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Effect of process parameters on friction in aluminum sheet forming

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Abstract. The bending under tension (BUT) test is used to mimic aluminum sheet forming process and study the effect of friction on drawing force. Multidraw Drylube E1 was used to lubricate the samples. Experiments were designed and executed to study the effects of rolling direction, lubricant amount, roll temperature and contact pressure on the drawing force. Strain in the sample was measured using digital image correlation (DIC) technique. Real area of contact is calculated using height distribution histograms of the surface in contact. Apart from the back force, variations in drawing force results from changes in bending and unbending force and friction force. The results imply that the friction force will not necessarily increase with increasing the back force and it depends on the contact pressure.

Introduction

Sheet metal forming is one of the most prominent manufacturing processes in many different industries. Friction has been shown as a key parameter in sheet metal forming that directly affects the formability of the final product. Different parameters determine friction, such as surface topographies and mechanical properties of sheet metal and forming tool, lubricant properties, contact pressure, strain and temperature in sheet metal and tool contact [1]. Therefore, it is necessary to understand the effect of these parameters on friction for the proper design of the process.

Many researchers have studied the effect of different parameters on friction in aluminum forming, using different test methods such as strip draw test, draw-bead simulator, pin-on-plate test, flat-on-flat tests and bending under tension (BUT) test. Tung et al. [2] developed an in-situ tribotest method to study the correlation between friction coefficient and process parameters. These included the tooling material and the lubricant in warm and hot aluminum forming process. Zhou et al. [3] examined the influence of Electro-Discharge-Texturing (EDT) of aluminum automotive sheet at different contact pressures and sliding speeds using a flat-on-flat friction test. They found that EDT texturing reduces the friction coefficient at relatively high contact pressure, but increases it at relatively low contact pressures (below 62 MPa). Dou et al. [4, 5] carried out research on aluminum alloy stamping and warm stamping process. Their approach used a pin-on-disk sliding wear test and studied the effects of temperature, sliding speed and normal load on friction coefficient. They concluded that friction coefficient increases for samples in higher temperatures. Wu et al. [6] conducted high temperature strip drawing for aluminum sheets. The results showed that the friction coefficient increased with an increase in preheating temperature of the die, applying a larger normal load or reducing the sliding velocity. Shafiee Sabet et al. [7] conducted pin-on-plate experiments on aluminum sheets and showed the friction coefficient tends to decrease with increasing nominal contact pressure and sliding velocity, but increase with an increase in the surface temperature. Meiler et al. [8, 9] compared the application of different dry film lubricants with oil lubricants for aluminum sheet forming within the automotive industry. They showed that by using hot-melt lubricants, apart from advantages in reducing the manufacturing and assembly time due to eliminating washing and relubricating processes, increased formability, homogeneous sheet thickness distribution and reduced scattering of the results can be achieved.

Some studies compared different friction test methods. Trzepiecinski [10] showed that for the tested steel sheets, in the BUT test, in contrast to the strip drawing test, with increasing the contact pressure, the friction coefficient tends to increase. Out of all the studies, only a few used the BUT test for investigation on friction in aluminum forming [11, 12]. In the BUT test, a strip, which is under tension, experiences bending and unbending over a fixed roll (and free rotating roll for measurement without friction). The BUT test can simulate the actual forming conditions at die and punch radius without adding any complexity and provides the opportunity to examine the effect of each parameter separately. Since the contact pressure is not the same all over the contact roll, different parts of the sample width experience different friction conditions. Multiple studies have investigated friction using BUT test, but few have addressed aluminum.

Initially, Vallance et al. [13] used the BUT test to study the friction behavior of coated steels in forming and showed that it is a suitable test for both fundamental and production operation studies. Their results indicate that the friction coefficient in coated steels varies with contact pressure. Later, Nanayakkara et al. [14] studied the effect of different roll diameters and different lubricants on BUT test results of galvannealed steel and concluded that the contact pressure together with the lubrication regime can determine the friction coefficient. Lemu and Trzepiecinski [12, 15] investigated the effect of lubrication condition (dry or lubricated) and tool surface roughness, using the BUT test for steel, brass and aluminum sheets. They evaluated the bending force numerically, in order to eliminate the variation of experimentally calculated bending force, specially when steady-state condition is not achieved during the test.

In overall, bending under tension experiments mimic basic kinematics of a real sheet metal forming. Therefore, it provides a quick assessment of different parameters on friction in real production setting. In this study, the influence of different parameters on frictional behavior of aluminum sheets with hot-melt lubricant are investigated using bending under tension experiments. The effects of back force, sheet rolling direction, roll temperature and hot-melt lubricant amount on friction in sheet forming of aluminum grade, AA5182 with EDT surface will be presented.

Materials and Methods

Material and Surface Properties. Aluminum sheets of AA5182 with EDT surface and 1.5 mm thickness were tested. The mechanical properties of the sheets were determined along three directions using uniaxial tensile tests according to ASTM E8M while the strains were measured using the DIC technique (GOM Aramis 3D). Fig. 1 depicts the true stress-true strain results of the tensile tests. AA5182 sheets in rolling direction had a slightly higher yield stress and hardening curve. The yield stress was 137 MPa in rolling direction (RD), 136 MPa in diagonal direction (DD) and 134 MPa in Transverse direction (TD).

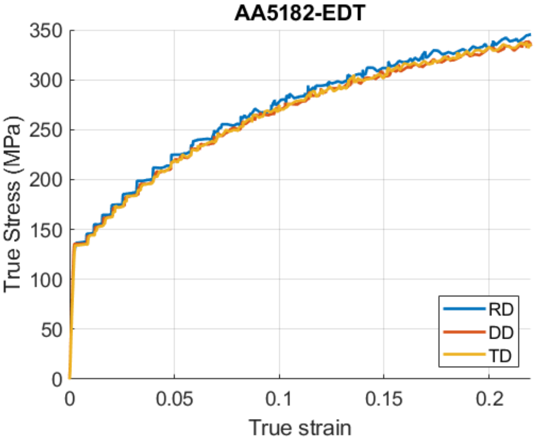


Fig. 1. True stress-true curves of aluminum sheets.

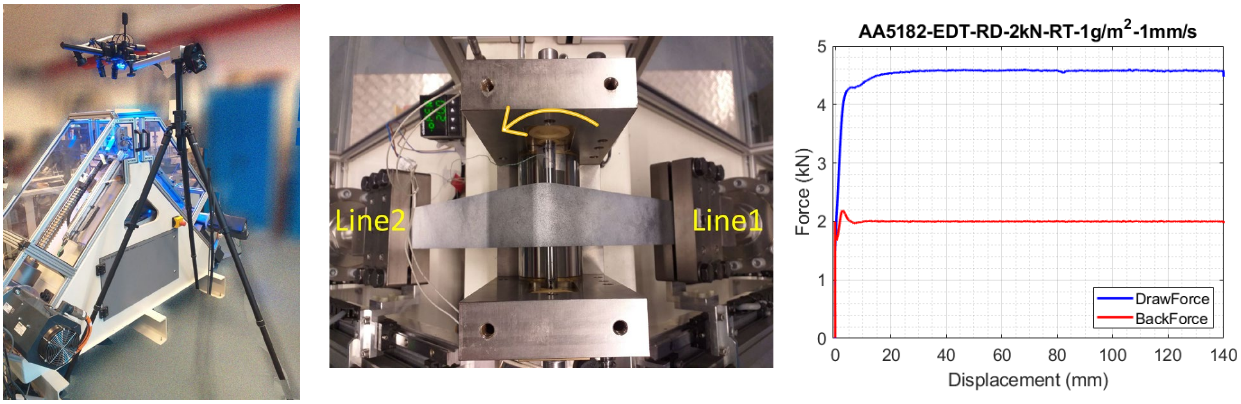
Strips of 50 mm×600 mm were cut from the sheets in three different directions, RD, DD and TD.

To choose proper values for test parameters like roll diameter, back force, and lubricant amount a preliminary study were done. Using the finite element (FE) simulation, contact pressures for different roll diameters, 10 mm and 20 mm, and back forces of 1 kN to 4 kN were assessed for AA5182 material (1.5 mm thickness). The average contact pressure in the contact area for 10 mm roll was between 36 MPa to 62 MPa, while for 20 mm roll, it was lower, between 15 MPa to 20 MPa. Therefore, roll with 10 mm diameter was chosen. The roll for BUT test was made from GGG-70 cast iron and roll surface was polished to 0.15 µm roughness. 1 kN, 2 kN and 4 kN back forces were selected for the experiments.

Different amounts of Multidraw Drylube E1 were used to lubricate the samples. The solidification point of the E1 lubricant is approximately 40°C. Assuming that the lubricant will distribute to fill the valleys and stay in one height level, the lubricant amount was calculated using confocal images of strips to achieve different lubrication conditions. The results show that 1.4 g/m^2 drylube is needed to fill all the valleys. Therefore, three levels for lubricant amount were selected to be 0.5 g/m^2, 1g/m^2 and 2 g/m^2, to test different lubrication conditions.

In order to make a repeatable and controllable procedure to apply the hot-melt lubricant on BUT samples, a laboratory-scale setup was manufactured. In this setup the specimen is placed on a moving saddle which is pulled by a rope, connected to a servo motor. The distance between the hot spray gun and the specimen is adjustable. Air pressure and temperature can also be adjusted. The amount of lubricant on the specimen has been calibrated based on the speed of spraying. Additionally before the test, the weight of the applied lubricant was measured for 20% of the samples, to make sure it will not deviate from the expected amount.

Bending Under Tension Experiments. The bending under tension (BUT) test setup and DIC setup are shown in Fig. 2.a. First, sample was bent over the roll and clamped in the grippers, then the back force was applied and finally it was pulled down for 140 mm. The GOM Aramis setup was used to look at the sample from the top on the bending area and measure the strain in the strip while it was passing the roll. In Fig. 2.b. line 1 applies the back force and line 2 applies the draw force. Using an analog voltage output from the BUT machine, the displacement in Line 2 (the drawing gripper) was recorded for each image taken by the DIC. The strip is pulled down with a constant speed (1 mm/s) while the machine tries to keep the back force constant. In Fig. 2.c, the force in line 1 and 2 is shown against the displacement of line 2 (the drawing gripper). For the rest of this paper, to make the results more comparable, the difference between these two forces against displacement of line 2 will be depicted.



a *b* *c*

Fig. 2. a) BUT and DIC setup. b) Aluminum strip bent over the fixed roll. c) A sample of force-displacement curves output.

Finite Element (FE) Simulations. FE simulations of the BUT test without friction has been done to distinguish between bending and unbending forces and estimate the friction force. It has been assumed that the friction force does not affect the bending and unbending force, therefore, this force can be calculated by considering the coefficient of friction equal to zero in the simulation.

The FE simulations were done using MSC Marc software. First the strip was bent over the roll, then the back force was applied and finally the strip was drawn for 50 mm. Five elements in the thickness and fine elements in the deformation zone with 0.5 mm in the length direction and 1mm in the width direction were selected after performing a mesh sensitivity analysis for strain results. BUT test simulations were conducted for a coarser mesh size (1 mm by 1 mm) and also a finer mesh size (0.5 mm by 0.5 mm). It has been seen that the strain results of different simulations converged by reducing the mesh size. But the contact pressure results are mesh size dependent. A mesh size with 0.5 mm in the length direction and 1 mm in the width direction was chosen for the FE simulations.

Design of Experiments. Experiments were designed to see the effects of different parameters. Three levels were considered for each variable. A central design with defined parameters was selected (strip in rolling direction; roll in room temperature; 2 kN back force; 1 g/m^2 lubricant). In each test, the level of only one variable is changed. All tests were repeated at least once to ensure the repeatability of the results. Fig. 3 depicts all the conducted experiments with the number of experiments conducted at each point (number in parentheses). The test order was selected completely random.

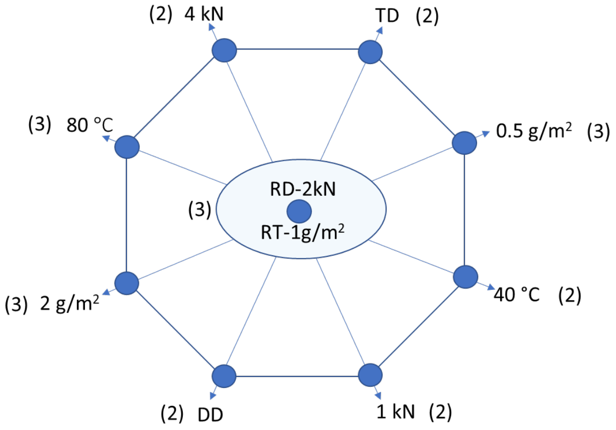
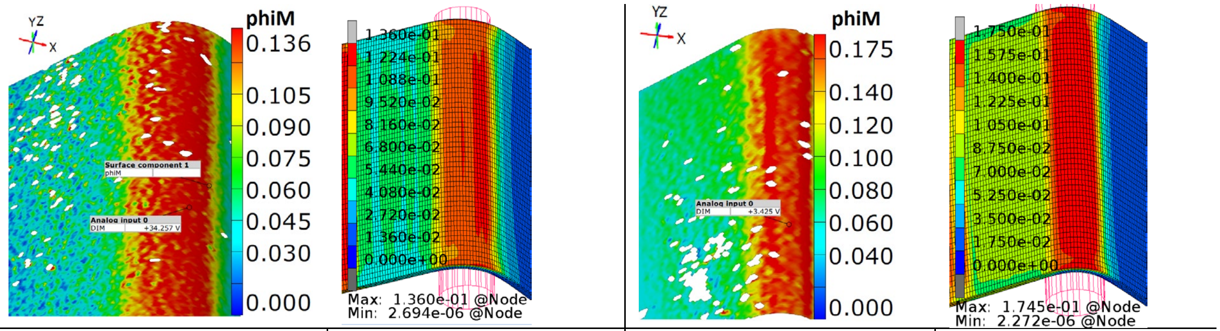


Fig. 3. Design of experiments and all tests and repetitions done.

Surface topography of the sheet before and after the test are measured using confocal microscope with the resolution of 0.64 µm/pixel. The real contact area of the surface that was in contact with the roll at the end of test, is calculated using the height probability density distribution histogram. It is assumed that the maximum height with the maximum in probability is the flattened height, for a background see [16].

Results and Discussions

In order to validate the FE model, von Mises equivalent strain results from DIC measurements and simulations were compared for two cases with 2 kN and 4 kN back forces. Fig. 4 shows the results after drawing the sample for 26.7 mm to the left. Edges of the samples are not included in the DIC measurements. There are also some points, the white holes in the strain map, where software was unable to calculate the strain. This was due to the painting pattern of the samples. Since the strain deviation along the width is quite small, the strain at those points can be considered to be the same as the neighborhood points.



DIC – 2 kN back force | FE – 2 kN back force | DIC– 4 kN back force | FE – 4 kN back force

Fig. 4. Von Mises equivalent strain comparison from the DIC and simulation.

The results of contact pressure for different back forces are illustrated in Fig. 5. In these simulations, the material properties of AA5182 have been used and a frictionless contact is assumed. The contact pressure increases with increasing back force from 1 kN to 2 kN but decreases with increasing back force from 2 kN to 4 kN. The decrease in contact pressure is due to an increase in contact area, as it is evident in the contact pressure map.

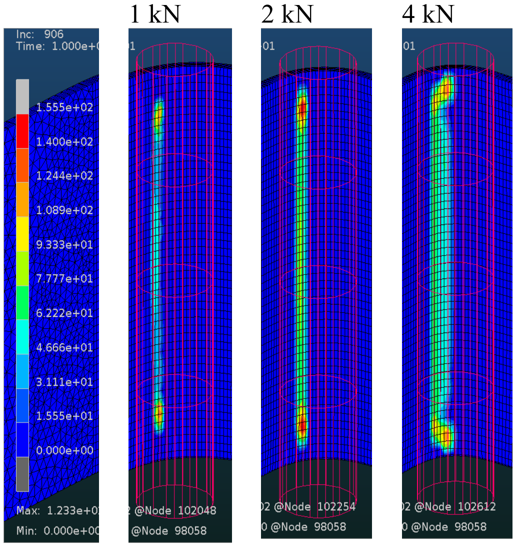


Fig. 5. Contact pressure results from simulations for BUT test of AA5182 sheets.

The delta-force–displacement (delta-force is the difference between drawing force and back-force) curves for different back forces are depicted in Fig. 6 for AA5182-EDT. These results show that the delta-force will increase with increasing back force. This happens due to mainly change in the bending and unbending force and also variations in the friction force, caused by the contact pressure changes (shown in Fig. 5). In order to see the effect of friction force, the effect of bending and unbending force must be subtracted from the total delta-force. The draw force result of FE simulation without friction, can be interpreted to be equal to bending and unbending force. Effects of different back forces (therefore different contact pressures) on friction force can be seen by subtracting the draw force results of FE simulations without friction from the draw force results of experiments. At 40 mm displacement the initially bent area has already passed the deformation zone. Therefore, the average draw force between 40 mm and 50 mm displacement was used to compare the data. Table 1 compares the results of simulations and experiments in different conditions.

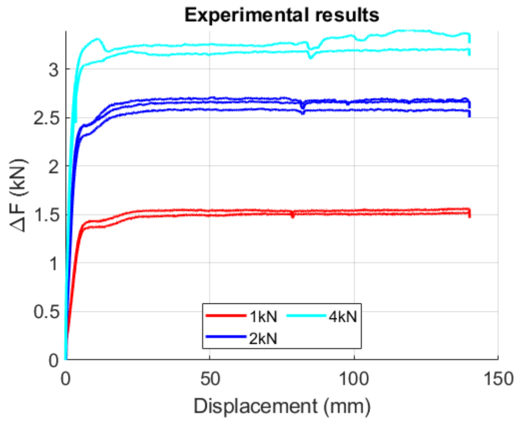


Fig. 6. Effect of different back forces on difference between draw force and back force.

Table 1. Effect of different back forces on draw force and friction force results.

Back force (kN)	ΔF (kN) experimental results	ΔF (kN) simulation results with μ=0	Friction force (N) of experiments	Average Coulomb's friction coefficient*
1	1.520	1.005	515	0.226
2	2.646	1.770	876	0.204
4	3.204	2.514	690	0.090

*Friction force of the experiments divided by the total normal force to the contact calculated from FE analyses.

Considering a constant coefficient of friction for the BUT test, the friction force will increase with increasing back force from 1 kN to 4 kN due to increasing the normal force. However the experiments imply that the friction force increases from 1 kN back force to 2 kN, but decreases from 2 kN and 4 kN, even though the normal force has been increased. Hence, the results indicate that the coefficient of friction depends on pressure distribution at the contact and decreases with increase in contact pressure [1].

Test results for different lubricant amounts, orientation of strip with respect to rolling direction and roll temperature are depicted in Fig. 7. The amount of lubricant in the selected range (0.5 g/m^2 to 2 g/m^2), appears to have no significant effect on the draw force. One explanation can be related to not having hydrodynamic pressure and distribution of the hot-melt solid lubricant on the surface. If hydrodynamic pressure does not build up due to low sliding velocity and the fact that lubricant is not fluid, asperity ploughing, and shear of boundary layers determine the coefficient of friction.

The lubricant might cover both valleys and asperities instead of just filling the valleys. In that case the shear of lubricant layer plays an important role in determining the friction forces. Further study needs to be done to understand the lubricant behavior and effects. The sheet orientation regarding to the rolling direction also did not affect the force significantly, although further investigation needs to be done to draw a conclusion. Using different roll temperatures, RT, 40°C, 80°C, appears to affect the friction force. The draw forces for roll in room temperature and 40°C are almost the same while that for roll in 80°C is slightly higher. The increase in the draw force can be explained by the increase of the friction force due to reduction in viscosity of lubricant since its melting temperature is approximately 40°C.

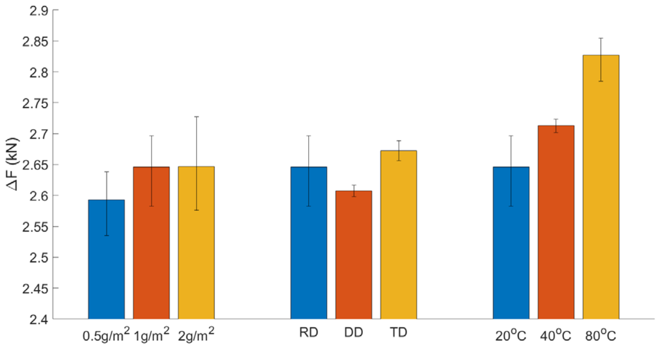
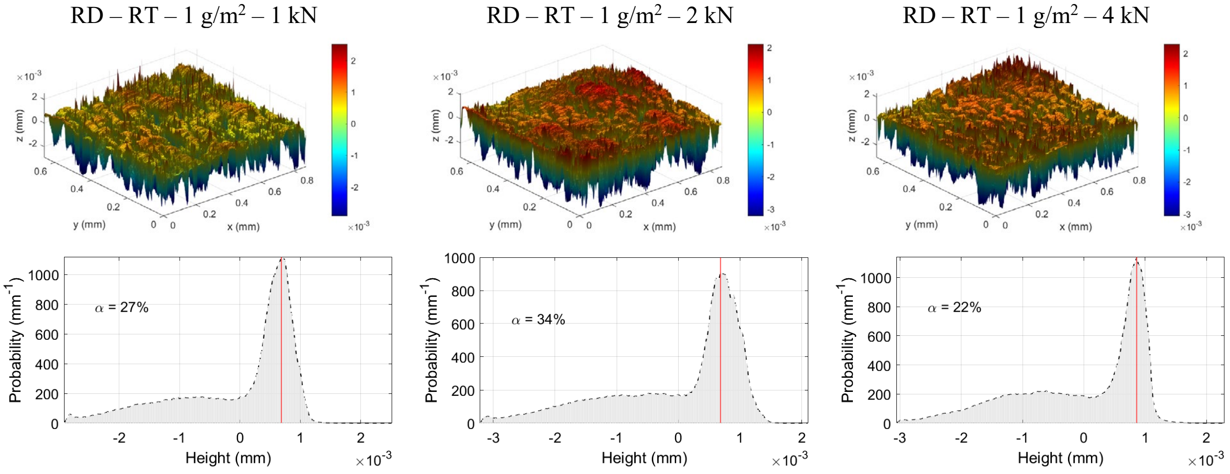


Fig. 7. The effect of lubricant amount, rolling direction and roll temperature on difference between draw force and back force.

Real area of contact has been calculated using the surface height probability density histogram [16]. Fig. 8 shows the surface topographies and height probability density histograms of the BUT samples with 1 kN, 2 kN and 4 kN back forces. The red lines show the heights with maximum probability and the numbers (α) are the percentage of area below the curve to the right which are the real area of contact. The real area of contact for different test repetitions and conditions are shown in Fig. 9. The real area of contact for samples with 4 kN appears to be smaller than samples with 1 kN and 2 kN. This is in agreement with FE simulation results, which show that the contact pressure for 4 kN is lower than contact pressure for 2 kN, however, the contact area in the case of 4kN is larger than the one from 2kN case.


RD – RT – 1 g/m^2 – 1 kN

RD – RT – 1 g/m^2 – 2 kN

RD – RT – 1 g/m^2 – 4 kN

Fig. 8. Surface topographies and height probability density histograms of BUT samples.

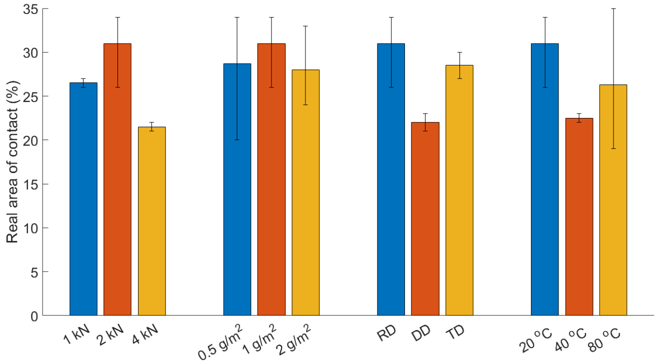


Fig. 9. Real area of contact from height distribution histograms for different BUT tests.

Conclusions

The BUT test was used to examine the effects of different parameters on the friction force. The bending and unbending force contribution to the difference between draw force and back force can be determined by FE simulations of the experiment with the friction coefficient of zero. The FE simulation was validated using DIC. The contact pressure distribution over the width is not uniform and close to edges there are contact pressure peaks.

The force-displacement results imply that with increasing back force, friction force will not necessarily increase. Increasing the back force from 2 kN to 4 kN causes the strip to follow the roll curvature better that increases the contact area and consequently reduces the local contact pressure (element level). This results in a friction force decrease. In other words, the average coefficient of friction decreases with increasing back-force. By looking at the real area of contact, it can also be seen that for 4 kN back force the real area of contact is smaller (due to lower contact pressure) and therefore, the coefficient of friction is smaller. There was no significant difference in the draw force results regarding different lubricant amounts and rolling directions of the sheet. However, for the roll at 80°C, the draw force is slightly higher than RT and 40°C. This can be explained by melting the lubricant at high temperature and reduction in drylube viscosity.

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