Dry Forming of Aluminium Sheet Metal: Influence of Different Types of Forming Tool Microstructures on the Coefficient of Friction

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Abstract. In the sheet metal forming industry, lubricants are applied in forming processes to expand the technological boundaries by reducing friction and wear. The friction between a tool and sheet metal is crucial to the deep drawing process. Due to economic and ecological reasons, the aim of the manufacturers is to reduce or even avoid the use of lubricants. Consequently, this approach enables both a shortening of the process chains and an essential saving of resources. The advantages of structured forming tools in lubricated processes concerning the reduction of the coefficient of friction by the appearance of lubricating micro pockets are well-known. However, without using lubricant, this effect does not work. In this case, the true contact surface is reduced by structuring the forming tool which affects the tribological system.

In this paper, the influence of microstructures with different geometries and surface treatments (uncoated/a-C:H:Si-coating) on the coefficient of friction in dry forming is compared to the frictional behaviour of unstructured forming tools using lubricant as reference. Machining of the forming tool functional surfaces before coating is performed by milling to generate tribological effective microstructures. With the use of a strip drawing plant, the effects of different surface structures and materials on the coefficient of friction are investigated. Beyond that, a numerical simulation based on FE analysis is used to predetermine the surface structure. This requires a consideration of the normal pressure dependency on the coefficient of friction in the FE-model. Additionally, the strip drawing plant is used to evaluate the wear behaviour of the different microstructures and materials.

Keywords: Al alloys, Coating, Deep drawing, Friction, Lubricant free forming, Microstructures

Introduction

Forming technology is faced with a twofold challenge with the focus on friction behaviour while forming aluminium alloys. On the one hand, high wear stress appears which is caused by hard aluminium oxides on the surface of the workpiece or aluminium alloys containing a high percentage of Si. This leads to scoring on the tool surface or the formation of aluminium sequins.

On the other hand, the cracking of the oxide layer is possible, leading to an appearance of highly adhesive inner material which is adhering to the tool’s surface through atomic binding effects [1]. Caused by relative movement between the friction partners, the binding is detached and material is torn out of the tool or workpiece. Not only the tool life is shortened by the consequences of adhesive wear but also scoring of the workpiece and fractures during deep drawing processes can occur caused by a strong increase of the coefficient of friction. Further on, workpieces, tools and machines become
polluted by aluminium sequins followed by abrasive interferences of particles as well as the attrition of tool surfaces [2, 3]. For the reduction of the described wear mechanisms and the extension of the tool life, increasingly more hard coatings are used besides lubricants to protect the tools [4]. Only a few micrometres thick, these hard coatings can be manufactured by Physical Vapour Deposition (PVD) as well as by Chemical Vapour Deposition (CVD). Thicker coatings (50 µm to a few mm) can be produced by build-up welding supported by laser.

Another possibility of influencing the tribological behaviour between the tool and the workpiece and caused by this, controlling the material flow, is the texturisation of the tool surfaces. Numerous studies have shown how material flow can specifically be supported as well as hampered by using micro- and macrostructures [5–7].

The rethinking concerning ecology and the demand for dry manufacturing involving a “lubricant free factory” came into being by the growing ecological understanding which started with the detection of the greenhouse effect at the beginning of the 20th century [8] and came into force with the signing of the “Agenda 21” in 1992 by the then 172 UN-members [9]. Due to the lack of a universally valid description of “dry forming”, the following definition proposed by Vollertsen [10] can be used from a process chains view: “Dry metal forming is a process where a workpiece leaves the forming tool without the necessity of cleaning or drying before further production steps such as coating or joining processes.”

Lubricant free forming technology has been investigated since the 1980s. Priorities for research have been the usage of ceramic based tools [11, 12], self-lubricating layer systems [13] and anti-abrasion coating of tool surfaces. Thereby, DLC-coatings besides TiCN- and TiC-TiN-layer systems show a high potential for wear protection and the reduction of the coefficients of friction depending on the combination of workpiece and tool [14–18].

In this paper, the influence of microstructures with different contact areas and surface treatments (uncoated/a-C:H:Si-coating) on the coefficient of friction in dry forming is compared to the frictional behaviour of unstructured forming tools using lubricant as reference. With the use of a strip drawing plant, the effects of different surface structures and materials on the coefficient of friction are investigated.

**Experimental**

**Structuring**

It was proved by Reihle [19] that the higher the normal pressure is, the lower the coefficient of friction will be. To verify this effect, the surface of the drawing tools was structured [20]. The aim was to have a variation in the contact area and the effective surface pressure respective.

To avoid a preferred direction, rotation-symmetric elements (calottes) were chosen and arranged in a grid. To obtain the real contact area, the projected area of the calottes has to be subtracted from the functional surface of the tool. Due to this matter, the real contact area by 960 calottes could be reduced to 75%. By using 480 calottes, the reduction is 87.5%. The drawing tools were made from cold working steel 1.2379 (X153CrMoV12) and heat-treated up to a hardness of 60 HRC. After the heat-treating process, all of the functional surfaces were ground and polished for reaching a roughness value of $R_a = 0.02 \mu m$.

The polished functional surfaces were structured by a coated cemented carbide ball end milling cutter (diameter: 0.8 mm, FIGURE 1). Machining was performed at a four-axis micro cutting centre in the gantry design (Kugler Microgantry®).
FIGURE 1. Cutting part of the ball end milling cutter, right on top: without working depth (WD), right at bottom: with working depth.

To avoid the sharp edges of the calottes to the adjacent functional surface, a radius of about 100 µm was manufactured. By subsequent polishing, the radius was partially removed (Fig. 2b). The tool radius \( r \) as well as the depth of removal \( h \) defines the diameter of the calottes, which is estimated using the following equation 1 for the length of a chord \( s \) in a circle:

\[
h = r - \sqrt{r^2 - \frac{s^2}{4}}
\]

Based on this equation a depth of removal of \( h = 87 \) µm is calculated for a diameter of the calottes of 500 µm. To reach a contact area of 75%, the calottes were arranged to each other with a gap of 1 mm in both directions. For 87.5%, the gap was 1.5 mm.

To avoid the contact between the centre of the milling tool and the functional surface of the drawing tool the workpiece was inclined with an angle of 45° to the spindle. This led to a movement of all three coordinate axes at the same time for the machining of the radius of the calottes, but the tool wear in the centre of the cutter could be prevented (cutting speed: \( v_{c,centre} = 0 \) m/min). The machining parameters corresponded with the recommendations of the tool manufacturer: depth of cut per tooth \( f_z = 0.01 \) mm, cutting speed \( v_c = 80 \) m/min and depth of cut \( a_p = 10 \) µm.

After analysing the machined surface, burr at the radius in the intersection area was detected (Fig. 2a) as well as slight deviations of the calottes to their theoretical dimension, which is caused by the utilized ball end milling cutter. On the one hand, the tool has a working depth for the purpose of an increased depth of removal but, on the other hand, it also has a lower stiffness, which led to tool deflections. To remove the burr and correct the contour of the calottes, the milling programme was performed again without changing the depth of removal and, furthermore, using tools without working depth (FIGURE 1, right on top).

The structure of the functional surface was characterised by a confocal laser scanning microscope (Keyence VK-9700) with 50 times magnification. After the measurement, the data were evaluated with the surface analysing software MountainsMap digital surf.

FIGURE 2. a) Structured functional surfaces with burr (contact area 75%, before coating)  
b) Single calotte without burr (after polishing, before coating)
After the wear protective coating (a-C:H:Si, thickness: ca. 2 µm) has been applied on the drawing tool, the functional surface was investigated per scanning electron microscope (SEM). The SEM recordings are characterised by a great depth of field, which are however not suitable for quantitative surface evaluation (FIGURE 3a). Occasional coating delamination can be detected on the ground of calottes (FIGURE 3b). These might be caused by stresses during the cooling phase of the coating operation due to the concave geometry or burrs, which could not be eliminated completely by the polishing process. However, an influence on the intended strip drawing experiments can be excluded because there will be no contact between the coating delamination on the bottom of the calotte and the aluminium sheet metal.

![FIGURE 3. a) Structured and coated functional surface with a contact area of 75% b) Coating delamination on the bottom of the calotte](image)

By coating the drawing tool, no increase of roughness on the functional surfaces has been detected. The thin layer of the carbon coating has no significant levelling effect and thus the drawing tool functional surface structure was presented nearly unchanged.

### Strip drawing test

Having a realistic determination of the coefficients of friction, a strip drawing test was used. Important tribological process parameters such as sheet metal material, lubrication, coating and structure of the tool surface have been considered to be as close as possible at the real forming process (FIGURE a).

By using the strip drawing test with flat drawing tools it was possible to simulate the tribological system between blank holder and sheet metal. The sheet metal, fixed on a sliding device, was pulled under the drawing tool loaded with a normal force $F_N$ (FIGURE b). No tangential force application was used. The friction force was determined by a measurement device. Assuming the Coulomb friction, the coefficient of friction $\mu$ was calculated. Due to the strip width of 50 mm and the effective width of the drawing tool of 40 mm, there is no influence of the sheet metal’s burr on the test results.

To ensure the most precise results, the normal force $F_N$ was used to influence the normal pressure $p_N$. The tests were made at room temperature and the tools were not heated. During the tests, the sliding velocity of the strip was kept constant. The velocity of 50 mm/s was in the typical ranges of common deep drawing processes. The coefficients of friction $\mu$ were determined for seven different load horizons (normal pressure) from 1 MPa to 17 MPa. Each variation of the coating (coated/uncoated), the surface structuring of the functional surfaces and lubrication were analysed and compared. The test conditions and the test matrix are shown in TABLE 1 and Table 2.


![Experiment set up strip for the strip drawing test](image)

**FIGURE 4.** a) Experimental setup strip for the strip drawing test

b) and c) Drawing tool and principle of the strip drawing test

<table>
<thead>
<tr>
<th>TABLE 1. Experimental matrix strip drawing tests</th>
</tr>
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<tbody>
<tr>
<td>Coating of the drawing tool</td>
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<tr>
<td>-----------------------------</td>
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<tr>
<td>Structuring of the drawing</td>
</tr>
<tr>
<td>tool</td>
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<tr>
<td>Lubrication condition</td>
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<tr>
<td>Test number</td>
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</tbody>
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**TABLE 2. Experimental conditions strip drawing tests**

<table>
<thead>
<tr>
<th>Strip</th>
<th>AA5182-H111, electro discharge textured (EDT) surface, drawing direction was parallel to the rolling direction, delivery condition dry and clean; ( t = 1.0 \text{ mm}, \text{ width 50 mm, length 1000 mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing tool</td>
<td>1.2379, full hardened (58 + 2) HRC, grinded and polished, functional surfaces: ( \text{Ra} &lt; 0.02 \text{ \mu m} )</td>
</tr>
<tr>
<td>Drawing additives</td>
<td>Lubrication applied using a roller, ca. 2 g/m² WISURA ZO 3368</td>
</tr>
<tr>
<td>Coating</td>
<td>a-C:H:Si; thickness of coating: ( (2 \pm 0.5) \text{ \mu m} )</td>
</tr>
</tbody>
</table>

The test procedures were made at 0° rolling direction of the sheet metal. Tests with uncoated and unstructured drawing tools, made from 1.2379, as well as tests with a-C:H:Si-coating and unstructured drawing tools, made from substrate 1.2379, were made as a reference. These reference tests were conducted by using lubrication. The following tests were performed under the mentioned conditions, using coated drawing tools but no lubrication. Due to the structured functional surfaces and the contact area of the drawing tool, respectively, the effective normal pressure was influenced in a specific way. Afterwards, macroscopic and microscopic analyses of the functional surfaces of the drawing tool and the sheet metal surfaces were performed. It has to be taken into account that per test series one and the same drawing tool was always used.
Results

Reference strip drawing tests with lubrication

The diagram in FIGURE shows the evolution of the coefficient of friction with the normal pressure for the reference strip drawing tests with uncoated and a-C:H:Si-coated, unstructured drawing tools against EN AW-5182-H111 under the use of lubrication (2 g/m²). With both drawing tools 35 strips were drawn in each case (five strips per normal pressure). In comparison to the uncoated drawing tool, the coefficient of friction of the coated drawing tool decreases significantly less with increasing normal pressure. This can be explained by the fact that the surface structure of the drawing tool was preserved by the hard coating and thus no smoothing during the drawing process could take place.

\[
\begin{array}{c|c|c}
\text{Drawing tool} & \text{Drawing additive} & \text{Coefficients of friction} \\
\hline
\text{uncoated (1.2)} & \text{WISURA ZO 3368, 2 g/m²} & 0.10 \\
a-C:H:Si-coated (2.2) & & 0.08 \\
\end{array}
\]

FIGURE 5. Coefficient of friction over the normal pressure for the reference strip drawing tests

On both drawing tools, abrasive traces of wear could be detected on the functional surface after the experiments. The wear pattern was distributed homogeneously over the entire width of the functional surface of the uncoated drawing tool. In contrast, as expected, only a few scratches were visible on the coated drawing tool due to the higher hardness and high wear resistance of the carbon layer (FIGURE ). However, the occasional scoring indicates a locally limited premature failure of the coating. It can be assumed that in these regions hard abrasive particles from the aluminium oxide layer of the metal strip led to a local overloading of the layer. The profile sections shown in FIGURE and FIGURE show a maximum groove depth of approx. 0.9 µm for the uncoated and approx. 2.0 µm for the coated drawing tool. Adhesive wear was not visible on both drawing tools.

FIGURE 6. Overall view of the functional surfaces
To assess the surface topography of the sheet, light micrograph images were made before and after the drawing tests. In FIGUREa, the stochastic surface structure of the sheet in the state as delivered can be clearly seen, which corresponds to the typical appearance of EDT (electrostatic discharge texturing) sheets. The photographs shown in FIGUREb show the sheet surfaces after the reference drawing test with lubricant and a surface pressure of approx. 17 MPa. The surfaces that were exposed to the functional surfaces of the drawing tools show a uniform smoothing out, which is visible through the changes in the degree of gloss (oblique illumination). A difference between the sheet surfaces which were mechanically stressed with the coated and uncoated drawing tools cannot be seen. Abrasive or adhesive wear marks are not present on both strips.

FIGURE 9.  
a) Sheet surface as delivered  
b) Sheet surface after reference drawing strip drawing tests

Strip drawing test without lubrication
In the experiments carried out without lubricant and coating with unstructured drawing tools, strong aluminium adhesions on the functional surfaces of the drawing tools were already evident after the first attempt at a surface pressure of 1 MPa (FIGURE 10a). Due to the adhesive wear, there was a significant increase in the coefficient of friction up to \( \mu = 0.59 \) (average over the stroke) compared to the lubricated tests (\( \mu = 0.14 \) uncoated or coated \( \mu = 0.12 \)). The evolution of the coefficient of friction with the stroke is shown in FIGURE 11. For better visual representation, the curve was smoothed by the formation of moving averages. No conclusions could be made about the abrasive wear behaviour because only one trial was performed. The investigations of the sheet surfaces conducted after the strip drawing tests have shown a strong scoring in a longitudinal direction (FIGURE 10b). For applications with high quality standards, such topographical changes in the sheet surface are not permitted.

![FIGURE 10](image1.png)

**FIGURE 10** a) Functional surfaces of the uncoated drawing tools after strip drawing test  
  b) Sheet surface after drawing tests without lubrication and 1 MPa normal pressure

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**Strip drawing test without lubrication and microstructured drawing tools**

In FIGURE 12, the Evolution of the coefficient of friction with the stroke for the unstructured and structured drawing tool is shown under 1 MPa normal pressure (regarded to the unstructured drawing tool). For better visual representation, the curves were smoothed by the formation of moving averages. The analysis of the coefficients of friction showed that the unstructured drawing tool had with \( \mu = 0.71 \) (average over the drawing path) the largest coefficient of friction. The drawing tools structured with the calottes showed with \( \mu = 0.55 \) (average over the drawing path) a decreased coefficient of friction of approximately 22%. The cause of this greatly increased coefficient of friction, in comparison to the lubricated experiments, is due to the aluminium deposits on the drawing tools. The visual inspection of the functional surfaces of the drawing tools showed already after one trial strong adhesive signs of wear under 1 MPa normal pressure (FIGURE 13). The pick-up contaminations occur here mainly near the edges of the
functional surfaces of the drawing tool. In some areas, a superposition of the calottes with Aluminium adhesions occurred, so that the structure in these areas became ineffective. A comparison between the two curves shows that the curve progressions of the two structured drawing tools are very close together. An unambiguous assignment of the influence of the contact area to coefficient of friction was thus not possible due to the spread in values. The investigations of the sheet surfaces conducted after the strip drawing tests have shown a strong scoring in a longitudinal direction (Fig. 14). For applications with high quality standards such topographical changes in the sheet surface are not permitted.

**FIGURE 12.** Coefficient of friction over the stroke – a-C:H:Si-coated steel unstructured and structured with 75% and 87.5% contact area

**FIGURE 13.** Overall view of the functional surfaces of an a-C:H:Si-coated unstructured and a microstructured drawing tool after a drawing test

**FIGURE 14.** Overall view of the sheet surfaces after drawing tests without lubrication and 1 MPa normal pressure.

**FE-Simulation**

In parallel with the experimental studies, numerical investigations were also carried out within the framework of the present paper. Based on the strip drawing tests of unstructured and uncoated drawing tools with lubrication the Coulomb friction model for numerical simulation process has been extended in such a way that the influence of the normal pressure $p_N$ can be observed on the coefficient of friction $\mu$. The results of the performed lubricated reference drawing tests have clearly shown that
the coefficient of friction decreases markedly at high normal pressures, due to the smoothing of roughness asperities (FIGURE). In order to consider this effect in the numerical simulation, the coefficient of friction was defined as an exponential function of the normal pressure as follows (Eq.3):

$$
\mu(p_N) = \mu_0 \left( \frac{p_N}{p_{NO}} \right)^{n-1}
$$

(3)

The reference coefficient of friction $\mu_0$ is in this case 0.06 at a reference normal pressure $p_{NO}$ of 9 MPa and the exponent $n$ is 0.4. This mathematical description correlates very well with the experimentally measured coefficient of friction, as shown in FIGURE.

**FIGURE 15.** The coefficient of friction as a function of the normal pressure.

The normal pressure-dependent friction model according to Eq. 3 was integrated over a user-subroutine into the FE software Simufact.forming and strip drawing tests of unstructured and structured drawing tools with a contact area of 75% and 87.5% were simulated numerically.

The normal force $F_N$ was chosen so that with the unstructured drawing tools a constant normal pressure of 5 MPa results. The normal pressure which occurs with structured drawing tools is higher and not evenly distributed due to the reduced contact area. In FIGURE the distribution of the normal pressure in relation to the contact area is shown. It can clearly be seen that the normal pressure of the drawing tool is not homogeneous and that the normal pressure is higher around the area of the structuring than in the other regions. This local normal pressure increase by almost a factor of two must be considered in the development of suitable coatings for dry forming.

**FIGURE 16.** The distribution of the normal pressure in relation to the contact area.
Due to the increased normal pressure $p_{N0}$ at a reduced contact area, the coefficient of friction $\mu$ is finally reduced by greater smoothing effects. **FIGURE** shows the relationship between the contact area and the resulting coefficient of friction $\mu$.

![FIGURE 17. The relationship between the contact area and the resulting coefficient of friction $\mu$](image)

The simulations have shown that the structuring of the forming tools results in a reduction of the friction force in dry forming due to smoothing effects. As there were no hydrodynamic effects taken into account in the simulation, the transferability of the results is guaranteed for dry forming processes. However, it must be ensured experimentally that no adhesion between the contact partners occurs.

### Summary and Outlook

The performed strip drawing tests with structured and a-C:H:Si-coated drawing tools have shown in principle that the coefficient of friction at dry metal forming can be reduced to a certain extent by the structuring of the drawing tool. The related reduction of the contact area of the functional surfaces of the drawing tool and the resulting effects on the coefficient of friction could be remodelled via FE-simulation. However, the level of the determined coefficients of friction is still far too high at the present time compared to the lubricated forming. Even at low normal pressures of 1 MPa, extensive adhesions at the functional surfaces of the drawing tool and strong scoring in the sheet surface occurred with the use of the a-C:H:Si coating system and the EN AW-5182-H111 sheet metal. The examined material combination is, therefore, not recommended for the dry forming of complex sheet metal parts. It is expected that the high quality requirements for sheet metal parts in terms of drawing depth and surface quality cannot be met.

The aim of ongoing activities is to develop appropriate CVD diamond layers [21] which are in their characteristics closer to diamond but often assigned to the class of diamond like carbon (DLC) coatings. Due to the crystallisation, the hardness, conductivity and optical band gap can be the same as by a genuine diamond. Thereby, better coating properties can be obtained. However, the high process temperatures induce residual coating stresses and the CVD diamond layers have a higher surface roughness due to the special manufacturing process. In order to exploit the potential of CVD diamond layers, therefore, a treatment of the surface is required, on the one hand, and the adhesion must be increased by introducing intermediate layers, on the other hand.

Furthermore, the use of a minimal lubrication by vanishing lubricants for evaporative degreasing is conceivable. However, it is questionable whether the self-chosen definition of dry forming is still met. Additives possibly contained in the vanishing lubricant may remain on the sheet metal surface.
This could have a detrimental effect on subsequent process steps, such as the cathodic dip painting in which modern car bodies still have to undergo.

**Acknowledgements**

The author wants to thank the German Research Foundation (DFG) for the financial support of the project “Lubricant free deep drawing of aluminium sheet metals for car body construction” in the priority program 1676 “Sustainable Production by Dry Forming Technology”.

**References**