The effect of aging on friction, wear, and lubrication of diesel engine oil during usage

Author
Philipp Beutler, Thermo Fisher Scientific
Karlsruhe, Germany

Keywords
HAAKE MARS iQ Air Rheometer, Phenom XL, tribology, rheology, engine oils, energy efficiency

Introduction

In 2017, approximately 23 % of the total global energy consumption resulted from tribological contacts with 20 % needed to overcome friction and the remaining 3 % needed to replace parts worn out by wear and wear-related failure.[1] Understanding the underlying friction mechanisms and improving the tribological properties can help increase energy efficiency and reduce carbon emissions as well as wear.

When performing tribological measurements, the experimental approach is different compared to rheological measurements. As rheology is the science of flow and deformation, the bulk properties of a material like viscosity or viscoelasticity are of interest. In contrast to this, tribology focuses on the motion of substrates in relative motion to each other. These so-called tribo-pairs are in close contact with one another, either with or without the presence of a lubricant.

Hence, tribology is the science of friction, wear, and lubrication. As viscosity plays an important role in the lubrication process, monitoring the rheological properties of a lubricant is crucial. Therefore, despite their differences, rheology and tribology are closely linked and cannot be considered separately.

In real-world applications like the friction reduction in internal combustion engines, effective lubrication helps reduce the fuel consumption and hence the carbon emissions of vehicles. However, certain viscosity-modifying additives in engine oils are subject to aging or degradation during usage. Therefore, this application note focuses on quantifying the effect of aging on the rheological as well as tribological properties of a diesel engine oil. To illustrate the resulting wear on the tribo-pairs, scanning electron microscopy (SEM) was used to evaluate wear marks.

Materials and methods

For this study, a Thermo Scientific™ HAAKE™ MARS™ iQ Air Rheometer equipped with electrical upper and lower temperature control modules was used. Counter cooling was provided by a chiller. Figure 1 shows the rheometer setup.

The subject of this investigation was a diesel engine oil characterized as SAE 5W-30 according to the Society of Automotive Engineers (SAE). To quantify the influence of aging and degradation, an engine oil from the original container was compared to the same oil in use for 30,000 km.

The rheological measurements were performed using a 50 mm 1° cone and plate geometry. Prior to starting the measurement routine, a temperature of 100 °C was set. After sample loading and trimming, a measuring gap of 50 µm was set and the temperature was held constant for 120 s to ensure a homogenous temperature distribution within the sample. A steady-state viscosity measurement was conducted in a shear rate $\dot{\gamma}$ range from 1 to 1000 s^{-1}. Figure 2 shows the HAAKE RheoWin™ measurement procedure used for the rheological measurements.

The tribological measurements were performed using a ball on three plates setup as shown in Figure 3.

Figure 1: HAAKE MARS iQ Air Rheometer configuration.

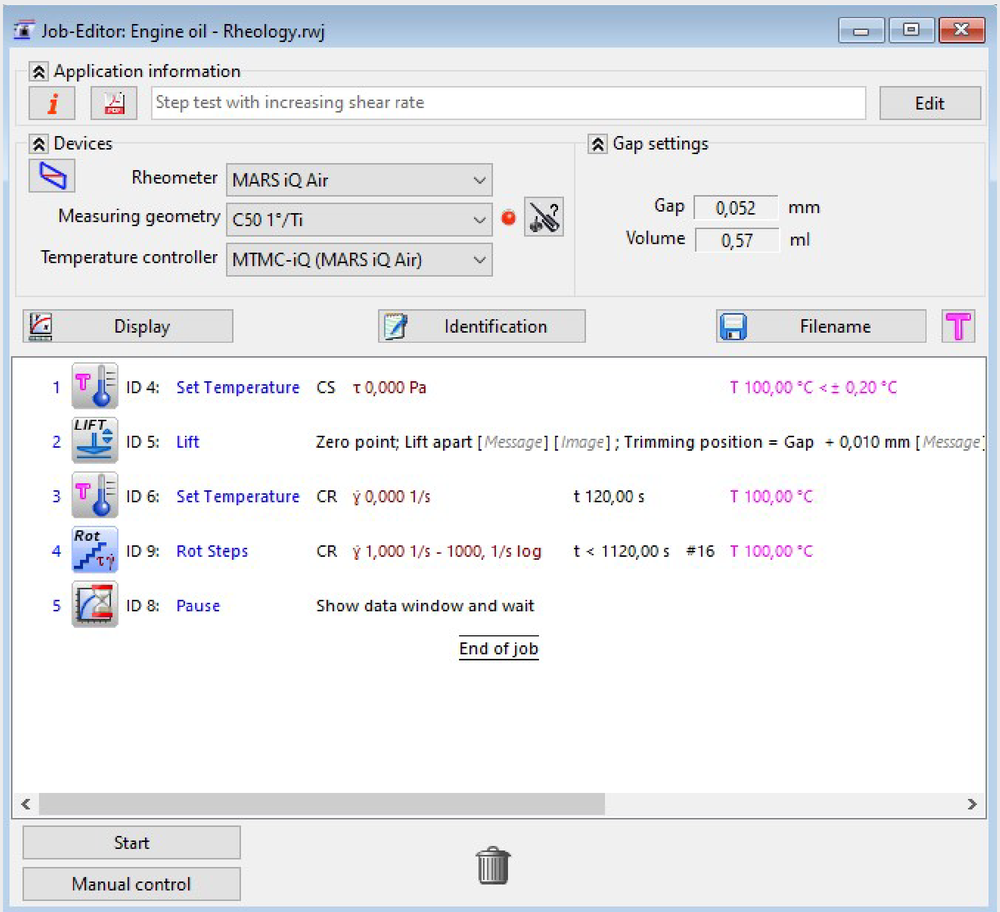

Figure 2: Measurement routine HAAKE RheoWin Software for rheological measurements.

Figure 3: Tribology measuring geometry consisting of a ball on three plates setup.

The tribo-pairs consisted of a stainless-steel ball as well as three stainless-steel plates. The normal force was set to a constant value of 5 N and the sliding velocity of the ball was increased from 0.05 to 300 mm/s to generate complete Stribeck curves. After sufficient preconditioning of the contact surfaces, the 4th measurement run was chosen for evaluation (see below). Figure 4 shows the HAAKE RheoWin Software measurement procedure used for the tribological measurements.

During operation, the surfaces of a tribo-system are subject to wear. In general, tribo-pairs show high initial wear at the beginning of operation.[2] Due to its transient character, this so-called running-in derives from the wear down of microscopic surface asperities by plastic deformation which results in a reduction of friction over time. This phenomenon can usually be observed during the first measurement runs.[3] To obtain reproducible measurement data, it is therefore necessary to perform the same experiment for several runs using the same tribo-pairs while changing the lubricating sample between each run. Once the tribological data does not change significantly anymore and the curves overlay, the end of the running-in period is reached. This is usually the case after 2–3 runs. Figure 5 shows the respective flowchart for guidance.

A Phenom™ XL Benchtop SEM was used to evaluate the wear marks on the surface of the tribo-pairs. All samples were fixed onto aluminum holders with double-sided carbon adhesives. All images were taken at an acceleration voltage of 10 kV.

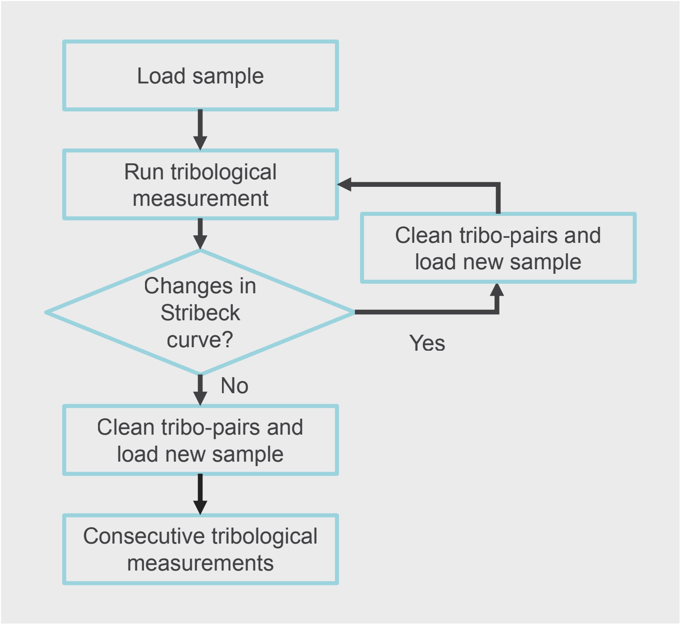

Figure 5: Flowchart for determination of end of running-in.

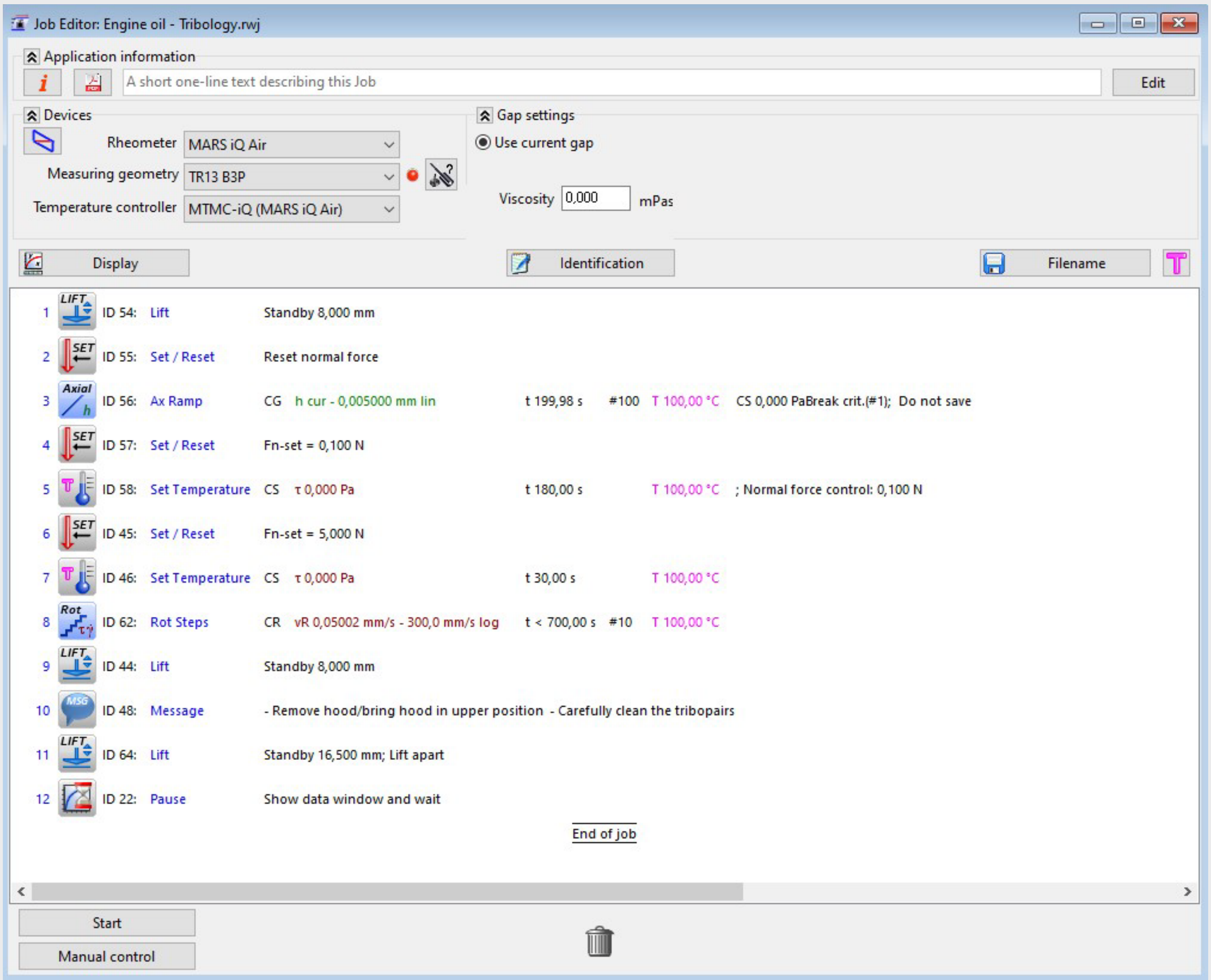

Figure 4: Measurement routine in HAAKE RheoWin Software for tribological measurements.

Results & discussion

Engine oils consist of base oils blended with various additives to improve viscosity, inhibit rust and corrosion, and modify friction as well as wear properties, among other things. The additive content usually ranges up to 25 %. During operation, some oil components are degrading due to the application of load and temperature during the internal combustion process. Due to this degradation, these additives are depleted or decomposed which leads to a change in physical or chemical properties.[4]

Figure 6 shows the viscosity curves of both substances investigated in this study to analyze the impact of usage on their flow properties.

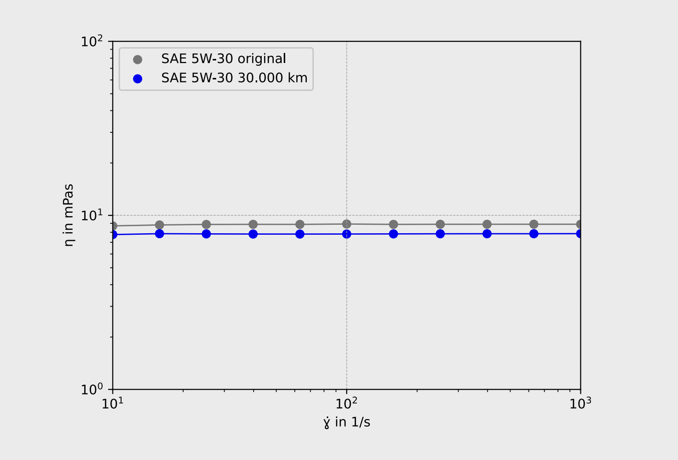

Figure 6: Comparison of viscosity curves of SAE 5W-30 with 0 and after 30.000 km of milage in an internal combustion engine.

As expected from engine oils, both samples show a shear rate independent viscosity, and can therefore be characterized as Newtonian liquids. Besides this, the viscosity changes approx. 14 % from 8.9 mPas for the original sample to 7.8 mPas for the used sample. This decrease in viscosity is most likely related to the degradation of viscosity-improving additives.

Although viscosity is a crucial factor for a lubricant`s performance, it is also important to characterize the actual lubrication properties. For this, tribological measurements on the tribo-system similar to the one in use in the actual application are the experimental test method of choice. In general, a tribo-system can be simplified according to Figure 7.

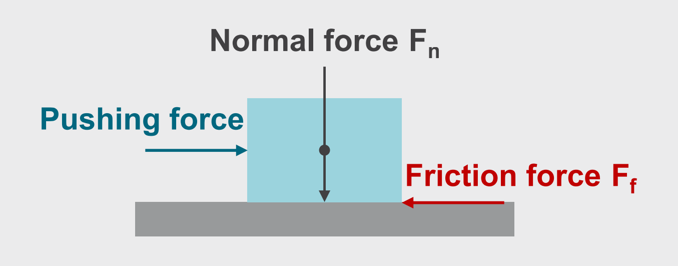

Figure 7: Schematic of a tribo-system.

A body is pressed towards or onto a surface either due to gravitation or an externally applied force. As soon as the body is moved, it will experience a resistance resulting from the friction between the body and the surface. According to this, friction can be quantified by calculating the coefficient of friction (COF) μf according to equation (1).

$$\mu f = \frac{F_f}{F_n} \quad (1)$$

In a tribo-system containing tribo-pairs as well as a lubricant, changes in tribological properties are commonly illustrated in so-called Stribeck curves. At low sliding speeds vR, the tribo-pairs are in direct contact with each other resulting in high friction or a high coefficient of friction. This range is also commonly known as boundary lubrication. With increasing speed, lubricant is dragged between both surfaces due to hydrodynamic forces reducing the contact area and therefore the friction. Hence, the tribo-system leaves the boundary lubrication and enters the mixed lubrication regime. The more liquid is dragged between the tribo-pairs, the larger the gap between them gets. As soon as the lubricant fully separates both tribo-pairs, the friction results only from the internal friction of the lubricant itself, which corresponds to its viscosity. This state is often referred to as a hydrodynamic lubrication regime.

By applying this concept of frictional behavior to the tribo-system steel—engine oil, as presented in this study, the tribological properties of both substances can be identified according to the Stribeck curves presented in Figure 8.

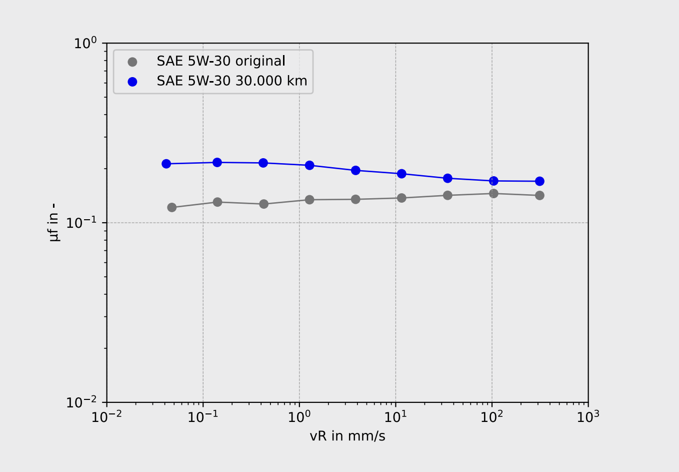

Figure 8: Comparison of Stribeck curves of SAE 5W-30 engine oils with 0 and after 30.000 km of milage in an internal combustion engine.

In contrast to the viscosity curves presented in Figure 6, the tribological behavior of the two screened substances shows a different trend. The original SAE engine oil shows a slight overall increase in friction behavior but in general, the friction does not change much during the entire measurement. According to this observation, despite a little resistance against flow originating from the sheared lubricant, there should be little to no wear present. In contrast to this, the used SAE 5W-30 oil shows a short plateau below a sliding speed of 1 mm/s indicating boundary lubrication before entering a slight mixed lubrication regime. This could be a result of particles like soot or other residuals from decomposed additives present in the engine oil that are increasing the friction at low sliding speeds before they are teared down by the load of the rotating tribology geometry. Additionally, the gap will get larger due to hydrodynamic forces originating from an increasing sliding speed, which also leads to a slight decrease in friction. At high sliding speeds above 100 mm/s the friction behavior appears to be similar to the original oil, but nevertheless shows slightly higher friction coefficients.

The effect of these differences in friction properties on the surfaces of the tribo-pairs can be evaluated optically by means of scanning electron microscopy (Figure 9). The size of the wear marks resulting from the ball of the upper tribology geometry sliding on the lower plates are indicated with a blue circle for the respective lubricants used.

The differences in lubrication are obvious and reflect the results of the tribological experiments. 4 runs with the new SAE 5W-30 resulted in a wear mark with a diameter of about 300 µm, whereas 4 runs with the used engine oil led to a wear mark of about 2000 µm, almost 7 times larger. In conclusion, it is most likely that particles originating from surface abrasion together with soot or decomposed additives could accelerate the wear down of the surface. Besides this, the high friction also results in a higher energy consumption and therefore more carbon dioxide emissions. Hence it is recommended to change the engine oil to prevent the wear down of the engine as well as to increase its efficiency.

Conclusion

In this application report, the effect of aging of a diesel engine oil during usage was evaluated with a rotational rheometer as well as a scanning electron microscope. Due to the degradation of additives, the flow as well as the tribological properties changed dramatically, severely influencing the contact surfaces within an internal combustion engine and hence the lifetime of the engine parts. Together with the obvious mechanical reasons, rheological measurements together with tribological measurements can be useful tools for investigating the lubricating properties of engine oils. These characterization techniques can also help to increase the overall energy efficiency as well as reduce carbon emissions enabling the transition towards more sustainability.

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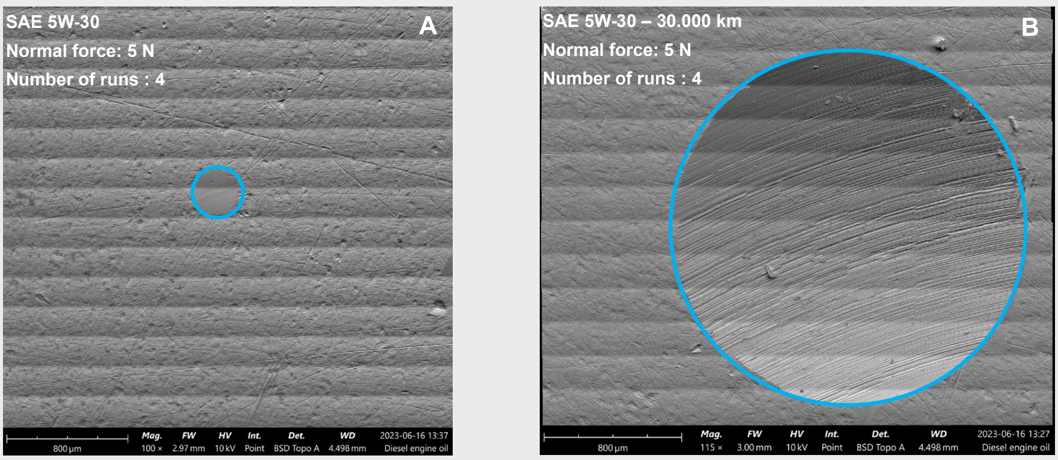

Figure 9: Comparison of SEM pictures of the stainless-steel plate substrates used in the tribological experiments with the SAE 5W-30 engine oils with 0 (A) and after 30.000 km of milage in an internal combustion engine (B) as lubricant.