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Experimental Evaluation of the Influence of Different Types of Lubricants on the Tribological Resistance of Quenched and Tempered 42CrMo4 Steel

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This study investigates the influence of selected commercially available lubricants on the tribological behaviour of quenched and tempered 42CrMo4 steel intended for highly loaded mechanical and firearm components. Ten oils available on the domestic market were selected according to their ability to reduce friction, protect metallic surfaces and avoid silicone or PTFE-based additives. Reciprocating Ball-on-flat tests were performed using a Bruker UMT TriboLab with a G40 steel ball under a normal load of 50 N, a stroke length of 10 mm, a sliding speed of 0.3 m/min and a test duration of 20 min. The worn surfaces were evaluated using a LEXT OLS5100 3D laser confocal microscope. The dry reference sample reached the highest coefficient of friction, μ = 0.548, and the highest wear volume, 0.11127 mm³. In contrast, all lubricated samples showed substantially lower friction values, μ = 0.102–0.131, and wear volumes of 0.00264–0.00491 mm³. The best performance was achieved by BRUNOX® LUB&COR®, which provided the lowest friction coefficient and wear volume. Morphological analysis revealed severe adhesive and abrasive wear under dry conditions, whereas lubricated surfaces exhibited reduced damage and protective tribo-oxidative layers. The results confirm that lubricant viscosity, film stability and surface interactions significantly affect friction and wear of 42CrMo4 steel.

Keywords: Steel, Coefficient of friction, Wear, Lubrication

1 Introduction

42CrMo4 steel is one of the commonly used low-alloy structural steels intended for dynamically and tribologically loaded machine components. It is primarily used in applications requiring a combination of strength, toughness, hardenability, and suitability for subsequent heat or thermochemical treatment. It is also widely applied in the field of firearms and weapon systems, for example, in the manufacture of highly loaded components exposed during operation to intense friction, wear, elevated temperatures, and local damage to functional surfaces [1–4]. In the quenched and tempered condition (+QT), it provides a suitable substrate for further improvement of surface functional properties, particularly in terms of friction, wear resistance, and component service life [5,6]. Autay et al. reported that the tribological behaviour of 42CrMo4 steel cannot be explained solely by its hardness, since the coefficient of friction and wear volume also depend on the microstructure, applied load, and contact conditions [5]. For different microstructural states of 42CrMo4 steel, coefficient of friction values ranging approximately from 0.57 to 0.86 were recorded, confirming the significant influence of the material condition on the friction process [5].

An important approach to extending the service life of 42CrMo4 steel is the modification of its surface layer or surface topography. The literature reports the application of nitriding, nitrocarburising, PVD coatings, boriding, duplex layers, ball burnishing, and the formation of oil pockets on the surface [6–12]. Sofronov et al. investigated Cr/CrTiAl and Cr/(CrTiAl)N/CrTiAl PVD coatings deposited on 42CrMo4 steel in the quenched and tempered condition and measured hardness values of 27.3 GPa and 37.5 GPa, respectively, while the corresponding coefficients of friction reached μ = 0.362 and μ = 0.325 [6]. Panfil-Pryka et al. investigated the tribological behaviour of gas-nitrided 42CrMo4 steel at temperatures ranging from 23 °C to 400 °C. For a nitrided layer produced at 570 °C for 5 h, the average coefficient of friction increased from 0.73 at room temperature to 1.14 at 200 °C, but subsequently decreased to 0.69 at 400 °C [9]. These results demonstrate that the tribological properties of 42CrMo4 steel are sensitive not only to chemical and thermal surface treatment but also to the actual friction conditions.

In addition to surface treatments, lubrication plays a decisive role because the lubricant forms a separating film between the contacting surfaces. This film can reduce direct metal-to-metal contact, adhesive damage, abrasive wear, and energy losses. Skulić et al. demonstrated that lubricant viscosity is one of the key factors affecting the coefficient of friction, power losses, and the efficiency of transmission mechanisms [10]. In worm gear systems with a 42CrMo4/ZA12 material pair, low coefficients of friction ranging approximately from $\mu = 0.067$ to 0.044 were achieved. A higher lubricant viscosity promoted the formation of a more effective oil film and increased efficiency by approximately 1–2% [10]. The authors also reported that oils with a higher viscosity, such as 680 mm^2/s, provided the highest efficiency values at higher rotational speeds and loads [10]. These findings indicate that lubricant viscosity can significantly affect the stability of the lubricating film, the coefficient of friction, and consequently the wear intensity. In addition to viscosity, however, the chemical composition of the lubricant, its ability to adhere to the surface, its capacity to form a protective film, and the stability of the lubricating layer throughout the tribological test must also be considered.

The aim of the present study is to experimentally compare the tribological properties of selected commercially available lubricants applied to the surface of 42CrMo4 steel in the +QT condition. The evaluation is focused primarily on the evolution and average values of the coefficient of friction, wear volume, and the morphological characteristics of the worn surfaces following ball-on-flat testing. The study builds upon existing knowledge concerning the effects of microstructure, surface treatment, lubricant viscosity, and the nature of the tribological contact on the behaviour of 42CrMo4 steel. Its main contribution lies in the practical comparison of the effectiveness of different lubricants under identical testing conditions.

2 Materials and methods

The experimental material used in this study was the low-alloy structural steel 42CrMo4 (DIN 1.7225, STN 15 142). This steel is characterised by high strength and ductility and is therefore mainly used for dynamically loaded machine components and highly stressed machine parts, such as shafts, gears, pins, pressure vessels, and weapon components. It exhibits good machinability and is also suitable for various heat-treatment processes. The presence of alloying elements contributes to its good hardenability and makes it suitable for thermochemical treatment, such as nitriding. Owing to its relatively high carbon content, the steel is difficult to weld; however, after soft annealing, welding is possible in an Ar or CO_2 shielding atmosphere. The chemical composition and mechanical properties of the investigated steel are presented in Tables 1 and 2.

Tab. 1 *Chemical composition of 42CrMo4 (wt. %)*

	C	Mn	Si	Cr	Mo	P	S
Material datasheet	0.38-0.45	0.60-0.90	<0.40	0.90-1.20	0.15 – 0.30	<0.025	0<.035
Spectral analysis	0.42	0.75	0.13	0.92	0.19	0.19	0.003

Tab. 2 *Mechanical properties of 42CrMo4*

	Tensile strengh Rm [MPa]	Yield strengh Re [MPa]	Hardness [HB]
Material datasheet	900 - 1100	700 - 900	260-320
Mechanical analysis	984	867	310

The material used in the experiment was supplied in the quenched and tempered (+QT) condition, consisting of quenching followed by high-temperature tempering. After quenching, the material was tempered at 600 °C for 1 h. The resulting mechanical properties, namely a hardness of approximately 310 HV, an ultimate tensile strength of 984 MPa, and a yield strength of 867 MPa, correspond to this condition and are listed in Table 2. The microstructure of the material is shown in Figure 1 and consists of homogeneous, fine tempered martensite with acicular to lamellar features uniformly distributed throughout the material volume.

Experimental specimens for the evaluation of tribological properties were manufactured from the prepared material. Their shape and dimensions are shown in Figure 2. Prior to testing, the specimen surfaces were ground to an average areal surface roughness of $Sa = 0.34$ μm. Tribological tests were performed using a Bruker UMT TriboLab system employing a reciprocating ball-on-flat configuration. A G40 steel ball with a diameter of 4.76 mm was used as the counterbody. A new ball with a polished surface was used for each measurement in order to eliminate the influence of previous wear on the experimental results. The surface roughness of the ball was constant at $Ra = 0.32$ μm.

The test parameters were set to a constant normal load of 50 N, a reciprocating stroke length of 10 mm, a sliding speed of 0.3 m/min, and a total test duration of 20 min. Three measurements were performed on each specimen at three different locations. After

completion of the tribological tests, the wear tracks were evaluated using a non-contact LEXT OLS5100 laser confocal 3D microscope. The acquired 3D topographies were used to assess the wear characteristics and determine the volume of removed material in accordance with the principles of areal surface texture evaluation specified in ISO 25178.

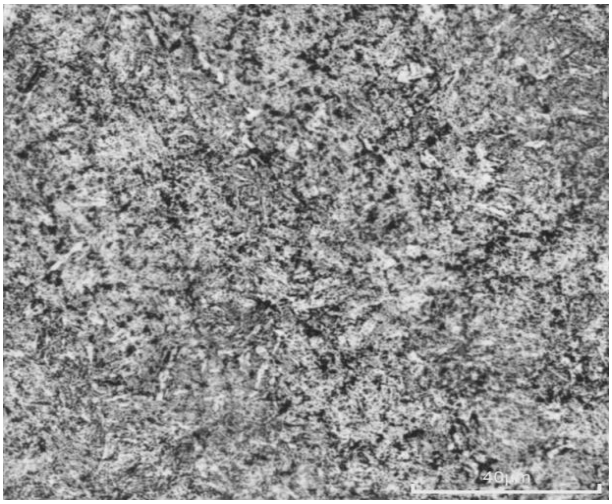


Fig. 1 *Microstructure of the experimentally investigated 42CrMo4 steel*

Ten types of oils were included in the experiment (Table 3) and were required to meet the following criteria: (a) minimise frictional resistance at the exposed contact surfaces of firearms, (b) provide long-term protection of metal components during storage or exposure to adverse environmental conditions, (c) be available on the domestic market with the expectation of continued future availability, and (d) contain neither PTFE nor silicone due to chemical risks, the potential degradation of lubricating properties, and the toxicity of decomposition products to humans at the high temperatures generated during firing.

Before each measurement, the specimen surface was mechanically cleaned and degreased with ethanol. Subsequently, approximately 0.1 ml of the tested oil was applied to the specimen surface using a dropper. The oil was evenly spread over the area of the intended contact to form a continuous thin lubricating film between the 42CrMo4 steel surface and the G40 steel ball. The same amount of oil and the same application procedure were used for all tested lubricants to minimise the influence of differences in specimen preparation on the tribological test results.

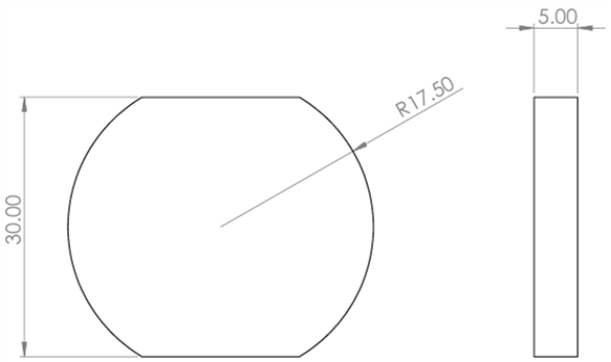


Fig. 2 *Shape and dimensions of the test specimens for the ball-on-flat test*

Tab. 3 *Experimental oils used in the tests*

Sample No.	Manufacturer	Product Name	Viscosity at 40 °C [mm²/s]	Form
1	SHERON	Konkor 101	0.81	Oil
2	COYOTE	Konkor 101	12.5	Oil
3	BALLISTOL	Gunex	28	Oil
4	BALLISTOL	Premium Oil	28	Oil
5	BRUNOX	Waffenpflege	4	Oil
6	BRUNOX	LUB&COR	85	Oil
7	WD-40 Company	WD-40	2–3	Aerosol
8	MOBIL	Vactra No. 2	67.8	Oil
9	INTERFLON	Lube TF	23	Aerosol
10	INTERFLON	Fin Super Dry Lube	23	Oil

3 Results

3.1 Surface Roughness Characterisation

Before the tribological tests, the initial surface topography of the G40 steel ball and the ground 42CrMo4 specimen was evaluated. The ball, with a diameter of 4.76 mm, exhibited a regular spherical shape without significant local defects, as shown in Fig. 3. The measured surface roughness of the counterbody was Ra = 0.32 μm. A new ball was used for each measurement, thereby eliminating the influence of previous wear on the tribological test results.

The reference surface of the ground 42CrMo4 specimen exhibited an oriented texture with parallel grooves in the grinding direction (Fig. 4). The surface was homogeneous and free from significant local damage, with an average areal surface roughness of Sa = 0.34 μm. Since all specimens were prepared simultaneously under identical conditions, this surface can be considered representative of the initial state before tribological loading. The same initial surface

preparation enabled an objective comparison of the effects of the individual lubricants on the coefficient of friction and wear volume.

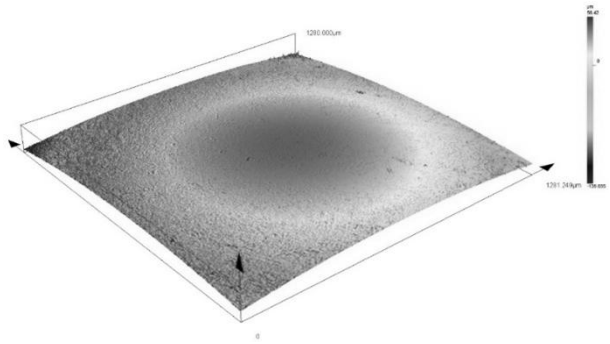


Fig. 3 *3D surface topography of the G40 steel ball*

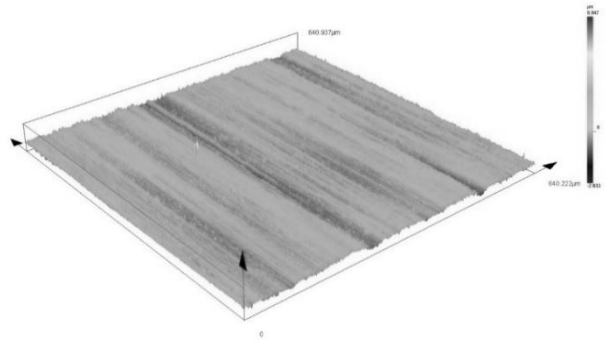


Fig. 4 *3D surface topography of the ground 42CrMo4 steel sample*

3.2 Analysis of the Coefficient of Friction

The evolution of the coefficient of friction as a function of time was monitored on the experimental specimens during the reciprocating ball-on-flat test. A total of 11 specimens were tested, with specimen 0 tested without lubricant and used as the reference condition for dry contact. Figure 5 shows the evolution of the coefficient of friction for selected specimens 0, 3, and 6.

The coefficient of friction exhibited two typical stages: an initial running-in stage followed by a steady-state stage. During the running-in stage, more pronounced changes and fluctuations in the COF values were observed. These were associated with the gradual adaptation of the contacting surfaces, local smoothing of surface asperities, and the formation of a stable contact area. After this stage, the coefficient of friction stabilised at a relatively constant level, the magnitude of which depended mainly on the presence and type of lubricant used. A failure stage, which is generally characterised by a sharp increase in the coefficient of friction due to lubricant film breakdown, a significant change in surface roughness, or severe wear of the contact pair, was not observed during the test.

The highest coefficient of friction values were recorded for the unlubricated reference specimen 0. The average COF reached 0.548, which is associated with direct metal-to-metal contact and a greater contribution of adhesive and abrasive interactions. In contrast, specimens 3 and 6 exhibited substantially lower coefficients of friction of 0.128 and 0.102, respectively. Compared with dry contact, this represents a reduction in the coefficient of friction of 76.65% for specimen 3 and 81.39% for specimen 6. These results confirm the significant effect of lubrication on the stabilisation of the frictional contact and the reduction of resistance to motion.

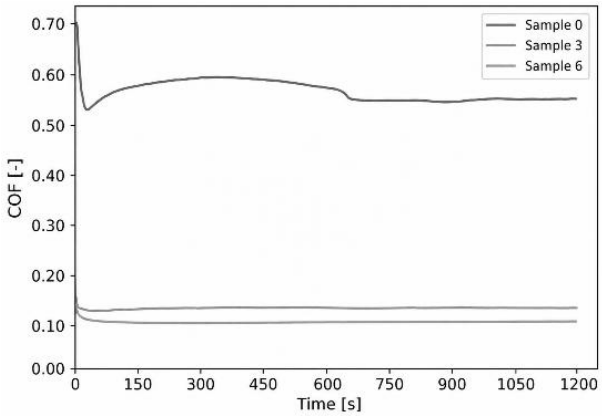


Fig. 5 *COF as a function of time for selected specimens 0, 3, and 6*

In all coefficient of friction versus time curves, an initial increase in COF was observed at the beginning of the measurement, followed by a short-term decrease and subsequent stabilisation of the values. This behaviour corresponds to the running-in stage of the tribological contact, during which the initial interaction between the surface asperities of the steel ball and the specimen surface occurs. During this stage, the surface asperities are gradually deformed, flattened, and partially removed, which may lead to increased formation of wear debris. After the contact stabilised, a lubricating film formed within the contact zone, and a tribological layer gradually developed, the coefficient of friction values became stable. Subsequent changes were limited to slight fluctuations, which may be attributed to local changes in surface topography, the movement of wear particles within the contact zone, and progressive surface wear. A similar trend was also observed in the study by the authors of [13], who reported that the coefficient of friction initially increases due to the more intensive involvement of surface microasperities in the friction process, whereas it subsequently decreases as the contact stabilises.

The average coefficient of friction values for all tested specimens are shown in Fig. 6. The highest average value was recorded for the unlubricated reference specimen 0, for which the coefficient of friction reached $\mu = 0.548$. The specimens with

applied lubricants exhibited substantially lower COF values, ranging from μ = 0.102 to μ = 0.131. Compared with dry contact, this represents a pronounced reduction in the coefficient of friction, confirming the effectiveness of the lubricating film in limiting direct contact between the metal surfaces. The reduction in COF also indicates the potential of the tested lubricants to reduce wear intensity and extend the service life of functional components.

The lowest average coefficient of friction was obtained for specimen 6, for which the COF reached μ = 0.102. This result indicates the best tribological performance of the corresponding lubricant in terms of friction reduction. Specimen 6 was tested using an oil with a viscosity of 85 mm²/s, which was the highest viscosity among the tested lubricants. The higher viscosity may have contributed to the formation of a more stable and continuous lubricating film, which more effectively separated the metal surfaces and reduced their direct contact. In contrast, the highest coefficient of friction among the lubricated specimens was recorded for specimen 2, for which the COF reached μ = 0.131. The oil used had a viscosity of 12.5 mm²/s, which was not the lowest viscosity within the tested set. This indicates that the resulting tribological behaviour was not governed solely by viscosity, but was probably also influenced by other factors, such as the chemical composition of the lubricant, its adhesion to the surface, its ability to form a protective film, and the stability of the lubricating layer during the test.

The influence of lubricant viscosity on tribological behaviour was also confirmed in the study by the authors of [10], who reported that increasing lubricant viscosity improved the efficiency of the tribological system by approximately 1–2%. According to these authors, the highest efficiency values were achieved at higher rotational speeds and loads when oils with higher viscosity were used. These findings are consistent with the results of the present study, in which the specimen tested with the highest-viscosity oil exhibited the lowest average coefficient of friction.

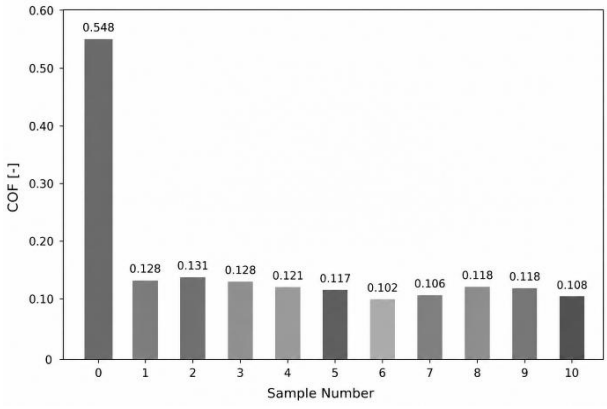


Fig. 6 *Comparison of the average COF values of the individual specimens*

3.3 Wear Analysis

The microscopic evaluation of wear on the experimental specimens was based on the analysis of the transverse profile of the wear track, while both the volume of removed material and the material displaced to the sides of the wear track were assessed. Methods for evaluating wear tracks are essential for the correct processing of the results. Different evaluation approaches were discussed by the authors in [12], who concluded that surface topography measurement can be used for the characterisation of wear types and for microscopic wear measurement. Digital filtering, even using a robust Gaussian filter, should not be applied to the large-width valley formed during wear. When necessary, i.e. when substantial waviness is present, a modified filter should be used. For a flat surface, only levelling using a first-degree polynomial is appropriate. The application of a second-degree polynomial may cause serious distortion of the wear-track cross-section, which can lead to incorrect estimation of volumetric wear. It was found that the average errors may reach up to 30%.

The surface of the wear track obtained in the second measurement of specimen No. 3 is shown in Fig. 7. The topographical map revealed a depression in the contact area caused by material removal as a result of tribological loading. The depth of the groove was 0.0085 mm. The edge regions of the wear track exhibited local elevations formed by plastic deformation and the displacement of material out of the contact area. Their height ranged from 0.0089 to 0.00965 mm.

The wear rate was determined on the basis of transverse profiles of the wear track. For each wear track, three transverse profiles were evaluated at different locations, from which the cross-sectional areas of removed and displaced material were determined. As shown in Fig. 8, the area marked as [1] represents the area of material removed from the specimen surface, manifested as the formation of a groove. Area [2] corresponds to the area of material displaced to the sides of the wear track as a result of plastic deformation of the surface layer.

The net wear cross-sectional area was determined as the difference between the area of removed material and the area of displaced material. The average net wear cross-sectional area was then calculated from the three measured profiles. The volume of removed material was calculated by multiplying this average area by the length of the wear track and subsequently converting the units to mm³. The wear volume values determined for the individual specimens were used to compare the effectiveness of the tested lubricants and are graphically presented in Fig. 8.

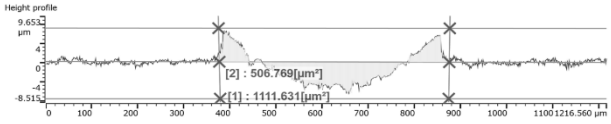


Fig. 7 *Cross-sectional profile of the wear track*

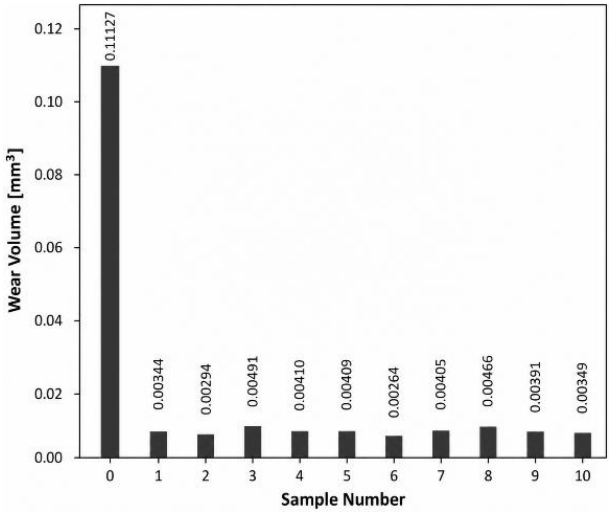


Fig. 8 *Wear of specimens 0–10*

The results presented so far, namely the coefficient of friction and wear, confirmed that the unlubricated reference specimen 0 exhibited by far the highest wear volume, reaching approximately 0.11127 mm³. In contrast, all specimens tested with lubricants showed several-fold lower wear values, demonstrating the significant effect of lubrication on reducing wear of the contacting surfaces. The lubricated specimens exhibited wear volumes ranging approximately from 0.00264 mm³ to 0.00491 mm³. The lowest wear volume was recorded for specimen 6, reaching approximately 0.00264 mm³, for which an oil with a viscosity of 85 mm²/s was used. This result also corresponds to the lowest coefficient of friction measured for this specimen, namely 0.102, and is consistent with the findings reported in [10]. Viscosity is a highly important characteristic of oil and varies with temperature and pressure. In general, oils with higher viscosity result in lower power losses in the gear mesh and lower coefficients of friction owing to improved oil-film formation, which consequently leads to higher efficiency [10].

In contrast, higher wear values were observed for specimens 3, 8, 9, and 10 when oils with lower viscosities ranging from 23 to 67 mm²/s were used. These results indicate a less effective ability of the lubricants to form a stable protective film between the contacting surfaces [5–14]. Oils with very low viscosity, used for specimens 1, 5, and 7, with viscosity values of 0.81, 4, and 2–3 mm²/s, respectively, exhibited intermediate wear values. This may be explained by the fact that total wear is also affected by other factors, such as the physical and chemical properties of the oil and the thickness of the oil layer, which were not investigated in the present study. The effectiveness and lubricating performance of lower-viscosity oils may also be improved by increasing the hardness of the surface layer through thermochemical treatment, such as nitriding [1,2,11], boriding [3], or by ball burnishing [8].

After the tribological test, the wear characteristics of the individual specimens were evaluated. As discussed above, the most pronounced differences in wear behaviour were again observed between the reference specimen 0 and specimen 6, as shown in Fig. 9. The unlubricated reference specimen exhibited extensive adhesive surface damage. Pronounced pits and fragments caused by material pull-out were observed on the worn surface. This is consistent with the fact that specimen 0 exhibited both the highest coefficient of friction and the greatest wear volume, reflected in the largest amount of removed material.

Specimen 6, which exhibited the lowest COF and the lowest wear volume, was characterised by more stable tribological contact behaviour. Extensive dark to black regions oriented in the direction of sliding were observed on its surface. These regions represent oxide layers formed during the tribological process as a result of the combined effects of mechanical loading, locally elevated temperature, and chemical interaction with the surrounding environment [15]. This was also confirmed by the authors of [5], whose SEM micrographs of martensitic microstructures identified predominantly oxidative wear. This mechanism was dominant in the WQT/OQT microstructures, corresponding to water quenching followed by tempering and oil quenching followed by tempering, and was characterised by oxidation of the rubbing surfaces.

The oxides formed during sliding may have acted as an intermediate separating layer between the contacting surfaces, thereby limiting direct metal-to-metal contact. The resulting tribo-oxidative layer reduced adhesive interactions between the steel ball and the specimen surface, which was reflected in a lower coefficient of friction and reduced wear intensity [14].

The protective effect of the oxide layers formed on the surface of specimen 6 corresponds to the lowest measured coefficient of friction and the lowest volume of removed material among all tested specimens. It can therefore be assumed that the combined effect of the lubricating film and the oxide layer formed during testing contributed significantly to wear reduction and improved the tribological properties of the investigated specimen.

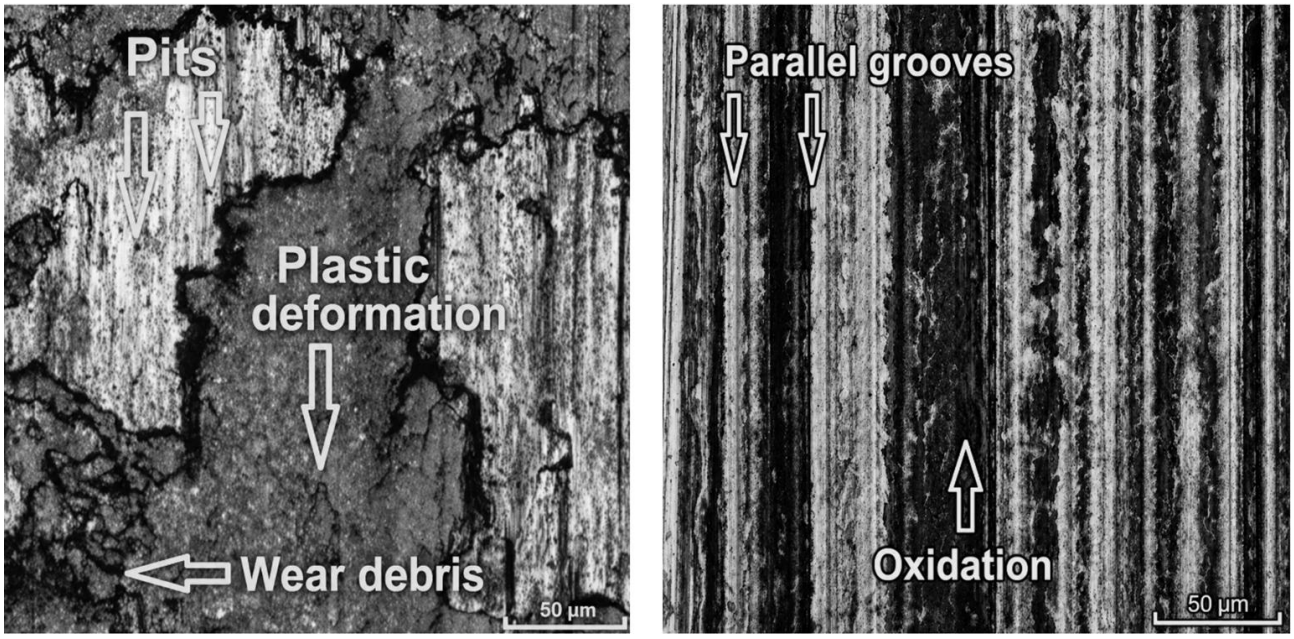


Fig. 9 *Wear mechanisms of specimens: a) 0; b) 6*

4 Discussion

The results of the present study confirm the fundamental influence of lubrication on the tribological behaviour of 42CrMo4 steel in the +QT condition. The unlubricated reference specimen exhibited the highest coefficient of friction, $\mu = 0.548$, and the highest wear volume, 0.11127 mm³. This was associated with direct metal-to-metal contact, more intensive adhesive interaction, plastic deformation, and local material pull-out. After lubricant application, the coefficient of friction decreased to $\mu = 0.102–0.131$, while the wear volume was reduced to 0.00264–0.00491 mm³, representing a substantial reduction in both friction and material removal. This trend is consistent with the findings reported by the authors of [13,14], according to whom a lubricant forms a separating film between the contacting surfaces, reduces the involvement of microasperities in the friction process, and limits energy losses.

The best results were obtained for specimen 6 lubricated with BRUNOX® LUB&COR® oil with a viscosity of 85 mm²/s. This specimen exhibited the lowest coefficient of friction, $\mu = 0.102$, and the lowest wear volume, 0.00264 mm³. The higher viscosity probably contributed to the formation of a more stable lubricating film, which is consistent with the conclusions of Skulić et al. [10], who confirmed the beneficial effect of higher viscosity on the efficiency of a tribological system. However, the results also show that tribological behaviour cannot be explained solely by viscosity, since specimens lubricated with lower-viscosity oils did not automatically exhibit the highest wear values. The resulting friction and wear behaviour was therefore also influenced by the chemical composition of the lubricant, its adhesion to the surface, the stability of the lubricating layer, and its ability to form a protective film [14].

Morphological analysis confirmed that adhesive and abrasive damage, accompanied by pits, fragments, and plastic deformation, predominated under dry-contact conditions. In contrast, specimen 6 exhibited more stable wear behaviour and the presence of oxide-rich regions. These tribo-oxidative layers may have acted as a protective intermediate layer between the steel ball and the specimen surface, thereby limiting direct metal-to-metal contact and contributing to lower friction and wear. A similar role of oxidative wear mechanisms in martensitic microstructures was also reported by Autay et al. [5] and, more generally, by Quinn [15].

The reliability of the wear evaluation was also supported by the profilometric approach based on transverse profiles of the wear track, since Pawlus and Dzierwa [12] emphasised the importance of appropriate surface-topography processing when quantifying wear volume. The obtained results therefore confirm that the combination of a suitable lubricant, a stable lubricating film, and the possible formation of a tribo-oxidative layer is crucial for reducing the coefficient of friction and extending the service life of tribological contacts made of 42CrMo4 steel. It may also be assumed that further improvement in wear resistance could be achieved by combining lubrication with surface-layer modification, such as nitriding, boriding, or ball burnishing, as reported in [2–4,11].

5 Conclusions

The present study evaluated the effect of selected commercially available lubricants on the tribological properties of 42CrMo4 steel in the quenched and tempered (+QT) condition. The tests were performed using a reciprocating ball-on-flat method, and the worn surfaces were subsequently analysed using a 3D laser confocal microscope. Based on the obtained results, the following conclusions can be drawn:

- Lubricant application resulted in a substantial reduction in the coefficient of friction and wear intensity compared with dry sliding. All tested oils significantly reduced the coefficient of friction relative to the reference specimen. The percentage reduction in COF ranged from 76.1% to 81.4%.
- Lubrication contributed to a pronounced decrease in wear intensity, with the individual oils reducing the volume of removed material by approximately 95.6–97.6% compared with the reference specimen. The results clearly confirmed that the presence of a stable lubricating film is a key factor affecting the service life of the tribological system.
- The best overall tribological performance was achieved by specimen 6 lubricated with BRUNOX® LUB&COR®. This oil produced the lowest coefficient of friction (0.102), the lowest wear volume (0.00264 mm^3), and stable tribological contact behaviour throughout the entire test.
- Morphological surface analysis revealed extensive dark oxide-rich regions characteristic of the wear behaviour of the martensitic structure. These regions represented protective tribo-oxidative layers formed during wear. The layers acted as a separating interlayer between the contacting surfaces, thereby reducing adhesive wear and stabilising the tribological process.
- No linear relationship was demonstrated between the coefficient of friction and wear intensity. The experimental results showed that a lower coefficient of friction does not automatically correspond to the lowest wear intensity. This was confirmed by specimen 2, which exhibited the highest coefficient of friction among the lubricated specimens (0.131), while simultaneously achieving the second-lowest wear volume (0.00294 mm^3). In contrast, specimen 10 exhibited a very low coefficient of friction (0.108), but reached a wear volume of 0.00349 mm^3.
- Lubricant viscosity affected both the coefficient of friction and the wear rate. A higher oil viscosity may contribute to a lower coefficient of friction and reduced wear. This was demonstrated by specimens 6, 8, and 3, tested with oils having viscosities of 85 mm^2/s, 67.5 mm^2/s, and 28 mm^2/s, respectively. However, specimens tested with low-viscosity oils (1, 7, and 5) did not exhibit the highest coefficients of friction or wear rates. These findings confirm the complexity of tribological processes and the need to evaluate lubricants using several parameters simultaneously.
- Morphological analysis of the surfaces confirmed the predominance of adhesive and abrasive wear mechanisms. Typical signs of plastic deformation, groove formation, material transfer, and local removal of surface layers were identified on the tested specimens. The unlubricated reference specimen exhibited severe surface damage caused by direct metal-to-metal contact. In contrast, the lubricated specimens showed considerably less severe damage, demonstrating the protective function of the lubricating film.
- During the wear of the martensitic structure, an oxide layer formed on the surface and acted as a protective barrier. This layer reduced direct contact between the two metal surfaces and consequently decreased both the coefficient of friction and the wear rate. In combination with the lubricant, it significantly improved the tribological properties of the contacting materials. In general, the martensitic structure exhibited the lowest wear rate and coefficient of friction.

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