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Lubricant free deep drawing process by macro structured tools

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ABSTRACT

Avoiding lubricants in forming processes like the deep drawing process is an important way to save resources in today's industry. In this paper, a method will be presented for the elimination of lubrication in the deep drawing process by means of a new macro structured tool design. This structuring enables the control of friction forces as well as the material flow. The paper will present the basic process principle, an analytical model for the process design and experimental results. Starting with symmetrical geometries, the outlook will be given for three-dimensional, complex parts.

1. Introduction

In metal forming, especially in the deep drawing process, lubricants are used to reduce the friction between tool and workpiece. Thereby, the lubrication reduces forming energy and forming steps, increases the forming limit and tool life, while preventing galling, seizure and surface damages to the products. In addition, the disposal of a large amount of lubricant waste is a serious environmental and economic issue [1]. Furthermore, using any lubricant in metal forming processes requires cleaning of the forming parts, usually several times between subsequent production steps, in order to obtain a semi-finished part [2]. Therefore, various green manufacturing strategies under laboratory conditions have been developed by manufacturers [3], but a lubricant free deep drawing process is not known to the authors.

Within the scope of this paper, a new, lubricant free, deep drawing process is designed, which ensures the process limits despite the absence of lubricants. Since the largest contribution on the drawing force is from the friction in the flange area, this part of the tool will be adapted by macroscopic structuring.

2. Methodology and approach

In deep drawing the process window is limited by the occurrence of wrinkles and bottom cracks. Elimination of lubrication increases the friction forces, and thus the deep drawing force will be increased. As a result a bottom crack becomes more probable. Therefore, it is necessary to decrease the acting friction force, especially in the flange area, to ensure a large process window. 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. To achieve that, macro structured deep drawing tools are developed, that have only line contact with the sheet metal, see Fig. 1(a). As a result of this measure, the risk of wrinkling in the unsupported sheet metal

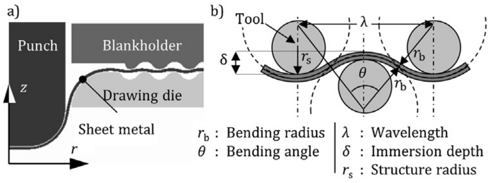

Fig. 1. (a) Cross section of a lubricant free deep drawing tool and (b) setting parameters and resulting bending geometry.

areas is increased, because the usually utilised blankholder force is not applicable. By increasing the geometrical moment of inertia of the sheet, this effect is avoided. For the developed process, this is achieved by immersing the blankholder slightly into the drawing die inducing an alternating bending mechanism. This creates a wave structure in the flange with the desired increased geometrical moment of inertia. Contrary to draw beads, which are primary used to control the material flow, 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. Consequently, by using a macro structured deep drawing tool, four positive and stabilising effects are achieved:

- reduction of the contact area up to 80%,
- increasing the resistance of the sheet against wrinkling,
- reduction of the blankholder force of up to 90%,
- and possible material flow control by the amount of immersion.

The given risk of high tool wear is reduced due to the low contact pressure in macro structured tools. Furthermore, Kunze et al. showed in [4] that for industrial applications, the wear resistance can be improved up to 90% by a combination of ta-C coating and a laser patterning (DLIP). Additionally, this coating results in a 15% lower friction. Fig. 1 schematically illustrates the macro structured tools with important geometrical parameters.

The wavelength λ and immersion depth δ are two process parameters which determine the geometry of bending and are used as setting parameters in order to ensure a stable process for

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the deep drawing with macro structured tools. The resulting bending radius r_b and angle of bending θ affect the tendency for wrinkling as well as the risk of material crack. In order to determine the critical values of these parameters, the resultant forming energy will be considered.

In general, smaller immersion depth and higher wavelength result in larger bending radii that decrease the buckling stiffness of the sheet. Therefore, the risk of wrinkling in the flange area increases. Oppositely, higher immersion depth and smaller wavelength lead to higher bending radii as well as higher total forming energy, which favours bottom cracks.

Therefore, a stable process needs an intermediate level of the bending radius in the macro structured tool resulting from a suitable choice of the two contradicting parameters wavelength λ and immersion depth δ. For a time efficient handling of this conflicting correlation, the following analytical model is developed.

3. Modelling of the influencing effects

The analytical model describing the influence of input parameters onto the risk of wrinkling and bottom cracks during deep drawing is presented successively. The energy method used is able to predict the required punch force in order to compare it with the maximum drawing force before bottom crack. The process limit wrinkling is considered by an analytical stability analysis.

3.1. Calculation of total energy

The total energy for deep drawing with macro structured tools consists of the ideal energy in flange area E_{id}, the energy to realise the alternating bending as well as bending at the radius of the drawing die E_b, and the energy to overcome the friction on the contact area E_f, see Fig. 2.

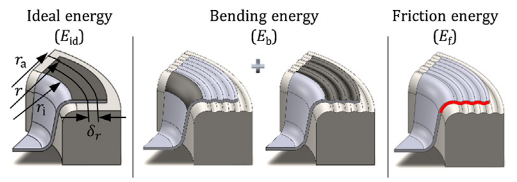

Fig. 2. Superposition method for energy calculation.

The summation of all energy terms results in the total energy E_t:

$$E_t = \int F_t \cdot dh = E_{id} + E_b + E_f \tag{1}$$

F_t and dh represent the punch force and punch displacement. Based on the 'principle of virtual work', it is possible to calculate the ideal energy for rotational symmetric geometries [5]. The virtual energy for plastic deformation of a certain volume has to be equal to the product of the according applied force and virtual punch displacement. Therefore, the ideal energy can be calculated incrementally as follows:

$$E_{id} = \sqrt{\frac{\bar{r}+1}{\bar{r}+1/2}} \cdot \delta V \cdot \int_{r_i}^{r_a} \sigma_y(r) \cdot \frac{1}{r} dr \tag{2}$$

Here, $\bar{r}$ and δV are the average vertical anisotropy and change of flange volume in each increment, respectively.

The instantaneous yield stress σ_y of any point in the flange area of rotational symmetric blanks with an initial radius of r_0 can be determined as a function of the current outer flange radius r_a and the corresponding radius of the point r [6]. In the following equation, the constants a and n are the material properties.

$$\sigma_y(r) = a\left[\frac{2}{\sqrt{3}} \ln\left(\frac{\sqrt{r_0^2 - r_a^2 + r^2}}{r}\right)\right]^n \tag{3}$$

As detailed in Fig. 2, the sheet undergoes additional alternating bending steps in the flange area. The energy for the alternating bending in the structured surface as well as bending at the radius of the drawing die can be calculated with the help of 'principle of virtual work':

$$E_b = \left(r_b + \frac{s_0}{2}\right) \cdot \sqrt{\frac{\bar{r}+1}{\bar{r}+1/2}} \cdot \delta V \cdot \int_0^{\theta} \frac{\cos(\theta)}{r(\theta)} \cdot \sigma_y(\theta) d\theta \tag{4}$$

Here, s_0 is the initial sheet thickness and r_b and θ are the bending radius and bending angle, respectively. The current yield stress $\sigma_y(r)$, depending on the radius and the virtual punch displacement, can be determined by Eq. (3).

The derivation of frictional forces between the part and the die is based on the explicit use of local pressure and the local friction force acting along the contact length, as originally pursued by Euler [7]. Considering the equilibrium condition, the friction forces between the sheet and the macro structures of the flange and drawing die radius can be written as follows:

$$E_f = E_{id} \cdot e^{\mu\theta} \tag{5}$$

Here, μ and θ are the friction coefficient between drawing die and part and deflection angle, respectively.

With the ability to calculate all individual energy terms for deep drawing with macro structured tools, it is possible to design the most energy efficient process regarding the process input parameters. In addition to the energy consideration, the stability of the process has to be examined regarding wrinkling and bottom cracks.

3.2. Stability analysis – wrinkles

Due to the partially free, unsupported areas of the material in the flange, an examination of the process stability regarding wrinkling is necessary. Considering the sheet geometry during the alternating bending process, each contact between sheet and tool can be seen as a local support with active stabilising forces.

Since the outer radius of the sheet is only supported from one side during the entire process (element 1 in Fig. 3), it is less stabilised than the other regions (compare element 2 in Fig. 3). Additionally, element 1 shows the maximum tangential compressive stresses σ_t with minimum stabilising radial tensile stresses σ_r. Summarising, area 1 is the critical part of the sheet regarding wrinkling and the stability analysis is done for this element.

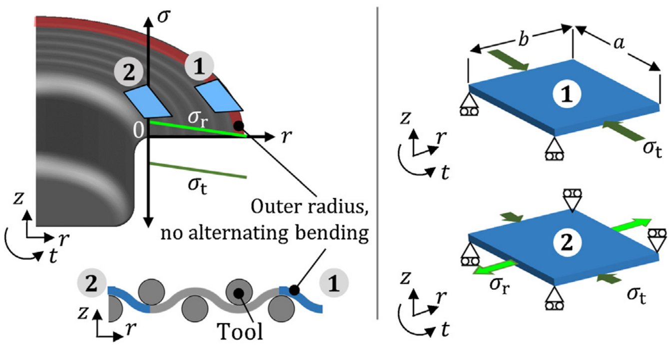

Fig. 3. Stress states of critical sheet metal areas for buckling analysis.

By taking into account that area 1 undergoes no alternating bending, σ_r and σ_t are the acting stresses in this region. Considering the force equilibrium condition and Trescas yield criterion, the two components can be written as:

$$\sigma_r(r) = \sigma_y(r) \cdot \ln\left(\frac{r_0}{r}\right) \tag{6}$$

$$\sigma_t(r) = \sigma_r(r) - \sigma_y(r) \tag{7}$$

Finally, the free end of the sheet can be modelled as a rectangular plate, supported on one side and free in movement at the other side, which sustains the highest tangential compressive stress, see Fig. 3. By assuming this, the equation for equilibrium can