RESEARCH ARTICLE

Base lubricants for green stamping: The effects of their structure and viscosity on tribological performance

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Abstract: The requirements for green and sustainable manufacturing mean that stamping lubricants must be continuously re-evaluated and re-designed. In this investigation, the tribological performance of four base oils with different chemical structures (paraffinic and naphthenic) and viscosities (2 and 20 cSt), as well as water, was evaluated for the stamping of steel sheets and compared with a non-lubricated contact. Most lubricants reduce the coefficient of friction and maintain a similar wear coefficient for steel sheets as in dry contacts. Low-viscosity (LV) naphthenic oil performs very like both high-viscosity (HV) oils. A surprising exception is the LV paraffinic oil, with several-times-higher friction and wear compared to dry contact. This is due to the excellent wetting-spreading and very low cohesion forces that enable oil to escape from extremely thin-film contacts because the viscosity is so low, leading to lubricant starvation. In contrast, HV oils provide a sufficiently thick lubricating film, while strong cohesive forces help in the film's strength, lessening wear, and reducing friction. In thin-film lubrication with LV oils, such as when stamping, it is thus extremely important that the lubricant's wetting behaviour and viscosity are sufficient to provide enough film in the contact and prevent starvation, thus ensuring lower friction, less wear, and a longer lifetime of the contact.

Keywords: stamping; viscosity; water; paraffinic oil; naphthenic oil; wetting

1 Introduction

The need for green and sustainable manufacturing means there are ever-more-stringent legislative restrictions on the use of many high-performance materials and lubricants commonly used in stamping [1–3]. For this reason, stamping tribology, in particular the stamping lubricants, needs to be continuously re-evaluated and re-designed. This is a challenging task as it does not only include the design of new green additives/lubricants, and/or adapting novel materials, it also needs to consider the compatibility of all these components in the contact. This requires a thorough understanding of the interactions taking place at the interface between the lubricant and the contacting surfaces.

Stamping is known as one of the most important manufacturing processes in the large-volume production of parts for different sectors. It consists of a number of metal-forming operations. These operations are very complex, because a single stamping cycle is composed of different sub-processes in which several different contacts are generated, e.g., contact with the punch, contact with the die, and contact with the blank holder [4–10]. Each of the contacts depends differently on the materials and the operating conditions. The latter are most of the time very demanding (high pressures, velocities, local contact temperatures, and shear rates), which results in high friction at the tool–metal-sheet interface and in turn results in die and tool wear as well as shorter lifetimes [7–10].

To reduce the friction and prevent premature failure of the die and tool, a proper lubrication technology must be used. It is important to emphasize that the lubricant is the same for very different contacts in the stamping tool/die interaction during manufacturing [7–10]. The lubricant is therefore required to perform well under various working conditions. At the same time, it should be adapted to the tool–metal-sheet interface and therefore the physico-chemical properties of the lubricant must be considered as they provide relevant information about the lubricant's performance for stamping operations [11–13]. These properties affect the solid–liquid interactions and in turn the wetting of the contacting surfaces by the lubricants [14]. Although a good wetting capability, high shearing and adhesive strength, as well as full spreading, are desired properties of the lubricant to enhance the lubrication and protect the contacting surfaces, they can also result in chemical reactions on the surfaces [15]. These reactions make it difficult to completely remove the lubricant from the finished parts, which requires stronger cleaning agents, so increasing costs and pollution [6, 16].

In the stamping of metal sheets, a wide range of metalworking lubricants is used. These lubricants are divided into straight oils, emulsions, and synthetics [6]. While in the case of more severe contact conditions straight oils and emulsions (soluble oils, semi-synthetic) are usually applied, for less-severe conditions even fully water-based lubricants (i.e., water-based synthetics) can be used [17]. However, in the literature there are no clear—and even fewer scientifically verified—limiting contact conditions, for which a certain type of lubricants could be used. Although nowadays potential lubricants used in practice are more systematically studied [18], a proper lubrication technology in industry still lacks evidence and a scientific basis. The reason is the complexity of realistic laboratory simulations, the high cost of tools, and the potential failures in real-scale industrial applications. This is slowing the introduction of improvements and replacements for the lubricants currently in use with more appropriate green varieties that would decrease friction and protect surfaces against wear, and would at the same time comply with the ever-more-stringent environmental regulations, standards, and public awareness [1–3].

The tribological performance of various lubricants for stamping applications has been evaluated so far using either standard tribology tests or in-house-customized versions [7, 19–25]. However, the main problem with these studies is that they often lack information about the lubricants' basic properties, while the influence of their physicochemical properties on the solid–liquid interactions is usually neglected [26]. These parameters are of paramount importance for understanding the lubricants' tribological performance for stamping applications and in turn for the development of high-performance green lubricants that can replace existing, environmentally problematic ones. In addition, studies are mostly performed for fully formulated lubricants [19–25], while an understanding of the performance of a single lubricant's component, such as the lubricant's base, is completely missing.

In this study we have evaluated the tribological performance of water and four base oils with different viscosities (2 and 20 cSt) and chemical structures (paraffinic and naphthenic) that are used in the stamping of electrical steel sheets. Since in practice some steel sheets are stamped in dry conditions [26–32], a dry contact was also evaluated. In addition to the tribological testing and post-analyses of the contacting surfaces' morphology and topography, the surface tension and wetting capabilities of all the base lubricants were also measured. The latter is crucial for understanding the steel-sheet–lubricant and the tool–lubricant interactions and in turn their influence on the tribological properties of the studied contact configurations. Such a comprehensive study has been performed for the first time and is important for further development of greener and more sustainable lubrication technologies in stamping industry.

2 Experimental

2.1 Materials

The selected metal sheet was standard electrical steel (Isovac 800-65K, Voestalpine, Austria) with a thickness of 0.65 mm. The WC-Co ball (ISO K40, Meusburger, Austria) is a common tool material in stamping, with a composition of 86.6% WC and 11.8% Co. The ball has a diameter of 10 mm and a roughness S_a of 10 nm.

Two low-viscosity (LV) vanishing oils with different chemical structures, i.e., paraffinic LV oil (Isopar-M, Exxon Mobil, Houston, USA) [33] and naphthenic LV oil (NYNAS NS 3, NYNAS, Stockholm, Sweden) [34, 35] were selected. In addition, two oils with high viscosity (HV) and different chemical structures, i.e., paraffinic HV oil (PURITY 1020, Petro-Canada lubricants, Ontario, Canada) [36] and naphthenic HV oil (NYNAS T 22, NYNAS, Stockholm, Sweden) [37, 38], were selected. Demineralized water was also studied, because it is used as a base fluid for emulsions and synthetic lubricants that are commonly used for stamping. The main properties of the lubricants used are summarized in Table 1.

2.2 Tribological tests

The tribological tests were performed at 25±2 °C on a reciprocating-sliding device (Bruker, Massachusetts, USA) using a WC-Co ball, to represent the actual tool material, and a steel sheet, as the counter body. We used the same configuration as applied in stamping. The normal contact load was 185 N, which corresponds to a Hertzian contact pressure of 3.3 GPa. During the tests the ball slides over the steel sheet with a frequency of 2.5 Hz, which corresponds to a sliding speed of 0.05 m/s. The length of the sliding stroke was 10 mm, and 10,000 cycles were completed for each test. During the test the selected lubricant was continuously added into the contact to maintain a volume of 20 μL in the contact area, ensuring the contact was uniformly lubricated during the whole of the test, but still with a very small quantity, a characteristic of stamping contacts. Tests without a

Table 1 Viscosity and density of lubricants, as reported by the producers [33–38].

Base lubricant	Viscosity at 40 °C (mm^2/s)	Density at 15 °C (g/cm^3)
Water	0.7	0.999
Paraffinic LV oil (low viscosity)	2.0	0.791
Naphthenic LV oil (low viscosity)	2.9	0.860
Paraffinic HV oil (high viscosity)	21.9	0.860
Naphthenic HV oil (high viscosity)	22.0	0.900

lubricant were also performed for a comparison. The coefficient of friction was recorded, as was the evolution and the steady-state value of the coefficient of friction. For each lubricant at least three repetitions were made. The average thickness of the lubricating film under the conditions used is, according to the Hamrock-Dowson equation [39], very low for both LV oils, i.e., around 5 nm. On the other hand, both HV oils resulted in an about 4-times-thicker lubricating film of around 20 nm.

2.3 Surface analyses

After the tribological tests the steel sheets and the WC-Co balls were further analysed. For the steel sheets, where significant wear was always observed, the wear volume was determined with an optical interferometer (Bruker-ContourGT-K0, Bruker, Massachusetts, USA) using scanning white-light interferometry (SWLI). According to the measured wear volume, the corresponding wear coefficient was calculated.

Several steel sheets were selected for additional analyses to reveal the origin of their specific friction and wear performance. The adhesion-force measurements were conducted using an atomic force microscope (AFM) (MFP-3D Origin, Asylum Research, Oxford Instruments) in the contact scanning mode. The measurements were made on at least 10 different areas for a fresh sheet-steel surface and inside the wear track after 1 and 10,000 cycles, to acquire statistically representative results. The adhesive forces were determined with ARgyle Light Software. X-ray photoelectron spectroscopy (XPS) measurements were conducted with a PHI-TFA XPS spectrometer (Physical Electronics, USA) equipped with an Al-monochromatic X-ray source and a 16-channel hemispherical electron energy analyzer. Quantitative information about the surface composition was obtained from the wide-energy-range spectra. The XPS spectra were recorded on at least two different areas for a fresh surface and inside the wear track after 1 and 10,000 cycles.

No wear was observed on the WC-Co balls. Instead, Fe transfer films from the steel sheet were formed. For this reason, analyses with a scanning electron microscope (SEM) (JEOL JSM IT100, JEOL, Japan),

including EDX analyses, were made for the WC-Co balls to determine the presence and the surface area of the Fe transfer film from the steel sheet to the WC-Co ball.

2.4 Wetting analyses

To evaluate the interactions of the lubricants with the contact materials, the surface tension and the contact angles of the lubricants on the steel sheet and the WC-Co tool were measured using a contact-angle goniometer (KSV Instruments, Finland). For these measurements, WC-Co discs were used instead of balls (to represent the tool), because it is not possible to measure the contact angles on round surfaces. The surface tensions of the lubricants were determined using the pendant-drop method. For each lubricant, five measurements were made. A corresponding dispersive component of the surface tension was calculated by measuring the contact angle on non-polar PTFE using the Wu model [40], while the polar component was further determined using the Fowkes model [41]. The contact angles of the lubricants were measured on the steel sheet and the WC-Co disc for periods of 15 seconds. For each lubricant the tests were repeated several times and the average values as well as the standard deviations are reported in the results.

3 Results

3.1 Tribological behaviour

From the average steady-state coefficient of friction it is clear that the lubricants, with the exception of the paraffinic LV oil, reduce the coefficient of friction compared to the dry contact (0.46). Another characteristic is that the coefficient of friction decreases with an increase in the viscosity (Fig. 1). The paraffinic HV and naphthenic HV oils have almost the same properties; they are also the most stable and have the lowest coefficient of friction, equal to 0.15, with a negligible running-in phase (Fig. 1(a)). An only slightly higher coefficient of friction, equal to 0.17, also with a insignificant running-in phase, was observed for the naphthenic LV oil (Fig. 1(a)). On the other hand, the water and the dry contact exhibit a significant running-in phase and a higher coefficient of friction

in comparison to the HV oils, i.e., 0.22 and 0.46, respectively. Surprisingly, the friction associated with the paraffinic LV oil exhibits instability during the sliding, and it increases for most of the test, and remains unstable. It has by far the highest value of 0.87 at the end of the test.

3.2 Surface analyses

The wear coefficients of the steel sheet for dry and lubricated contacts are presented in Fig. 2. These two contacts exhibit a similar wear coefficient, i.e., around 1.0×10^{-5} mm^3/(N·m). The contact lubricated with the paraffinic LV oil is again an exception, as it results in an order-of-magnitude higher wear coefficient of the steel sheet, i.e., around 1.5×10^{-4} mm^3/(N·m).

Figure 3(a) shows SEM images of the WC-Co ball specimen at the same magnification with marked contact areas for the dry and lubricated contacts. The
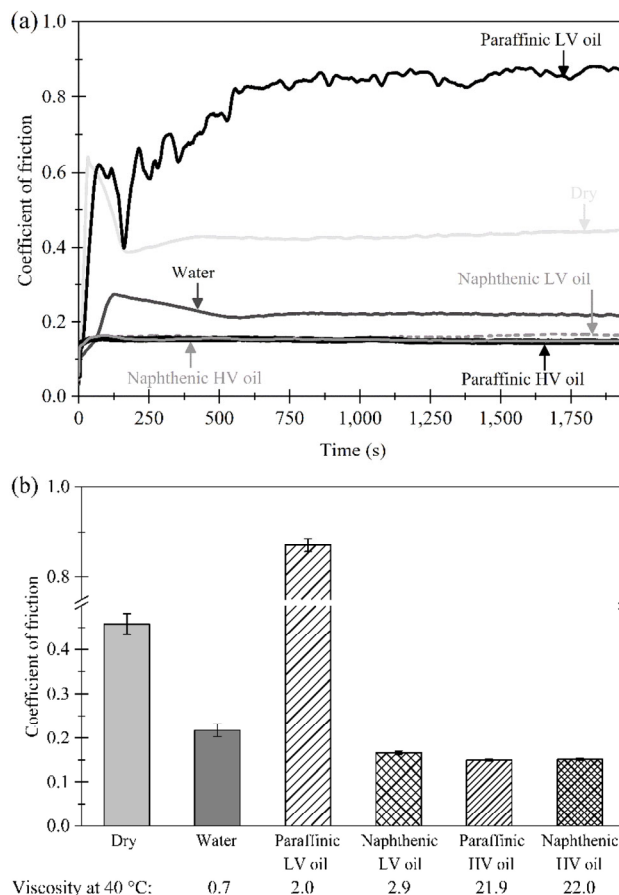

Fig. 1 (a) Evolution of the coefficient of friction during 10,000 cycles (representative tests are shown) and (b) average steady-state coefficient of friction for dry and lubricated steel sheet/WC-Co contact.
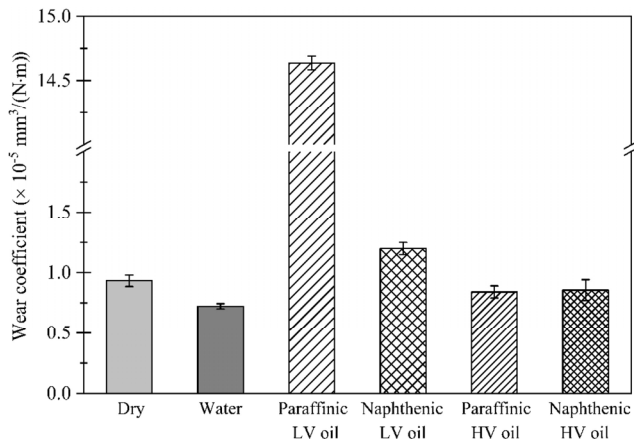
Fig. 2 Wear coefficient of the steel sheet for dry and lubricated contacts.

lubricants decrease the contact area, compared to dry contact, except for the previously mentioned paraffinic LV oil, which had a contact area even larger than that for the dry contact. An energy dispersive X-Ray spectroscopy (EDX) analysis showed that the material, which is unevenly distributed within the contact area, corresponds to an iron (Fe) transfer film from the steel sheet (see the Fe mapping in Fig. 3(b)). Such a transfer of softer sheet metal material to a much harder tool is common in stamping, in particular when metal sheets do not contain protective enamel coatings [42]. The EDX images were taken at different magnifications to reveal the details of the distribution of the Fe transfer film. In general, the transfer film is,
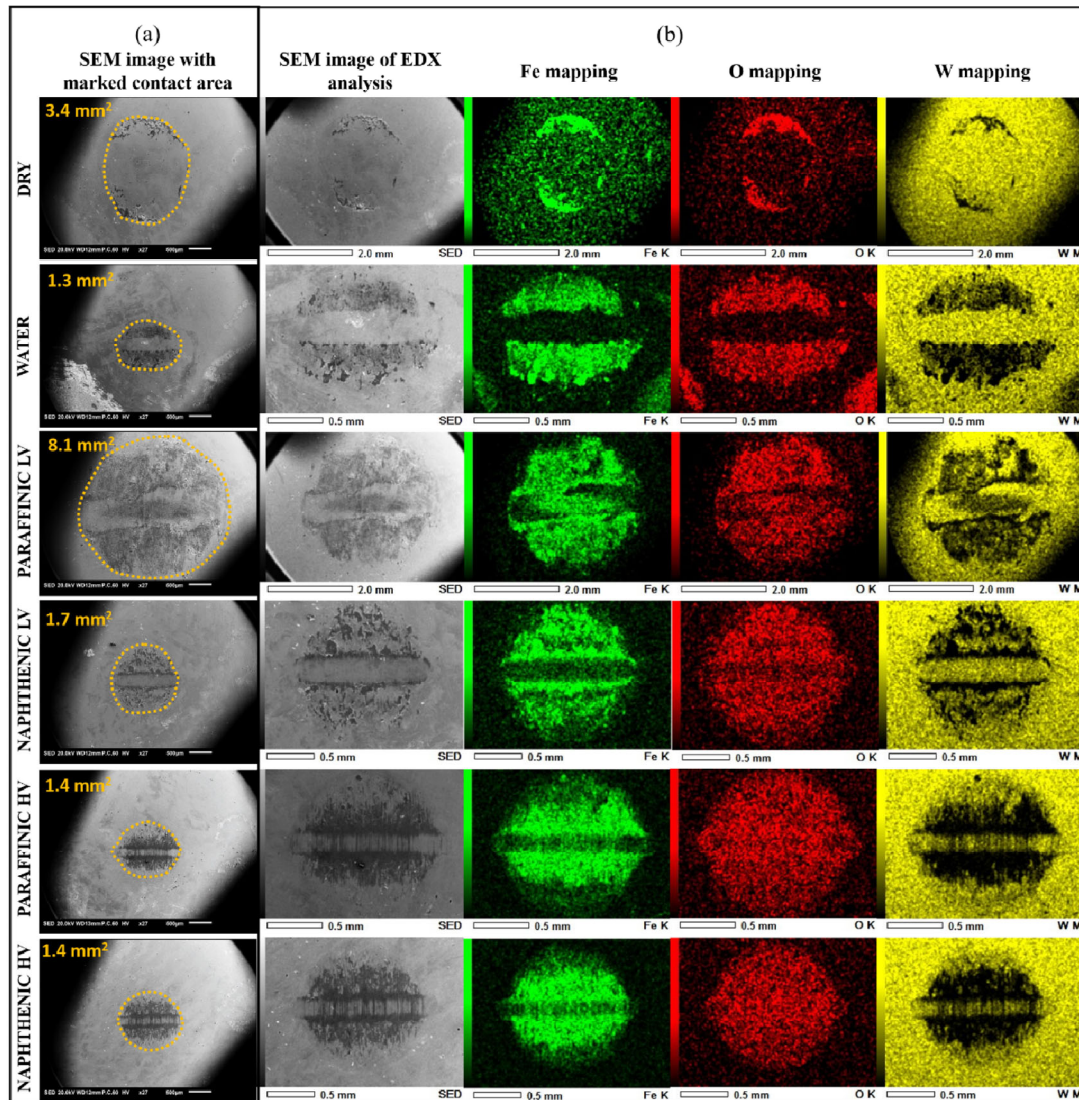
Fig. 3 (a) SEM images of the WC-CO balls taken at the same magnification, with the marked contact area and (b) the EDX maps of Fe, O, and W within the contact area.

to a large extent, pushed out of the central part towards the edge of the contact. This is especially notable for the dry and water-lubricated contacts, for which there is no transfer film in the central part of the contact. In contrast, the contacts lubricated with the LV and HV oils also show some Fe film in the central part.

All the transfer films are oxidized (see the oxygen (O) mapping in Fig. 3), indicating an increased temperature within the contact during the sliding. In addition, the absence of tungsten (W) on some areas within the contact, which is nevertheless the main constituent of the ball specimen, is an indication of a very thick transfer film of Fe in these areas (see the W mapping in Fig. 3). This is clearly more pronounced with the dry contacts and the LV lubricants (the water and both LV oils).

3.3 Wetting properties

The measured surface tensions of the lubricants along with their corresponding dispersive and polar components are reported in Fig. 4. The higher surface tension and the higher polar component of a lubricant indicate stronger internal cohesion forces and a reduced ability for the rapid spreading of the lubricant over the solid surface.

Water has the highest surface tension of 72.0 mN/m and a prevailing polar component of 51.8 mN/m. On the other hand, all four oils have much lower surface tensions and prevailing dispersive components (Fig. 4). However, there is a significant difference in the surface tensions between these oils. Both LV oils have lower surface tensions of 24.2 mN/m and 28.2 mN/m for the paraffinic LV and the naphthenic LV oil, respectively, compared to the HV oils with surface tensions of 30.3 mN/m and 30.9 mN/m for the paraffinic HV and the naphthenic HV oils, respectively. Furthermore, the naphthenic oil always has a higher surface tension and polar component than the paraffinic oil with the same viscosity (Fig. 4). This difference is especially pronounced for the LV oils, where the polar component of the surface tension of the naphthenic LV oil is 4.3 mN/m, which is 10-times higher than that of the paraffinic LV oil (0.4 mN/m). The higher polarity of the naphthenic oils compared to the paraffinic oils can be attributed to the high

proportion of cyclic hydrocarbons in the naphthenic oils [43].

The measured values of the contact angle of the water and the oils on the steel sheet are presented in Fig. 5. The contact angle of the water is stable during the period of the measurement (Fig. 5(a)) with a
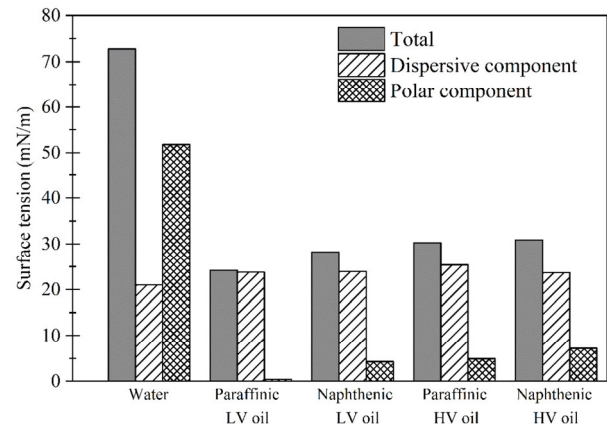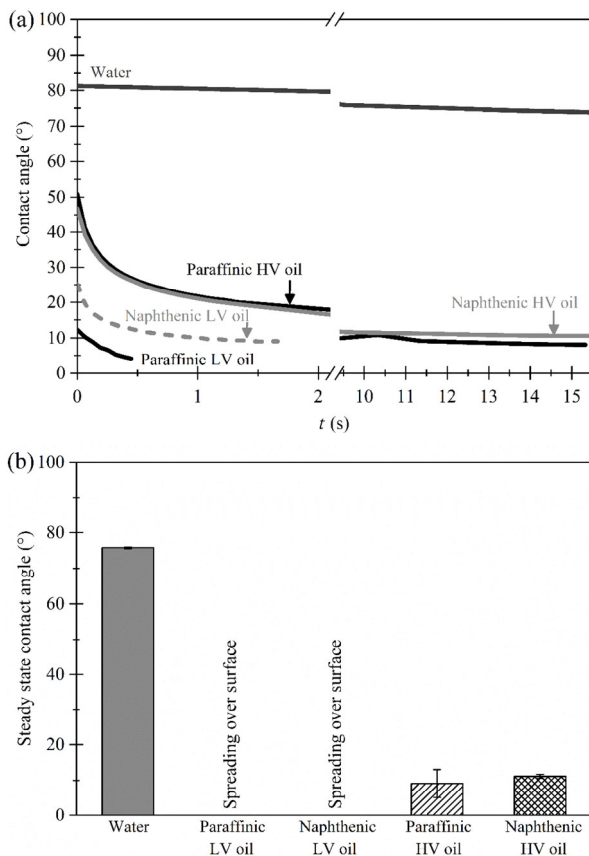
Fig. 4 Total surface tension and corresponding dispersive and polar components of the lubricants.
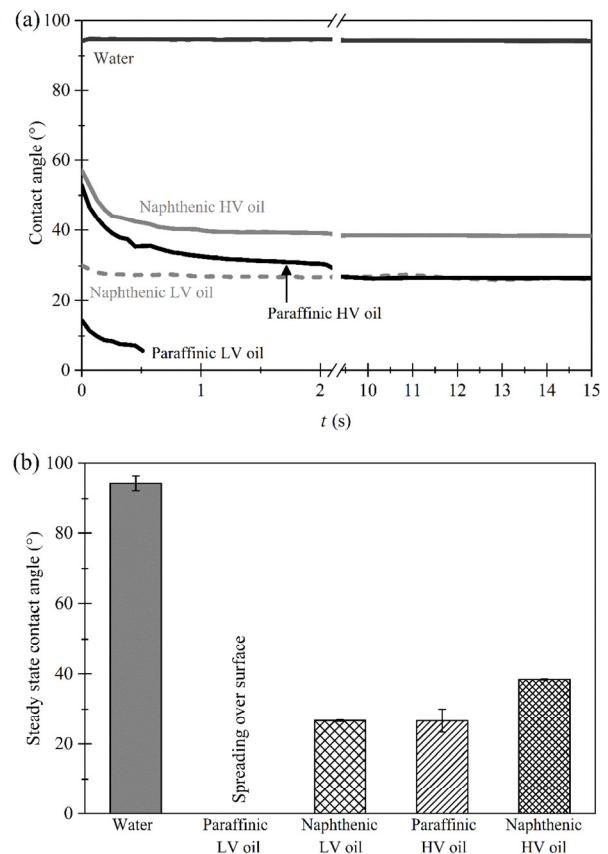
Fig. 5 Contact angles of lubricants on steel sheet: (a) evolution of contact angles during 15 seconds of measurement and (b) steady-state contact angles.

highest steady-state value of 94.4° (Fig. 5(b)). This is in agreement with it having the highest surface tension and polarity (Fig. 4). On the other hand, the oils show a slight decrease in the contact angle before reaching the steady state 2–3 seconds after being deposited onto the surface of the steel sheet (Fig. 6(a)). Among all the oils, the naphthenic HV oil exhibits the highest steady-state contact angle (38.5°), followed by the paraffinic HV and the naphthenic LV oils (26.7°) (Fig. 5(b)). The paraffinic LV oil is also an exception in wetting performance (the same as noted for friction and wear), since it exhibits rapid spreading over the steel sheet, i.e., a rapid decrease in the contact angle, resulting in it being unmeasurable (Fig. 5). This is in agreement with the oil having the lowest surface tension and polarity, presented in Fig. 4.

The measured values of the contact angles of the water and oils on the WC-Co disc are presented in Fig. 6. In this case all the lubricants show a decrease in the contact angles before reaching the steady-state

value (Fig. 6(a)), which for all the lubricants is lower than in the case of the steel sheet (compare Figs. 5(b) and 6(b)). Water has again the highest steady-state contact angle of 75.8°, followed by both HV oils, i.e., naphthenic HV (11.1°) and paraffinic HV (9.1°). Both LV oils spread out completely over the WC-Co disc in less than 2 seconds after the deposition (Fig. 6(a)), resulting in an unmeasurable contact angle (Fig. 6(b)).

3.4 XPS and AFM analyses of metal sheet surfaces after different test durations

The very surprising tribological differences (see Section 3.1) between the naphthenic and paraffinic LV oils were investigated in greater detail to reveal the tribochemical effects. For this purpose, a very short tribology test with just a single cycle was performed under the same conditions as when using 10,000 cycles. After 1 cycle there is a very small difference in the coefficient of friction of the paraffinic LV oil (0.12) compared to naphthenic LV oil (0.14), with the paraffinic LV oil being even slightly better. Therefore, the previously observed difference is obvious only after 10,000 cycles (Fig. 7), indicating that the difference originates from the interface and tribochemical effects, which need to develop with sliding, rather than the viscosity itself.

To explain the difference in the short- and long-term effects for the LV oils, XPS and AFM analyses were conducted. As shown in Fig. 8(a), the fresh, unworn surface of the steel sheet is mainly composed of carbon C (79.7 at.%) and oxygen O (15.9 at.%), whereas the amount of Fe is only 0.9 at.%. After sliding, for all
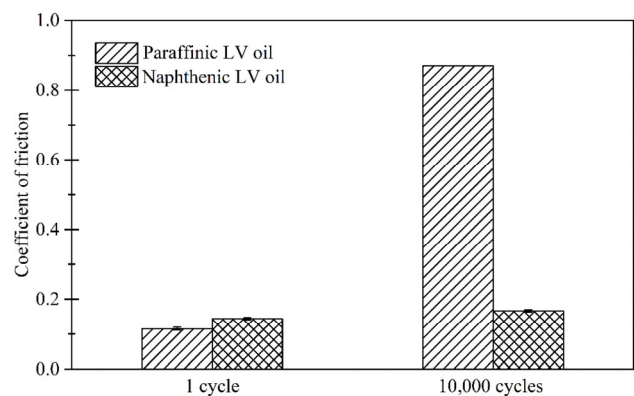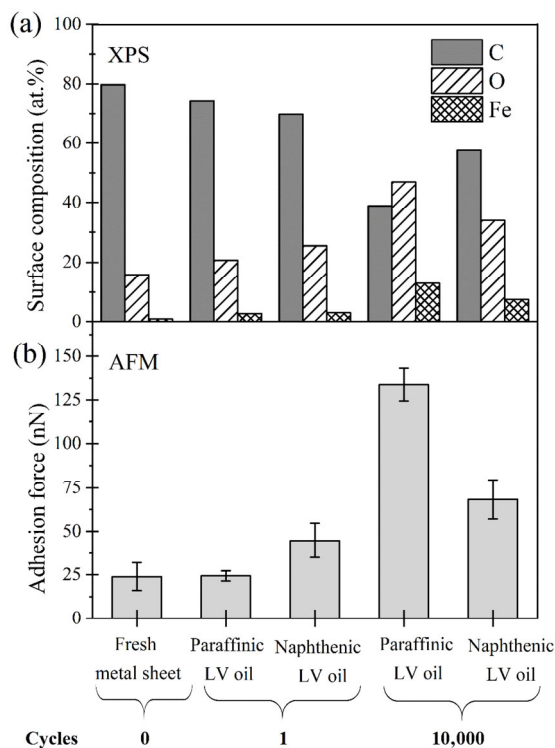

Fig. 6 Contact angles of lubricants on WC-Co disc: (a) evolution of contact angles during 15 seconds of measurement and (b) steady-state contact angles.

Fig. 7 Coefficient of friction for both LV oils after 1 cycle and 10,000 cycles.

Fig. 8 (a) Surface composition (XPS) and (b) adhesion force (AFM) of unworn/fresh steel sheet and on steel sheet wear tracks after 1 and 10,000 cycles for paraffinic and naphthenic LV oils.

surfaces, the amount of C is decreased, whereas the amounts of Fe and O are increased (Fig. 8(a)).

After 1 cycle, the differences in the surface composition of the steel sheets lubricated by the naphthenic LV and paraffinic LV oils are still quite small; however, there are some differences. Namely, at the naphthenic LV lubricated surfaces the amounts of Fe (3.0 at.%) and O (25.5 at.%) are slightly higher, whereas the amount of C is slightly lower, compared to surfaces lubricated with the paraffinic LV oil (Fe of 2.8 at.%, O of 20.7 at.%). This agrees with the slightly higher coefficient of friction for the naphthenic LV oil (0.14) in comparison to the paraffinic LV oil (0.12) (Fig. 7), since the higher amounts of Fe and O and the smaller amounts of C suggest greater adhesion between the contacting surfaces, which was confirmed by measuring the adhesive force using the AFM (Fig. 8(b)).

The differences become very clear after 10,000 cycles. The steel sheet lubricated with the paraffinic LV oil possesses more Fe (12.9 at.%) and O (46.9 at.%) and less C (38.8 at.%) than the naphthenic LV oil (Fe of 7.5 at.%, O of 33.9 at.%, and C of 57.6 at.%). This

clearly indicates a stronger transfer film and higher contact temperatures in the case of the paraffinic LV oil due to their being less protection of the surfaces, resulting in the much higher adhesion (Fig. 8(b)), which agrees with the high coefficient of friction (Fig. 7).

4 Discussion

For base oils the viscosity is usually the most important parameter, due to the absence of intensive tribochemical interactions that occur because of the additives. This work showed that HV oils, both paraffinic and naphthenic, perform the best, exhibiting the lowest friction and wear. LV oils should thus perform less well, which was the case in our study. However, a surprisingly poor and very different behaviour was observed with the paraffinic LV oil, compared to naphthenic LV oil. In fact, this behaviour was even worse than with water and dry contacts, which is surely counter-intuitive and requires an explanation. We discuss this anomaly below, together with other phenomena, and describe the mechanisms behind the effects.

4.1 Influence of the viscosity and the wetting of oils

For convenience, all the key empirical findings for the LV and HV base oils are summarized in Table 2.

Both the HV oils, i.e., paraffinic HV and naphthenic HV, have similar viscosities. Table 1 shows an about 20-nm-thick film that ensures good surface protection (Figs. 2 and 3). This is a four-times-thicker film than the LV oils, and 20 times thicker than the water film. Moreover, their wetting parameters are similar, and some variations in the contact angle with steel (Fig. 5) obviously do not prevail over the viscosity, since their performance is indeed very similar. In addition to the viscosity and films' thicknesses, their highest surface tension among all the tested oils and therefore the strongest cohesion forces within the lubricant molecules [44] provide the strongest film and so further promote good lubrication behaviour (Fig. 9(a)). Thus, they form strong protective lubricating films between the surfaces, ensuring low adhesion and thus low friction (Fig. 1) and wear (Fig. 2).

In contrast, the LV oils have only a 5-nm-thick film,

Table 2 Comparison of the tribological and wetting performances for the paraffinic and naphthenic oils.

Oils	Low viscosity (LV) oil			High viscosity (HV) oil		
	Paraffinic		Naphthenic	Paraffinic		Naphthenic
Coefficient of friction	0.87	$\gg$	0.17	0.15	$=$	0.15
Wear coefficient of steel sheet (mm^3/(N·m))	1.5×10^{-4}	$\gg$	1.2×10^{-5}	0.8×10^{-5}	$\approx$	0.9×10^{-5}
Size of contact area on WC-Co ball (mm^2)	8.1	$\gg$	1.7	1.4	$=$	1.4
Viscosity (mm^2/s)	2.0	$\approx$	2.9	21.9	$\approx$	22.0
Film thickness (nm)	5	$=$	5	20	$=$	20
Surface tension (mN/m)	24.2	$<$	28.2	30.3	$\approx$	30.9
Contact angle on steel (°)	<5	$\ll$	26.7	26.7	$<$	38.4
Contact angle on WC-Co (°)	<5	$=$	<5	9.1	$\approx$	11.1
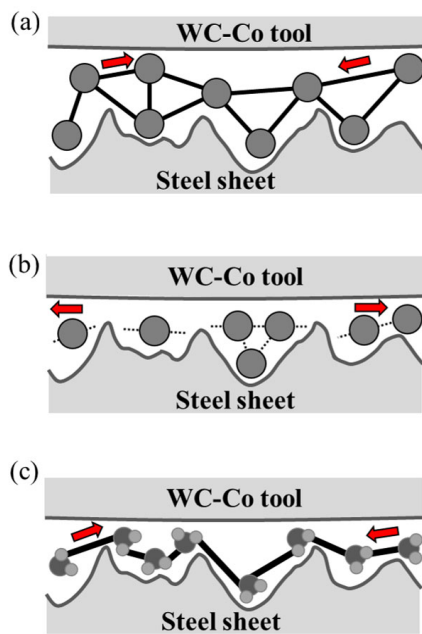
Fig. 9 Thin-film lubrication mechanisms for different lubricants: (a) oil with higher surface tension (strong cohesion forces), (b) oil with lower surface tension (weak cohesion forces), and (c) water (very strong cohesion forces and ultra-thin film).

which is indeed very low, compared to the surface roughness. Accordingly, in the absence of additive adsorption mechanisms and the formation of boundary films, it is very important for the lubricant to stay in contact under high pressures and maintain at least this protective fluid film during sliding.

Under such LV and thin-film conditions, the dramatic difference between the paraffinic LV and naphthenic LV oils is very surprising, as mentioned earlier. Moreover, the paraffinic LV oil provides better wetting on the steel sheet and on the WC-Co ball compared to the naphthenic oil (Figs. 5 and 6). This is a desirable property of a lubricant; however, its tribological performance in our study is very poor compared to the naphthenic LV oil (Figs. 1, 2, and 3). Its good wetting also indicates that the paraffinic LV oil spreads much more quickly over both contacting surfaces (Figs. 5(a) and 6(a)). This suggests a possible wetting-based "escape" of the oil from the contact, where the oil tends to occupy the free surfaces as much as possible. In addition, the paraffinic LV oil has an about 14% lower surface tension and an even 10-times-lower polar component compared to naphthenic LV oil (Fig. 4, Table 2). This is a clear indication of the much weaker cohesive forces between the lubricant molecules [45] of the paraffinic LV oil than the naphthenic LV oil, strongly supporting the suggestion of the oil's escape from the contact.

These results further promote the idea that under high contact loads with a lubricant of LV, very good wetting with strong spreading behaviour, and very low cohesion forces, the thin-film lubrication is disrupted, the film becomes insufficient, leading to lubricant starvation (Fig. 9(b)). This mechanism is very important for understanding the lubrication in stamping, where our contact conditions were deliberately selected to provide just a thin film of lubrication to mimic the lubrication in such cases. This is because only a very small quantity of lubricant is present in the contact of the steel sheet's surface in the course of the stamping cycle.

To further verify and prove this hypothesis, additional tribological tests with both LV oils were performed under the same testing conditions, but

with fully flooded conditions (the steel sheet was completely immersed in the oil). The results are presented in Fig. 10 and clearly show that under fully flooded conditions the paraffinic LV oil shows very good performance, with a coefficient of friction of 0.16, more than 5-times less than the thin-film lubrication. On the other hand there is no change in the coefficient of friction for the naphthenic LV oil with sufficient lubricating film under both thin and fully-flooded conditions.

To summarise, in thin-film lubrication, such as in stamping, it is extremely important that the wetting behaviour is tailored in combination with the viscosity and other properties, to enable enough film to be in the contact and prevent oil starvation. Based on these results it will be interesting to test the used hypotheses by a systematic variation of viscosity or cohesive energy or thickener in our future studies.

4.2   Long-term wear effect of paraffinic LV oil

Another observation from this study is that the differences in the wear performance of LV oils are expressed only after a large number of cycles, where an increase in the amount of Fe and O on the steel sheet (Fig. 8), as well the Fe transfer film on the WC-Co surface, is found (Fig. 3). Strong spreading of the paraffinic LV oil, resulting in lubrication starvation,
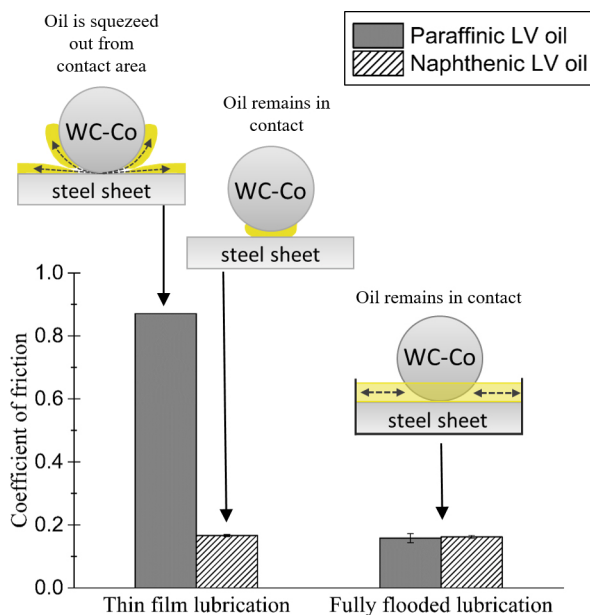
Fig. 10 Coefficient of friction for paraffinic LV and naphthenic LV oils under thin-film and fully flooded lubrication.

gives not only higher friction, as discussed above, but also an increased contact temperature. This causes oxidation, more exposed steel sheet, and so increased adhesion to the WC-Co ball (Fig. 8). This of course means wear of the steel sheet and poor contact integrity of the WC-Co (tool) material, due to the transfer film, eventually leading to a catastrophic contact behaviour. However, increased wear is only observed after an increased number of cycles, as evidenced in our methodology. Accordingly, the proper base-oil structure and the tailoring of its wetting and viscosity properties is essential (in addition to friction) also for the wear and surface lifetime prior to failure, which in this study was much better for the naphthenic LV oil than the paraffinic LV oil.

4.3   Water lubricated contacts

Water, despite having the lowest viscosity (Table 1), exhibits tribological properties comparable to the tested oils. This can be explained by it having the highest surface tension and polarity (Fig. 4), which means the strongest cohesive forces between the liquid molecules, schematically shown in Fig. 9(c). It means that the LV lubricant, i.e., the water, cannot be easily squeezed out of the contact and the strong van der Waals network protects the surfaces from wear. Owing to this, water lubrication leads to similar wear of the steel sheet (Fig. 2) as the oils. The size of the contact area on the WC-CO balls is even the lowest (Fig. 3) and the amount of the Fe transfer film on the WC-Co surface is comparable to that for oils (Fig. 3). However, water leads to a higher coefficient of friction than the oils, which is due to it having the lowest viscosity (Table 1) and direct impacts due to topographical compliance and interactions.

4.4   Non-lubricated ("dry") contacts

The final surprising mechanism in this study that needs to be explained is the much higher coefficient of friction and wear for the contacts lubricated with the paraffinic LV oil compared to the dry contact (Fig. 1(b), and Table 2). In the dry contacts there is a direct contact between the steel sheet and the WC-Co ball, and with absence of any lubricant film giving far the largest contact area (see Fig. 3) from the very early stage. This large contact area, in turn, decreased

the real contact pressure and the contact temperatures, and thus the adhesive Fe transfer film. Such contact conditions result in quite different contact conditions and thus more complex for direct comparison to lubricated ones. In contrast, the paraffinic LV oil initially still forms a thin lubricating film (when not starved) and prevents wear to some extent. This results in a smaller contact area, but a higher contact pressure, which increases the contact temperature and so the chemically derived adhesive wear. The direct effect of this is the transfer of the Fe film on the WC-Co counter surface (Fig. 3) in the early stages of the sliding. However, the transfer film also means that the two surfaces become chemically similar, which enhances the adhesive wear (more than in the dissimilar surfaces) that is known to have a high wear rate as well as a high coefficient of friction due to the adhesive bonds, which gradually increased the wear. Accordingly, when compared to the non-lubricated surfaces, this leads to the paradox of a much higher wear and coefficient of friction for the poorly and starved thin-film-lubricated steel surfaces that are initially dissimilar, but become similar due to the adhesive transfer film. This mechanism also explains wear behaviour for other oils in comparison to dry contact. Despite these oils are not completely squeezed out from the contact, they cannot prevent initial transfer of Fe-film to the WC-Co ball, because of higher contact pressure induced by lower contact area (see Fig. 3). Therefore, due to prevailing adhesive wear, very thin lubricating film cannot prevent further film transfer and thus cannot provide significantly lower wear coefficient compared to dry contact.

5   Conclusions

1) Most lubricants reduce the coefficient of friction in comparison to dry contact (water by 56%, naphthenic LV oil by 64%, naphthenic and paraffinic HV oils by 67%) and maintain similar wear coefficients for the steel sheets as in dry contacts. The naphthenic LV oil performs very similarly to both HV oils. A notable exception is the paraffinic LV oil with a several-times-higher friction and wear compared to the dry contacts. There was no wear on the WC-Co balls.

2) Water provides wear performance comparable to oils, which can be attributed to its very high surface tension and polarity, resulting in strong cohesive forces and a network of strong van der Waals bonds. On the other hand, the LV water is not able to separate the contacting surfaces, which leads to a high coefficient of friction.

3) The HV naphthenic and paraffinic oils provide a sufficiently thick lubricating film, while the strong cohesive forces help in its strength, protecting from wear and reducing friction. Small variations in the wetting between the paraffinic and naphthenic HV oils does not affect their tribological behaviour.

4) The LV naphthenic and paraffinic oils perform very differently. Due to the LV and consequently a thin film, paraffinic LV oils with very good wetting (spreading) and very low cohesive forces, combined with high contact loads, lead to an insufficient lubricating film that tends to squeeze out of thin-film contacts, and lead to lubricant starvation. This results in a several-times-higher friction and wear compared to the naphthenic LV oil with almost equal viscosity.

5) In thin-film lubrication, such as in stamping, it is extremely important that the wetting behaviour is tailored in combination with the viscosity (and other contact properties) to enable enough film in the contact and prevent starvation, thus ensuring low friction, wear and contact lifetime.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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