Deep drawing of DC06 at high strain rates

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Abstract. Velocity effects in production technology provide technological and economic advantages, but they require consideration of strain rate dependent material behaviour in numerical process modelling. This paper proposes a deep drawing process with DC06 at high strain rates of up to 100 s⁻¹. Basis of the investigation are the results of the inverse parameter investigation at high strain rates in [1]. In addition to the velocity dependent flow curve in numerical modelling, the damage parameters are also taken into account. The drawing ratio and the punch velocity that affects the strain rate and the stress state in the deep drawing process are varied while the blank holder force is constant. Due to the high punch speed and the pronounced inhomogeneity of the strain rate over the work piece volume, the punch speed and punch force is very well suited to verify the numerical results. Additionally, the mesh dependency of the temperature evolution in the sheet metal is examined for further investigations of the adiabatic heating of the work piece during deformation in experiment and simulation. In this context, the deep drawing tools as well as the results of the numerical and experimental investigations are presented and discussed.

1. Introduction

The use of speed effects in production engineering enables the exploitation of technological and economic advantages [2], which also applies to high speed forming and high-speed cutting processes [3]. High-speed effects enable manufacturing with higher quality and without additional finishing in contrast to conventional processes [4]. In order to describe and model high-speed processes in detail, suitable data on the flow curve and failure behaviour for different strain rates that occur are of central importance, since materials subjected to high-speed forming often exhibit extended forming limits [5]. Furthermore, it was shown in [6] that the coefficient of friction decreases with increasing velocity in strip tensile tests with minimum quantity lubrication. The same result was obtained in an analysis of the influence of punch speed on the process window in micro deep drawing [7] by demonstrating the reduction of the friction coefficient with increasing punch speed.

The challenge of material characterisation at high velocities is the accurate measurement of the material parameters due to the high testing speeds, small specimen size and limited accessibility of the sample. An alternative approach to direct measurement of stress and strain for determining material properties at high strain rates is an inverse parameter identification. In [1] Psyk et al. successfully developed an approach using an accelerated hammer in order to implement high speed tensile and shear tests. They used a pneumatic acceleration to achieve hammer speeds of up to 8 m/s and corresponding
strain rates in the test specimen of up to $10^3$ s$^{-1}$ and an electromagnetic acceleration for realizing even higher hammer speeds (up to 30 m/s) and corresponding strain rates of up to $10^5$ s$^{-1}$ in the specimen. The method is based on measuring auxiliary test parameters and using them as input data for the parameter identification in an inverse simulation. More recently, the identified material data was refined and supplemented with values considering more moderate strain rates ($10^{-1}$ s$^{-1}$ to $10^2$ s$^{-1}$) [8].

In this study, the pneumatic test setup is modified in such way, that it can be used for investigating deep drawing at high strain rates. In this context, the punch acceleration and the punch force are measured in order to characterize the process. The research results presented in [1] and [8] will be used to model the process numerically. This will provide deeper knowledge of high-speed deep drawing and enable a more comprehensive verification of the determined material parameters for strain rates in the range of up to $\dot{\varepsilon} = 100$ s$^{-1}$.

2. Experimental setup

The pneumatically driven accelerator based on the principle idea suggested in [9] enables high-speed deep drawing on a conventional press. It is presented in Figure 1 together with the deep drawing tools and the measuring sensors for the punch force and displacement. The main structure of the pneumatic device is taken from [10] and has been supplemented by the deep drawing tools. As detailed in [10] the piston of the accelerator is first filled with compressed air and when the press pushes the piston downwards, the air in the piston and the hammer chamber is compressed. While the compressed air in the hammer chamber is acting on the hammer flange, the hammer moves upwards into its starting position. In the further course of the stroke the highly compressed air in the piston streams into the upper part of the hammer chamber through the space between hammer cover and lifting rod. Consequently, the hammer moves downwards and when it passes the holes in the hammer cover, highly compressed air rushes into the hammer chamber and accelerates the hammer up to 6 m/s. In contrast to the testing device for the material characterisation, the hammer in the accelerator is equipped with a punch and the piezo load cell (9041A, KISTLER) is mounted between the punch and hammer for measuring the punch force during the deep drawing process. The punch acceleration is measured by an accelerometer sensor (8044, KISTLER) with a measurable acceleration up to 30,000 m/s$^2$. Subsequently, the punch displacement is calculated by integrating the acceleration signal of the punch twice. The investigated material is a deep drawing steel DC06 (1.0873) with a sheet thickness of $t = 1$ mm that has a significant strain rate dependency and is widely used in industry. The punch diameter is $d_{\text{punch}} = 40$ mm, the punch profile radius amounts $r_{\text{profile}} = 5$ mm, the inner die radius is $d_i = 42$ mm and the die edge radius is $r_{\text{die}} = 5$ mm. Depending on the initial blank diameter of $D = 52$ mm up to $D = 68$ mm, different drawing ratios from $\beta = 1.3$ up to $\beta = 1.7$ are investigated. The distance between blank holder and die is 1.15 mm for realising a distanced deep drawing.

![Figure 1. Test setup for deep drawing with high strain rates according to [9]](image)
3. Numerical investigation

3.1. High-speed tensile test
As already mentioned, the material characterisation from [1] and [8] provides the basis for the numerical investigations. Here, the determined material properties are initially verified by tensile tests at a strain rate \( \dot{\varepsilon} = 50 \text{ s}^{-1} \). For this purpose, the simulation with a quasi-static flow curve for a speed of \( \dot{\varepsilon} = 0.001 \text{ s}^{-1} \) and the simulation with strain rate dependent flow curves are each compared to the results of experimental tensile tests carried out on the high-velocity testing machine ZWICK HTM 16020. The specimen geometry and the strain rate-dependent flow curves for strain rates \( \dot{\varepsilon} = 0.001 \text{ s}^{-1} \) up to \( \dot{\varepsilon} = 180 \text{ s}^{-1} \) are summarised in Figure 2. Flow curves for higher strain rates are neglected due to the maximum considered strain rate of \( \dot{\varepsilon} = 100 \text{ s}^{-1} \) in the presented investigations.

The finite element model of the tensile test is built in LS-Dyna R12.0.0. The blank is meshed with fully integrated solid elements (ELFORM 2) with an initial element size of 0.5 mm x 0.5 mm and 0.2 mm in the sheet thickness direction without remeshing. The material behaviour is defined by material type MAT24 (piecewise linear plasticity) according to the flow curves in Figure 2. The damage description is based on the GISSMO model using MAT_ADD_EROSION and is defined by the instability strain \( \varepsilon_{\text{crit}} \) and failure strain \( \varepsilon_{\text{fail}} \) versus triaxiality, shown in Figure 2 and the damage exponent \( \text{DMGEXP} = 2.0 \) and the fading exponent \( \text{FADEXP} = 2.0 \).

![Flow curves and damage parameters](image)

**Figure 2.** Input parameters for numerical tensile test: Strain rate dependent flow curves (a), instability and failure strain for GISSMO-model (b) and geometry of the specimen (c) according to [8]

3.2. High-speed deep drawing
The FE-model of the deep drawing process is also built in LS Dyna R12.0.0 and the blank is meshed with fully integrated 3D shell elements (ELFORM -16) with nine integration points in sheet thickness, because in the case of deep drawing, through-thickness stresses are negligible. The initial element size amounts 0.2 mm with adaptive refinement. The minimal allowed element size is 0.05 mm. The
calculation was performed using an explicit model with a mass scaled solution. The FE-model of the rotational symmetrical cup is reduced to a quarter for saving resources and time in calculation. The deep drawing tools punch, blank holder and die are defined as rigid bodies and the friction is modelled by a Coulomb friction model with a friction coefficient of $\mu = 0.1$. In addition to the velocity dependent material parameters, adiabatic heating during the forming process is also taken into account. Similar to the simulation of the tensile test, the material behaviour in the deep drawing simulation is also defined by the flow curves presented in Figure 2 combined with the GISSMO model using MAT_ADD_EROSION.

3.3. Mesh sensitivity of temperature
For future consideration of the temperature development during forming of the cup, the influence of the element size on the temperature development is investigated. For this purpose, a square specimen with element sizes of 0.05 mm, 0.01 mm and 0.005 mm is modelled. The specimen is generally assigned room temperature $T_{RT} = 295$ K, with a small defined region being assigned an elevated starting temperature $T_i = 495$ K. The volume that is assigned the elevated temperature $T_i$ is the same for all three simulations. Here, a thermal-only calculation is performed to determine the mesh sensitivity dependency of the temperature independent of the forming process. The temperature distribution is calculated via material model T03 (THERMAL ISOTROPIC TD) based on the temperature depending parameters listed in Table 1.

| Temperature $T$ in K | 293 | 373 | 473 | 573 |
|----------------------|-----|-----|-----|-----|
| Heat capacity $c$ in J/(kg \cdot K) | 460 | 480 | 510 | 550 |
| Thermal conductivity $\lambda$ in W/(m\cdot K) | 57.5 | 55.7 | 43.4 | 39.6 |

4. Results and discussion
4.1. High-speed tensile test
In order to validate the material properties, the engineering stress-strain curve determined via numerical simulation of the tensile test was compared to corresponding measurements. This verification clearly shows the necessity of considering the strain rate dependency of the flow curve in numerical investigations, see Figure 3. While the simulation with the strain rate dependent material model shows good agreement with the experimental result, the engineering stress in the simulation with the quasi-static flow curve is clearly underestimated and does not correspond to experimental results. It is noticeable that the oscillations at the beginning of the stress curve are more pronounced in the numerical results than in the experiment, although here, the simulation with strain rate dependency reproduces the experimental results better. The oscillation is due to the impact as a result of the high velocity.
The strain in the experimental setup is optically recorded by an extensometer Rudolf 200XR. Therefore, the front side of the specimen is primed white and two sharply drawn black lines define the measuring area. In numerical simulation, the strain is measured by a virtual extensometer that is modelled with two lines similar to the measuring principle of the experimental extensometer.

4.2. High-speed deep drawing

Based on the knowledge of the verification the strain rate dependent material model is used for numerical simulation of the deep drawing tests with punch velocities up to \( v_p = 9 \text{ m/s} \), but for the sake of completeness, also in this case additional comparative simulations with quasi-static material parameters were carried out. Here the punch force and punch displacement are evaluated as relevant process variables, since these can be measured in the experiments. Similar to the tensile test, the numerical results differ depending on punch velocity and resultant strain rate. Figure 4 shows exemplarily the required experimentally and numerically determined punch forces for different drawing ratios \( \beta = 1.3 \) and \( \beta = 1.5 \) at a fixed punch velocity of \( v_p = 4 \text{ m/s} \). Due to the larger blank diameter \( D_0 = 60 \text{ mm} \) for the drawing ratio \( \beta = 1.5 \), there is a larger punch displacement, and due to the larger forming, the punch force is also significantly larger than for the drawing ratio \( \beta = 1.3 \). The resultant cup height is 13.8 mm for a drawing \( \beta = 1.5 \) and in case of \( \beta = 1.3 \) the cup height amounts 7.7 mm.

There is a good agreement between the experimentally determined force curve and the numerically determined force curve with strain rate-dependent material modelling. In contrast, the required punch force is significantly underestimated by up to 50% in the simulation with quasi-static material modelling due to the lower flow stress at low strain rates. The cell data was smoothed by a moving average with a smoothing width of seven data points.

![Figure 4](image.png)

**Figure 4.** Experimentally and numerically determined punch force for drawing ratios of \( \beta = 1.3 \) (left) and \( \beta = 1.5 \) (right).

Numerical results show that an average strain rate \( \dot{\varepsilon}_{\text{average}} = 37 \text{ s}^{-1} \) is obtained, with extreme strain rate values between \( \dot{\varepsilon}_{\text{min}} = 20 \text{ s}^{-1} \) and \( \dot{\varepsilon}_{\text{max}} = 70 \text{ s}^{-1} \) for a punch velocity of \( v_p = 4 \text{ m/s} \). The distribution and development of the strain rate for three different states during the deep drawing process for \( \beta = 1.5 \) is shown in Figure 5. Based on the different process stages, it can be seen that the areas with the highest strain rate shift according to the forming zone in the sheet and that the strain rate varies locally within a process stage.
While at punch velocities up to \( v_p = 7 \) m/s only the punch force varies as a function of the strain rate, the simulation with a punch velocity of \( v_p = 9 \) m/s that results in strain rates up to 100 s\(^{-1}\), also shows a change in the damage of the material. If the strain rate dependence of the flow curve is not taken into account at these high velocities, the simulation shows a material failure, depicted in Figure 6, which is caused by the impact of the punch at very high velocity. In contrast, a cup is completely drawn, if the material is modelled in a strain rate dependent mode. This shows very clearly that for technological forming processes with high process speeds, it is very crucial to determine the material properties for high strain rates so that material behaviour and failure are modelled realistically and a process simulation enables realistic predictions.

**Figure 5.** Strain rate distributions at different states of the deep drawing process for a punch velocity of \( v_p = 4 \) m/s and a drawing ration \( \beta = 1.5 \).

4.3. **Mesh sensitivity of temperature**

The results of the sensitivity study of the temperature regarding the mesh size shows a significant difference in the temperature development. The temperature evolution for the investigated element sizes is shown in Figure 7. The final temperature of coarse meshing differs from the final temperature of fine meshing. Already after the short time of 0.6 ms the temperature difference amounts 36.1 K between the finest mesh and the coarse mesh with an element size of 0.05 mm. As a large part of the mechanical work is converted into heat during forming with high strain rates and thus high temperatures are reached in the work piece, a significant influence of the mesh size on the temperature calculation is to be expected.

If the temperature is predicted incorrectly, this can have a negative effect on the temperature depending flow stress and thus on the calculated process prediction. Furthermore, it has been shown that the mesh dependency is more pronounced for irregular meshes, which usually cannot be avoided along
curved edges, as in the investigated specimen in Figure 7. Comparison tests with regular rectangular elements with element lengths of 0.05 mm and 0.005 mm show only a temperature difference $\Delta T = 24$ K between both cases compared to irregular meshes.

Accordingly, fine meshing in the forming area is necessary to realistically represent the development and distribution of the forming heat during the process. Consequently, fine elements are necessary in numerical investigations with high strain rates and temperature dependency. In the case of deep drawing with high strain rates, a sub-modelling with fine meshing of selected areas is conceivable in order to save calculation time and resources.

For the presented numerical investigations on deep drawing, a maximum temperature $T = 395$ K within the cup is obtained at an average strain rate of 100 s$^{-1}$ and a drawing ratio $\beta = 2.0$. The course of the temperature in the cup is shown in Figure 8. However, the element size of 0.5 mm in the modeled cup is comparatively large with respect to the results on the mesh sensitivity of the temperature. In future investigations, suitable modeling needs to be developed in order to correctly represent the temperature in the cup and, at the same time, to keep the computational time low.
5. Conclusion and outlook
The investigations show an approach for deep drawing of DC06 with maximum strain rates up to $10^3 \text{ s}^{-1}$ in numerical studies. The material parameters determined in earlier investigations [1] were verified in experimental tests with a local maximum strain rate of $\dot{\varepsilon}_{\text{max}} = 70 \text{ s}^{-1}$. Due to the time and position dependent distribution of the strain rate during the deep drawing process, the average strain rate in the forming areas of the deep drawn cups amounts to $\dot{\varepsilon}_{\text{average}} = 37 \text{ s}^{-1}$. It was shown that the determination of the strain rate dependent flow curve is essential for realistic numerical results. In comparative calculations with quasi-static material parameters, the punch force was underestimated by 50% compared to the experimental result.

Further investigations concern the integration of temperature measurement and increasing the punch velocity up to $v_p = 10 \text{ m/s}$ in the experimental setup to verify the numerically determined material damage at strain rates higher above $100 \text{ s}^{-1}$ and to realize a drawing ratio up to $\beta = 2.0$. In addition, the modeling of the cup needs to be adapted in such a way that the temperature development can be correctly predicted taking into account the mesh sensitivity of the temperature with a suitable computation time.

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References
[1] Psyk V, Scheffler C, Tulke M, Winter S, Guillaume C and Brosius A. 2020, Determination of Material and Failure Characteristics for High-Speed Forming via High-Speed Testing and Inverse Numerical Simulation, JMMP 2020, 4(2). 31.
[2] Neugebauer R, Bouzakis K-D, Denkena B, Klocke F, Sterzing A, Tekkaya A E and Wertheim, R. 2011, Velocity effects in metal forming and machining processes. CIRP Annals – Manufacturing Technology, 60, S. 627-650
[3] Barthel T and Drossel W-G. 2014, Energieeffizienz beim Scherschneiden. Internationale Konferenz “Neue Entwicklungen in der Blechumformung”, 283-292
[4] Davies R., Austin ER. 1970, Development in high speed metal forming, New York: Industrial Press Inc
[5] Psyk V, Kurka P, Kimme S, Werner M., Landgrebe D, Ebert A and Schwarzendahl M. 2015, Structuring by electromagnetic forming and by forming with an elastomer punch as a tool for component optimisation regarding mechanical stiffness and acoustic performance. Manufacturing Rev. 2.23
[6] Mehic B, Engler S and Huskic A. 2015, Entwicklung einer Streifenziehversuchsanlage zur Untersuchung des Reib- und Verschleißverhaltens von tribologisch beanspruchten Oberflächen, Forschungsforum Österreichischer Fachhochschulen 9
[7] Vollertsen F and Hu Z. 2010 Analysis of punch velocity dependent process window in mirco deep drawing, Production Engineering, 4, 553-559
[8] Galiev E, Winter S, Reuther F, Psyk V, Tulke M, Brosius A and Kräusel V. 2022, Applied Science. MDPI, Local temperature development in the fracture zone during uniaxial tensile testing at high strain rate experimental and numerical investigations, (submitted)
[9] Yanagihara N, Saito H, Nakagawa T. Proc. 1980 Conf. 21st International Machine Tool Design and Research 21, 123-128
[10] Tulke M, Scheffler C, Psyk V, Landgrebe D, Brosius A. 2017, Procedia Engineering, Conf. ICTP 207, 2000-2005