



## Tool concepts for dry forming

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### Abstract

In order to achieve an efficient use of resources, a decreasing usage of lubricants is an important goal in forming processes. Therefore, a new approach for a lubricant free deep drawing process shall be realized. One basic element of this approach is the use of macro-structured tools in order to reduce the friction forces and control the material flow. This paper presents the basic process principles and the results of analytical investigations, FE-simulations and experiments for a process design without lubrication.

**Keywords:** Dry forming, Deep drawing, ta-C coating, Macro structuring

### 1 Introduction

In metal forming and especially for deep drawing processes, lubricants are used to considerably reduce the friction between tool and workpiece. These lubrications reduce the forming energy, increase the forming limit, reduce the number of forming steps, increase tool life, help to avoid of galling and lead to a refinement in surface finishing of products. Hence, lubricants are usually expected in the metal forming process for efficient operation and reduction in energy consumption. However, the disposal of large amounts of lubricant waste is a serious environmental and economic issue, e.g. [1].

### 2 State of the art

The raised awareness of environmental problems and the requirements to establish solutions decreasing the impact on working environment as well as external environment has initiated ever increasing efforts to develop new, environmentally benign tribological systems for sheet metal forming.

Since the year 2000, legislation in Europe and Japan has been increasingly preventive with respect to the industrial application of harmful lubricants. In the year 2006–2007, the EU introduced new legislation, REACH, aiming to establish a high level of protection of human health and the environment from the risk posed by chemical exposure [2, 3, 4].

A deep drawing process in advanced high strength steels and stainless steels implies very difficult tribological situations. This is due to their comparatively high strength, inferring large contact stresses at the tool and

workpiece interface, partly due to the microstructure of the sheet materials involving multiphase structures and a strong tendency to pick-up and galling when the lubricant fails. However, due to the health and environmental risks of lubricants, legislation has been aiming to minimize the use of lubricants in manufacturing processes in EU as well as Japan for the last decade [5, 6, 7]. Additionally, using any lubricant in metal forming requires cleaning of the forming parts, usually several times between subsequent production steps, in order to obtain a clean and grease-free surface [8, 9].

For this reason, various green strategies, as semi-dry processes or minimum quantity lubrication (MQCL), have been implemented by manufacturers especially for cutting technologies [10], but none of them can realize a total lubricant free metal forming process. This is because of some important tasks of lubrication in metal forming. The lubricant is able to reduce the friction, decrease the total deformation force and energy, prolong the tool life, and more importantly to avoid galling [11, 12]. Therefore, a reduction of the lubricants will result in a smaller process window regarding drawing ratio and forming limit. Hence, the negative impact of the elimination of lubrication has to be countered with an adapted tool concept to ensure a stable and proficient deep drawing process.

In order to maximize the result of any effort to reduce the negative ecological and economical side effects of lubricant in production techniques, a completely lubricant free metal forming process with adapted tool de-

sign should be developed to fulfil all functions of lubrication in the process while also being able to control the friction forces and material flow during the process.

### 3 Objective and approach

In sheet metal forming, lubricant free deep drawing is an attractive process but difficult to be applied in general without an advanced design of tools. Therefore, development of a deep drawing process with new tool design is necessary to produce accurate goods in dry condition. In order to achieve that, some process parameters such as blank holder force, geometry and thickness of the blank, drawing ratio and material need to be considered.

Within the scope of this paper, the elimination of the lubrication by means of an adapted tool concept is investigated. The implementation of such a lubricant free deep drawing process is the aim of a new basic research project. The central approach is the control of the friction forces and material flow and also enlargement of the process window by substituting the conventional tools with the new concept.

Reducing the contact area in metal forming decreases the sum of friction forces but also increases the surface pressure. Structuring the deep drawing tools can reduce the effective contact area between blank and tools up to 80 % compared to conventional deep drawing tools. Figure 1 illustrates schematically the structured tools.

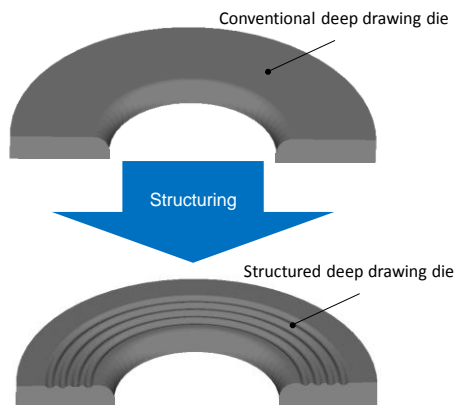


Fig. 1: Structuring a standard deep drawing tool

In deep drawing the blank undergoes a tensile stress in the radial direction and a compressive stress in the tangential direction. These stresses in addition to the applied load and the contact condition between the blank and the tools must be controlled to avoid failure, which might appear in two main forms: wrinkling and fracture.

Wrinkling occurs in the flange area when the blank holder force is too low. In this case, the compressive stresses can surmount the blank holder force resulting in the buckling phenomenon which appears in the form of wrinkling. This can affect the process window. A higher blank holder force can help to avoid the instabilities in form of wrinkling, but also interferes with material flow and results in the fracture of blank. Therefore, controlling the stress states in the flange area during the process with the blank holder force is always required to avoid the possible failures in conventional deep drawing processes.

Generally, the blank holder force causes high contact pressure between blank and tools in the flange area which results in high friction force in this area. Therefore, in this paper, the blank holder force will be substituted with continually alternating bending of the blank during the process.

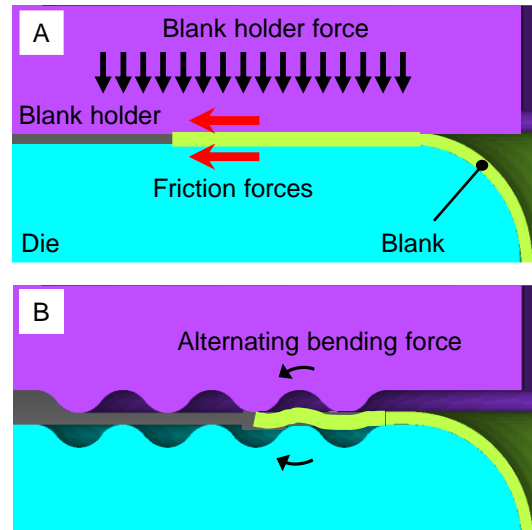


Fig. 2: Reduction of friction forces in flange area by means of macro structuring, A) standard tools, B) Structured tools

The continually alternating bending increases the stiffness of the blank by this reduces the chance of buckling due to the tangential compressive stresses in the flange area. Furthermore, the friction between blank and blank holder is significantly reduced since there is no more holding force from blank holder. Design validation of such new structured tools requires an analytical and numerical model based on FEM and experimental results.

In order to prevent adhesion effects caused by the lack of lubricant the surface chemistry of the tools has to be improved by suitable coating. Generally, the flange area and tool edge radius are the most critical frictional areas in deep drawing tools, therefore, tetrahedral amorphous carbon (ta-C) is used for coating the surface of the structures in order to improve the surface condition. Ta-C coating can reduce the friction coefficient and also prevent possible wear effects in these areas. A control of the friction coefficient can be achieved by Direct Laser Interface Structuring (DLIS), which is used to change the surface properties of the ta-C coating selectively. By changing the laser parameters (fluence or pulse number) ta-C coating can be locally graphitized, delaminated (only nanometers thick coating) or be removed.

Therefore, in this paper a combination of the tool-structuring and ta-C coating will be presented in order to reduce the friction forces while also being able to control the material flow during the whole process to prevent the possible failures like wrinkles and fracture.

### 4 Numerical and experimental results

As mentioned above, to reduce the contact area between tools and blank, the surface of tools should be structured in macro scale of a couple of millimeters. For analyzing the effect of macro-structuring, the conventional deep drawing process is compared with the new

designed tools regarding the required forming energy using the finite element method. Figure 3 illustrates the conventional and structured deep drawing tool's configuration. Based on preliminary calculations, the period of the waves in new structured tools should be approximately 8 mm to be able to use the advantages of the alternating bending in flange area while limiting the risk of the blank getting jammed between the structures.

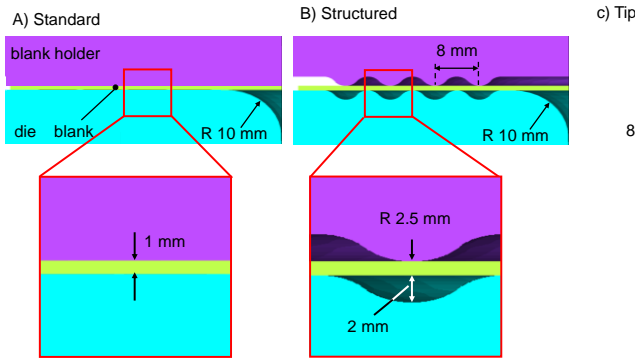


Fig. 3: Geometry of conventional and structured tools used in FEM analysis, A) standard tools, B) structured tools

DC04 has excellent formability, which facilitates cold forming operations, and are ideal for deep drawing. Hence, a blank of DC04 with 180 mm diameter and 1 mm thickness is subjected for deep drawing process with standard and also structured tool using “simufact.forming” software. To reach the limiting drawing ratio of 1.8, a punch with 100 mm diameter is used. The blanks in all three simulations are meshed as solid-shell elements with size of 0.5 mm, and in order to simulate the process more accurately. 7 shell layers with 5 integration points are considered for each element in order to be able for consider the effect of bending in an appropriate way. Figure 4 shows the results of numerical analysis based on Coulomb friction model (friction coefficient steel vs. steel 0.05) with bilinear approach for standard and structured tools based on the total stamp force for forming the work-piece and also the share of friction on total force.

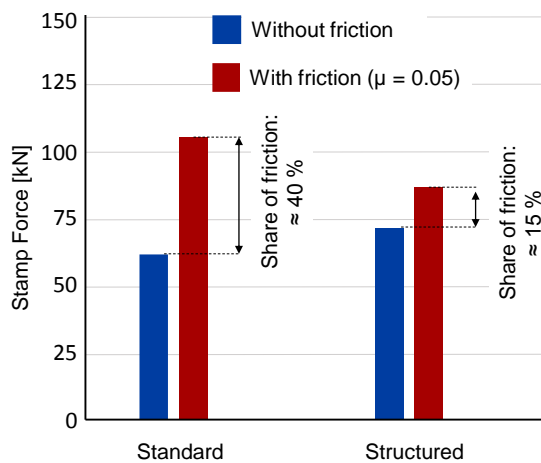


Fig. 4: FEM results regarding the total stamp force for deep drawing

The proposed tools with defined geometry are also tested experimentally in order to distinguish its transferability. The results are presented in figure 5.

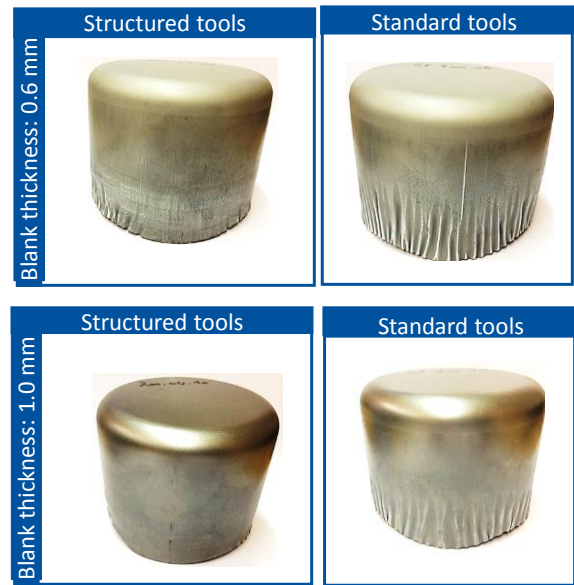


Fig. 5: Experimental results of deep drawing using standard and structured tools

Here the deep drawing process are carried out with blanks from DC04 with 200 mm diameter. The method was applied to blanks of different thicknesses to show that it is possible to control the material flow with structured deep drawing tools for a variety of blanks. As can be seen in figure 5, using structured tools reduces the risk towards wrinkling compared to standard tools. Additionally, these tools should be coated with new developed ta-C coatings as described above.

In order to analyze the influence of ta-C films on the friction coefficient of the drawing edge radius, the draw bend test was used in this study. Figure 6 illustrates the concept of the applied draw bend test machine. This test allows to draw a strip of blank across a prepared surface with high surface pressure creating similar conditions as in real deep drawing processes.

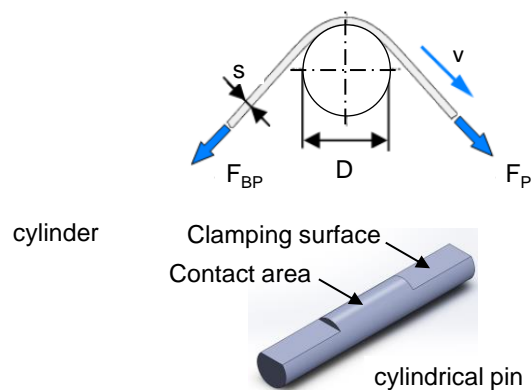


Fig. 6: Concept of draw bend test for analysis of ta-C coatings

The most significant simplification compared to the real deep drawing process is that the tangential compressive stress and the corresponding material flow is not considered. Nevertheless, this setup is applicable to simulate the kinematic during the deep drawing process. A

blank strip is drawn over a fixed or rotatable radius with a specified velocity ( $v$ ) at the drawing side and a back-pull force (FBP) at the other side. In this case cylindrical pins with a diameter of 10 mm are chosen for testing of the ta-C films. Since coating the pins impairs their surface finishing, they were brushed after coating to have a similar surface roughness as before. In this study, the arithmetical mean roughness ( $R_a$ ) of pins lies between 0.15-0.19  $\mu\text{m}$ , and also their ten-point mean roughness ( $R_z$ ) change from 1.05 to 1.75  $\mu\text{m}$ . Littlewood and Wallace mentioned the pulley equation in order to derive friction coefficients from the experiments [13]:

$$\mu = \frac{2}{\pi} \ln \frac{F_p - F_B}{F_{BP}} \quad (1)$$

Where  $F_p$  and  $F_B$  are the required force to draw and bending the strip over the radius at a prescribed velocity.

The ta-C coated- brushed pins are graphitized using Direct Laser Interference Patterning method to change their diamond properties into graphite locally in order to improve their frictional behavior. Micro graphite lines in contact area of pins are parallel to pulling force direction with 10  $\mu\text{m}$  distance and 1  $\mu\text{m}$  depth.

Specimens are cut from commercially-sourced DC04 steel of 1 mm thickness, 20 mm width and 1,000 mm length. The strip has been cold-rolled, and each one was cleaned using a citrus based cleaner and finally wiped with acetone to remove all traces of pre-lubricant. The drawing tools used in the tests are made from 100Cr6 (heat treated tool steel). Two conventional lubricants for deep drawing process with industrial application (Raziol ECLF-100 with 70 [ $\text{mm}^2/\text{s}$ ] viscosity at 40°C, and also Aqua-Form as a water-based non-combustible deforming wax) with a wide range of viscosities are used to achieve different tribological conditions and film thicknesses. To investigate the reproducibility of the measurement, a minimum of seven experiments have been carried out. The results are shown in Figure 7. As it is presented in Fig. 5, usage of Raziol and Aqua-Form can reduce the friction coefficient of an uncoated tool up to 35 % and 50 %, respectively. Coating the workpiece with ta-C film is also able to reduce the friction coefficient up to 25% comparing to the uncoated one in lubricant free condition.

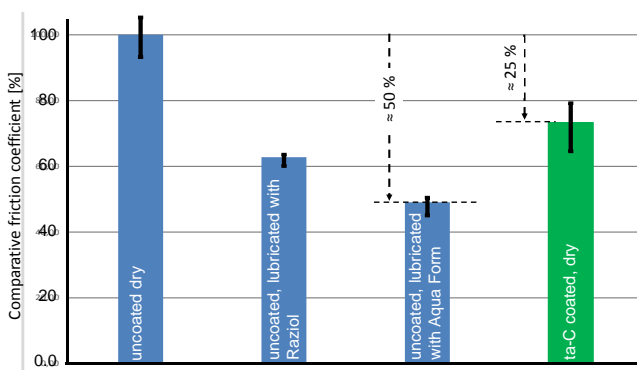


Fig. 7: Experimental results of ta-C coatings

## 5 Conclusion and outlook

Using the macro-structured deep drawing tools with the aim to minimize the friction forces and to control the material flow is a promising approach to achieve a dry forming process in the near future. Numerical and experimental results show that substituting conventional deep drawing tools with structured tools can reduce the share of friction forces from total stamping force. This approach also allows to control the material flow and produce wrinkle-free components. The combination of all possibilities coming from geometry as well as the surface modification will enable the process designer to influence the friction and forming behavior in a very precise way without a relevant reduction of process window. Besides the structuring of the tools, the usage of a ta-C coating will lead to minimized friction forces and will protect the tool surface regarding wear.

Micro structuring of the blank via laser can also reduce the effective contact area between tool and sheet. Therefore, micro structuring of the blank is considered as the third approach for lubricant free deep drawing and will be investigated in the future.

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