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Article

Application of $CaCO_3$ as Anti-Friction Lubricant Additive to Improve Robustness in Sheet Metal Forming of High-Strength Aluminum

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Abstract

High-strength aluminum is a good candidate for use in light-weighting applications, but forming it is difficult due to its low formability. Elevated temperatures are therefore necessary to improve formability, but this reduces lubricant performance. The use of calcium carbonate ($CaCO_3$) as a lubricant additive in warm- and hot-forming of high-strength aluminum is evaluated by strip-drawing tests at room temperature, 225°C and 425°C. Further, the influence of tool surface roughness on the performance of the particles in reducing friction is evaluated. Lastly, the particle-additivated oil is compared to fully formulated, commercially available warm- and hot forming oils. The results show that $CaCO_3$ particles are suitable for improving tribo-systems in warm- and hot-forming of aluminum, and that they can robustify processes where preparation and maintenance of tool surfaces is difficult as the tribo-system is less sensitive to the tool surface. The performance of the particle-additivated oil was similar to the commercial lubricants at room temperature and 225°C, but was worse at 425°C. However, due to the low cost and effort necessary to prepare the particle-additivated oil, it is a promising alternative to existing lubricant additives.

Keywords

tribology, warm forming, aluminum, lubricant additive, friction, solid particle, calcium carbonate

1 Introduction

High-strength aluminum is a promising material when constructing lightweight structures. However, they have low formability at room temperature and must therefore typically be formed using warm- or hot forming processes [1]. This raises challenges for the tribo-system, as lubricants are generally less effective at increased temperatures, or are not compatible with existing processes [2]. As with other aluminum alloys, the propensity for galling is high when forming high-strength aluminum even at room temperature [3]. Lubrication is therefore paramount in the forming of aluminum, warm, hot, or cold. Lubricants typically consist of a base-oil and additives, where the choice of these components and their respective concentrations constitute the formulation of the lubricant and enable its performance [4]. Lubricant formulations can be tailored to work under specific conditions [5], such as at elevated temperature or under extreme pressures, although this can necessitate the use of environmentally harmful additives such as chlorinated paraffins [6]. Suitable lubrication, realised through tailoring of lubricant formulation, can help mitigate galling, and reduce friction, thereby allowing the process limits to be extended [7]. Increasingly restrictive legislation is likely to limit the use of various lubricant additives [8], so the need for additives that do not cause concern is clear.

The use of solid particles as lubricant additives is increasing in modern lubricant formulations due to their effects on friction and wear [9]. The behaviour of particles with different average diameter in combination with a constant surface roughness of sliding partners is shown in Fig. 1. Generally, particles that are larger than surface valleys act to separate surfaces and thereby prevent metal-to-metal contact, whereas particles that are smaller fill up these valleys and homogenise contact pressure [10].

Temperatures used in warm and hot forming of aluminum are typically in the range of 200°C – 400°C, or high enough to improve formability and low enough to prevent grain growth. Lubricants used in these processes must therefore include components that allow the lubricant to perform well at these high temperatures. This is often accomplished through the use of additives, such as viscosity index improvers or antioxidants that help to keep the lubricant stable as the temperature increases [11]. The use of solid particles as lubricant additives has also been shown to improve anti-seizure performance [12] and stabilize the tribo-system [13]. The effect of including solid particles that are not affected by the temperature is illustrated in Fig. 2.

The change in particle behavior as function of surface

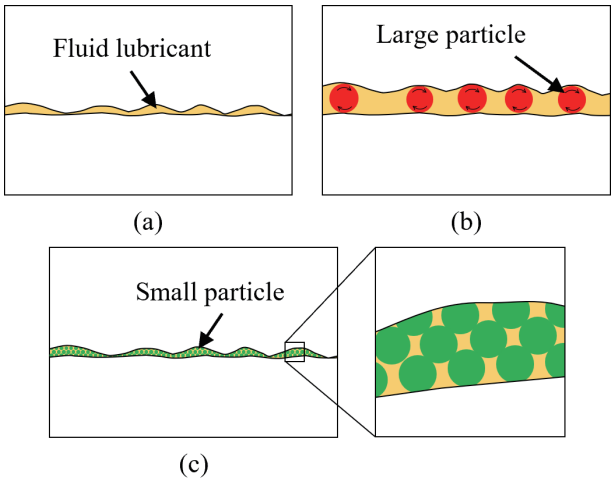

Fig. 1 Particle behavior shown by (a) tribo-system with no particles, leading to metal-to-metal contact, (b) tribo-system with large particles that separate the surfaces and promote rolling over sliding, and (c) tribo-system with small particles that artificially smooth the surfaces and distribute pressure more uniformly

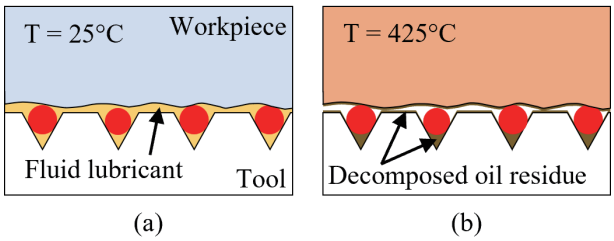

Fig. 2 Influence of varying temperature on lubricant that contains solid particles for a given surface of tool and workpiece shown by (a) room temperature at which both oil and particles contribute to friction reduction, and (b) at elevated temperature at which oil decomposes and partially evaporates and contributes less to friction reduction

roughness is illustrated in Fig. 3. When the surface roughness is larger than the particle size, valleys on the surface can contain more than one particle. Eventually, with increasing surface roughness, the particle performance effect is diminished as, for a given number of particles on the surface, they become less able to separate the surfaces. When the surface roughness is approximately equal to the particle size, which was found to be the ideal scenario by Shimotomai et al. [12], the particles are trapped in asperity valleys but as they are approximately equal in size to the valleys, they stick out. This allows the particles to separate the surfaces and prevents the particles from being wiped off the surface easily. It is likely that particles that are trapped in asperity valleys in this way are constrained from rotation due to the multiple contact points. The last case considered in this work is the case of the particle size being larger than the surface roughness. In this scenario, it becomes less likely that the particles will become trapped in asperity valleys. This leads to the particles being freer to rotate, reducing friction, but also leads to them being easier to wipe off the surface. This influence of surface roughness on particle behavior is shown in Fig. 3, assuming that the number of particles matches the number of asperity valleys on the surface.

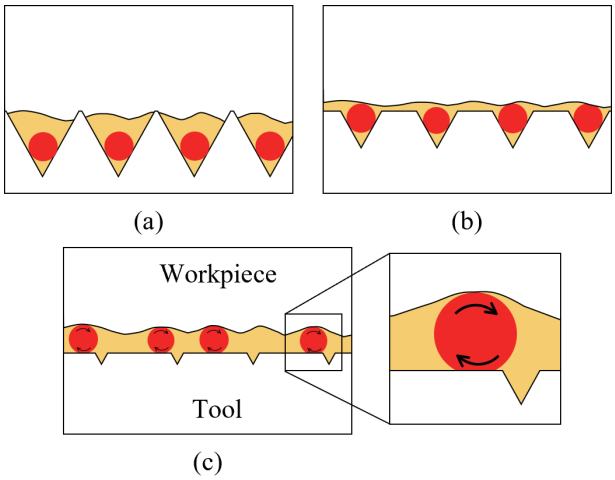

Fig. 3 Role of particles in lubrication for different tool surfaces: (a) Surface roughness is larger than particle size, (b) surface roughness is approximately equal to particle size, and (c) surface roughness is smaller than particle size

The particles used in this work, $CaCO_3$, are not affected much by the temperatures found in warm- or hot-forming of aluminum [14]. The particles are easily sourced, relatively soft and available in many average sizes [15]. More importantly, $CaCO_3$ is known to be environmentally benign and not harmful to humans [16] and is therefore not likely to be restricted in its use in this context by legislation. In this work, the performance of solid $CaCO_3$ particles used as lubricant additives for reducing friction in warm- and hot-forming of aluminum is evaluated and compared to existing, fully formulated lubricants using strip-drawing tests. The effect of tool surface preparation on the performance of the particles is also evaluated to highlight the underlying mechanisms of the particle behavior.

2 Materials and methods

The lubricant used in this work included paraffin oil as a base-oil. A base mixture of $CaCO_3$ particles (commerically known as PolyPlex 2 [17]) with an average diameter of 2 μm, and paraffin oil was diluted by adding more paraffin oil to arrive at a nominal mixture having a concentration of 40 mass% $CaCO_3$. The base mixture was prepared as part of other work [13], by first dissolving Tween60 [18] in paraffin oil at 1,900 rpm using a high-speed dissolver and then dispersing the particles in the oil mixture at 3,500 rpm to a concentration of more than 40 mass% $CaCO_3$. In all tests, approximately 10 g/m^2 of lubrication was applied to the tools and not the workpiece as this gives an indication of the resistance of the lubricant to being wiped off the tool. Further, lubricant applied to the workpiece would not withstand the high temperature over the heating period.

A strip drawing configuration with included heating unit was used in this work to evaluate the friction coefficient for a given set of parameters. This configuration is based on applying a known normal force (F_n) to a workpiece that is clamped between two tools. The workpiece is then drawn to impose sliding between the workpiece and tools, and the necessary drawing force (F_d) is measured. This is illustrated in Fig. 4, where the strip is first heated in the heating unit (a) and the heating unit then opened and the strip moved so that the heated region of the strip lies between the tools. The tools are then closed and a load is applied so that the nominal normal

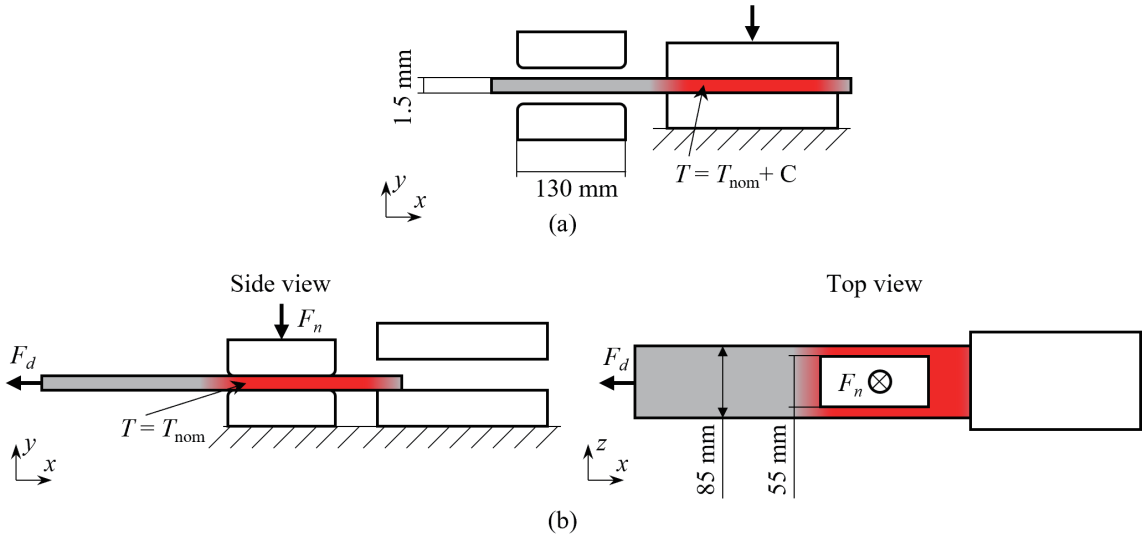

Fig. 4 Strip drawing test configuration in which (a) a region of the strip is heated up, and (b) normal pressure is applied prior to drawing

pressure is reached (b), and finally the strip is pulled to impose sliding between the strip and tools. Two series of tests were performed in this work, each test condition being repeated at least three times. A drawing speed of 100 mm/s, a drawing length of 80 mm, and a normal pressure of 3 MPa were used in all tests. Further details about the testing machine applied in this work are given by Schell et al. [2]. Workpieces used in all tests were 85 mm wide and 1.5 mm thick EN AW-7075 T6 in the as-delivered state. The initial surface of the workpiece was mill-finish, having a surface roughness of Rz = 1.85 μm ± 0.16 μm, with a defined texture along the drawing direction. The tools were made from Unimax tool steel from Uddeholm that had been hardened to 57 HRC prior to testing and surface modification. The contact face of the tools was 55 mm × 130 mm in size, giving a contact area of 7,150 mm^2. For some tests, aluminum was found to have been deposited on the surface of the tool. Whenever this occurred, the tools were treated with 15% sodium hydroxide to dissolve the aluminum. Before every test, the tools and workpiece were cleaned with acetone.

The first test series involved the evaluation of the influence of temperature on the performance of the particles. In these tests, the workpiece was heated up in a plate-heater up to a temperature that is slightly above the nominal test temperature. The temperature was measured at this stage by thermocouples integrated into the heating unit. The heated area of the workpiece was then transferred between the strip drawing tools, after which normal force was applied and the test proceeded as normal. The time necessary to transfer the workpiece from the heater and to the tools meant that the temperature of the workpiece was reduced. This was accounted for by heating the workpiece to a temperature slightly above nominal, allowing it to cool down to the nominal temperature in the test. The temperature immediately preceding test execution was not measured, but rather inferred based on previous mesaurements with a pyrometer by Schell et al. [2]. Three nominal temperatures were used in this work, 25°C, 225°C and 425°C.

The second test series involved the evaluation of the influence of tool surface roughness on the particle performance. Starting from the same tools as were used in the high-temperature test, which were ground perpendicular to the drawing direction, the tools were gradually polished to reduce the surface roughness in two steps, after which they had a mirror-like finish. This ensured that the general shape of the surface was consistent between tests. The tools were then ground coarsely perpendicular to the drawing direction to get a higher surface roughness but a similar overall texture as before, and finally sandblasted to get an even higher roughness. After sandblasting, the tools had a surface that was similar to coarse sandpaper, and did not include a defined texture due to the isotropic nature of the sandblasting process. The surfaces of the tools were imaged using a μSurf confocal microscope from Nanofocus after each modification, allowing for the characterisation of the surface roughness. Surface roughness was characterized across the surface texture, along the sliding direction applied in testing. The measured surface roughness is shown in Fig. 5, and a typical surface is shown in Fig. 6 for the different states. The surface of tools used for trials in which temperature was varied is shown in Fig. 6(c), having a fine ground finish.

Lastly, the effectiveness of the particle-additivated oil in reducing friction was compared to fully formulated, commercially available forming lubricants. Some properties of the lubricants that were used in this work are given in Table 1. The commercial lubricants are formulated for use in warm conditions, either as release agents or specifically as warm-/hot-forming lubricants.

3 Results and discussion

3.1 Influence of temperature

As the tools were lubricated rather than the workpiece, the temperature of the oil did not start to increase until contact was established. When this happened, due to the small amount of oil on the surface, it can be assumed that the temperature of all of the oil increased rapidly before sliding began. As the temperature of the oil increases, its viscosity decreases, and it starts to evaporate and decompose. This affects the lubricity of the oil, degrading its performance in friction reduction. The particles are affected less, with potential changes being limited to a reduction in particle hardness and an increase in compressibility. This will have minimal effect on the capability of the particles to reduce wear/friction in the system. The results of testing at three temperatures, 25°C, 225°C and 425°C, are

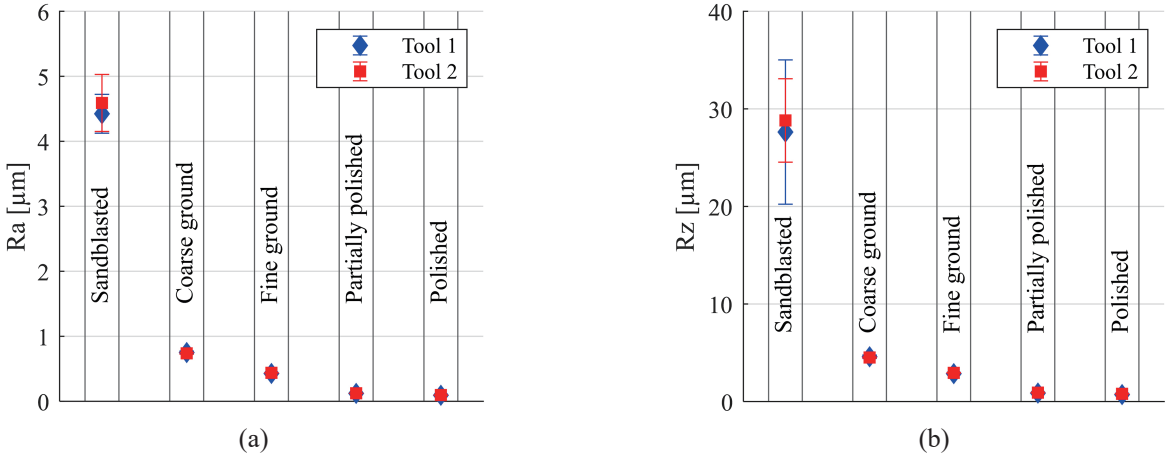

Fig. 5 Surface roughness of tools for given preparation strategies measured in (a) Ra value and (b) Rz value

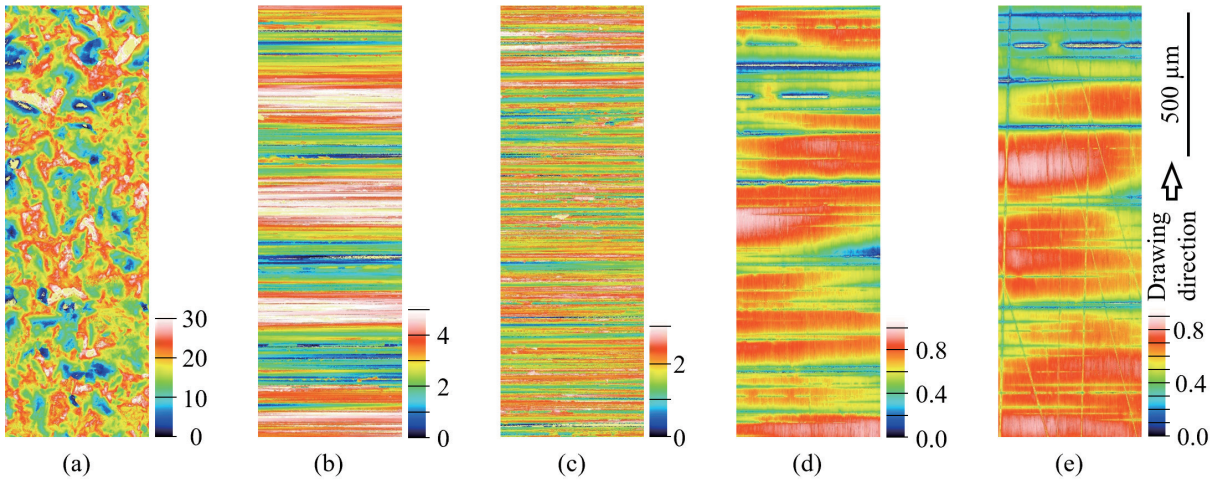

Fig. 6 Surface of tool after (a) sandblasting, (b) coarse grinding, (c) fine grinding, (d) partial polishing, and (e) further polishing. Scale bars have units of µm

Table 1 Properties of lubricants applied in this work

Lubricant	Base fluid	Description
Oil with particles	Paraffin oil	Mineral oil with surfactant and solid $CaCO_3$ particles
MECHANO-LUBE® 6D1 (BN dispersion)	Water	Water based boron nitride dispersion [19]
MECHANO-LUBE® 1VP574 (Gr dispersion)	Water	Water based graphite dispersion containing special releasing aid [20]
Putrol NW V 1933-30 N-1 (Drawing oil)	Mineral oil	Special drawing oil for aluminium and copper alloys [2]

shown in Fig. 7. Comparing any solid line from a test using pure oil to the corresponding dashed line from a test using a particle-additivated oil shows that including 40 mass% of particles in the lubricant drastically improved the capacity for friction reduction. As the lubricant was applied to the tool rather than the workpiece, it was wiped off as the workpiece was drawn through the tools. This resulted in a gradual increase in friction as the lubricant was wiped off for both the pure oil and the particle-additivated oil. Purely considering friction, one would therefore look at the initial few millimeters of sliding, which shows that the friction of the tribo-systems that included particles is consistently lower than of those that did not include particles. At the highest test temperature, the workpieces used with pure oil fractured, whereas those that were used with particle-additivated oil did not. This shows that the particles can help prevent seizure as they separate the surfaces, even if they

are not supported by the oil. Increasing the temperature applied in the test also led to an increase in adhesive transfer from the workpiece to the tool in both cases, although this was more apparent for the pure oil, where the surface of the workpiece was also extensively scratched. This further showed that the chance of seizure can be reduced by including solid particles in the lubricant formulation.

3.2 Influence of surface roughness

The rougher the tool surface was, especially when asperity valleys were deeper or asperity peaks higher, the ability of the particles to separate surfaces decreased. The results of testing with different tool surfaces are shown in Fig. 8(a), with Fig. 8(b) showing a close-up of the profiles at low levels of friction. Considering first the solid lines, showing tests performed with pure oil, the friction decreases as the surface roughness becomes smaller. This is due to the more uniform distribution of pressure leading to less localized friction, less ploughing and plastic deformation of the workpiece surface. As the surface roughness was increased, localized pressure peaks started

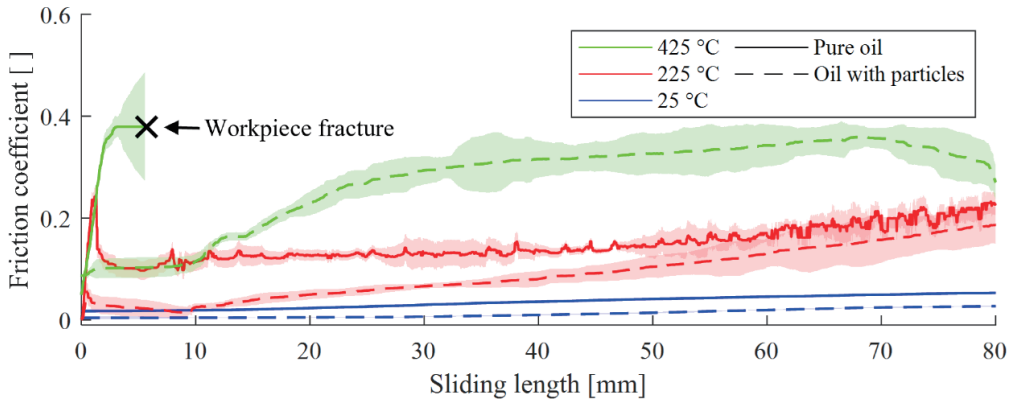

Fig. 7 Friction coefficient for tests performed with workpieces at different temperatures and lubricants with and without particles. Tools used in these tests had a fine ground surface, shown in Fig. 5(c).

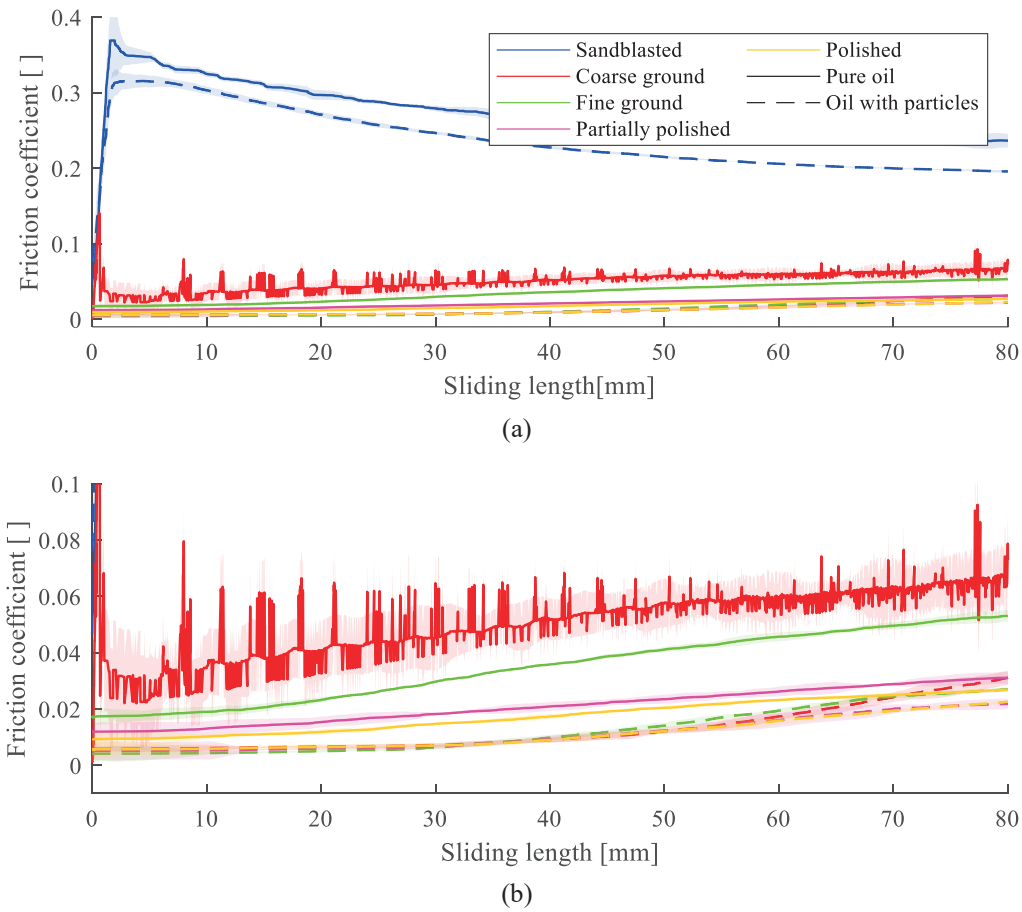

Fig. 8 Results from friction testing shown by (a) all data and (b) close-up of lower friction level to highlight differences. Legend is consistent for both figures.

to occur, which increased the overall measured friction. The pressure peaks resulted in increasing transfer of aluminum to the tool surface in localized areas. Considering now the tests performed using different tool surfaces with particles shows that the influence of the roughness on friction is negligible until the extreme roughness of the sandblasted surface was reached. This shows that, as long as the surface valleys are not too deep or asperity peaks too tall, the particles perform in the same way. Even for the extremely rough surface, the friction measured using the particle-additivated oil was smaller than that of the pure oil, indicating that the particles are still working to reduce friction, likely through artificial surface mending. The transfer of aluminum to the tool surface when including particles was reduced compared to that found when using pure oil for all surfaces, although signs of transfer were still clear when applying the sandblasted surface. This shows that the $CaCO_3$ particles are useful in applications where preparing tool surfaces to a certain standard is difficult and improves the robustness of the system in the face of wear-induced surface changes as the friction is not affected much.

3.3 Comparison to commercial lubricants

Figure 9 shows a comparison between the particle-additivated oil and commercially available warm forming lubricants, tested by Schell et al. [2], at different temperatures. It should be noted that the surface of the tools used in tests involving the particle-additivated lubricant are in the fine ground state, having a surface roughness of approximately Rz = 3.0 μm, whereas the tools used for the commercial lubricants are closer to the polished state, having a surface roughness of approximately Rz = 0.44 μm. As shown in Figs. 8(a) and (b), surface roughness has very little effect on the frictional behavior of the particle-additivated oil, so the influence of surface roughness on the comparison shown in Fig. 9 should be minimal.

The particle-additivated oil showed a similar performance to the drawing oil in reducing friction at room temperature, with the average friction being well below 0.1. The Gr and BN dispersions showed a considerably higher friction as they are not thermally activated at that temperature. As the temperature is increased, the particle-additivated oil is less effective than the drawing oil but shows a similar behaviour to the Gr dispersion. The effectiveness of the particle-additivated oil degrades further as the temperature is increased further, so that it shows the highest friction of the tested lubricants at a temperature of 425°C. This shows that the fully formulated, commercial lubricants are better for use in warm- or hot forming than the particle-additivated oil. However, the low effort necessary to formulate the particle-additivated oil compared to its performance shows that there is potential in using $CaCO_3$ particles in warm- and hot forming. This is especially the case when comparing directly to the boron nitride dispersion, as boron nitride particles are considerably more expensive than an equivalent weight of $CaCO_3$ particles.

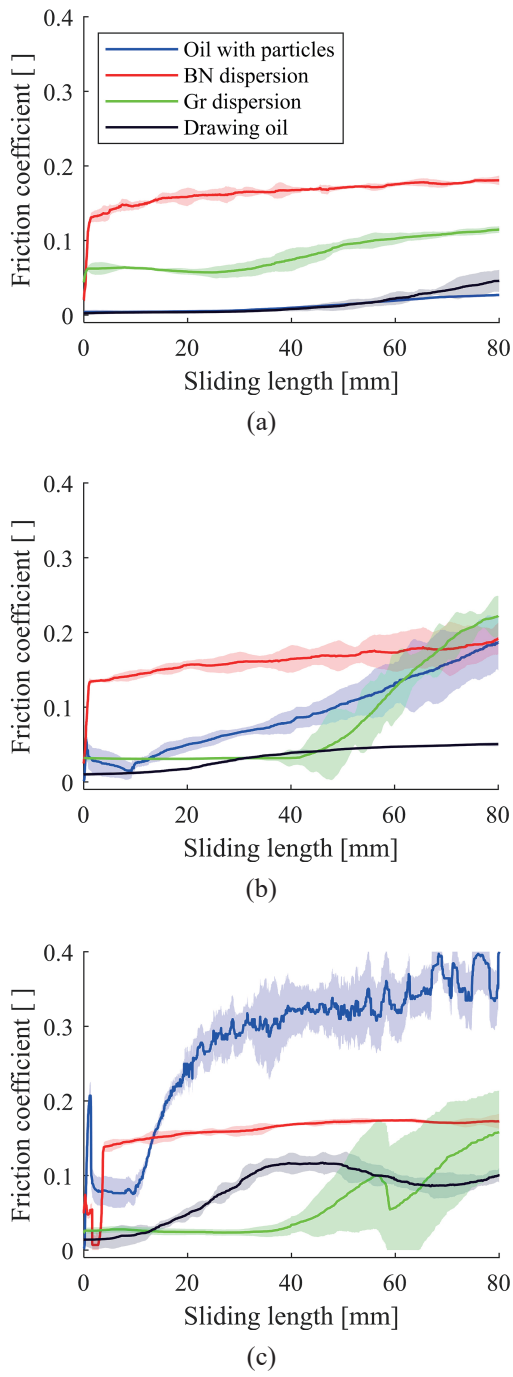

Fig. 9 Results of strip-drawing tests for different lubricants at (a) room temperature, (b) 225°C, and (c) 425°C. Data for commercial lubricants are taken from [2]. The legend shown in (a) is consistent for (b) and (c).

4 Conclusions

The performance of paraffin oil with and without $CaCO_3$ particles was tested in strip-drawing tests at different temperatures and for different tool surfaces. Based on the results presented in this work, the following conclusions can be drawn:

- The use of $CaCO_3$ particles as a lubricant additive is suitable to improve the capacity of paraffin oil for friction reduction at medium to high temperatures. Further, it is suitable as an anti-seizure additive.
- The use of solid particles in lubricant formulation means that the surface roughness of the tool affects friction less. The tools therefore do not have to be fully polished to minimize friction and will be more robust to surface changes due to wear. As long as particles are allowed to enter the contact interface, they artificially smooth contacting surfaces and promote rolling over sliding, thereby reducing friction. This can help to homogenize friction across surfaces and improve system robustness.

- The particle-additivated paraffin oil had a lower performance in friction reduction compared to fully formulated oils that are designed for warm- and hot forming. However, the results show that $CaCO_3$ particles are promising as components of warm- and hot forming lubricants.
- $CaCO_3$ may be applied in cases where post-processing of tools is difficult, or where elevated temperatures are used. Rough tool surfaces would lead to scratches on workpieces anyway, which can be reduced by use of particle-additivated lubricant.

Future work on the topic of correlating surface roughness to performance of the particle additive could include microscopy analysis of a surface that is saturated by particles. Applying the same amount of particle-additivated lubricant to surfaces having varying surface roughness should then lead to a difference in the real contact area, which could explain how the particles behave in the contact interface.

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