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# Dry deep drawing of a rectangular cup assisted by volatile media injected from laser-drilled microholes

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## Abstract

Technical, economic and legal requirements lead to increasing demands on lubricants in sheet metal forming. Moreover, the effects of lubricant application on the environment become more and more relevant. The long-term goal in sheet metal forming is to reduce the amount of lubricant used in order to conduct sheet metal processing without lubricants in future. Based on the efforts of dry forming, a new procedure for the lubrication of deep drawing processes with volatile media as lubricant substitution is being developed at the University of Stuttgart. This method enables the insertion of an intermediate medium under high pressure through laser-drilled microholes into the tribological system without subsequent, cost-intensive cleaning processes as the volatile media evaporate without residue when the pressure is reduced to ambient pressure.

During the first and second funding period of this research project, a general applicability of volatile media as lubricant substitutes was demonstrated by means of strip drawing experiments and a simple academic test component of an U-shaped profile. For this purpose, several problems in the area of fluid supply to the tool were solved. In this report, new findings from investigations of the pressure state of volatile media in the tool contact zone, depending on number, nozzle type and arrangement of laser-drilled microholes, are presented. In addition, results of the optimized laser drilling process are included. These investigations serve as a base for the new, more realistic implementation of the new approach of dry forming in a deep drawing tool. The design of this tool for the deep drawing of a rectangular cup is presented here in detail. Initial investigations of the deep drawing process have also shown that volatile lubricants can be used to realize a significantly enlarged process window compared to conventional lubricants. This promising result shows the wide range of applications for the new tribological system in deep drawing processes.

**Keywords:** Dry metal forming, Deep drawing, Laser micro drilling, Friction investigations

## 1 Introduction

In sheet metal forming, mostly mineral oil- or wax-based lubricants are used to reduce friction and wear in forming tools. In doing so, lubricants sometimes contain toxic additives and the formed components have to be cleaned for subsequent process steps in a cost and time-consuming manner. For this reasons, lubricant avoidance has a positive effect on the environment and the economic efficiency of production processes. Therefore, a new tribological system for sheet metal forming is being developed at the University of Stuttgart in cooperation with the Institute for Metal Forming Technology (IFU) and the "Institut fuer Strahlwerkzeuge" (IFSW) that eliminates the use of conventional, oil- or wax-based lubricants. Via laser-drilled microholes, which can be used as a kind of nozzle incorporated into tool surface, volatile media are released into contact zone between sheet metal and tool surface, in which these media temporarily act as lubricant and subsequently evaporate without residue. So far, friction investigations have shown that both $CO_2$ and $N_2$ work quite sufficiently as a good temporarily acting lubricant media. To find the most suitable medium for the application in sheet metal forming, especially in deep drawing processes, further investigations and results will be presented in this report. Focus of current work is put on the investigation of the pressure conditions of the volatile media in the tool contact surface. Direct measurements of pressure and temperature under stationary flow conditions were carried out using a modified strip drawing test rig. Another major challenge already solved was


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the process-safe production of the laser-drilled microholes with a drilling depth of more than 6 mm in the hardened deep drawing tools. It was possible to further optimize the process of the laser-drilling. With the determined adjustment parameters for the laser drilling of leading channels for the volatile media, a real tool was manufactured to produce first sheet metal components, a rectangular cup. The results of these experiments reveal the potential of dry deep drawing process using volatile media.

## 2 Experimental investigation on pressure in tool contact zone

It is essential for the comprehension of friction behaviour of volatile fluids (e.g. $N_2$ or $CO_2$) in dry deep drawing to investigate predominating conditions in contact zones of tool and sheet metal. Aim of the carried out experiments is to determine the instantaneous pressure conditions in the contact zone of deep drawing processes. CFD-Simulations of complex laser-drilled feed channels for volatile fluids and textured sheet metal surfaces are very complex and influenced by manifold parameters. Therefore, experiments were carried out to measure local pressure conditions in the contact zone directly.

A modified experimental strip drawing test rig was used for these analyses in order to measure normal forces, drawing velocities etc. and with this test rig fluid feedings were visualized and depicted, too.

An easy setup is chosen to investigate the behaviour of the pressure in the contact zone by using stationary fluid conditions. Stationary fluid conditions can be obtained by remaining the velocity of the sheet metal test strip stationary (velocity = 0 mm/s).

### 2.1 Stationary investigation

To get a closer look on the conditions in the gap between sheet metal and tool surface influenced by the volatile fluids first stationary experiments are carried out.

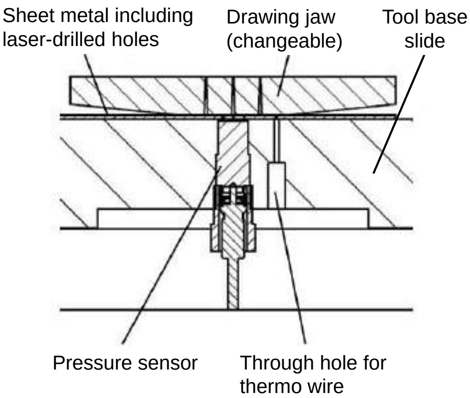


Figure 1: Section of test rig for direct pressure measurements in the contact zone between tool (drawing jaw) and sheet metal.

Benefits of this approach are that dynamic influences like the drawing velocity can be eliminated. So basic findings of the influence of varied parameters can be obtained. Type of nozzle shape, numbers and arrangement of lased drilled microholes, the normal pressure in the contact zone, the pressure and the sort of volatile fluid have been varied in such extended lab tests.

As shown in Figure 1 the test rig for direct pressure measurements in the contact zone of tool surface and sheet metal persists of the drawing jaw, a strip of sheet metal, a tool base slide, a sensor for the fluid pressure and a hole for a thermo wire.

The design of the drawing jaw is conducted changeable. This facilitates different numbers, arrangements and geometries of laser-drilled holes in the testing rig. The sensor for the pressure measurements is located at the opposite side of the sheet metal in the tool base slide and not in the drawing jaw. This was necessary because the sensors dimensionally requires too much space to install it in the drawing jaw. To ensure transfer same pressure of the volatile fluid from the upper side of the sheet metal to its lower side the investigated strip of sheet metal was also supplied by lased drilled microholes perpendicular to the surface. To ensure local static pressure conditions near the pressure sensor, a pressure loss through the microholes in the sheet metal strip has to be avoided. This was achieved by avoiding a flow of volatile fluid into the gap between sheet metal stripe and lower tool base slide. In this way the local static pressure of the volatile fluid in the upper contact zone can be measured directly.

Having performed such experiments that manner new findings of the conditions of applied volatile fluids in the contact zone were achieved. Subsequent an excerpt of gained results comparing the fluids $N_2$ and $CO_2$ at normal pressures 5, 10 and 15 MPa are presented.

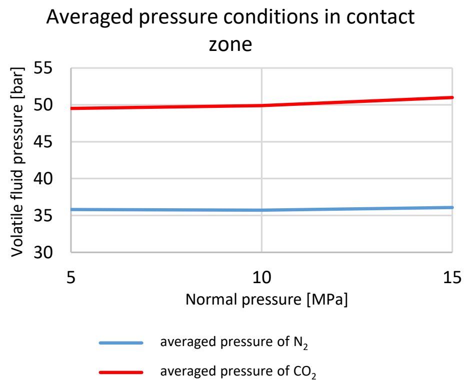


Figure 2: Pressure conditions in contact zone of tool surface and sheet metal stripe averaged for depicted normal pressures and fluids for all drawing jaws.

In order to ensure a good comparability of performed experiments with different volatile media, the pressure at the supply valve has been set to the same level in all experiments. All volatile media are taken from a gas cylinder. Carbon dioxide in the conventional gas cylinder is present as a 2-phase area, where gaseous and liquid $CO_2$ are present at the same time. $CO_2$ is taken out of a standard gas bottle or cylinder in liquid state, so that the pressure cannot be adjusted and remains constant depending on level of exit temperature. For this reason, the pressure of nitrogen is set to the same value as for carbon dioxide at the supply valve (T=20°C, p≈ 60 bar).

Nevertheless, the pressure in the contact zone of $CO_2$ and $N_2$, averaged over all drawing jaws, differed remarkably from each other (see Figure 2). With $CO_2$ the mean values ranged about 15 bar higher than with $N_2$, which means that the pressure losses of $N_2$ are significantly higher than those of $CO_2$ under the same geometric conditions and by use of same drawing jaws.

This can be justified by the phase change from liquid to gaseous in $CO_2$, where $CO_2$ first flows into the drawing jaw in a liquid state. In the contact zone and partly already in the micro boreholes, the $CO_2$ then changes into the gaseous state. This is accompanied by cooling and expansion. The specific volume increase at 20°C, due to the phase change, is nearly a factor of four. For this reason the flow rate for $CO_2$ in the liquid state is considerably lower and thus also the pressure losses decrease there.

The averaged pressure of the two fluids in Figure 2 shows no significant dependence on rising normal pressure. Only when results of the fluid pressure measured in contact zone of individual drawing jaws are compared, impact on the course of the volatile fluid pressure can be detected, especially with increasing normal pressure of $N_2$. With a small number of holes, i.e. a smaller mass flow, the joint pressure increases with increasing surface pressure. With a larger number of holes, the pressure remains at approximately the same level with increasing surface pressure, leaving slight fluctuations behind (see Figure 3).

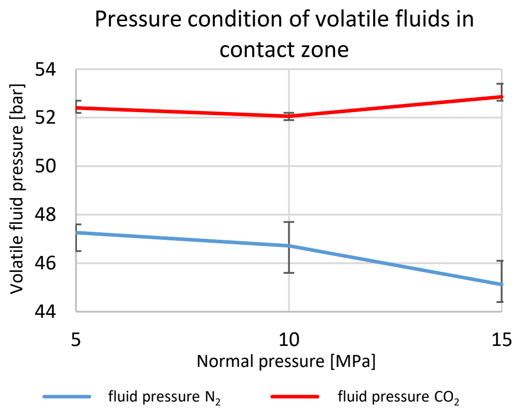


Figure 3: Volatile fluid pressure in contact zone at different normal pressures; drawing jaw with 9 laser-drilled microholes (3x3) as a diffusor was used.

In general it can be observed that the pressure fluctuations of individual repeated measurements with $N_2$ as fluid remains considerably higher than with $CO_2$. This effect is most likely also due to phase change and the associated effects of $CO_2$.

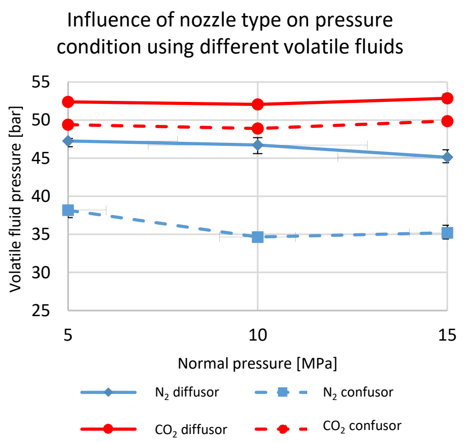


Figure 4: Influence of nozzle types on pressure condition in contact zone using drawing jaws with diffusor and confusor fluid feeding.

Another interesting result was achieved by investigating various microhole geometries. For example, diffusers and confusors were inserted into the various drawing jaws by means of laser drilling. As can be seen in Figure 4, both $CO_2$ and $N_2$ achieve higher pressure values in the contact zone through diffusers. This effect is particularly pronounced with nitrogen. As higher pressure in the contact zone improves the separation of tool surface and sheet metal, friction and wear was reduced considerably. This suggests that better results can be achieved with fluid feeds by use of diffusers. This finding also coincides with the results of the friction tests performed in the past funding period.

### 2.2 Conclusions on level of fluid pressure in contact zone

The experimental knowledge gained from the stationary investigations of the pressure in the contact zone between tool and sheet metal has enabled a deeper understanding of the effects and their influence on friction in deep drawing process.

The findings of the investigations of the pressure in the tool contact zone were applied to the following experiments on deep drawing of rectangular cups. For example, the feed holes were manufactured as diffusors and their number and distribution of required laser-drilled holes were defined on the basis of the findings from the preliminary investigations.

Further investigations conducted on the influence of dynamic effects on the pressure level in the tool contact zone and thus on the friction conditions at the tool radii are aims of future investigations in this area. For this purpose a modified Duncan-Shabel-Test has to be equipped by laser drilled tooling inserts for the supply of volatile media. In addition, the results obtained from the investigations of the pressure conditions in the tool contact zone will be included into enhanced friction modelling.

## 3 Basic laser drilling limits

Laser-drilling of deep holes into tool steel material is still a major challenge. Decreasing quality with increasing depth of the holes was observed and reported in numerous publications, e.g. in [1]. One of the major reasons for reduced quality during laser processing with ultra-short laser pulses is the so-called heat accumulation [2]. In addition, the limited pulse energy evidently limits the maximum drilling depth: With increasing hole depth the total wall surface area of the microhole increases. This means that the average laser fluence (i.e. the laser pulse energy divided by the wall surface area) decreases. If the average fluence reaches the ablation threshold fluence, only very slow and localized drilling can occur. This limit is called "quality depth limit" in the following.

Heat accumulation and the quality depth limit were investigated for the required geometry of the microholes. For the experiments, the prototype kW-class ps-laser of the IFSW was used [3]. The passive disk-amplifier of this laser allows very high pulse energies, which are necessary for laser drilling of deep holes. The focused laser beam was moved on a circle over the surface of the sample. A helical drilling optics (GL-Trepan) was used to move the laser beam and to adjust the diameter of the circle. Furthermore, GL-Trepan allows adjusting the inclination angle of the beam relative to the surface, which is useful for longitudinal shaping of the holes. The properties of the laser, the helical drilling optics, and the focusing optics are summarized in Table 1.

Table 1: Properties of the IFSW kW-class-ps laser system and the GL-Trepan drilling optics.

| IFSW kW-ps laser | |
|---|---|
| Pulse duration | 8 ps |
| Wavelength | 1030 nm |
| Average power | ≤ 650 W |
| Max. Pulse energy | ≤ 2.2 mJ |
| Repetition rate | ≤ 300 kHz |
| $M^2$ | < 1.3 |
| Polarization | Linear |
| Collimated beam diameter | 5.2 mm |
| **Helical drilling optics (GL-Trepan, GFH GmbH)** | |
| Rotation speed | 0-30'000 rpm |
| Hole diameters | 0-1500 µm |
| Inclination angle | 0°- 4° |
| **Focusing and ablation threshold** | |
| Focal length | 400 mm |
| Focus diameter | 140 µm |
| Polarization | Circular |
| Focus position | On the surface |
| Max. Fluence | 15 J/cm$^2$ |
| Ablation threshold (Steel, 8 ps, 1030 nm) | 0.1 J/cm$^2$ |

### 3.1 Heat accumulation

Heat accumulation was identified as the major quality-reducing effect for deep-hole drilling [4]. Following these results, the repetition rate was fixed to 60 kHz. However, also at this low repetition rate, a slight increase of the pulse energy from 2.0 mJ to 2.2 mJ leads to the onset of heat accumulation effects as shown in Figure 5 on the surface of the sample (top), as well as inside the material (bottom), marked with red arrows.

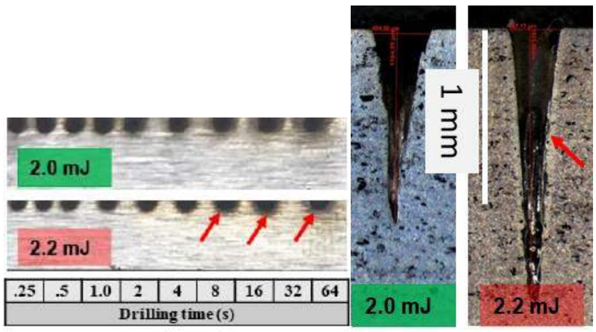


Figure 5: Appearance of a heat affected zone on the surface (left) and inside the material (right) with slightly increased pulse energy from 2.0 mJ to 2.2 mJ at the repetition rate of 60 kHz after $60 \cdot 10^3$ pulses, marked by red arrows.

Continuous drilling resulted in thermal damage of the hole entrance. To allow using the maximum pulse energy the optimum drilling strategy was adapted, i.e. drilling breaks included. To investigate the limits, drilling intervals of 0.5 s were interrupted with a decreasing duration of the breaks in-between these drilling intervals. Figure 6 shows that decreasing the break between the drilling intervals from 2.0 s to 0.5 s results in the appearance of dross around the hole on the surface of the sample, marked with a red arrow.

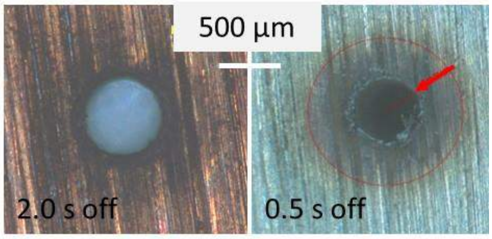


Figure 6: Decreasing the break between the drilling intervals from 2.0 s to 0.5 s results in the appearance of dross on the surface of the sample, marked by a red arrow.

Therefore, the correct strategy has to be applied when increasing the pulse energy keeping the repetition rate of the laser constant.

### 3.2 Investigation of depth limit

The influence of the pulse energy on the drilling progress, i.e. the hole depth as a function of the number of applied pulses is shown in Figure 7.

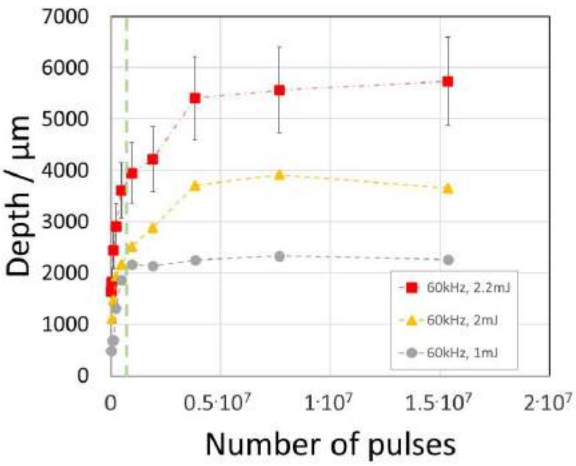


Figure 7: Hole depth as a function of the number of pulses for the pulse energies of 1 mJ, 2.0 mJ, and 2.2 mJ. the green dashed line indicates the end of the fast drilling phase.

In the beginning of the drilling process, up to about $5 \cdot 10^5$ pulses (indicated by the dashed green line), the drilling progress is very fast. In the case of 2.2 mJ this is to a depth of about 4 mm. This fast phase is followed by a very slow, irregular progress showing saturation behavior. However, the maximum depth which can be reached in this phase is very sensitive to the drilling parameters such as repetition rate, focus diameter, and focus position, and details such as beam profile, pointing stability, and local material properties. The hole depth which is reached after the fast drilling phase corresponds to the above-mentioned "quality depth limit".

# 4 Laser drilling of the microholes in the deep drawing tool

## 4.1 Requirements

The required position and geometry of the microholes in the deep drawing tool is shown in Figure 8. In total, 254 microholes had to be drilled. The depth of the holes was either 5 mm or 6.7 mm, depending on the position of hole in the tool arrangement. The hole angle relative to tool surface was either perpendicular or 35°.

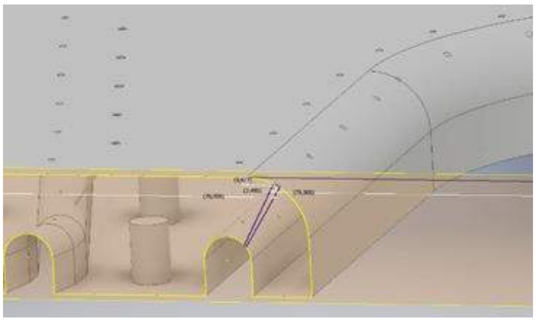

Figure 8: Geometry and position of the microholes.

## 4.2 Laser-drilled microholes

As a result, from the basic investigations described above, the microholes were drilled with 60 kHz, the maximum available pulse energy of 2.2 µJ, and the above-mentioned drilling strategy of 0.5 s drilling interval follow by a 2.0 s break. In Figure 9 a typical cross-section of a laser-drilled, deep microhole for the deep drawing application is shown.

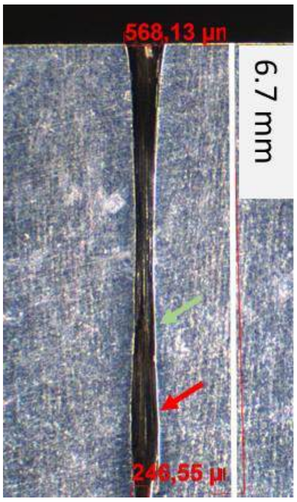


Figure 9: Typical cross-section of a laser-drilled, 6.7 mm deep microhole for the deep drawing application. The green arrow indicates the "quality depth limit", the red arrow the widening of the hole due to the very long drilling time.

The net drilling time was 60 s and 320 s for the 5 mm and the 6.7 mm holes, respectively. Although the depth of 6.7 mm was reached, the respective drilling time was very long, i.e. the drilling was exceeding the quality depth limit. This manifests in the longitudinal shape of the hole as seen in Figure 9. Down to a depth of about 4 mm (marked with a green arrow), the shape is conical and very regular. This depth corresponds to the "quality depth limit" (cf. Figure 7). For larger depths, the very long drilling time leads to an irregular widening of the hole cross-section. However, the holes were free of heat affected zones and free of burr on the surface. Overall, the quality was acceptable for the deep drawing experiments. Nevertheless, further improvement is necessary and will be investigated in the future, as discussed later in this chapter.

## 4.3 Manufacturing of the deep drawing tool

The system setup during the drilling process and the completed deep drawing tool are shown in Figure 10 left and right, respectively.

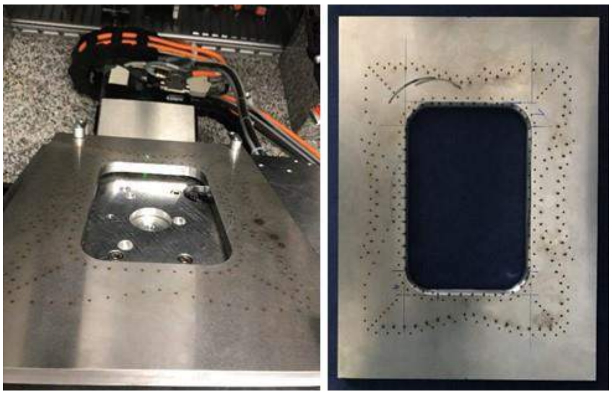

Figure 10: System setup during manufacturing (left), and processed deep drawing tool (right).

Due to constraints of the micro-processing station, positioning of the blank with respect to the absolute coordinates of the holes and the angle relative to the surface was done manually using auxiliary tools. This caused in particular inaccuracy of the focus position relative to the surface of the blank, which resulted in scattering of the hole diameters of bout ±15%.

## 4.4 Conclusion on laser drilling

Laser drilling of very deep holes up to 6.7 mm was successfully demonstrated. However, further optimization of the drilling process is required. This includes the following:

- Optimize drilling strategy, i.e. further reduce the repetition rate, reduce breaks, and find the optimum trade-off between repetition rate and break duration.
- Optimize the longitudinal hole shape for our dry deep drawing application by varying the focus position during the drilling process, adapt the parameters of the GL-Trepan optics, and increase the laser pulse energy.
- Verify the quality depth limit and optimize the depth e.g. with a reduced focal spot diameter and using assist gas during drilling.
- Optimize the mechanical setup for laser drilling to improve the reproducibility of the hole diameter and shape.

## 5 Dry deep drawing of a rectangular cup

### 5.1 Tool design

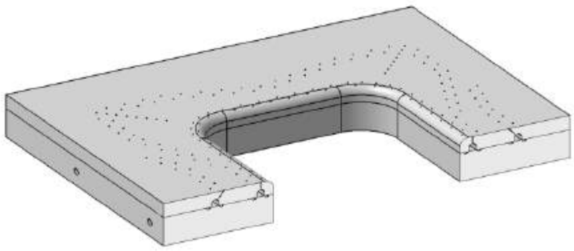

Figure 11: Cross section through the segmented die of the forming tool.

In order to reduce the drilling depth for the laser process without reducing the tool strength a segmented tool design was chosen (see Figure 11). The base plate contains the holes for the media supply and a sealing to avoid a uncontrolled flow out between the plates while the upper plate contains different supply channels and laser-drilled microholes. The position of the supply channels determines the location of microholes. In order to avoid a free flow out of the media through the microholes at the end of the forming process the position of the supply channels was optimized using a sheet metal forming simulation of the blank draw-in. As a result, one ring channel was integrated next to the die radius and four additional channels are arranged with regard to the blank draw-in. Each supply channel can be controlled separately by a valve to stop free flow out of liquid during deep drawing.

One row of microholes was drilled perpendicular into the supply channel having a depth of 5 mm and one row was incorporated by an angle of 35° and a length of around 7 mm. Additional microholes were placed in the die radius area. In total, 154 microholes were distributed over the tool surface of the die. For the blankholder, the same design was chosen though without radius. Here, 100 microholes were drilled into the tool.

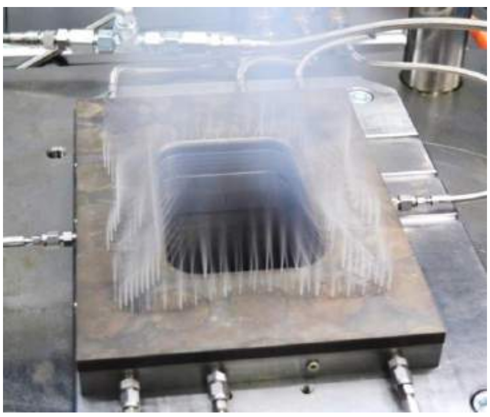

Figure 12: Free flow out of the $CO_2$ through laser-drilled microholes in the die of the deep drawing tool.

Due to some problems in the tool manufacturing, it was necessary to re-mill the die radius after die laser drilling. For this purpose, the tool was connected to a compressed air system applying a pressure level of 2 bar during the milling process. By doing so, surprisingly none microhole was blocked due to the machining process. Also after the final hardening process of the tool, no blockage of the microholes could be observed. The final assembly of the die tool is shown in Figure 12 while a free flow out of the $CO_2$ through the laser-drilled microholes is activated.

### 5.2 Experimental setup

The aim of this project is the development of a new method for dry metal forming by using volatile media injected through laser-drilled microholes. Focus of research project is put on the investigation of any practical e.g manufacturing oriented feasibility of this new approach. Therefore, emerging process limits have to be investigated and compared to the conventional deep drawing process using mineral oil- or wax-based lubricants. An established method is the determination of the process window. Usually, the blankholder force and the drawing ratio is varied in the deep drawing process in order to find maximum drawing depth without wrinkles or cracks. By doing so, the valid process window can be determined where no cracks and no wrinkles in the flange area appear. For non-rotational parts the drawing depth is used instead of the drawing ratio.

All drawing experiments were carried out using electrolytic galvanized sheet material DC05. The sheets were cleaned manually and then degreased in a acetone bath in order to remove all prelube oil on the sheet. Liquid $CO_2$ having an initial pressure level $p_{initial}$ of 60 bar and gaseous $N_2$ at the same pressure level were used as temporarily acting lubricant for dry metal forming. The supply of the media was controlled by the ram movement. The supply was switched on in the moment of the first contact between the tool and the sheet and shut down at the bottom dead center of the press. Additionally, drawings with the lubricant Wisura ZO3368 (1.5 g/m²) were investigated using the same tool. All tests were carried out on an AIDA servo press at a speed of 6 strokes per minute which corresponds approximately to 100 mm/s at the beginning of the forming process.

### 5.3 Experimental results und discussion

Presented approach for dry metal forming was tested successfully and so, a rectangular cup was deep drawn using $N_2$ and $CO_2$ as temporarily acting lubrication for the very first time. In accordance with former tests results investigating the coefficient of friction [5] and the deep drawing of a U-shaped profile geometry [4], the new lubrication system performed better than the conventional one using a mineral oil-based lubricant (see Figure 13).

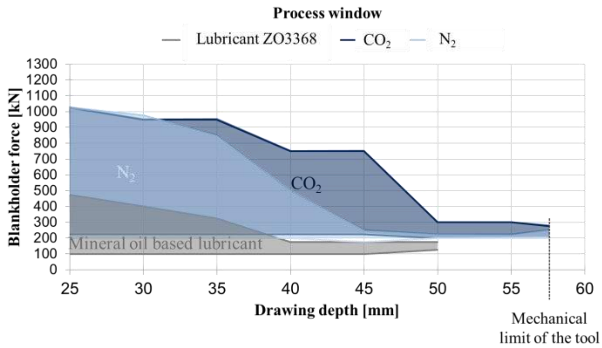


Figure 13: Process windows for deep drawing of a rectangular cup using different lubrication systems

The maximum drawing depth could be increased to 57.5 mm by using $CO_2$ and $N_2$. This depth corresponds to the mechanical limit of the tool. By using lubricant ZO3368 only 50 mm as a maximum drawing depth was achieved. Also the fracture limit was raised up to 50% depending on the drawing depth by using $CO_2$ as well as $N_2$. Thereby, $CO_2$ performs better for deeper cups than $N_2$. It is assumed that this is caused by different pressure levels acting in the gap between the sheet and the tool resulting by the different media (see results in chapter 2.1). In general this pressure in the gap $p_{gap}$ is influenced by microholes (position, numbers, nozzle type), the initial pressure level of the injected media $p_{initial}$ and the sealing effect between tool surface and the sheet. Also the sealing effect is influenced by many factors such as the blankholder force $F_{Blankholder}$, the tool and sheet surface roughness and the thinning and thickening of part flange during deep drawing. Finally, there are interactions between the sealing effect, the pressure level $p_{gap}$ and the height of the mean gap $h_{gap}$ between the sheet asperities and the forming tool. A schematic illustration of the conditions in the gap and the applied designations are shown in Figure 14.

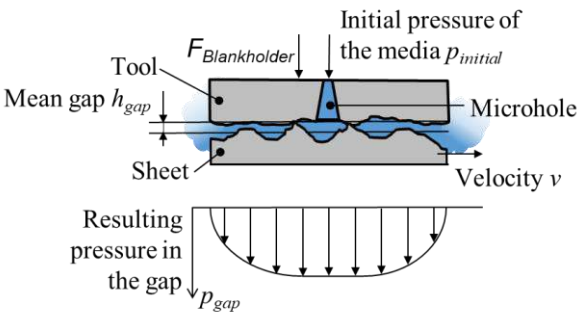


Figure 14: Schematic illustration of the resulting pressure between sheet and tool.

By deep drawing with volatile media acting as lubrication not only the fracture limit, but also the wrinkle limit was increased noticeably (see Figure 13). Also this effect can be explained by the assumption that the mean gap $h_{gap}$ and the pressure $p_{gap}$ mainly do influence the sheet metal forming behaviour. For lower blankholder forces a higher gap $h_{gap}$ occur without or with minimum contact areas between the tool and the sheet asperitives. While forming, wrinkles of 1st order develop due to increasing tensions in the blank without prevention by the blankholder. Thereby, the pressure in the gap, which is a scalar quantity acting in all directions, cannot avoid the local development of wrinkles. The outflowing gas through the wrinkles support such development additionally. Other tests indicate that the wrinkle limit is raised further by using a pressure $p_{initial}$ of $N_2$ higher than 60 bar. However, also the fracture limit can be increased extremely. This confirms the assumption that the resulting pressure level $p_{gap}$ of the volatile media between the sheet and tool mainly influences the friction behaviour and therefore the forming limits in the deep drawing process of this new approach.

In addition to those investigations on process limits in deep drawing, the cooling effect on the sheet surface caused by the Joule-Thomson effect during the relaxation of $CO_2$ and $N_2$ was investigated. The temperature was measured optically after the deep drawing process using a thermal camera.

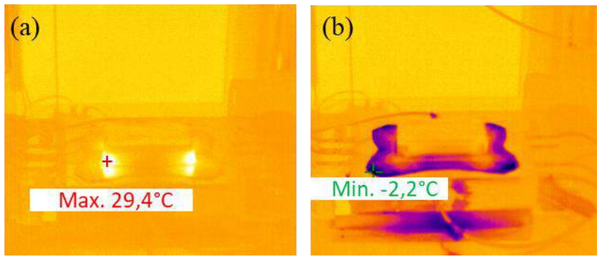


Figure 15: Measured temperature on the sheet surface after deep drawing using (a) nitrogen and (b) liquid carbon dioxide as lubricant

In Figure 15 the visualized temperature is shown using nitrogen (a) and liquid carbon dioxide (b) as lubricant for the same process having a drawing depth of 35 mm and a blankholder force of 275 kN. The maximum measured temperature (29.4°C) after deep drawing using nitrogen is almost similar to the sheet temperature when using mineral oil-based lubricants (30.1°C). The heating in the corner of the cup is caused by dissipating forming energy and friction heat. By contrast, using liquid $CO_2$ as temporally acting lubricant reduces the sheet temperature in the flange area down to -2.2°C (see Figure 15 (b)). Compared to the first deep drawing experiments using a U-profile geometry [4], a cooling effect of only a few degrees Celsius were measured. The cooling effect merges much more significantly when deep drawing the rectangular cup. Additional to that the control of valves also plays an important role. Finding the right timing to switch on and off the flow of media appear more complex for the drawing process of a rectangular cup having curved arrangements of microhole positions onto the tool surface and more complex draw-in compared previous drawn part as described. Another reason might be given by effect of changing flange thickness during drawing counteracting to local blankholder force. Small gaps between the tool and the sheet induced by small wrinkles of 1st order can occur supporting the flow out of the $CO_2$ and therefore the cooling of the sheet due to high velocity of media. According to these results, the flow control and also the position of microholes have to be optimized in further research work in order to reduce observed extreme cooling of the sheet. A different approach is given to use the cooling effect actively to reduce the heating in drawing process, while heating of parts due to friction heat and dissipating forming energy is undesirable.

However, on the whole presented results show that a dry forming by means of temporally acting volatile media is possible, which not only allows an equivalent substitution of mineral oil-based lubricants, but also an enhancement of the process limits in sheet metal forming. Especially using nitrogen with a pressured level adjusted to the respective process conditions are extremely promising.

## Outlook

The progress in the use of volatile media as lubricant substitutes in the deep drawing process in this paper was demonstrated based on achieved results. Thus, numerous technological challenges in the manufacturing of precise micro-drilling by laser drilling were mastered, but also deepened knowledge could be gained experimentally and simulatively by examining emerging friction conditions in the tool contact zone. Furthermore, after deep drawing of approximately 300 cups under dry as well as lubricated conditions no microholes were blocked by zinc abrasion or other effects. So it can be assumed that blockage of the microholes is not a limitation factor for this new approach. In a next step, these results have to be confirmed by prospective deep drawing endurance tests. Further performed measures also will be implemented into the test stand in the coming funding period. The tool radii of a new testing rig, which are subjected to high friction and wear loads, will be provided with feedholes for volatile media flow too. Complex friction conditions in corner areas and interaction with deep-drawing process will be investigated in this new special testing rig. A further goal of research is to expand the range of applications for zinc-coated steel sheets to include selected aluminium sheet materials, which poses enormous challenges with regard to a more complex tribological system and its susceptibility to failure. Furthermore, the theoretical knowledge of the friction behaviour of volatile media in the tribological system is to be further deepened in order to understand and specifically influence the occurring effects and thus to ensure robust and stable deep drawing processes.

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## References

[1] Döring, S.; Richter, S.; Tünnermann, A.; Nolte, S.: "Evolution of hole depth and shape in ultrashort pulse deep drilling in silicon", Appl. Phys. A 105, 69–74, (2011).

[2] Weber, R.; Graf, T.; Berger, P.; Onuseit, V.; Freitag, C.; Wiedenmann, M.;Feuer, A.: “Heat accumulation during pulsed laser materials processing”, Optics Express 22 (9), 11312–11324 (2014), and Erratum thereto in Optics Express 22 (23), 28232, (2014).

[3] Negel, J. P.; et al.: "1.1 kW average output power from a thin-disk multipass amplifier for ultrashort laser pulses", Optics Letters, vol. 38, no. 24, pp. 5442-5445, (Dec 2013).

[4] Woerz, C., Zahedi, D.; Umlauf, G.; Liewald, M.; Weber, R.; Graf, T.; Tovar, G.: „Tiefziehen eines U-Profils mit flüchtigen Medien als Schmierstoffersatz“, Dry Metal Forming Open Access Journal, (2017) Dry Met. Forming OAJ FMT 3 050-061, (2017).

[5] Woerz, C., Liewald, M., Singer, M.: “Investigation of Tribological Conditions in the Strip Drawing Test Using Liquid CO2 and N2 as a Volatile Lubricant”, Proceed. of 7th ICTMP, ISBN: 978-616-92565-0-2 , pp.140-148, (2016).