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The influence of Particle Hardness on Wear in Sheet Metal Forming

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Abstract. Particles exist in any tribo-system, whether it is closed to the environment or not. These particles originate from various sources, for example: contaminants such as dust or fibres from the environment; wear debris from abrasive/adhesive wear; and particles that are intentionally included in lubricant formulations. The particles affect the tribo-system in which they occur, but it is not always clear how. In this work, three types of chemically inert particles of similar size but different hardness are mixed with an otherwise pure oil and tested tribologically. Three tribological testing methods, pin-on-disc, four-ball, and bending-under-tension, are used to investigate the effect of the particles on friction and wear under sheet metal forming conditions. The hardness of the particles had a large effect on wear development, but little to no effect on the coefficient of friction found by pin-on-disc testing. Including particles of any hardness helped the oil in which they were included resist variation in load, leading to less wear for higher loads compared to the pure oil.

Introduction

Various types of particles are endemic to tribological systems. Some particles are added to a tribo-system on purpose, while others enter the tribo-system accidentally or are unintentionally created through tribological or chemical mechanisms. There are essentially three sources by which the concentration of particles in a running tribo-systems increases over time. One of the sources are particles that are generated through tribological mechanisms such as adhesive or corrosive wear. These can be of different shapes and chemical compositions but would generally include some part of either the workpiece or tool. Another source is the environment, which can introduce particles of material such as dust or fibres from fabrics into the tribo-system. Lastly, depending on the lubricant formulation, the use and aging of the lubricant can lead to bacterial growth, which eventually forms bacterial cells [1]. These cells can be considered solid particles, but often help by improving the wear resistance of the lubricant rather than degrading it. These sources cause an increase in the concentration of particles in a tribo-system, with some particles already existing within the tribo-system, due to e.g., improper cleaning [2] or particles being included in the lubricant formulation.

The presence of particles in a tribo-system is often considered unwanted and has even been used as an indicator of mechanical systems undergoing severe wear [3]. Jiang and Wang [4] investigated the effect of wear particles of different sizes and concentration on wear in a locomotive engine. They applied a roller-on-roller test using a base-oil that included some concentration of particles collected from used oils and filters from running locomotive engines. Their result showed that the concentration of particles and the size of the particles are positively related to the amount of wear that occurs in the tribological test. The particles they used consisted mainly of iron and oxidation products, but also included some copper and aluminium. Abou El

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Naga and Salem [5] investigated how the presence of wear particles in a lubricating oil affected the degradation of the oil. They found that metallic particles can have a catalytic effect and speed up the oxidation of various chemicals in the lubricant composition. An increasing concentration of particles made this effect more pronounced, meaning that the effectiveness of the lubricant was degraded even more quickly. In their paper on the tribology in the wheel-rail contact of locomotives, Olofsson et al. [6] discussed the role that particles play in wear. The role is, independently of where the particles originate, essentially twofold. On one hand, the particles are free to move in a contact interface and therefore lead to three-body abrasive wear. Olofsson et al. note that the hardness of the particles in this case does not have a large effect on the wear rate, provided they are at least 20% harder than the surfaces in contact. This effect is the same as that used by other researchers investigating the use of solid particles in lubricant formulation. On the other hand, the particles can become embedded in a surface and initiate severe two-body abrasive wear.

Many researchers have investigated intentionally adding solid particles to a lubricant to improve the lubricant's tribological performance. Luo et al. [7] added alumina particles with an average size of 78 nm to an oil and found that the particles improved the friction reduction and wear resistance properties of the oil under four-ball and thrust-ring conditions at loads of 147 N and 200 N respectively. The particles they used are harder than the active test components, which had a hardness of between 44 - 66 HRC and were thought to promote rolling over sliding as well as forming a tribo-film that helps resist wear. Padgurskas et al. [8] used iron, copper, and cobalt particles to improve the friction and wear behaviour of a lubricant under four-ball test conditions. They included mixtures of the particles, which showed an even larger improvement in tribological performance compared to single particle lubricants, with the best mixture being equal concentrations of iron and copper. Li et al. [9] investigated the effect of wear particles in a lubricant used in a rolling process and found that the wear particles had an anti-wear and anti-friction effect, at least under the four-ball conditions applied in their work. However, the particle also affected the stability of the lubrication mechanism in a deleterious way, which lead to increased wear after some time. In other work [10], the efficacy of $CaCO_3$ particles of two sizes for improving tribological conditions was evaluated. The particles were added to a base oil, along with a surfactant to ensure proper dispersion, and then tested by applying pin-on-disc testing, four-ball testing, and bending-under-tension testing. The particles were found to drastically improve the tribological performance of the base oil, through what appeared to be physical mechanisms. Peng et al. [11] evaluated the wear resistance of a tribo-system that included SiO_2 particles of different sizes and found that as the size of the particle decreased, the wear resistance and friction reduction improved. At some point, the size of the particles exceeded some critical point and the wear amount, and friction, became higher than for the pure lubricant. An increased concentration of the particles emphasized this behaviour even more.

In summary, depending on the specific properties of particles, such as size and hardness, they can have different effects on the tribo-system in which they are added. Some property of particles in a tribological system means the difference between their acting as abrasives, causing wear, and their acting as ball-bearings to promote rolling over sliding, reducing wear. In this work, three types of particles are added to pure paraffin oil with the aim of investigating the effect of the particle hardness on their role in wear, with a focus on sheet metal forming. Therefore, $CaCO_3$ particles are used as they have been shown to be beneficial to tribo-systems, $BaSO_4$ particles as they are slightly harder than the $CaCO_3$ particles, and SiO_2 particles as they are much harder than the other particles.

Experimental Methods and Materials

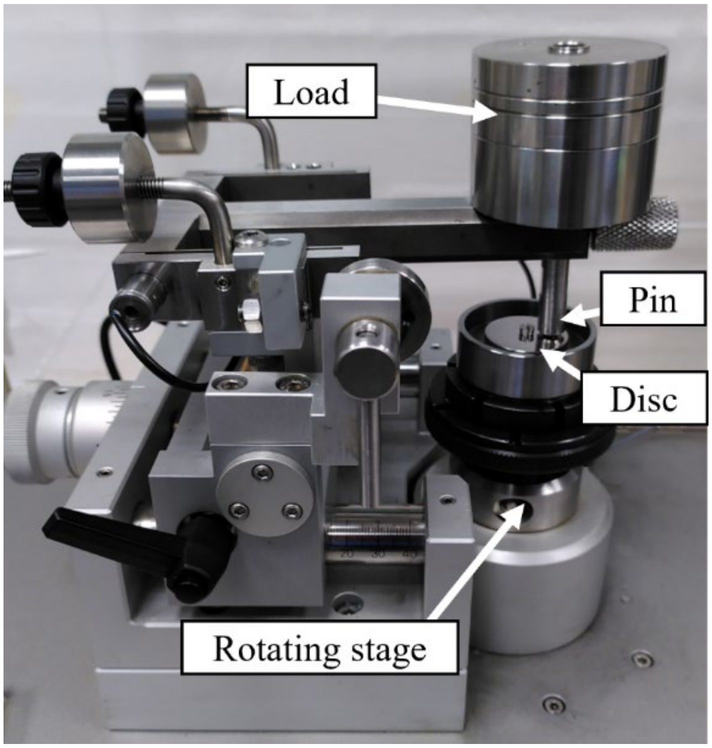
Particles. Some of the properties of the particles used in this work, given in supplier datasheets, are shown in Table 1. The size of the particles is similar, with the SiO_2 particles being slightly larger but in the same range. The hardness of the particles is given on the Mohs-scale which shows that the $CaCO_3$ particles are softest, the $BaSO_4$ being slightly harder and the SiO_2 particles being significantly harder. All particles used in this work had a nodular shape, i.e., almost spherical.

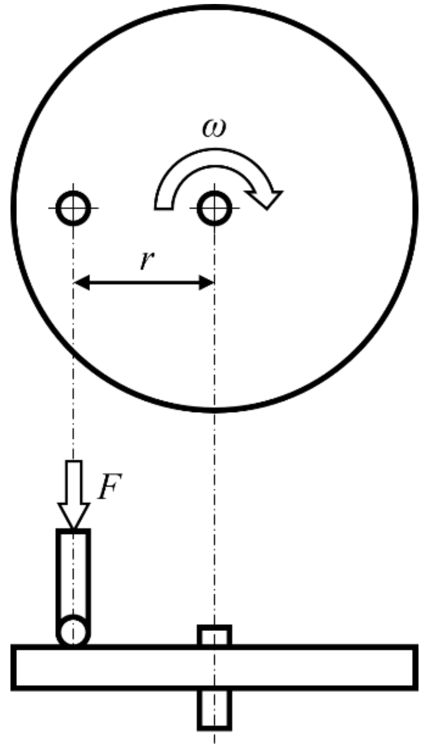
Table 1. Properties of particles used in this work.

Chemical formula	$CaCO_3$	$BaSO_4$	SiO_2
Commercial name	Polyplex 2	Portaryte® B 10	Silverbond M500
Particle size D10% [µm]	~ 0.4	0.8	2.2
Particle size D50% [µm]	2.0 - 2.6	2.6	5.0
Particle size D90% [µm]	~ 5.4	8.2	11.7
Hardness [Mohs]	3.0	3.5	7.0
Bulk density [g/cm^3]	0.8	1.7	0.42
Oil absorption [g/100ml]	17.4	10	23
Source	[12]	[13]	[14]

The lubricant mixtures tested in this work are derived from base mixtures that contain the specific particle, Ph. Eur. grade paraffin oil as the base oil, and Tween60 as surfactant to allow proper and homogeneous dispersion of the particles in the base oil. The base mixtures were prepared in a similar way, involving first dissolving the surfactant in the paraffin oil using a Dispermat CV3-Plus high-speed dissolver, followed by adding the particles and dispersing them using the same high-speed dissolver. The resulting base mixture was then diluted by adding more paraffin oil to arrive at a lubricant mixture of a fixed nominal concentration. The lubricant mixture was then agitated before use to ensure proper dispersal of the particles in the base oil. The nominal concentrations of single particle types tested in this work are 10 wt%, 20 wt% and 40 wt%. They were prepared using a scale that has a resolution of 10 mg, leading to the uncertainty of concentration being less than 1% of the nominal concentration.

Tribological Testing. Pin-on-disc testing involves placing a pin into contact with a rotating disc under some load, as shown in Fig. 1. Also shown in the figure is the specific testing machine used in this work, which is a standard *CSM Instruments Tribometer*. The tribometer has a built-in force transducer that measures friction load, allowing the device to calculate the friction coefficient based on the applied load. In this work the pin-on-disc test was performed according to DIN 50324:1992 for testing of friction. Two loads were applied, 1 N and 10 N, to investigate how the difference in load affects the tendency of the particles for being embedded in surfaces and affecting friction in that way. The disc component used in this testing is made from *Vanadis 4E*, a tool-steel from *Uddeholm* that has been ground and polished to a surface roughness of Ra = 0.06 µm after hardening to 62 HRC. The pin component consists of a ball-holder and a ball, which is made from EN 1.4301 steel, with a hardness of 25 HRC, grade G100 and diameter Ø6 mm. The amplitude of roughness of surfaces that were in contact was therefore much smaller than the particle size for all particle types. A fresh part of the discs and an unused ball were used in each test.





(a) (b)

Fig. 1. (a) Standard CSM Tribometer with pin-on-disc configuration. (b) Principle of the pin-on-disc test.

Test parameters, besides applied load and track radius, were kept constant through all tests. The sliding speed was set to 50 mm/s, with the total sliding distance being 100 m. The track radii were in the range 8 mm – 14 mm with the rotational speed being adjusted based on the track radii so that the linear sliding speed was constant. The amount of lubricant-particle mixture used in each test, 7 ml – 10 ml, was enough to submerge the disc component to a depth of at least 5 mm. The approximate kinematic viscosity of the mixtures used in this work is on the order of 200 ± 100 cSt, so according to the Hersey-number of the system, the boundary lubrication mechanism is dominant. Each test condition, i.e., particle concentration and type of particle, was repeated three times to account for reproducibility.

Four-ball testing involves establishing sliding contact conditions between three balls that are fixed in place and one ball that rotates under some load, as shown in Fig. 2. Also shown in the figure is the testing machine used in this work, which was custom-built for the Technical University of Denmark. In this work, four-ball testing was performed as a wear test as defined in the ISO 20623:2018 standard, applying a load of 300 ± 5 N or condition C2. The test was performed over a period of 3,600 ± 1 seconds at a constant rotational speed of 1,420 ± 20 rpm. For each test, a fresh set of 100Cr6 chromium steel bearing balls of hardness 60 HRC - 66 HRC, Ø12.7 mm, and grade G20, were used as test balls. 10 ml of lubricant were used in each test, ensuring that the balls were covered to a depth of at least 5 mm. This test enables the determination of how the presence of particles of different hardness in the lubricant affects the wear resistance properties of the lubricant under boundary lubrication conditions. A further two load levels, 150 N and 450 N were applied for a 10 wt% concentration of particles to see how the load level affects the particle behaviour. Each test condition, i.e., particle concentration, type of particle and load level, was repeated three times to account for reproducibility.

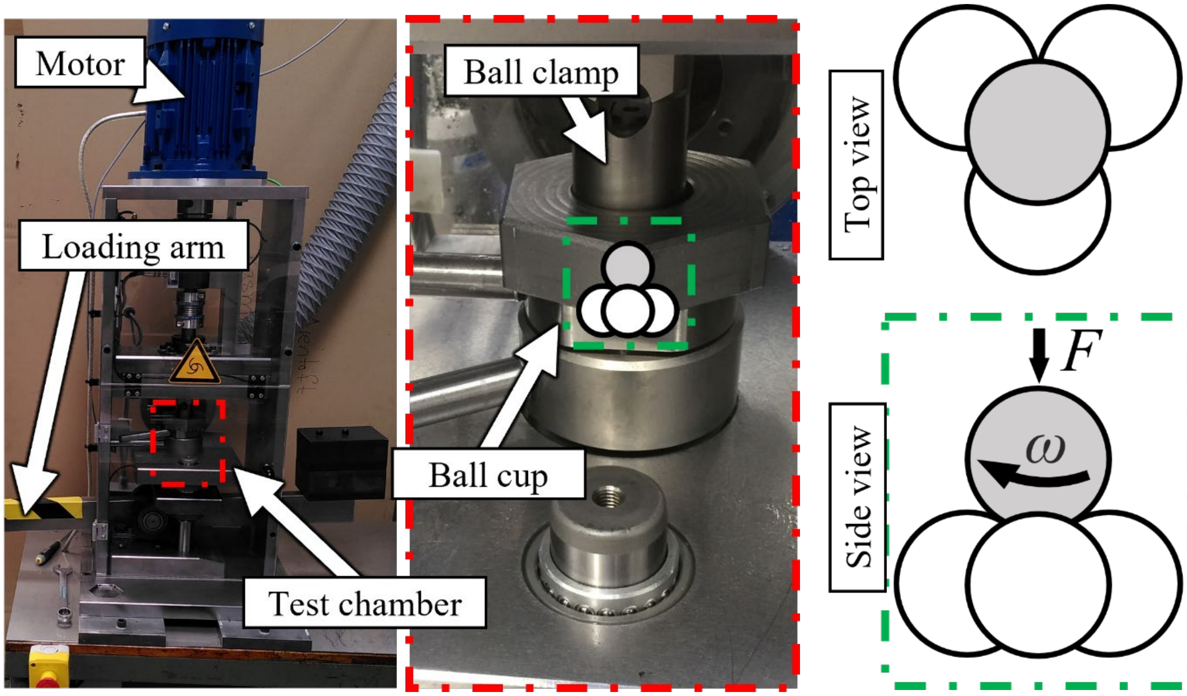
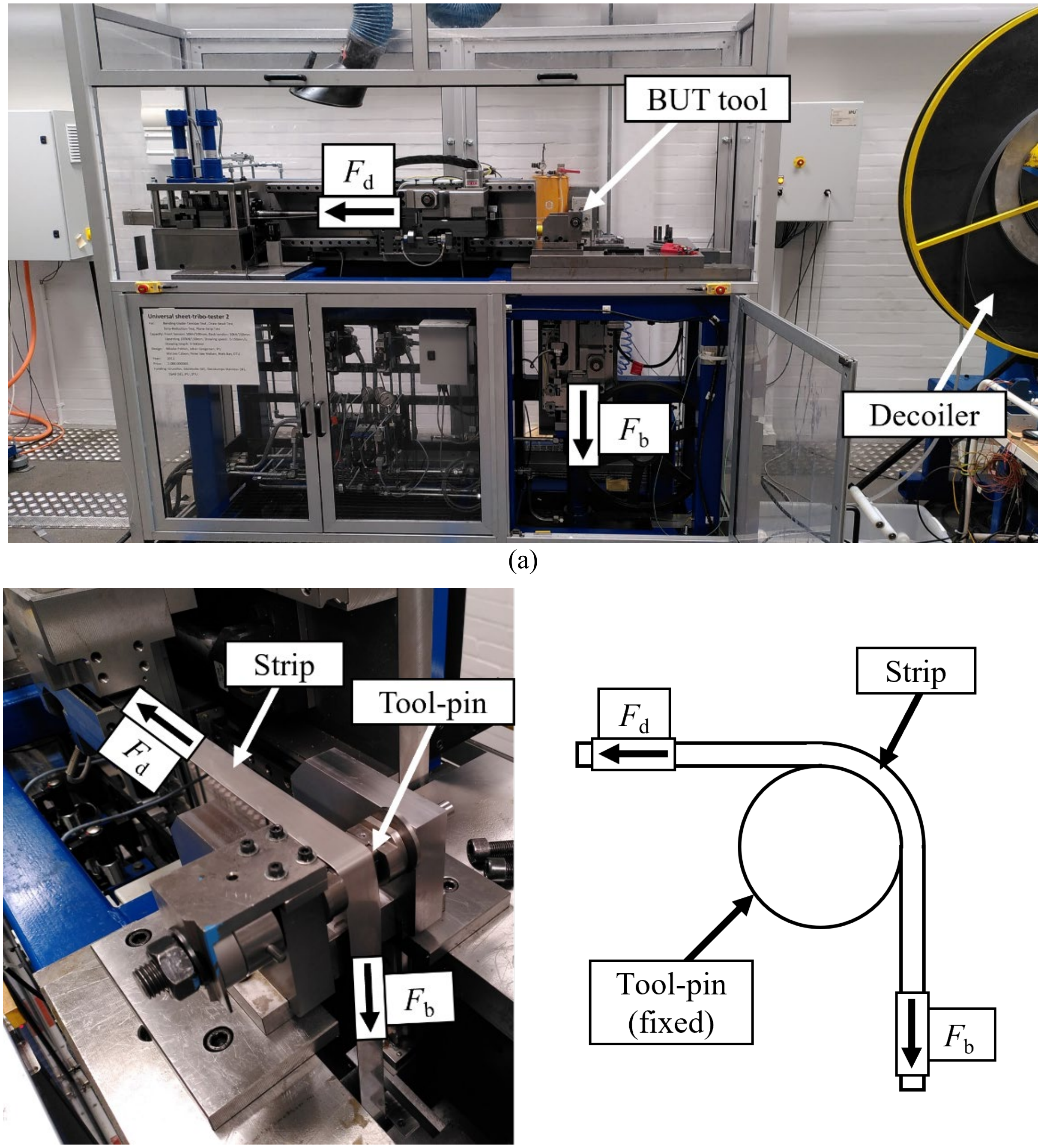


Fig. 2. (a) Four-ball testing machine including close-up of test chamber. (b) Principle of four-ball test.

Bending-under-tension testing was applied as a simulation of a deep drawing process to investigate how the different particles behave in a tribological system that is typically found in industrial sheet metal forming. The principle of the test revolves around bending a strip over a tool-pin under back-tension, as shown in Fig. 3. The difference between the back-tension force, F_b, and the drawing force, F_d, will then be due to the force required to deform the strip and friction. As the force required to deform the strip is nearly constant, then any increase in drawing force will be caused by an increase in friction in the tool-pin/strip interface. The nominal concentration of 20 wt% particles suspended in paraffin oil was applied here. The tool-pins were made from *Vanadis 4E* tool-steel hardened to 62 HRC and polished, while the strip was EN 1.4301 stainless steel with a 2B surface finish and a 30 mm x 1 mm cross-section. The edges of the strip are harder than the middle due to strain-hardening from roller cutting. A back-tension of 180 MPa ± 10 MPa was applied across 50 strokes, the sliding length of which was set to 30 mm. The sliding speed was 30 mm/s, with an idle time of 0.5 s between strokes which meant that the production rate was 40 strokes/min. Each test was repeated so that two data-sets exist for each test set-up.



(a)

(b) (c)

Fig. 3. Bending-under-tension (BUT) test shown by (a) an overview of the testing machine, (b) a close-up of the testing area, and (c) the principle of the test.

Optical Methods. An Olympus LEXT 4000 laser confocal microscope was used to capture images of wear scars on pin-on-disc discs, four-ball specimens and BUT tool-pins. Captured images were then processed in SPIP, an image processing software. Fig. 4(a) shows a typical disc after pin-on-disc testing, and the location of where images are taken of the wear scars on its surface. Fig. 4(b) shows a typical wear scar found in four-ball testing, along with where its parallel and perpendicular diameters are measured. Reported wear scar diameters are averaged between the two measurements. Fig. 4(c) shows the acquisition strategy employed for acquiring images of the surfaces of tool-pins used in BUT testing. The middle region of wear scars is imaged.

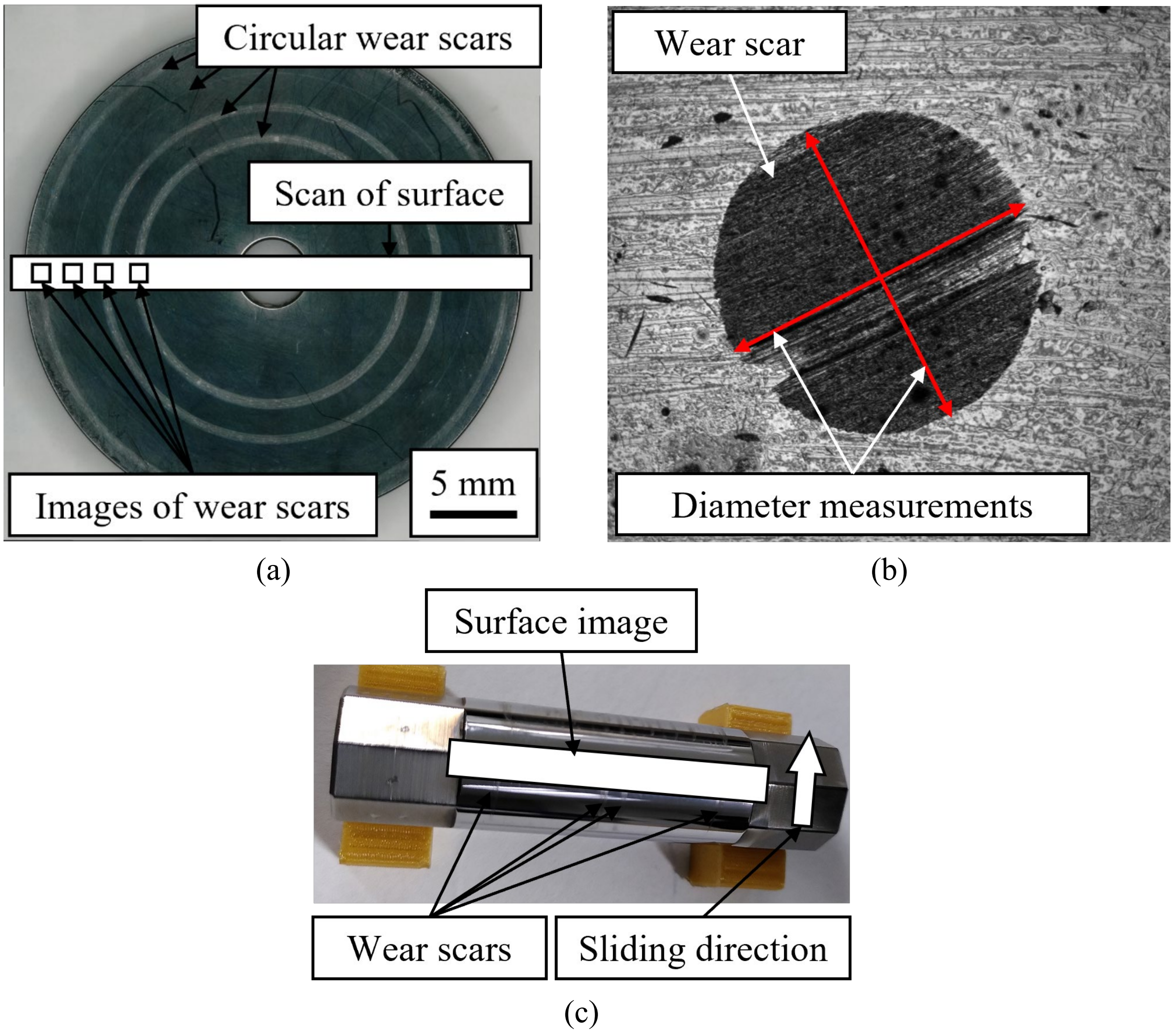


Fig. 4. Explanation of (a) acquisition of images of wear scars from pin-on-disc testing, (b) measuring of wear scars on four-ball specimens, and (c) acquisition of images of wear scars from tool-pin after bending-under-tension testing.

Results

Pin-On-Disc Testing. The influence of the particles on friction was estimated through pin-on-disc testing. The average friction coefficient is determined from the resulting friction profile, and all data-points from each test load are plotted together for comparison and shown in Fig. 5.

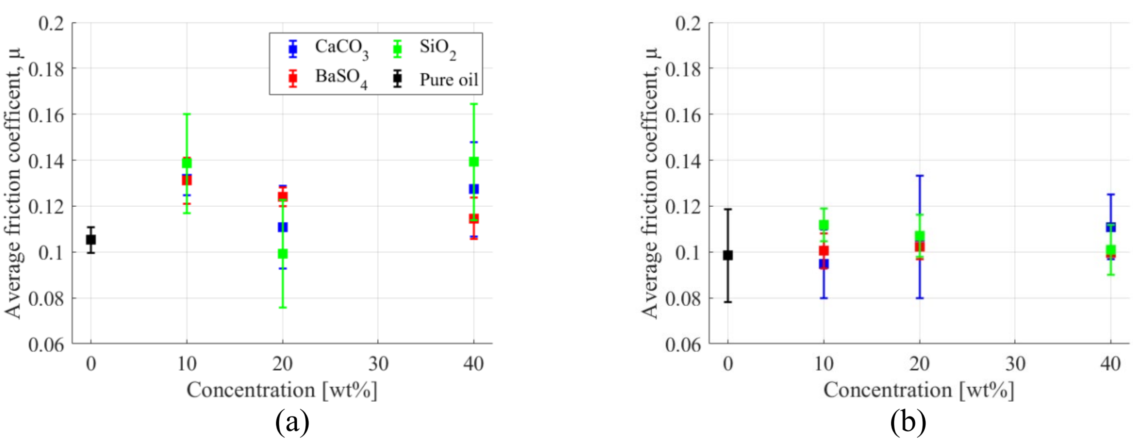


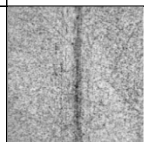
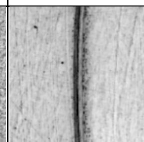
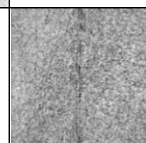
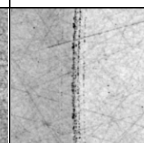
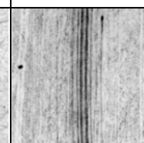
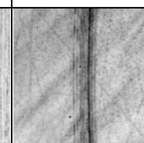
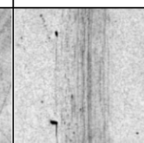
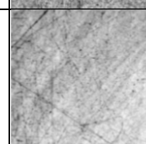
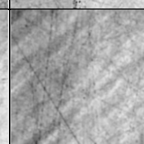
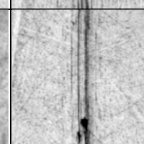
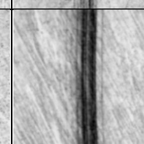
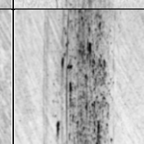
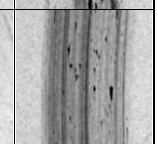
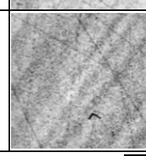
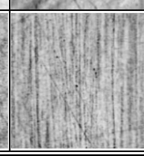
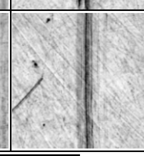
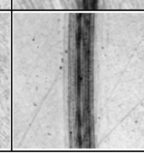
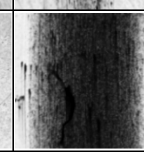
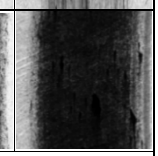
Fig. 5. Average friction coefficient found in pin-on-disc tests for (a) 1 N load and (b) 10 N load. Error bars denote standard deviation of data-set.

No influence by the particle type on friction could be found in the range of loads tested here. Further, compared to the pure oil, friction was not changed much by adding particles to the system. The wear scars that formed on the surface of the discs were, however, very different. Typical examples of the wear scars are shown in Table 2, where wear scar images were taken so that the centre of the disc was to the right of the wear scar. The wear scars from SiO_2 particles were clearly the most pronounced, the size of the wear scar increasing with the concentration of the particles. The $BaSO_4$ particles also showed severe wear scars compared to the pure oil, at least for higher concentrations, which showed very little wear. Applying $CaCO_3$ particles of a small concentration led to a reduction in the size of the wear scar. This effect was emphasized for increasing concentration of $CaCO_3$ to the point that no wear scar could be detected for 20 wt% and 40 wt% concentrations of $CaCO_3$. The applied load did not have much effect on the development of wear when particles were included, although it did increase wear in all cases.

Four-Ball Testing. Two sets of tests were performed using the four-ball configuration, varying either the concentration of particles in the mixture for a constant load, or varying the load for a constant concentration. The results of the former are shown in Fig. 6, whereas the latter is shown in Fig. 7. The wear scar diameter found in the four-ball tests clearly changed as function of particle concentration. For the SiO_2 particles, the wear scar diameter increased compared to the pure paraffin oil and then continued to increase for an increasing concentration of particles. The wear scar for the $BaSO_4$ particles of 10 wt% concentration was smaller than for the pure oil, but then increased with increasing concentration to a similar level as the pure oil. Wear scars found on balls used with $CaCO_3$ particles decreased in size compared to pure oil and were then stable for an increasing concentration of particles.

For changing loads, the behaviour was somewhat different. For the pure oil, as might be expected, the wear scar diameter increased with increasing load as there are no boundary additives included. Including particles prevented this increase, at least somewhat, reducing how much the wear scar diameter increased with increasing load. For a small load, the $CaCO_3$ and $BaSO_4$ particles showed a similar wear scar diameter as the pure paraffin oil. The wear scar diameter increased less with increasing load when these particles were included compared to the pure oil. This is similar to what Ji et al. [15] found for nano particles of $CaCO_3$ under four-ball test conditions in a range of loads using lithium grease as the base lubricant. They explained that for lower loads, the particles behaved based on the ball-bearing mechanism, but that as the load is increased and shearing of the surface becomes more likely, the surface energy of sheared surfaces causes a tribochemical reaction and leads to a boundary layer forming on the worn surface. The SiO_2 particles caused wear for small loads, but then prevented it from growing as the applied load is increased. This is likely due to the particles causing extreme wear in the beginning until the contact pressure is decreased enough that the particles could no longer penetrate the surface of the balls, and instead start to only act in a way that separates the surfaces.

Table 2. Typical wear scars found in pin-on-disc testing using the different particles.

Particle	None		$CaCO_3$		$BaSO_4$		SiO_2	
Load	1 N	10N	1 N	10 N	1 N	10 N	1 N	10 N
0 wt%			-	-	-	-	-	-
10 wt%	-	-						
20 wt%	-	-						
40 wt%	-	-						
0.5 mm								

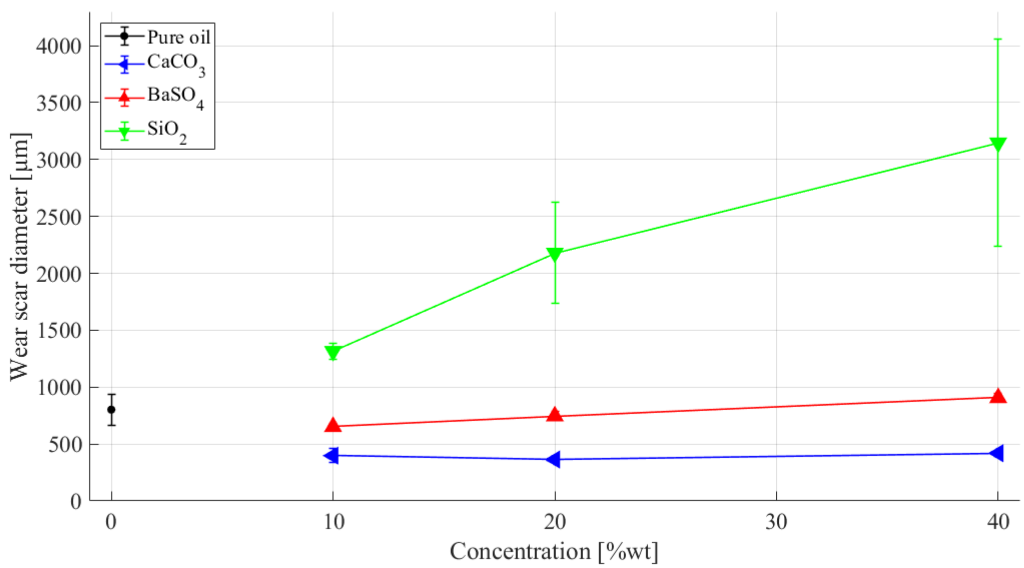


Fig. 6. Wear scar diameters from four-ball testing for different concentrations of particles for load of 300 N. Error bars are plus-minues one standard deviation of measured wear scar diameters.

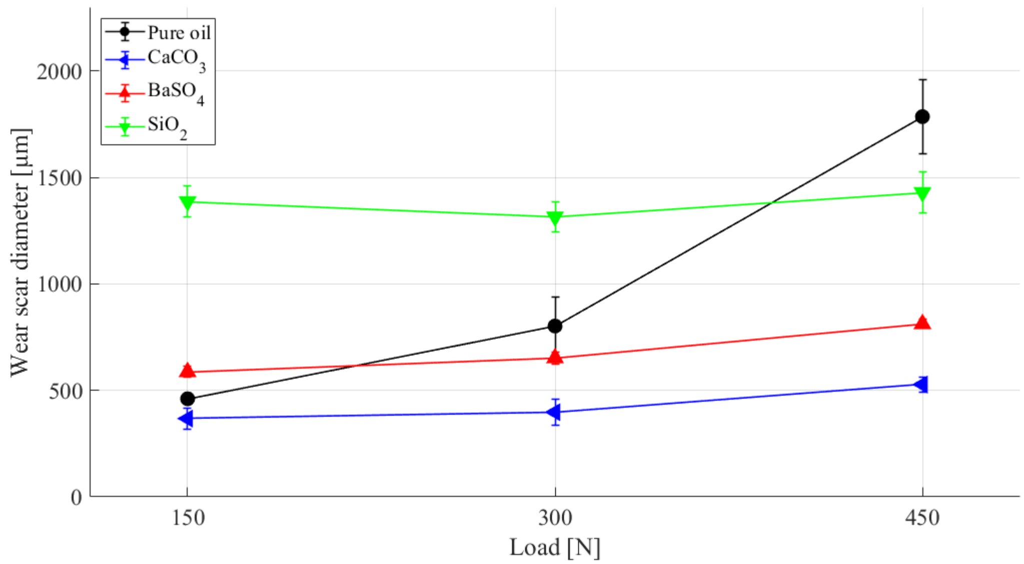


Fig. 7. Wear scar diameter from four-ball testing as a function of applied load for a constant 10 wt% particle concentration. Error bars are plus-minus one standard deviation of measured wear scar diameters.

Bending-Under-Tension Testing. Drawing force, F_d, profiles from BUT testing are shown in Fig. 8. The drawing force was influenced by the presence of particles and the particle type. For the pure oil (PO), pick-up quickly started to occur, leading to a steady increase in the drawing force until the end of the test. Including $BaSO_4$ particles showed a similar development of the force profile, although the force increased less. Including SiO_2 particles led to a quicker increase in force, indicating more severe conditions. The $CaCO_3$ particles showed only a small increase in force across the 1500 mm sliding length, indicating that they are beneficial to the wear resistance properties of the lubricant.

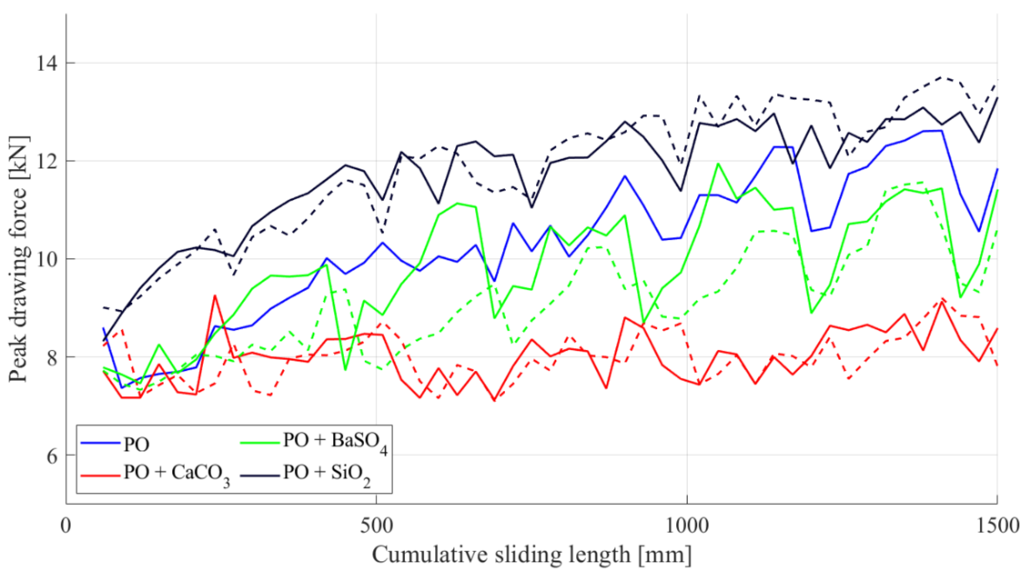
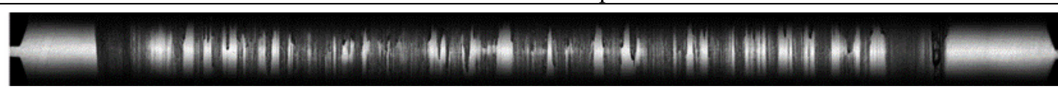
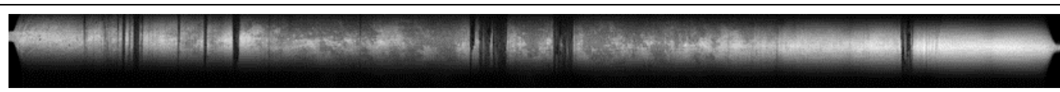
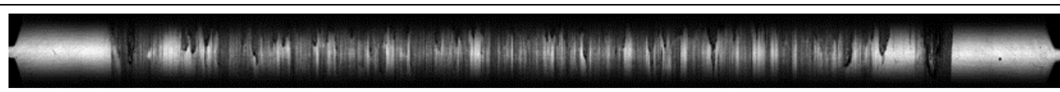
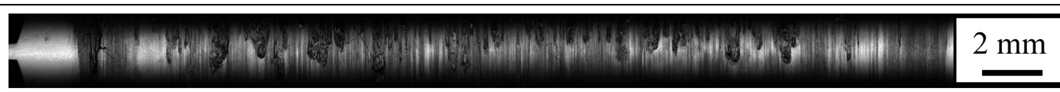


Fig. 8. Drawing force measured in BUT testing. Solid lines and dashed lines of the same colour are repetitions of the same test conditions. The concentration of particles was 20 wt%.

Images of the surfaces of selected tool-pins were captured and are shown in Table 3. The pure oil exhibited a high tendency for pick-up as can be seen on the surface of the tool-pin, which is consistent with the observations of the drawing force. The $CaCO_3$ particles prevented this and led to less wear on the tool-pin surface. The $BaSO_4$ particles helped in reducing wear, but the surface of the tool-pin ended up looking comparable to that of the pure oil. The SiO_2 particles clearly led to much more pick-up, potentially due to localised wear scars causing more favourable conditions for pick-up, or even heating up of the tool-pin near the surface.

Table 3. Surfaces of tool-pins used with different particles of 20 wt% concentration. The drawing direction is from bottom to top of figures. Solid profiles shown in Fig. 8 belong to the surfaces shown here.

Particles	Surface of tool-pins
None	
$CaCO_3$	
$BaSO_4$	
SiO_2	

Summary
Including particles in a tribo-system, either accidentally or intentionally, has a large effect on the wear development of the tribo-system. The hardness of the particles is a clear factor in how the particles affect the tribo-system, with harder particles increasing wear and softer ones inhibiting it through surface separation without surface penetration. Based on the results of this work, the following conclusions are drawn:

- Inclusion of particles of any hardness, in the force and concentration range tested here, had little to no effect on the coefficient of friction measured in pin-on-disc testing.
- The hardness of particles included in a tribo-system has a large effect on the development of wear in the tribo-system. A higher particle hardness leads to more severe wear.
- Including any particles in a tribo-system makes the system more robust in the face of varying loads. For a pure paraffin oil, wear readily increases with increasing load, but including particles reduced this effect, in the range tested here.
- The particle hardness was important for tribo-systems that include sheet metal forming conditions. High hardness, such as for the SiO_2 particles, lead to increased abrasion and more wear. The $BaSO_4$ did not change conditions much compared to the pure oil, at least not in terms of wear. The $CaCO_3$ particles promoted rolling of the particles as surface penetration was not possible and reduced wear compared to the pure oil.

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References

[1] B. Seidel, D. Meyer, Influence of artificial aging on the lubricating ability of water miscible metalworking fluids, Prod. Eng. 13 (2019) 425–435. https://doi.org/10.1007/s11740-019-00891-6
[2] M.R. Sari, A. Haiahem, L. Flamand, Effect of lubricant contamination on gear wear, Tribol. Lett. 27 (2007) 119-126. https://doi.org/10.1007/s11249-007-9215-z.
[3] T. Kjer, Wear rate and concentration of wear particles in lubricating oil, Wear 67 (1981) 217. https://doi.org/10.1016/0043-1648(81)90105-8
[4] Q.Y. Jiang, S.N. Wang, Abrasive wear of locomotive diesel engines and contaminant control, Tribol. Trans. 41 (1998) 605-609.
[5] H.H. Abou El Naga, A.E.M. Salem, Effect of worn metals on the oxidation of lubricating oils, Wear 96 (1984) 267-283. https://doi.org/10.1016/0043-1648(84)90041-3
[6] U. Olofsson, Y. Zhu, S. Abbasi, R. Lewis, S. Lewis, Tribology of the wheel-rail contact-aspects of wear, particle emission and adhesion, Vehicle System Dynamics 51 (2013) 1091-1120. https://doi.org/10.1080/00423114.2013.800215
[7] T. Luo, X. Wei, X. Huang, L. Huang, F. Yang, Tribological properties of Al2O3 nanoparticles as lubricating oil additives, Ceram. Int. 40 (2014) 7143-7149. https://doi.org/10.1016/j.ceramint.2013.12.050
[8] J. Padgurskas, R. Rukuiza, I. Prosyčevas, R. Kreivaitis, Tribological properties of lubricant additives of Fe, Cu and Co nanoparticles, Tribol. Int. 60 (2013) 224-232. https://doi.org/10.1016/j.triboint.2012.10.024
[9] Y. Li, Y. Chen, P. Gao, B. Zhong, F. Ai, L. Li, Y. Xiao, Research on influence of abrasive particles on lubricating performance of the emulsion for cold rolling strip, in: Proceedings of Chinese Materials Conference 2017, 2017, pp. 135-143. https://doi.org/10.1007/978-981-13-0107-0_13
[10] Ú. Arinbjarnar, M. Moghadam, C.V. Nielsen, Application of Calcium Carbonate as Green Lubricant Additive in Sheet Metal Forming, Key Eng. Mater. 926 (2022) 1133-1142. https://doi.org/10.4028/p-x87o62
[11] D.X. Peng, C.H. Chen, Y. Kang, Y.P. Chang, S.Y. Chang, Size effects of SiO2 nanoparticles as oil additives on tribology of lubricant, Ind. Lubric. Tribol. 62 (2010) 111-120. https://doi.org/10.1108/00368791011025656
[12] Calcit, PolyPlex 2, Calcit d.o.o., Stahovica, Slovenia, Jan. 2014. Available online: https://www.calcit.si/assets/PDF/ANG_SPLOSNI_KATALOG_2020_PolyPlex.pdf
[13] Sibelco, Portaryte® B. Sibelco, Maastricht, Netherlands, Mar. 2013. Available online: www.sibelco-specialty-minerals.eu
[14] Sibelco, Silverbond M500. Sibelco, Dessel, Belgium, Oct. 01, 2016. Available online: www.sibelco.eu
[15] X. Ji, Y. Chen, G. Zhao, X. Wang, W. Liu, Tribological properties of CaCO3 nanoparticles as an additive in lithium grease, Tribol. Lett. 41 (2011) 113-119. https://doi.org/10.1007/s11249-010-9688-z