EFFECT OF MOTOR OIL DEGRADATION AND METALLIC SURFACES' TREATMENT ON THEIR WETTABILITY

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This work examined and showcases the change in wettability of motor oils in relation to their degradation and treatment of the surface they wet. Wettability is a complex scientific discipline which focuses on the interplay of a liquid placed upon a surface, their surrounding atmosphere, their „compatibility", and their properties. Over 485 measurements were done, using the sessile drop method, to further showcase various aspects of wettability.

KEYWORDS

Contact angle, lubrication, motor oil, surface treatment, wettability

1 INTRODUCTION

The condition of a lubricant is a significant factor influencing the reliability and service life of mechanical systems. Oil condition is typically assessed through physicochemical analysis to evaluate lubricant degradation, contamination, and changes in its properties. Measuring the contact angle can offer a simpler approach to investigating changes in lubricant behaviour during operation.

Wettability is the ability of a liquid to adhere to and spread across the surface of a solid [Holub 2010]. It depends on numerous factors, including the properties of both the liquid and the solid, their polarity, surface free energy, and surface roughness [Zhang 2014]. The Wenzel and Cassie-Baxter models describe how wettability can change in response to variations in surface topography [Wang 2020]. Consequently, contact angles, which serve as a measure of how a liquid wets a surface, must be interpreted in the context of the specific liquid-surface combination.

Wettability can be measured relatively simply by determining the contact angle using the sessile drop method, which involves analyzing the profile of a droplet deposited onto a surface under controlled experimental conditions [Ponomar 2022]. This angle is defined as the angle between the plane of the solid surface and a tangent to the droplet's surface at the point of contact. This angle is denoted by the symbol Θ (theta).

The aim of this study was to investigate changes in the contact angles of three engine oils, sampled at various stages of operational use, on four surfaces with different treatments. Attention was also focused on the influence of surface treatment on the magnitude and variability of the measured contact angles. Furthermore, the study evaluates the potential and limitations of contact angle measurement as a supplementary method for assessing changes in the condition of a lubricant.

2 MATERIALS AND METHODS

The experimental investigation focused on the influence of engine oil service history and surface treatment on wettability. Contact angle measurements were performed using the sessile drop method on several metal surfaces and a polished silicon wafer. Engine oil samples collected at various stages of operational use were examined. The following sections describe the oils and surfaces tested, the measurement procedure, and the data processing methods.

2.1 Tested Motor Oils

Three engine oils from different types of internal combustion engines were examined. The first oil, an SAE 15W/50, was taken from the spark-ignition engine of a racing motorcycle, two other oils came from the diesel engines of military vehicles, specifically, an SAE 20W/50 used in a BVP-2 infantry fighting vehicle, and an SAE 15W/40 from a Tatra 810 military truck.

Oil samples were collected at various stages of vehicle operation and identified based on the distance travelled. Samples of unused oil were also included as a reference. Sampling intervals were determined by the operational availability of the vehicles rather than by a predetermined schedule. The distance travelled since the last oil change was determined from vehicle maintenance records and is summarized in Table 1.

For the BVP-2 vehicle, two separate oil samples were collected at the same mileage of 458 km without additional vehicle operation between sampling events. These samples were evaluated separately.

No independent physicochemical analyses such as measurements of viscosity, oxidation, or contamination levels were performed. Consequently, it was not possible to quantify the actual degree of oil degradation. Therefore, the research focused on changes in the contact angle in relation to the specific operational stages from which the samples were taken.

Oil	Vehicle	No. of samples	Range [km]
20W/50	BVP-2	6	0 - 676
15W/40	Tatra 810	4	0 - 2215
15W/50	Racing engine	3	0 - 350

Table 1. Overview of the tested oil samples

2.2 Tested Surfaces

Four surfaces were investigated to evaluate the influence of surface treatment on the wettability of engine oils. Three specimens were prepared from 42CrMo4 steel, while the fourth was a polished silicon wafer. The steel specimens were machined and ground before undergoing different surface treatments.

The first specimen (S1) was untreated ground 42CrMo4 steel, used as a reference engineering surface. The second specimen (S2) was plasma-nitrided 42CrMo4 steel. The third specimen (S3) consisted of TiCN-coated steel modified by laser surface texturing, which produced a regular pattern of micro-dimples. Laser texturing can modify surface wettability by changing surface topography and the interaction between the liquid and solid [HiLase 2026; Ijaola 2020]. The fourth specimen (S4) was a polished silicon wafer, selected as a smooth reference surface.

The investigated surfaces differed in their surface treatment, chemical composition, and topography. Consequently, the measured contact angles reflect the combined influence of these properties rather than surface roughness alone. The surface

roughness of the three steel specimens was measured in our laboratory and evaluated using the arithmetic mean roughness parameter (Ra). The measured values were 0.10 µm for the ground steel, 0.14 µm for the plasma-nitrided steel, and 0.19 µm for the laser-textured TiCN-coated steel. For the polished silicon wafer, a roughness value of 0.0005 µm was provided by the manufacturer; however, the corresponding roughness parameter could not be verified. The roughness values are summarized in Table 2.

Surface ID	Description	Roughness [µm]	Source
S1	Ground 42CrMo4 steel	0.1	Measured
S2	Plasma nitrided	0.14	Measured
S3	TiCN-coated laser-texture (micro dimple pattern)	0.19	Measured
S4	Polished silicon wafer	0.0005	Manu-facturer

Table 2. Overview of the tested surface samples

2.3 Contact Angle Measurement

Wettability was evaluated using the sessile drop method. Measurements were performed using an experimental workstation equipped with a digital camera (1920 × 1080 pixels) and a backlight positioned behind the specimen. The camera and specimen were aligned to obtain a clear side-view image of the droplet profile. The contact angles were evaluated from the recorded droplet images using the freely available ImageJ software with the Wettability plugin.

Before testing, the oil samples were homogenized. A fresh droplet with a nominal volume of 0.5 µL was deposited onto the specimen using a micropipette. The droplet profile was recorded approximately 30 s after deposition to allow the droplet to spread and stabilize. The contact angle was then determined from the recorded image.

For each oil sample–surface combination, repeated measurements were performed using newly deposited droplets. Between successive droplet measurements, the specimens were cleaned in an ultrasonic bath containing acetone to remove residual oil. The specimens were subsequently dried in a vacuum drying oven before the next droplet was deposited. Each measurement therefore represented a separate droplet, while the oil sample and surface type remained unchanged.

On the polished silicon wafer, some oil samples spread extensively, preventing reliable determination of the contact angle. These measurements were classified as not measurable (NM).

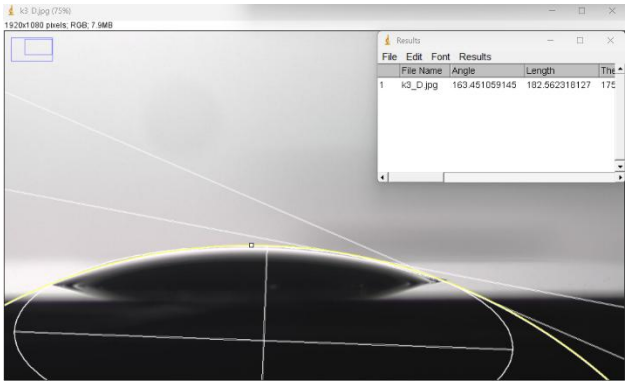


Figure 1. Contact angle evaluation in the ImageJ software

2.4 Data Evaluation

Approximately 485 valid contact angle measurements were obtained for the investigated oil sample–surface combinations. Depending on the combination, 6–12 individual droplets were evaluated. Measurements for which the contact angle could not be reliably determined were excluded from the numerical analysis and classified as not measurable (NM).

For each oil sample–surface combination, the arithmetic mean contact angle and sample standard deviation were calculated from the valid individual measurements. The uncertainty of the estimated mean was expressed using a two-sided 95% confidence interval based on Student's t-distribution.

The results were presented graphically as individual contact angle measurements together with the corresponding group means and 95% confidence intervals. A small horizontal displacement was applied to individual data points to improve their visibility; this displacement had no physical or statistical meaning.

The analysis was primarily descriptive. Individual droplets represented repeated measurements of the same oil sample on a given surface, rather than independent samples obtained from different vehicles or oil changes. Consequently, the observed differences were interpreted as differences between the tested samples, without assuming that they demonstrated a statistically established effect of lubricant degradation.

3 RESULTS

The measured contact angles are presented separately for each tested surface. The graphs show individual measurements (blue points), mean values (red points) and their 95% confidence intervals.
The horizontal axis represents the distance travelled since the last oil change. Each group of points corresponds to one oil sample collected at a given mileage. The individual blue points were slightly shifted horizontally to make overlapping measurements easier to see. This shift is only graphical and does not represent differences in mileage between individual droplets.

3.1 Untreated 42CrMo4 Steel

The untreated 42CrMo4 steel was used as a reference surface. A photo of the samples used is shown in Figure 2. The measured contact angles for all three motor oils are presented in Figure 4.



Figure 2. Untreated 42CrMo4 Steel



Figure 3. Nitrided 42CrMo4 Steel

The most visible difference was observed for the SAE 20W/50 oil from the BVP-2 vehicle. The mean contact angle decreased from 16.03° for fresh oil to 7.84° for the last collected sample. However, the values did not decrease continuously with increasing mileage, and some differences between individual sampling stages were observed.

The SAE 15W/40 and SAE 15W/50 oils also showed variations in contact angle between the sampling stages, but the changes were less consistent. Therefore, a common trend for all three oils could not be clearly identified.

These results show that the contact angle of the tested oils can change during their use. However, the measurements alone cannot confirm that these changes were caused by oil degradation, since the chemical composition and condition of the collected samples were not independently analysed.

3.2 Nitrided 42CrMo4 Steel

The plasma-nitrided 42CrMo4 steel (see fig. 3) showed different wetting behaviour compared to the untreated steel surface. The measured contact angles were generally lower, indicating better wetting of this surface by the tested motor oils. The results are presented in Figure 5.

For the SAE 20W/50 oil, the mean contact angle decreased only slightly, from 6.76° for the fresh oil to 6.16° for the last collected sample. Compared to the untreated steel, this difference was much smaller. The values also varied between individual sampling stages, without a clear continuous decrease.

The SAE 15W/40 and SAE 15W/50 oils showed relatively small changes between the tested samples as well. No common trend related to increasing mileage could be clearly identified for all three oils.

These results suggest that the nitrided surface was less suitable for distinguishing between the investigated oil samples based on their contact angles. However, the lower contact angles cannot be attributed to nitriding alone, since the surface properties, including chemical composition, were not independently evaluated.

3.3 TiCN-Coated Laser-Textured Surface

The third tested surface was TiCN-coated steel with laser-generated micro-dimples. A photo of the samples used is shown in Figure 6. The surface treatment was intended to modify the wetting behaviour of liquids. However, a surface showing hydrophobic behaviour with water does not necessarily behave in the same way with motor oils.

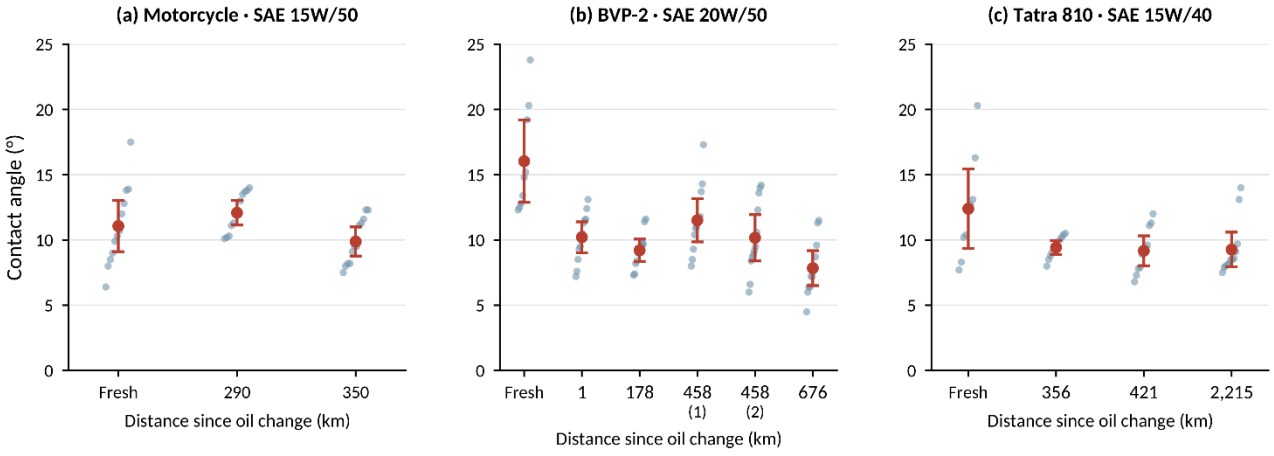


Figure 4. Contact angles of SAE 15W/50, SAE 20W/50 and SAE 15W/40 engine oils measured on untreated 42CrMo4 steel (S1). Individual measurements, mean values and 95% confidence intervals are shown. Horizontal displacement of individual points is used for visualization only.

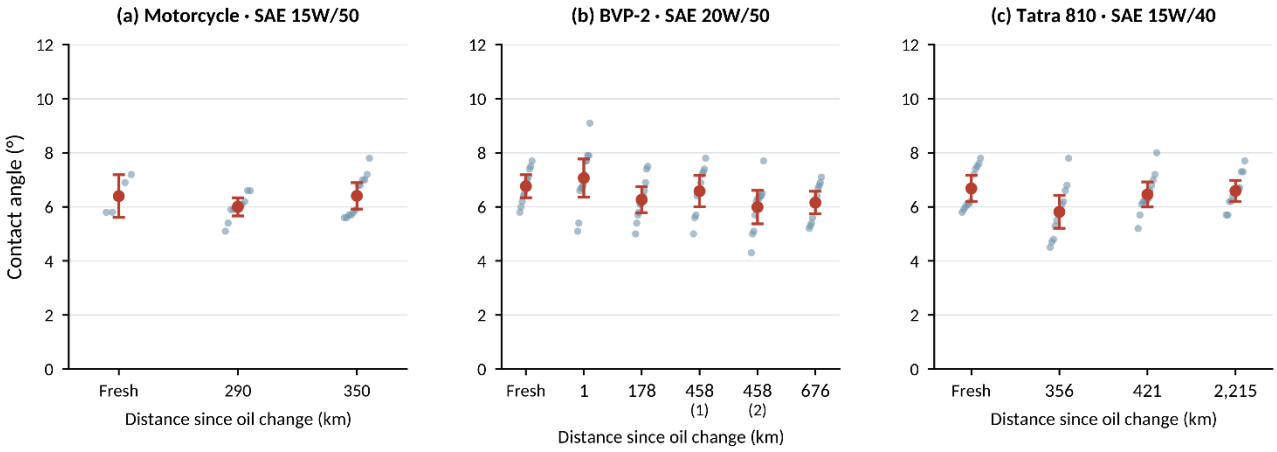


Figure 5. Contact angles of SAE 15W/50, SAE 20W/50 and SAE 15W/40 engine oils measured on plasma-nitrided 42CrMo4 steel (S2). Individual measurements, mean values and 95% confidence intervals are shown. Horizontal displacement of individual points is used for visualization only.



Figure 6. TiCN + laser surface

The measured contact angles were relatively low, mostly around 6–8°, as shown in Figure 7. This indicates good wetting of the tested surface by all three motor oils, despite its laser-textured structure.

For the SAE 20W/50 oil, the mean contact angle changed from 7.31° for the fresh sample to 6.74° for the last collected sample. The difference was small, and the values did not show a continuous decrease with increasing mileage. The SAE 15W/40 and SAE 15W/50 oils also showed variations between individual samples, but no clear common trend was observed.

Compared to untreated steel, the laser-textured TiCN-coated surface generally showed lower contact angles. The results were also relatively close to those obtained on the nitrided steel surface. This suggests that the investigated surface was not particularly sensitive to differences between the collected oil samples.

The results also show that surface texturing alone is not sufficient to predict wetting behaviour. The interaction depends on both the liquid and the solid surface, including their chemical and physical properties.

3.4 Silicon Surface

The polished silicon wafer was used as a smooth reference surface. Compared to the nitrided and laser-textured steel surfaces, the measured contact angles were generally higher and showed larger differences between individual oil samples. The results are presented in Figure 8.

For the SAE 20W/50 oil, the mean contact angle decreased from 16.73° at the first measurable sampling stage to 12.18° for the last collected sample. However, the changes between individual sampling stages were not completely continuous.

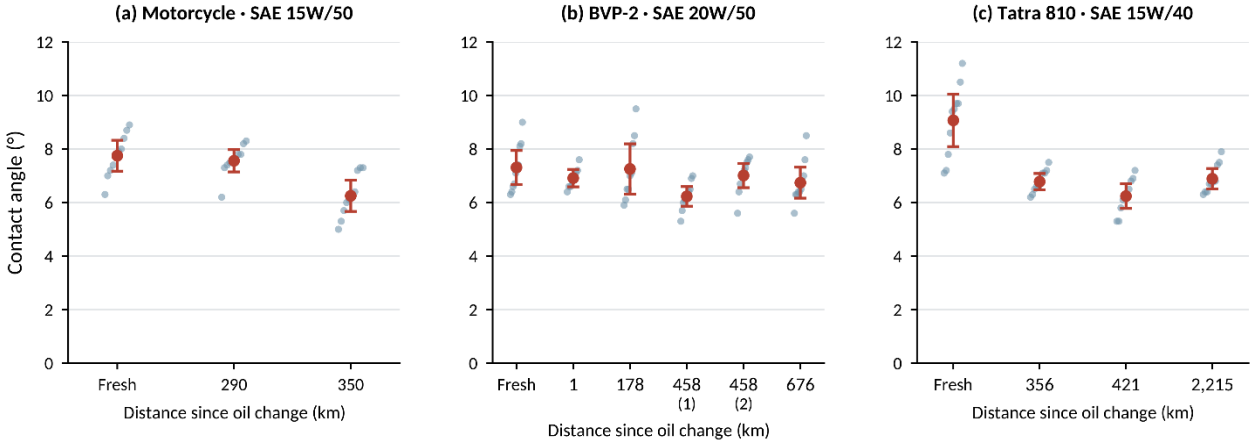


Figure 7. Contact angles of SAE 15W/50, SAE 20W/50 and SAE 15W/40 engine oils measured on laser-textured TiCN-coated steel (S3). Individual measurements, mean values and 95% confidence intervals are shown. Horizontal displacement of individual points is used for visualization only.

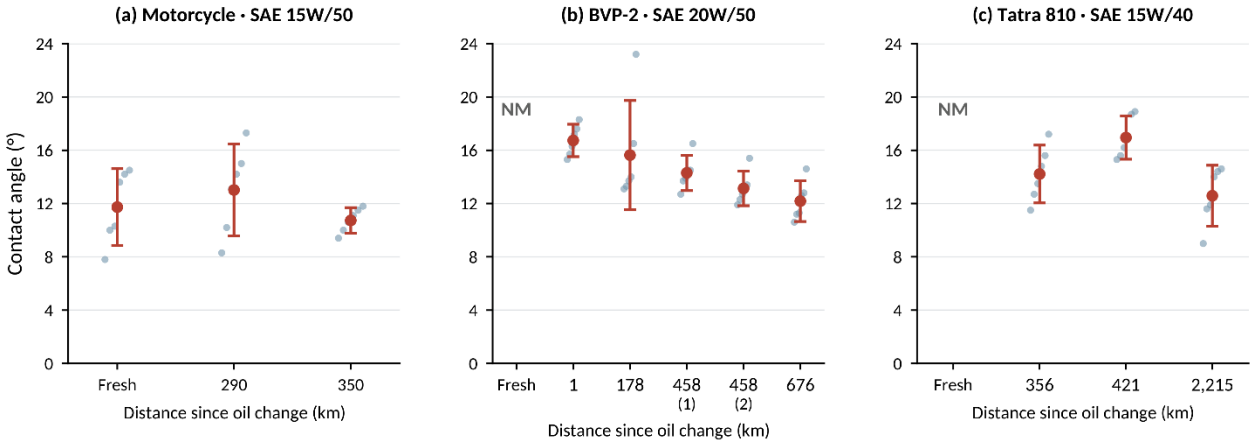


Figure 8. Contact angles of SAE 15W/50, SAE 20W/50 and SAE 15W/40 engine oils measured on polished silicon (S4). Individual measurements, mean values and 95% confidence intervals are shown. NM indicates samples for which the contact angle could not be reliably determined. Horizontal displacement of individual points is used for visualization only.

The other two motor oils also showed differences between the collected samples, but their behaviour was not identical. Therefore, it was not possible to identify one common relationship between mileage and contact angle for all three lubricants.

Measurements on the silicon surface were more difficult because some droplets spread extensively, making the contact angle impossible to determine reliably. This problem occurred particularly with the fresh SAE 20W/50 and SAE 15W/40 oils. These measurements were marked as not measurable (NM) and were not included in the statistical evaluation. The NM designation does not represent a zero contact angle.

The silicon surface showed relatively large differences between some of the measurable oil samples. However, the missing measurements, particularly for fresh oils, limit the possibility of comparing all sampling stages. The results suggest that silicon may be useful for further investigation of oil wettability, but its suitability for evaluating lubricant condition would require additional experiments.

4 DISCUSSION

Surface treatment had a substantial influence on the measured contact angles. Both nitriding and laser surface texturing resulted in lower contact angle values than the untreated steel surface for most of the investigated oil samples. Furthermore, both modified surfaces showed smaller differences in contact angle values between individual oil samples. This is well seen in Figure 9.

The differences between oil samples were more pronounced on the untreated steel surface and on the polished silicon wafer. In contrast, the modified engineering surfaces exhibited only minor changes throughout the investigated mileage range.

An interesting outcome of the study is that the untreated steel surface exhibits a more pronounced response to differences between lubricant samples than the modified surfaces. Both nitriding and laser surface texturing altered the absolute contact angle values but simultaneously reduced the visibility of changes between individual sampling stages. This can be linked to both the different structures of the surfaces and differences in surface energy of different coatings. However, the influence of these factors cannot be evaluated separately based on the present measurements.

The TiCN-coated laser-textured surface was originally intended to modify the wetting behaviour of the investigated lubricants through the introduction of regular micro-scale surface features. This structure was supposed to be highly hydrophobic. In this study, however, only motor oils were used, and the surface showed very low contact angles, indicating high wettability by these liquids. Although it is not enough to draw a conclusion that this is an absolute fact throughout all surfaces and liquids, it is noteworthy. Furthermore, with contact angles and changes in them this small, it is hard to draw any conclusion about the change of wettability because of degradation. The changes could be partly attributed to the uncertainty of the used wettability measurements. For future investigations, perhaps a surface that is oleophobic would be more suitable. This is further supported by the fact that some of the biggest changes in contact angle were observed on the surface with no surface treatment, which also showed relatively high values of contact angles.

The present study also highlights several limitations of contact angle measurements when applied to lubricant condition assessment. The observed changes in wettability were strongly influenced by the selected surface and varied among the investigated lubricants. Furthermore, the relatively small differences between some samples were often comparable to the measurement variability. Consequently, contact angle measurements alone are unlikely to provide a universally applicable indicator of lubricant degradation and should be interpreted together with additional information regarding the lubricant and surface properties.

The results highlight the importance of a consistent evaluation time. The shape of the deposited droplet continued to evolve after application, resulting in measurable changes in contact angle values. Consequently, strict standardization of the time interval between droplet deposition and image acquisition is necessary to ensure meaningful comparison of results. Future studies should investigate the complete time evolution of motor-oil droplets after deposition, rather than evaluating the contact angle at a single predefined instant. This is also important to take into consideration when trying to measure wettability of fast-evaporating liquids, like water. A droplet of a volume such as was used for this paper can change its volume rather quickly.

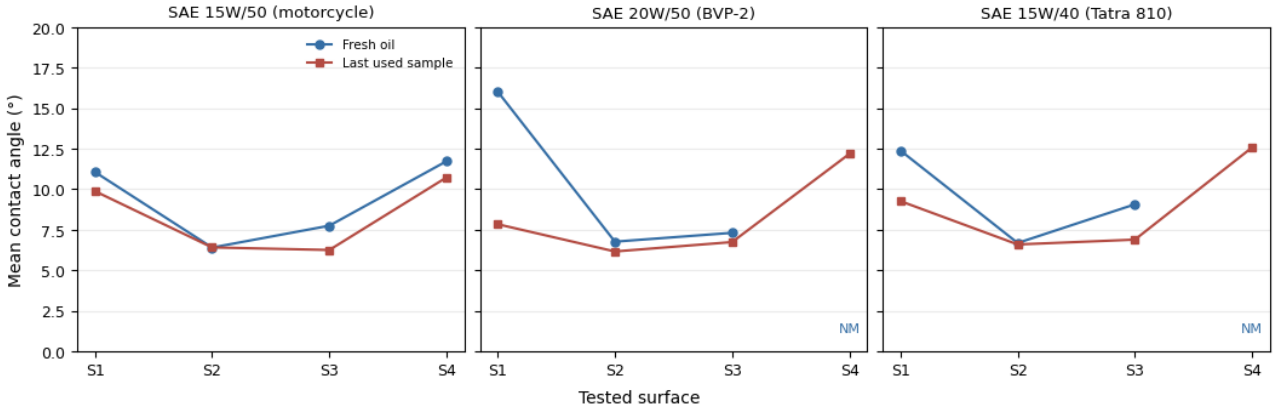


Figure 9. Comparison of mean contact angles measured for fresh oils and the last collected used oil samples on the four investigated surfaces. S1 – untreated steel, S2 – plasma-nitrided steel, S3 – laser-textured TiCN-coated steel, and S4 – polished silicon. NM indicates that the contact angle of the fresh oil could not be reliably measured.

Another important limitation is the influence of the operator during image evaluation. Small variations in the selection of the droplet boundary and baseline position in ImageJ can result in different contact angle values. This demonstrates that contact angle measurements remain sensitive to operator decisions and highlights the potential benefits of improved automation and standardized evaluation procedures. Human error can also occur when placing the droplet onto a surface. A small movement can affect the droplet, making it spread in an uneven manner.

Another factor this work does not investigate in detail is the surrounding atmosphere during measurements. Wettability depends not only on the liquid and solid but also on the surrounding atmosphere (for example, air humidity).

The increased variability observed for some used oil samples may indicate that changes in lubricant condition affect not only the average contact angle value but also the stability and reproducibility of droplet behaviour. Further investigation would be required to verify this assumption.

Another limitation of the present study is that lubricant degradation was represented solely by the distance travelled since the last oil change. Although increasing operating mileage generally corresponds to increased degradation, motor oil degradation is a complex process that involves simultaneous changes in viscosity, oxidation state, additive depletion, contamination, and wear-particle concentration.

Consequently, the observed changes in wettability cannot be attributed to any single degradation mechanism. Future research should therefore combine contact angle measurements with conventional lubricant analyses, such as viscosity measurements, oxidation monitoring, elemental analysis, or contamination assessment. Such an approach could help identify which degradation-related changes have the greatest influence on wettability and improve the interpretation of contact angle measurements as a diagnostic tool.

5 CONCLUSIONS

The present study was designed as an exploratory investigation into the potential use of contact angle measurements for assessing changes in motor oil condition during operation. The aim was not to establish a complete diagnostic method, but rather to examine the behaviour of different motor oils on selected surfaces and identify the possibilities and limitations of this approach.

The results showed that both the selected surface and the individual oil sample had a substantial influence on the measured contact angle. The untreated steel surface generally showed larger differences between the investigated oil samples, while the nitrided and laser-textured TiCN-coated surfaces exhibited lower contact angles and smaller variations. The polished silicon wafer also showed differences between oil samples, but extensive spreading prevented reliable measurements for some of them. No consistent relationship between operating mileage and contact angle was identified for all investigated oils and surfaces.

Although the measurements did not establish a direct relationship between contact angle and lubricant degradation, the study provided valuable information for further research. In particular, it highlighted the importance of surface selection, measurement repeatability, droplet behaviour, and the need for independent evaluation of lubricant condition. These findings suggest several possible directions for future investigations, including the use of surfaces with different wetting properties, monitoring the time evolution of deposited droplets, and combining contact angle measurements with conventional lubricant analyses.

The study therefore represents an initial step towards evaluating the potential of wettability measurements as a supplementary method for lubricant condition assessment.

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