Investigation on water as lubricant in combination with a structured tool surface in micro metal forming

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Abstract. The use of lubricants in forming processes is common because they reduce friction between the tools and workpiece during the forming process. Today, mainly mineral oils are used as conventional lubricant. In order to cut their amount in the future, the friction between tools and workpiece is investigated by using water as lubricant in this work. Therefore, the tools’ surfaces are structured with laser induced periodic surface structures (LIPSS) to make them hydrophilic and strip drawing tests are carried out at different traverse velocities to evaluate the resulting friction force. The results show that at a traverse velocity of \( v = 10 \text{ mm/s} \) the maximum friction force is lowest for the structured tool with water (\( F = 7.0 \text{ N} \)) in comparison with unstructured tools in combination with a conventional lubricant. Consequently, the potential of water as lubricant combined with a hydrophilic surface structure is highlighted.

1. Introduction

One of the main tasks of the forming-oriented research areas is to reduce energy consumption and environmental pollution [1]. In sheet metal forming, however, mainly liquid lubricants based on mineral oil are used [2] and thus contribute to environmental pollution. These lubricants also contaminate the surface of the workpiece and therefore make a cleaning necessary. This leads to a reduction of the process efficiency due to additional steps in the process chain [3].

As a result, in recent years the industry has increasingly used aqueous solutions to which additives have been added in order to improve the adhesion of the solution to the tools. The proportion of additives in these solutions can be held under 5 % as investigations show making these solutions capable for deep drawing processes and internal high pressure forming [1]. If water is applied to a friction test, the friction coefficient is halved from \( \mu = 0.30 \) to \( \mu = 0.15 \) [4]. In addition to reducing the coefficient of friction by using water as a lubricant, studies by Jia et al. [5] show that there is also a reduction in wear. For this purpose, friction tests were carried out using a bronze-graphite material and stainless steel (1Cr18Ni9Ti) under water at a speed of \( v = 0.53 \text{ m/s} \).

The composition of the water also plays a role regarding the friction behavior of two contact partners. The dropwise use of deionized water in a ball-on-plate test with friction partners made of rolling bearing steel (GCr15) at a load of \( F = 2 \text{ N} \) leads to friction coefficients greater than \( \mu = 0.5 \). The cause is attributed to the relatively large contact angle of deionized water on steel of \( \Theta = 80^\circ \). This results in metal-to-metal contact and thus, high friction coefficients as well as high abrasion.
During micro forming, the viscosity of the lubricant used also has a significant effect on the occurring process forces [7]. It is shown that the lubricant with the lowest viscosity (AK3080, $\nu = 52$ mm$^2$/s at $T = 20$ °C) has the highest punch forces in the process, while the lubricant with the highest viscosity (HBO 947/11, $\nu = 400$ mm$^2$/s at $T = 40$ °C) leads to the lowest punch forces during a strip drawing test with double deflection. The higher process forces can be explained by the lubrication pocket model and the resulting increase in friction during forming processes in the micro range. The lubrication pocket model is based on the size effect of the microstructure, which is described in [8]. The lower the viscosity of the lubricant used, the sooner it flows out of the cavities between the surfaces and prevents effective separation of the workpiece from the tool. This results in a solid contact with correspondingly high friction coefficients, which are reflected in the increased punch force. Vollertsen and Hu experimentally investigated the influence of the punch speed and the contact pressure on the friction function [9]. The friction function describes the coefficient of friction in dependency of the acting contact pressure between the blank and the tools during the forming process. For this purpose, strip drawing tests with double deflection were carried out, whereby tribological size effects could be displayed. These effects reveal in the change of the course of the friction function in dependency of the punch velocity. It was discovered, that increasing punch velocities caused decreasing coefficients of friction [10].

Due to the tendency of the water on untreated and smooth surfaces to move with the contact zone of two contact partners, the surface must be modified to prevent the water from moving. Such surface treatments result, for example, in laser induced periodic surface structures (LIPSS) which were described by Sipe et al. [11]. These structures enable the functionalization of surfaces and prevent or provide them from wetting with liquids. The degree of hydrophilicity or hydrophobia caused by LIPSS can be adjusted via the pulse overlap. Eckert's work shows that the surfaces made of aluminum (EN AW-1050A) become more hydrophilic with increasing pulse overlap [12].

As pointed out, water can improve the contact behavior between tools and worksheet during sheet metal forming, if the process conditions are selected accordingly. These include high punch velocities and the modification of the tool’s surfaces. For this reason, strip drawing tests were carried out in this work on a tensile testing machine using structured tools and water as lubricant to investigate their influence as a combination on the friction force in comparison with a conventional lubricant.

2. Methodology

2.1. Tool structuring

The structuring of the strip drawing jaws is made with a pico-second laser TrueMicro 5050 by Trumpf with the parameters shown in Table 1.

| wavelength $\lambda$ | laser power $p_l$ | spot size | scanning velocity $v_T$ |
|---------------------|------------------|-----------|------------------------|
| 1030 nm             | 2.5 W            | 46 $\mu$m | 500 mm/s               |

The strip drawing jaw consists of an aluminium bronze CW307G and the contact surface has an area of $A_c = 40$ mm$^2$. To create the LIPSS in this area, a zigzag trajectory with a line spacing of $d_s = 34$ $\mu$m was chosen. The trajectory was scanned once while Argon was used as shielding gas.

2.2. Strip drawing

The strip drawing tests were carried out on a tensile testing machine made by Zwick Roell. The machine is equipped with the experimental setup shown in Figure 1. It is built up from two strip drawing jaws which are framed and screwed down in tool holders. These holders are mounted on a linear guidance to allow only a horizontal movement of the strip drawing jaws. One of these jaws is in contact with a force sensor which detects the normal load $F_N$. To apply this load, the second jaw is pushed against a metal
strip and therefore against the other one and the force sensor using a built-in micrometer screw. The screw enables the precise adjustment of the normal load.

![Figure 1. Experimental setup for strip drawing.](image)

The metal strip is made from 1.4301 (X5CrNi18-10). A second force sensor that links the strip to the vertical axis of the tensile testing machine detects the friction force $F_R$. Using Coulomb’s law of friction, the coefficient of friction was calculated via:

$$\mu = \frac{F_R}{F_N}.$$  \hspace{1cm} (1)

In this equation $F_R$ represents the friction force while $\mu$ is the coefficient of friction and $F_N$ is the normal load. For the measurements, the normal force was set at $F_N = 15$ N. The drawing speed varies between $v = 1$ mm/s, $v = 5$ mm/s and $v = 10$ mm/s. Demineralized water in combination with a laser-induced periodic surface structure serves as lubricant. In order to be able to draw a comparison with conventional lubricants, the ester oil-based lubricant Wisura LS240A was used. Its properties are shown in Table 2. In this case, the tools were not structured. In addition, drawing tests were carried out with unstructured tools in conjunction with demineralized water and dry tools for further comparisons.

| base oil  | viscosity at 20 °C | density at 20 °C | dissociation temperature |
|-----------|----------------------|------------------|--------------------------|
| ester oil | 52 mm²/s             | 842 kg/m³        | 170 °C                   |

### Table 2. Properties of the used lubricant during strip drawing.

3. **Results**

The structuring of the tool surfaces with the laser parameters listed in Table 1 leads to the structured surface shown in Fig. 2. The resulting LIPSS are parallel to the tension direction of the metal strip and show a homogeneous spread over the contact area.

The friction coefficient resulting from the combination of the structure presented in Fig. 2 and demineralized water in simple strip drawing tests are shown in Fig. 3. For the comparison, additional experiments with unstructured tools and different lubricants as well as the dry condition of the unstructured< tools were carried out and shown in Fig. 3. As it is presented, the coefficient of friction decreases with increasing traverse velocity in case of a structured tool surface in conjunction with demineralized water from $\mu = 0.26$ to $\mu = 0.18$. This contrasts the increase in the coefficient with increasing forming speed from $\mu = 0.16$ to $\mu = 0.21$ when an unstructured tool with conventional
lubricant is used. An unstructured tool in combination with demineralized water and in a dry condition show the highest maximum friction forces at a traverse velocity of \( v = 10 \) mm/s. In addition, Fig. 3 shows that the process gets more stable in case of the structured tool with LIPSS and demineralized water since the deviations of the force values decrease with increasing traverse velocities. On the other hand, a dry and unstructured tool shows the highest deviations and therefore is the most unstable process.

![Figure 2](image1.png)

**Figure 2.** Representation of the LIPSS structures on the contact surface of the strip drawing jaws.

![Figure 3](image2.png)

**Figure 3.** Friction coefficient \( \mu \) in dependency of the traverse velocity \( v \) for different regimes of tool surfaces and lubricant.

It is in fact surprising that the coefficient of friction at a drawing speed of \( v = 10 \) mm/s is lowest for the structured tools and water as lubricant. This might be attributed to the low contact pressure (0.375 MPa) applied in the experiments and will be evaluated further.

4. Discussion
The given conditions of the strip drawing jaws, unstructured and dry, unstructured and water as lubricant, unstructured and conventional lubricant as well as structured and water as lubricant, lead in this order to decreasing friction coefficients at the highest traverse velocity. As Fig. 4 shows, the use of water as lubricant reduces the friction coefficient regardless of whether the strip drawing jaw’s surface is structured or not. This observation corresponds to those made by Kim et al. where the coefficient of
friction was halved from $\mu = 0.30$ to $\mu = 0.15$ [4]. In this work the friction coefficient was reduced from $\mu = 0.22$ with a dry tool via $\mu = 0.20$ using demineralized water as lubricant to $\mu = 0.18$ with a structured strip drawing jaw’s surface and water as lubricant at a traverse velocity of $v = 10$ mm/s.

However, using a traverse velocity of $v = 1$ mm/s a structured surface in combination with water shows a higher coefficient of friction than an unstructured tool with a conventional lubricant. Due to the difference in the viscosity between water ($v = 1$ mm²/s at 20 °C) and Wisura LS240 ($v = 52$ mm²/s at 20 °C), this phenomenon can be addressed to the lubricant pocket model, which was also used to describe the observations in [7]. According to the model described in [13], the high friction force and therefore the high coefficient of friction is a result of the proportion of open to closed lubricant pockets. The more open lubricant pockets exist in comparison to closed ones, the higher the friction force and the coefficient of friction are. If a lubricant with a low viscosity and a low traverse velocity are used, the lubricant has the possibility to escape from a lubricant pocket. In contrast, a lubricant with a high viscosity remains in the lubricant pocket. The former favors the number of open lubrication pockets, particularly at the edge of the contact between the sheet metal strip and strip drawing jaws. This could explain the increased coefficient of friction at low speeds for structured tools with water as lubricant in accordance with [7].

Work by [14] in the field of deep drawing in the macro range in turn shows that structured surfaces can reduce friction without the addition of a lubricant. Such observations are investigated especially in the field of dry forming. At this point, it cannot be excluded that a reduction in friction can be achieved by applying structures to tools in the micro range alone. Therefore, further investigations are needed to determine the role of water in the application of structures.

5. Conclusion
It can be concluded that the use of water in combination with a hydrophilic surface structure as well as increased traverse velocities enables the reduction of the coefficient of friction during strip drawing tests at least at low contact pressures. This opens up possibilities to place the LIPSS in regions like the drawing edge where there are high frictional stresses in order to reduce them and to deliver an alternative to conventional lubricants.

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