils have a kinematic viscosity of 220 mm^2s^{-1} at a temperature of 40 °C. The sustainable oil is based on a water-soluble, easily biodegradable polyalkylene glycol and an amine phosphate as an additive. The Shell Omala S2 220 GX is currently used as a transmission lubricant. Upon completion of the oil aging process, a comprehensive analysis is performed using the above experimental protocols. These analyses serve as a means to compare and contrast the performance as well as aging characteristics of the conventional and sustainable oils. By examining the results of the tests, valuable knowledge can be gained that will allow a thorough evaluation of the performance and aging characteristics of oils.

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