Improving the springback behavior of deep drawn parts by macro-structured tools

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Abstract. Many automotive parts are manufactured by means of sheet metal forming technology. The process limits in sheet metal forming are highly dependent on the material flow and friction forces. In most cases, it is beneficial to reduce the friction between tool and workpiece to expand the process limits and increase the lifetime of tools. Macro structuring of tools is a novel approach to reduce the amount of friction forces in the deep drawing process [1]. The induced alternating bending in sheet metal during the deep drawing with macro-structured tools leads to an increase of its geometrical moment of inertia and consequently stabilizes the sheet against wrinkling. An increase in the peak-to-valley height difference, which is directly associated with a greater restraining force in flange area, leads directly to improved dimensional accuracy in terms of springback behavior of workpiece. This positive effect of the increased restraining force is known from the literature [2], but in lubricant free deep drawing process it is not applied by means of conventional blankholder force but also geometrically through macro structuring of tools. Within the scope of this paper, the influence of alternating bending on the springback behavior of parts in deep drawing process with macro-structured tools is studied. Since the springback in a workpiece depends on its material, two industry relevant materials DC04 and Al5182 are chosen for numerical and experimental tests. For this purpose conventional deep drawing process is compared with lubricant free deep drawing process. To investigate the effect of alternating bending on springback behavior of the components in lubricant free deep drawing with macro-structured tools, the ring splitting method is used. In this test, a ring from each cylindrical deep drawn cups formed by standard and macro-structured tools will be cut out and subsequently split to open. The opening gap of split ring indicate the amount of tangential residual stresses in rotationally symmetric deep drawing parts which is an indicator for springback behavior. The results of this paper show that springback behavior of sheet metal parts can be reduced by increasing the peak-to-valley height difference during lubricant free forming process with macro-structured tools.

1. Lubricant free deep drawing process with macro-structured tools

Lubricant plays an important role in metal forming for significantly reduction of friction forces between tool and workpiece. Using the lubrication in forming process has several advantages from process, tool and workpiece point of view like reduction of forming energy, increase of process limits, extension of tool life, prevention of galling and also improvement in surface finish of the products [3]. Hence, lubricants are usually inevitable in the metal forming for successful operation and reduction in energy consumption. However, huge amount of used lubricant in today’s industry has economic and ecological disadvantages. Regarding economic aspects, VOLLERTSEN et al. [4] show that, using mineral-oil-based lubricants leads to an increase of production steps, because an additional post-treatment process is
required for cleaning the workpiece by means of degreasing agents which are usually solvent-based. TAUBE shows in [5] that more than 15% of the total cost of sheet metal working is spent on lubricating liquids including buying the lubricants, machines for their application and cleaning lubricated parts. Moreover, lubricants are often either harmful to health or harmful to the environment. Therefore, it is of great interest to develop a process which permit significant reduction of the amount of lubricating agents or even dry metal working. However, it has great difficulty in application to metal sheets in general. As one of the most promising methods, use of macro-structured deep drawing tools [6] is highlighted because of its performance to reduce the friction forces and simplicity in application. In [1] it is shown that in order to decrease the amount of friction force for a given friction coefficient, the integral of the contact pressure over the contact area has to be reduced by means of macro-structured tools. In this way, the contact area between the workpiece and tools will be reduced to some lines. Unfortunately, by minimizing the contact area in flange area, the risk of wrinkling because of tangential compressive stresses in the free, non-contact areas of the sheet metal will be increased, because the usually utilized blankholder force is not applicable. By increasing the geometrical moment of inertia of the sheet, this effect can be avoided. In this new developed process, it is achieved by immersing the blankholder slightly into the drawing die and inducing an alternating bending mechanism in the flange area. Contrary to draw beads, which are primary used to control the material flow through increasing the friction and bending forces, macro structured deep drawing tools are designed to reduce the friction force due to a minimal contact area and to increase the resistance against wrinkling. Depending on the geometry of macro structures, wave length $\lambda$ and peak-to-valley height difference $\delta$ are two process parameters which determine the bending mechanism and can be used as setting parameters to ensure a stable process. Figure 1 compares schematically the conventional deep drawing with macro-structured process and illustrates the bending mechanism during the process.

![Figure 1](image_url)

**Figure 1.** (a) Principle of conventional deep drawing, (b) principle of lubricant free deep drawing with macro-structured tools and (c) alternating bending mechanism during the lubricant free deep drawing process with macro-structured tools.

Obviously, a smaller peak-to-valley height difference and higher wavelength induce smaller curvature in sheet metal, leading to decreasing buckling stiffness in the flange area. As a result, the risk of wrinkling increases. Oppositely, a higher peak-to-valley height difference and smaller wavelength induce a bigger curvature in sheet metal resulting in an increasing deep drawing force, possibly causing bottom cracks. Therefore, for a given geometry, the wave length and peak-to-valley height difference should be determined in dependence of material properties in such a way that a stable process can be realised. In order to time efficiently identify these parameters for a stable process, an analytical model is developed by BROSIUS et al. in [1] and it is shown that the analytical and numerical results exhibit a
very good agreement with the experimental tests. Within the scope of this model, the bottom crack and wrinkling can be predicted preliminarily using the energy method and stability analysis respectively.

Summarizing the principles of lubricant free deep drawing with macro-structured tools, the new tool design can reduce the contact area up to 80% and the blankholder force up to 90% compared to the standard process. Therefore the amount of friction force in the flange area can be reduced up to 83% [6]. Additionally, it also increases the resistance of the sheet metal against wrinkling and it allows the control of the material flow by adjustment of the peak-to-valley height difference. Considering the energy terms of deep drawing process, the frictional energy in flange area of standard process is replaced partially by energy to generate the alternating bending in lubricant free deep drawing process with macro-structured tools. The additional energy to generate the alternating bending in lubricant free deep drawing process results in a non-frictional tensile force, which can be positively used as restraining force to control the material flow like using draw beads or to compensate the springback behavior of the workpiece as shown in the following.

2. Springback and residual stress in deep drawing process

The deep drawing of sheet metal induces complex deformations, which in different regions of the sheet metal can have vastly different accumulated plastic strains. Upon unloading by removing the tools, springback occurs which can change the shape accuracy of the part. Springback is caused by non-uniform residual stresses through the sheet thickness of the formed part that create a bending moment which causes a distortion of the workpiece upon unloading. Springback strains are almost completely elastic; non-linear recovery strains are usually small but, in extreme cases, they can have an amount up to 10% of the total recovery [7]. In the past, a number of studies have looked into ways of reducing springback, particularly the role of pre-straining, blankholder force and yield strength. Still, even in this case springback cannot be disregarded completely but it can be reduced which allows a more accurate shape geometry with smaller absolute tolerances [8]. The present study clarifies how and to what extent the alternating bending by lubricant free deep drawing process can affect the springback behavior of deep drawn parts.

2.1. Calculation of residual stress in rotational symmetric deep drawn cups

The ring splitting method, developed by SIEBEL and MÜHLHÄUSER [9] is one of the most common springback-measurement tests for deep drawing process. It offers an opportunity to evaluate the quality of the residual stress in the specimen. In this test, a ring will be cut out from the wall part of deep drawn cup and subsequently split open. The tangential residual stress can then be determined from the ring opening chord upon splitting. To determine the tangential residual stress in the wall of the cup, the ring opening gap $\Delta$ can be approximated with a circular arc:

$$2\pi r_1 = 2\pi r_0 + \Delta$$

(1)

or:

$$r_1 - r_0 = \Delta/2\pi$$

(2)

here $r_0$ and $r_1$ are the mean radius of intact and split ring. The maximum of tangential elastic bending strain due to the springback at the outer surface of the intact ring can be determined from bending theory as follows:

$$\varepsilon_{eb,\text{max, out}}^{eb} = \frac{t}{2r_0} - \frac{t}{2r_1} = \frac{t}{2} \left(\frac{r_1 - r_0}{r_0 r_1}\right)$$

(4)

and the maximum of tangential elastic bending strain at the inner surface is:

$$\varepsilon_{eb,\text{max, inn}}^{eb} = \frac{t}{2r_1} - \frac{t}{2r_0} = \frac{t}{2} \left(\frac{r_0 - r_1}{r_0 r_1}\right)$$

(5)

where $t$ is the thickness of the wall. Substituting Equation 1 into Equation 4:
\[
\varepsilon_{\text{max, out}}^{eb} = \frac{t}{2} \left( \frac{\Delta}{r_0 r_1} \right)
\] (6)

Since \(\Delta/2\pi \ll r_0\) it can be assumed that \(r_0 \approx r_1\) and the bending strain at the outer surface of the intact ring can be written as:

\[
\varepsilon_{\text{max, out}}^{eb} = \frac{t}{4\pi} \left( \frac{\Delta}{r_0^2} \right)
\] (7)

Therefore, the maximum of tangential elastic bending stress at the outer and inner surface be calculated as follows:

\[
\sigma_{\text{max, out}}^{el} = \frac{E \cdot t}{4\pi} \left( \frac{\Delta}{r_0^2} \right)
\] (8)

\[
\sigma_{\text{max, inn}}^{el} = \frac{E \cdot t}{4\pi} \left( -\frac{\Delta}{r_0^2} \right)
\] (9)

As the Equations 8 and 9 show the residual stresses are tensile at the cup outer surface and compressive at the inner surface. This is schematically shown in Figure 2.

**Figure 2.** (a) Cutting area in rotational symmetric deep drawing cup for splitting test, (b) springback in split ring and (c) tangential residual stress at inner and outer cup surface.

### 2.2. Equilibrium condition in wall of the cup

In the case that there is no springback in the workpiece, because of equilibrium condition the bending moments due to tangential stresses over the sheet thickness in wall part of the cup (intact ring) should be zero:

\[
M_b = M_b^{res} - M_b^{eb} = 0
\] (10)

Here, \(M_b^{res}\) is the bending moment because of residual stress in the intact ring and \(M_b^{eb}\) is the induced elastic bending moment which is necessary to close the splitted ring. Since \(M_b^{eb}\) is an elastic bending moment, it is symmetric over the sheet thickness and can be written as a function of its maximum value \(\sigma_{\text{max}}^{eb}\):
\[ M_{eb}^b = b \cdot \int_{\frac{t}{2}}^{t} \sigma_{max}^{eb} \cdot \frac{2x}{t} \cdot x \cdot dx \]  
\[ (11) \]

\[ M_{eb}^b = \frac{4}{3} b \cdot \sigma_{max}^{eb} \cdot \left(\frac{t}{2}\right)^3 \]  
\[ (12) \]

Substituting equation 12 in 10 and using equation 9, the opening gap \( \Delta \) due to springback can be derived as follows:

\[ \Delta = \frac{24 \cdot \pi \cdot r^2 \cdot M_{res}}{E \cdot t^4} \]  
\[ (13) \]

In order to evaluate the opening gap \( \Delta \) for each process, the residual bending moment in the intact ring \( M_{res}^b \) has to be calculated by means of FEM-simulations. This is described in the following section.

3. Results and discussion

3.1. Numerical results

In order to analyze the springback behavior of deep drawn parts with macro-structured tools numerical investigations based on FEM are carried out. Here, the flow curve of each testing materials is determined experimentally through uniaxial tensile test. The curves are extrapolated up to the equivalent plastic strain of 1.0 using the Voce model based on the following relation [10]:

\[ \sigma_y = \sigma_\infty - (\sigma_\infty - \sigma_{y0}) \cdot e^{(-m\varepsilon)} \]  
\[ (14) \]

where \( \sigma_\infty \) is the asymptotic value for saturation strength (ultimate strength), \( \sigma_{y0} \) is the initial value of isotropic hardening, \( m \) and \( \varepsilon \) are the characteristic strain constant and equivalent plastic strain, respectively. The corresponding parameters for the isotropic hardening based on voce model are listed in Table 1.

| Material | \( \sigma_\infty \) in MPa | \( \sigma_{y0} \) in MPa | \( m \) |
|----------|-----------------|-----------------|-------|
| DC04     | 400             | 175             | 9     |
| Al5182   | 375             | 150             | 9.5   |

Table 1. Parameters of Voce model for both testing materials.

The resulting flow curves for both testing materials are shown in Figure 3.

Figure 3. Flow curve of testing materials.
In the simulation sets, the deep drawing process with standard tools is considered as a reference and is compared with lubricant free deep drawing process with macro-structured tools by an immersion of δ = 0.2 and 0.4 mm. The FEM-results are based on a 2D FEM-simulation (simufact-forming v13.1) with an isotropic hardening assumption. The workpiece consist of eleven elements over its thickness with a maximum element size of 0.1 mm. The initial blank diameter is set to be D₀ = 180 mm while the sheet thickness is t₀ = 1.0 mm. The macro-structured tools have a constant wavelength of λ = 8.0 mm. The process is simulated with coulomb friction model (µ = 0.1). To simulate the standard process the distance between die and blankholder is set to sheet thickness. The simulations consists of two steps: deep drawing up to predefined height and consequently elastic unloading to simulate the springback of the parts. Figure 4 shows the simulated tangential residual stresses in thickness direction of the wall part of a drawn cup. The evaluated location is in 35 mm distance to the bottom of the part.

![Figure 4. Tangential stress over the sheet thickness in cup made from DC04 and Al5182.](image)

The residual bending moment in the intact ring \( M_{b \text{res}} \) can be calculated from tangential residual stress \( \sigma_{t \text{res}} \). Therefore, the opening gap \( \Delta \) from equation 13 can be evaluated based on numerical integration of the shown residual stress curves. In order to verify the results of developed model regarding the evaluation of opening gap for each process, experimental tests are performed.

### 3.2. Experimental results
The already simulated processes are subjected to the experimental test with a hydraulic press at room temperature. The macro-structured as well as standard tools are made from tool steel 1.2379 because of its very high resistance against abrasive and adhesive wear due to a high volume of hard carbides in its matrix, good toughness, very good dimensional stability and high mechanical strength. The macro-structured tools have a constant wavelength of \( \lambda = 8.0 \) mm. The blanks from DC04 and Al5182 with an initial diameter of \( D₀ = 180 \) mm and thickness of \( t₀ = 1.0 \) mm are cleaned using a citrus based cleaner and finally treated with acetone to remove all traces of pre-lubricants and to assure a comparable test condition. In both standard and macro-structured process in order to assure the distance between blankholder and die precisely, spacer rings are used. The samples which are subjected to be formed with standard process are lubricated with industrial oil “WISURA ZO 3368”. The deep drawn samples are
cut through electrical discharge machining (EDM) process to prevent the external residual stresses through cutting process, because it does not require high cutting forces for removal of material.

The opening gap of each ring after splitting is measured and listed in Table 3. Moreover, the calculated values for opening gap based on the half-analytical model are also present in the same table in order to compare with experimental results.

**Table 2. Opening gap of split rings based on experimental tests and calculated values.**

| Material | $\Delta$ for standard process in mm | $\Delta$ for macro-structured process in mm |
|----------|------------------------------------|-------------------------------------------|
|          | Measured  | Calculated  | $\delta = 0.2$ mm | Measured  | Calculated  | Measured  | Calculated  |
| DC04     | 50        | 48.7        | 45                  | 44.1      | 37          | 36.9      |
| Al5182   | 95        | 99.2        | 73                  | 81.1      | 64          | 71.8      |

The experimental results exhibit a very good agreement with the half-analytically determined opening gap of split rings. The small amount of errors between calculated and measured values are mostly because of the kinematic hardening behavior of materials during the alternating bending which is neglected in the simulations. However, the results reveal the fact that regardless of material, by increasing the peak-to-valley height difference in macro-structured deep drawing process the amount of springback can be reduced. Furthermore, the induced alternating bending in the new developed process leads to compensation of springback in the workpiece because of the restraining force to generate the alternating bending and also the further elastic-plastic deformation of the material during the bending mechanism. Figure 5 shows an overview of rings after splitting.

**Figure 5.** Results of ring splitting test for cups made by standard and macro-structured tools from DC04 and Al5182.

4. **Summary and conclusion**

Deep drawing with macro-structured tools is a new developed process which can reduce the friction force through minimization of contact area. The induced alternating bending to stabilize the sheet metal against wrinkling during deep drawing with macro-structured tools generate a restraining force in drawing direction. The created non-frictional restraining force can be used positively to compensate the
springback behavior of the workpiece. Furthermore, the additional plastic deformation during the alternating bending decreases the elastic strains as the main cause of springback in the workpiece.

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