

# Sheet-bulk Metal Forming a New Process for the Production of Sheet Metal Parts with Functional Components

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The first results of different new sheet-bulk forming methods are presented in the article. It is shown how an additional superimposing of oscillation can be attached to the forming punch in order to improve the forming limit of the sheet material. New coating and atmospheric plasma-nitriding methods for processing of the forming tools (for improving of hardness and wear resistance) are also represented in the article.

Keywords: SHEET-BULK METAL FORMING; REDUCE THE FORMING FORCES; PVD/PACVD COATINGS, ATMOSPHERIC PLASMA-NITRIDING

## Introduction

Sheet metal parts which are produced by common processes usually undergo a combination of deep drawing and stamping. This is resulting in two-dimensional stresses and strains causing a strong deformation of the blank. Compared to these deformations the change in the thickness of the sheet is rather small. In a contradiction of this the new sheet-bulk forming process combines the common deep drawing with bulk metal forming. The results of this combination are three-dimensional stresses and strains causing a local material flow in the direction of the thickness. In this way functional elements like small gears or actuators can be formed (see **Figure 1**).

The article presents the first results of different new sheet-bulk forming methods. It also shows how an additional superimposing of oscillation can be attached to the forming punch in order to improve the forming limits. It ends with the presentation of new coating and nitriding methods for the (highly stressed regions of the) forming dies.

## New methods for sheet-bulk metal forming

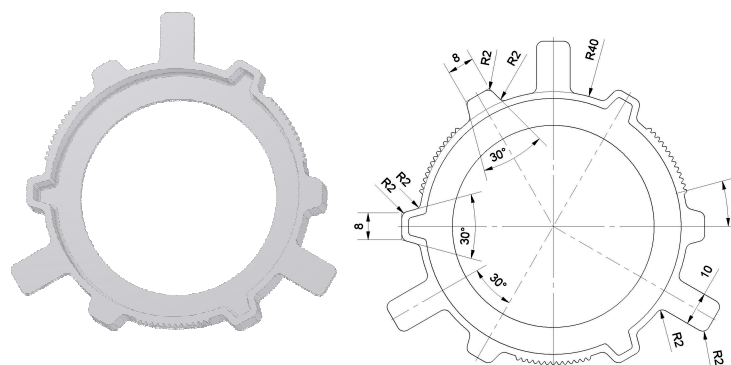
This first example is showing a process combination suited for manufacturing thin-walled functional components out of tailored blanks. Using an integrated deep drawing and upsetting tool, both the base body of the component in shape of a deep drawn

cup and features like catch elements as wells as local external teeth are manufactured.

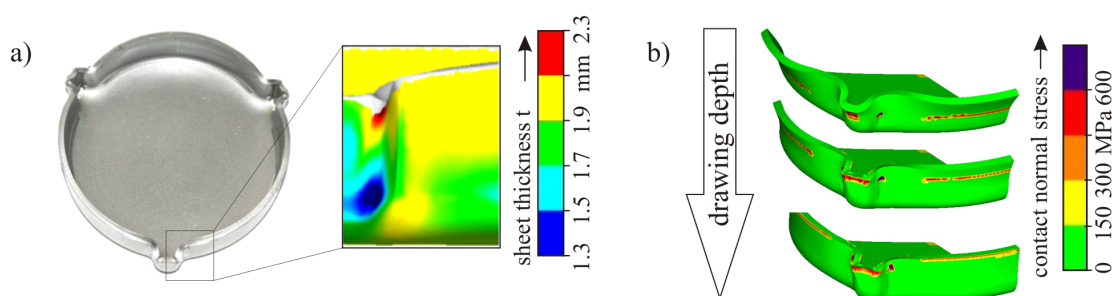
On one hand the catch elements, are directly formed within the deep drawing operation and can be edged using an additional upsetting operation. On the other hand, the deep drawing process is used to generate a process adapted semi-finished product for the subsequent integrated upsetting operation. By reduction of the height of the drawn round cup, thickening of the cup wall is initiated and the mould cavity of the gear teeth is filled.

**Figure 2** shows the deep drawn workpiece out of an experimental set-up. Using a blank sheet out of the mild deep drawing steel DC04 with initial sheet thickness of 2.0 mm and a diameter of 100 mm, a cup shaped base body with outer diameter of 80 mm and three integrated shape elements is formed in a single stroke. Due to the specific design of the workpiece, the punch and die geometry is designed respectively.

The analysis of current investigations shows, that the use of a blank holder has negative effects on the process with low drawing ratio regarding thinning in the area of the shape elements, where the load transmission from the drawing punch into the workpiece takes place. The irregular workpiece geometry causes in addition non-uniform draw-in and warping of the blank and in consequence areas of high local contact stresses between workpiece and tool. Simultaneously some areas of the workpiece have no or even loose contact, until the blank sheet is completely drawn in [1].



**Figure 1.** Demonstrator model of the research initiative



**Figure 2.** Deep drawn component with integrated functional elements with depiction of the maximum sheet thinning (a) and the differing contact conditions with ongoing drawing depth (b)

The use of an integrated deep drawing and up-setting process to manufacture a cup with an external tooth system is presented in **Figure 3**.

The initial blank of the same diameter and constant sheet thickness is deep drawn with the first active movement of the integrated deep drawing and upsetting tool. Due to the intended small drawing clearance in regard to buckling at the punch bottom radius during upsetting, the tooth heads of the internal teathed die is formed into the cup [2]. This results in an increased local strain hardening and simultaneously high local contact normal stresses up to more than 1,000 MPa. In combination with long relative motions between workpiece and tool, the danger of wear rises. With the second active tool movement, the cup wall is upset and a lateral material flow into the gear cavity is induced. This causes high contact normal stresses at the tooth root surface up to 1,400 MPa and non-uniform deformation over the height and also in the cross-section area. As the contact conditions are locally and temporarily changing, friction has strong influence on the mould filling and further process characteristics like the forming forces [3].

Another case study shows the differences between bulk-sheet metal forming and stamping. The chosen geometry is shown in **Figure 4** (left). It is a

cup with a gear ring at the border, made from a flat blank. A simulation of the forming process shows that there is a material flow into the plane of the sheet. While this material is missing in the region of the teeth an insufficient mould filling is obtained (see **Figure 4** (right)). To maximize the filling of the form very strong forces are required which result in high loads to the tools.

To realize a better filling of the die with significant lower forming forces new forming strategies have to be developed in order to control the flow of the material. One possible solution to stop the material flow from the forming zone into the sheet plane is the increasing of the friction between die and sheet in front of the teeth. Although this is in contrast to the common sense of classical deep drawing, the filling could be improved from 81% to 87% in the presented example.

Another possibility to control the material flow is to place flow barriers in the dies. Two possible locations for such elements are shown in **Figure 5** (middle and right).

A numerical analysis of the die filling shows, especially the groove in the upper die (**Figure 5** middle) is enhancing the filling of the teeth due to the avoidance of a material back flow. With a higher

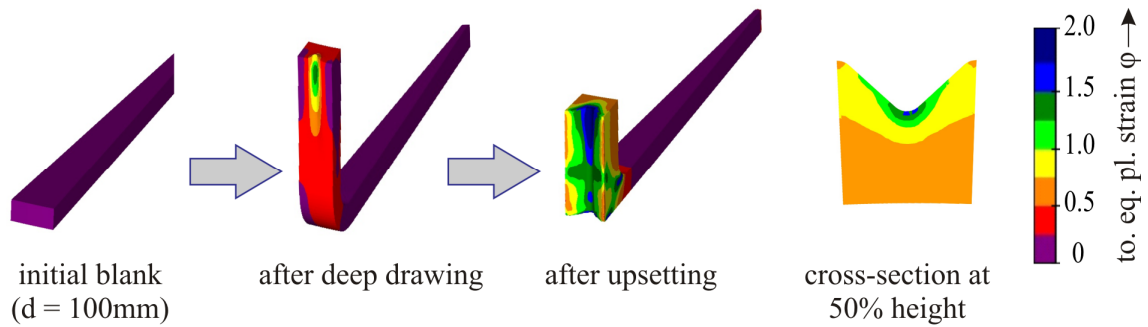


Figure 3. Immediate shapes of the workpiece and its strain hardening

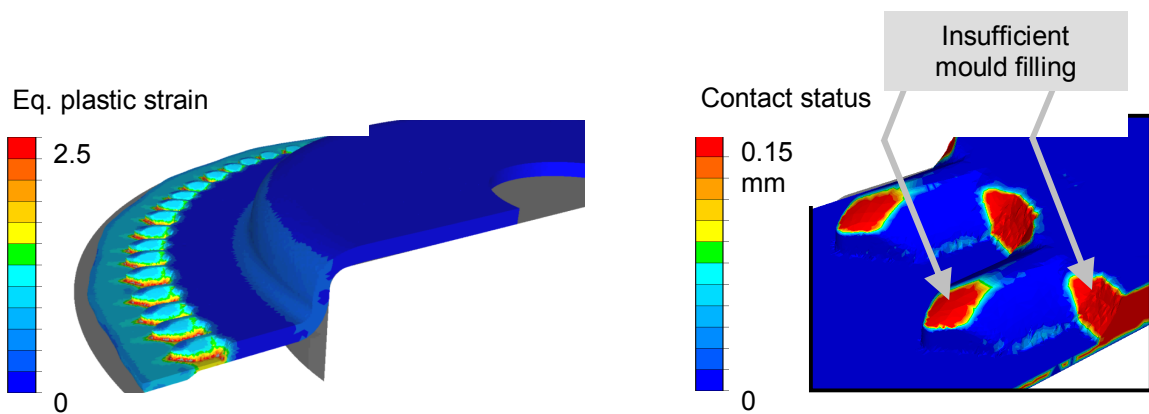


Figure 4. Simulation of the plastic strain (left) and the contact zone (right)

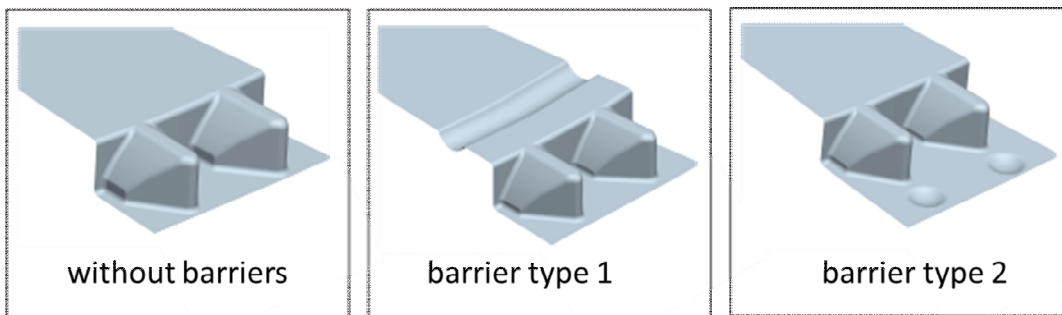


Figure 5. Modification of the forming die with different barricades for the material flow

friction coefficient of 0.3 in addition the filling can be increased up to 93.6%. The spherical barriers in front of the teeth are less useful because they influence the process only at a late point in time.

A main reason why the bulk-forming methods are not applied to sheets yet is the rise up of the forming forces with a decrease of the part's thickness. The use of incremental forming methods is suitable to receive small forming forces, though the sheets are rather thin. According to the small tools

the forming zone is limited to a small area resulting in small forming forces.

Regarding the long process time, accompanying with the kinematical forming with small tools, the incremental sheet-bulk metal forming could be used for prototyping and for small batches, or incremental forming operations can be implemented to follow-on dies in addition to conventional forming operations processes like deep-drawing, stamping or upsetting.

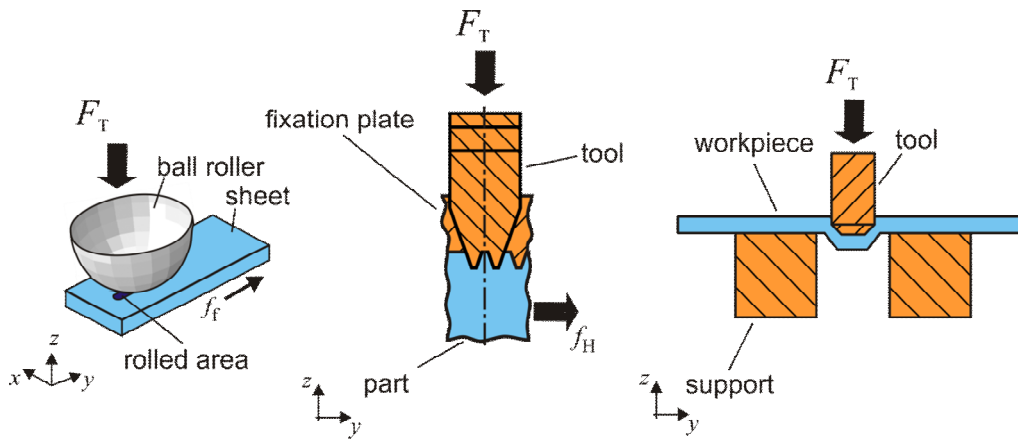
In **Figure 6** three possible incremental forming operations (incremental rolling, incremental coining of forming elements and incremental embossing) are shown.

A systematic analysis of these forming strategies, keeping the product-spectrum (e.g. synchronizer rings, pinions, bevel pinions) in mind, depicts the tools must act from a number of varying positions on the part. This requires a special machine concept that enables a flexible kinematic forming process. Towards the experimental set-ups are realized on different machines. E.g. the incremental rolling process is realized on a CNC-milling machine with a hydrostatic ball roller. The maximum force of the tool  $F_T$  is 400 kN. In a first study the influence of the rolling strategy (One-sided; alternating) and the number of repetitions ( $n = 2 \dots 80$ ) is investigated. These investigations examined applying a sheet made of DC04 with a thickness of 2 mm, shows that within an adapted rolling process, the material distribution as well as the mechanical properties can be influenced specifically.

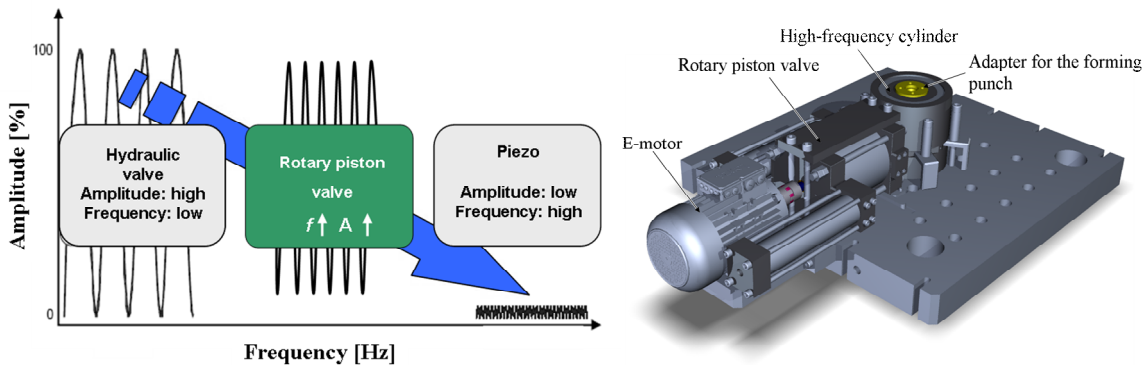
### How to oscillate the forming punch

Another possibility to reduce the high forming forces, which are occurring during sheet-bulk metal forming, is the superposition of dynamic process forces in the main flow of the machine. The decrease of the forming forces is realized by a reduction of the friction [4]. In addition the forming limit of the sheet material is improved [5].

The superposition of the oscillation is realized by a hydraulic oscillation device. This rotary piston valve combined with a high-frequency cylinder for a hydraulic actuation system is a complete new developed (see **Figure 7**). This technique allows high flow rates at a high frequency. Commercially available servo valves have a critical frequency about 500 Hz. The critical frequency decreases with increasing flow rates. Other devices like piezoelectric systems realize a high frequency with low amplitude (**Figure 7** on the left).



**Figure 6.** Applied forming operations in incremental sheet-bulk metal forming



**Figure 7.** Frequency range of different systems (left), hydraulic oscillation device with a rotary piston valve (right)

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The rotor and a stator are the main components of the valve. The rotor is driven by an electric motor and has drilled holes in radial direction and an opening in axial direction which is connected to the cylinder. The stator has channels in radial directions which are connected to the hydraulic accumulator through the upper channels and connected to the tank by lower channels. The lower channels have an offset of  $18^\circ$  with the upper channels. The frequency of the pulsation is therefore depending on the angular velocity of the rotor.

The high-frequency cylinder is designed to generate a high frequency oscillation as well as high force amplitude which are appropriate for superimposing oscillation. Compared to a standard cylinder, it works like a double acting cylinder which is enabled through the position control of the piston. This position control is provided by means of the upper and lower pressurized chamber which will be pressurized counteractively during the operation. In order to analyze the properties of the valve and compressibility effects to the dynamic of the high frequency cylinder, a CFD-simulation in ANSYS-CFX has been conducted to consider the properties of the oil and fluid forces [6]. The high frequency cylinder is located under the forming punch. Additionally the process is characterized by high tool loads which can be compensated by die shrink rings or strip wound container systems [7]. And finally an increase of the forming limit could be proved.

### Coating and nitriding to protect the tools

In order to enhance the durability of the tools the state-of-the-art in forming tool tribology which relies vastly on polished surfaces, oil-based lubricants, hard ceramic coatings and reaction layers has to be extended by new tribological measures. This goal can be reached by a synergetic combination of carbon based PVD/PACVD coatings and laser-produced surface textures.

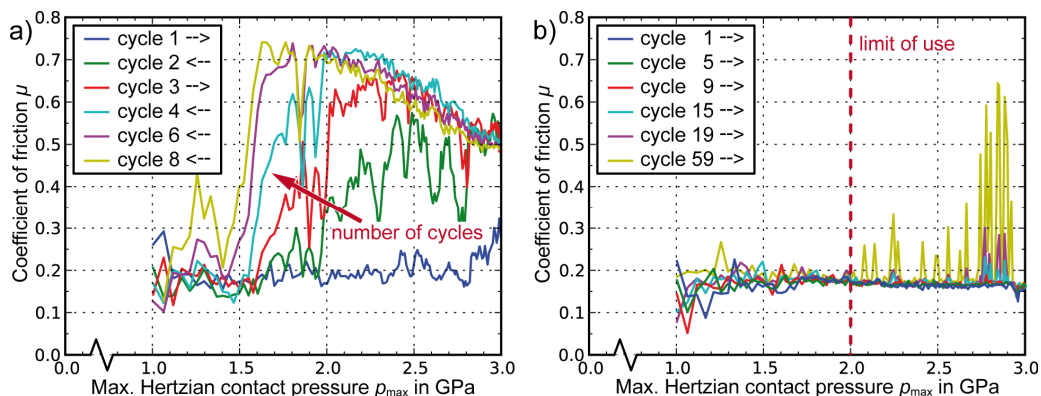
By means of a system analysis of the sheet bulk metal forming tools, local information relevant to tribology like contact pressure, sliding velocity, surface magnification, required friction conditions and expected wear mechanisms were collected. The results are used to partition the tools into tribological zones which require different surface modifications. Further, they allow choosing suitable tribological model tests and a best possible setup of the test conditions.

The investigated surface textures reduce abrasive wear due to trapping of hard particles. Further, isolated micro-pits with a diameter of 5-50  $\mu\text{m}$  and a depth of 1-10  $\mu\text{m}$  can enhance oil-based lubrication and hence reduce friction. In contrast, interconnected channel-like structures with a similar cross section

facilitate local displacement of the lubricant enabling a targeted increase of friction. Precise texturing of tool steel surfaces is performed using an ultra-short pulse laser and the coatings are applied afterwards. Under conditions of moderate to medium contact pressure ( $< 1$  GPa), the investigated amorphous carbon coatings provide a low friction coefficient of 0.1-0.2 in dry sliding against steel. The responsible mechanisms are graphitization [8], formation of a transfer layer on the counter body [9] and saturation of carbon atoms at the surface with H- and OH-end-groups [10]. However, the particular weakness of many amorphous carbon coatings is their susceptibility to mechanical failure due to cracking and delamination. The load-scanning test [11] is employed to evaluate tribological and mechanical loading limits of the coatings.

Two crossed specimens are forced to slide reciprocally against each other such that the contact spot moves on both specimens at the same time. During the movement, the normal load is gradually increased. The difference in the performance of different types of amorphous carbon coatings under conditions of medium to high load (1-3 GPa) is demonstrated by the friction coefficient versus contact pressure curves shown in **Figure 8**. A pure hydrocarbon coating (a-C:H) and a tungsten-modified hydrogenated amorphous carbon coating (a-C:H:W) were deposited on polished specimens of hardened and tempered cold work steel, respectively, and tested in dry sliding against uncoated polished specimens of the same steel. Both coatings had a thickness of about 3.5  $\mu\text{m}$  and a roughness  $R_a = 0.1$   $\mu\text{m}$ , but the a-C:H coating had a higher hardness of 24.5 GPa as compared to 13.3 GPa of the a-C:H:W coating. As indicated by rising friction, the a-C:H coating failed within only a few load cycles. The observed failure mechanisms were pick-up of steel, formation of tensile cracks and adjacent coating disruption. An interesting result of the tests is that under high loads, adhesion of steel of the counter body may play a significant role in the failure of amorphous carbon coatings.

These super hard coatings need a tough tool surface to be deposited on. Usually this is realized by annealing eventually in a combination with nitriding. Due to the weight and the size of the tools a local process is desirable. For this reason a new nitriding-process which can work under atmospheric conditions was developed. It is using a transmitted or a not-transmitted plasma-arc to dissociate and ionize the nitrogen. So far samples made of steel 1.3343 have been examined. After 5 runs under the plasma arc, the depth of the transition zone extends to 300  $\mu\text{m}$ , and the hardness increase of the materials surface is about 10 %.



**Figure 8.** Coefficient of friction versus contact pressure for a-C:H coating (a) and a-C:H:W coating (b) in dry sliding against polished cold work steel

## Conclusions

This work was supported by the German Research Foundation (DFG) within the scope of the Collaborative Research Centre SFB/TR 73. It is a result of the working group “Component Properties and Function” respectively the projects A1, A2, A4, A7, B4 and C5.

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## Объемная штамповка листа – новый процесс производства листового металла с функциональными составляющими

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В работе проведен анализ методов обработки давлением листового материала. Показано, что приложение колебательных движений к пуансону в процессе глубокой вытяжки приводит к снижению усилий деформирования, сил трения и увеличению срока службы деформирующего инструмента. Кроме того, наложение колебаний пуансону позволяет проводить процесс обработки малоуглеродистой стали с большей степенью пластической деформации. Также в статье рассмотрены методы поверхностного упрочнения: нанесение PVD и PACVD покрытий и метод атмосферного плазменного азотирования, применяемые для повышения механических свойств поверхности штампового инструмента.